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Content

Oral Presentations	4
Poster Presentations	168
Content of Oral & Poster Presentations	452
Content of Poster Presentations	457
Author Index	463

Oral Presentations

Opening Ceremony & Awards plenary session

O 077 - Two decades of non-thermal plasma applications based on dedicated and optimized high voltage pulsed power supplies (Innovation Prize Winner)

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ABSTRACT TEXT

The strong interplay between pulsed power electronics and plasma discharge physics and the subsequent development of innovative applications was the key motivation to apply for the EPS Plasma Innovation Prize, considering the major developments achieved in lithography, mercury free lightning and biomedical applications.

The collaborative work between plasma physicists and engineers started with the energetic photons generation, from soft X-ray to so-called Extreme UltraViolet (EUV), from compact and repetitive plasma discharges. In this context, the critical requirement was to deliver fast rising (kV/ns) high voltage, few tens of kV peak amplitude, waveforms leading to energetic electrons generation in X-ray diodes or EUV capillary discharges. This allowed first generating nanosecond duration X-ray pulses used for soft X-ray radiography. Capillary discharges powered by fast rising and damped voltage signals allowed for the development of tabletop EUV sources operated in the kHz regime with minimal debris generation for so-called new 13.5 nm EUV lithography applications [1].

The second topic focused on mercury free lighting. Low-pressure rare gas based discharges were studied and optimized to generate UV photons subsequently exciting phosphor emissions in the visible range. The critical need to offer efficient and long living (thousands of hours) mercury-free fluorescent tubes was achieved by developing compact power supplies delivering bipolar, high voltage, microsecond duration voltage pulses with a fine control of the duty cycle [2].

Today, work is ongoing for the development of cold plasma jets. Plasma jets are delivered from atmospheric pressure rare gas flushed dielectric barrier discharges powered by positive or negative polarity voltage pulses with optimized duration and repetition rate. The operation of DBD discharges with various voltage waveforms allowed for the study of the physics of ionization propagation, splitting in long tubes and in the ambient air in interaction with various targets, including those relevant for biomedical applications [3–6]. This longstanding effort allowed for the pioneer demonstrations of in vivo non-thermal plasma antitumor action, alone or in combination with chemotherapy and pulsed electric fields, the development of multi jets applicators for chronic wound care, resistant pathogen eradication, skin treatment for cosmetics or cancer applications and fiber treatment in long atmospheric pressure plasma columns [7–10].

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07/07/2025, 08:30–10:45, Room: Alfa

Opening Ceremony & Awards Plenary Session

O 002 - Astrophysical Shock Waves in the Violent Universe (Early Career Prize Winner)

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ABSTRACT TEXT

Multi-messenger astrophysics has opened a new window on the Universe, unveiling a rich zoology of transient astrophysical phenomena, from supernovae to gamma-ray bursts to blazar flares, fast radio bursts, or even flares around accreting black holes. Interpreting these exciting observations relies on collaborative efforts between phenomenology, theory, and numerical simulations at the interface between high-energy plasmas and particle astrophysics. A significant part of the research focuses on the physics of the leading dissipation and acceleration agent at play in these explosive and transient phenomena: astrophysical shock waves.

In neutron star mergers, relativistic shock waves formed in the optically thick equatorial cocoon and at the interface between the jet and the interstellar medium, respectively, shape the prompt gamma-ray and afterglow emissions of short gamma-ray bursts. In supernova remnants, weakly magnetized collisionless shocks demonstrate efficient electron heating and acceleration, raising critical questions about the mechanisms driving this energization. In magnetars, fast magnetosonic waves steepening into relativistically magnetized monster shocks may account for brief millisecond flashes of radio waves, known as Fast Radio Bursts. Throughout the talk, I will discuss our recent theoretical efforts, supported by large-scale kinetic simulations, to understand the physics of shock waves in these extreme astrophysical environments.

Plenary Session 2

O 003 - Advances in the physics understanding of transient thermal and runaway electron impact on tokamak plasma-facing components

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ABSTRACT TEXT

The preservation of the integrity of plasma-facing components (PFCs) constitutes a major challenge for fusion reactors. The PFC longevity and power handling capabilities are mainly threatened during unplanned transients such as edge-localized modes or major disruptions. These lead to incident plasma particles in the keV range, implying surface heating. Dedicated EUROfusion and ITPA coordinated experimental activities have provided a wealth of empirical data on metallic PFC melting induced by transient surface loads, which have guided the development of self-consistent physics models that enable high-fidelity simulations. Successful validation against multiple tokamak experiments has lent confidence in their predictive power.

The situation is rather different in the case of volumetric heating caused by runaway electrons (REs) with relativistic energies far into the MeV range. The RE incidence can induce material explosions driven by uneven thermal expansion and cause loss-of-coolant accidents. The workflow for their modelling is highly challenging and involves three distinct physics processes: the RE evolution during the final loss instability, the RE transport and thermalization in the solid, the PFC thermomechanical response to the RE load. The understanding of RE-PFC interactions constitutes the final frontier to be explored in the context of PFC damage.

Modelling approaches to attack the genuinely multi-physics problem of the PFC response to transients and runaway electrons will be reviewed, highlighting the central role of validation experiments.

Plenary Session 2

O 004 - Magnetic reconnection in space plasma

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ABSTRACT TEXT

Magnetic reconnection is a fundamental energy conversion process in plasmas that drives transport and leads to explosive large-scale magnetic energy releases such as substorms, solar flares and gamma-ray bursts. While these consequences such as acceleration and heating of the plasma are distributed over larger scales, magnetic reconnection operates as changes in the topology of the magnetic field take place inside a small region where electrons as well as ions are demagnetized. Geospace is an ideal plasma laboratory for studying how such magnetic reconnection operates in nature since plasmas and fields in action can be directly measured at high cadence. In particular, the in-situ measurement capability of the four Cluster and Magnetospheric Multiscale (MMS) spacecraft enabled to resolve kinetic physics of ions and electrons, respectively, and have significantly advanced the study of magnetic reconnection and relevant plasma processes in space. In this presentation, we summarize the current understanding of magnetic reconnection in space based on these multi-point observations in geospace. We also highlight several unsolved questions and introduce a newly proposed multi-point multiscale observatory in the Earth's magnetosphere, Plasma Observatory (PO), for studying cross-scale coupling of fundamental plasma processes in geospace including magnetic reconnection.

Plenary Session 2

O 005 - Perspectives on inertial fusion energy research at European XFEL

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ABSTRACT TEXT

The recent achievement of scientific breakeven at the National Ignition Facility has placed Inertial Fusion Energy as a potential candidate towards fusion energy generation. However, there are many questions to be answered on the route to a commercially available fusion plant. Several schemes are being proposed on how to achieve such a feat. The program Fusion 2040 initiated by the German government includes the goal to establish German hubs connecting academia, research institutions and industry for IFE research. The European XFEL (EuXFEL), and its High Energy Density Instrument – Helmholtz International Beamline for Extreme Fields (HED-HiBEF) is a natural candidate for such a hub. EuXFEL delivers bright x-ray pulses with narrow bandwidth, high spatial and temporal coherence and short pulse duration. This enables a wide arrange of techniques to be used in the diagnostic of solid density plasmas [1]. Here, we will show how many of the diagnostics implemented at the HED-HiBEF instrument at the EuXFEL can be applied to investigate plasmas relevant to IFE. We will show how the evolution of the electron density is probed via small angle x-ray scattering, which is also used to diagnose instabilities in short pulse laser-matter interaction as well as the evolution of the pore structure of foam targets [2]. Imaging is used to investigate shock compression in the 100–1000 nm range [3]. X-ray emission spectroscopy and inelastic x-ray scattering are used as temperature and plasmon diagnostic with eV and sub-eV resolution [4]. We will give an overview of the immediate topics that can be investigated with the current capabilities of the instrument: ablator physics, porous materials and wetted foams, instabilities and homogenization in shock compressed foams, opacities... Finally, a potential laser upgrade to multi-beam kJ and kJ-petawatt lasers will be discussed and what avenues of research it will enable when combined with the XFEL beam.

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MCF 1 - Turbulence and transport I

O 006 - Turbulent transport in stellarators: New insights from global gyrokinetic simulations

[Alejandro Bañón Navarro](#)¹, Felix Wilms¹, Don Fernando¹, Alessandro Di Siena¹, Gabriele Merlo¹, Hugo Cu Castillo¹, Frank Jenko¹

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ABSTRACT TEXT

Understanding and controlling turbulence is crucial for advancing optimized stellarators as viable alternatives to tokamaks in future fusion power plants. With powerful supercomputers, we can now investigate stellarator turbulence using advanced gyrokinetic simulations. One such tool, GENE-3D, extends the well-established GENE code to global simulations in non-axisymmetric geometries. In this talk, we provide an overview of our results, which include comprehensive validation studies using GENE-3D on the W7-X stellarator, focusing on multiple ECRH discharges and the impact of various magnetic configurations. Our findings reveal that turbulence is not solely driven by ion temperature gradient modes; trapped electron mode turbulence, largely driven by electron temperature gradients, plays a significant role. We also examine electron temperature gradient turbulence, once considered negligible in W7-X, and explore the influence of electromagnetic instabilities, including kinetic ballooning modes. Together, these insights offer a new perspective on stellarator turbulence. We further provide confinement predictions for two new quasi-helical stellarator configurations optimized for higher ITG mode thresholds. Lastly, we show how resonant wave-particle interactions between supra-thermal ions and ITG modes can suppress turbulence, improving the confinement properties of future stellarator designs. This work lays the foundation for next-generation stellarators with optimized neoclassical and turbulent transport.

MCF 1 - Turbulence and transport I

O 007 - Reduction or enhancement of stellarator turbulence by impurities

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ABSTRACT TEXT

The deliberate injection of impurities into the plasma core has been shown to increase the energy confinement time, and to reduce the turbulent fluctuations and the turbulent ion heat diffusivity in the Large Helical Device (LHD) [1] and in Wendelstein 7-X (W7-X) [2]. In this talk, we present a systematic study [3] of the impact of impurities on stellarator bulk electrostatic turbulence, with emphasis on the turbulent heat fluxes in W7-X. For comparison, LHD and ITER are also considered. By means of nonlinear multispecies gyrokinetic simulations with the code stella [4], we demonstrate that if the impurity density gradient and the bulk ion density gradient are parallel, impurities can significantly reduce (resp. enhance) turbulent ion heat losses. As a particularly interesting case, among the configurations compared, only in W7-X do impurities simultaneously reduce both the ion and electron heat flux (see figure), while the impurity heat flux remains low. In the scenario of turbulence reduction, the existence of an optimal impurity concentration at which the ion heat diffusivity is minimal is revealed as a universal feature. In this presentation, we will discuss these numerical results alongside experiments and recent analytical developments, which complement and support each other.

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MCF 1 - Turbulence and transport I

O 008 - Effective transport barriers without H-mode bifurcation in DIII-D negative triangularity plasmas

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ABSTRACT TEXT

Diverted negative triangularity (NT) plasmas in DIII-D achieve high thermal confinement ($H_{98y2} > \sim 1$) and normalized pressure $\beta_n > \sim 2.5$ [1]. At strongly negative average triangularity ($\delta_{ave} \leq -0.35$) these plasmas do not enter H-mode, but exhibit a narrow edge transport barrier on the order of ~ 2 ion gyro-radii wide, without a threshold in auxiliary heating power (no H-mode bifurcation). This barrier is supported by strong counter-current intrinsic rotation shear, consistent with preferential turbulent loss of co-current passing ions in NT plasmas as predicted by theory [2]. The rotational edge $\mathbf{E} \times \mathbf{B}$ shear increases well beyond values that would trigger an H-mode bifurcation in positive triangularity (PT) plasmas. The barrier significantly contributes to the enhanced global confinement observed in DIII-D NT plasmas.

Doppler Backscattering (DBS) data demonstrate reduced turbulence and very short (~ 1 cm) radial correlation lengths within the NT barrier in agreement with global XGC1 and JOREK-GK gyrokinetic simulations. Radial turbulence streamers/avalanches are mitigated or interrupted within the barrier layer (confirmed by a reduced Hurst exponent), and the measured $\mathbf{E} \times \mathbf{B}$ shearing rate locally exceeds the plasma-frame turbulence decorrelation rate within the narrow barrier. Gyrokinetic simulations also predict toroidal carbon rotation and $\mathbf{E} \times \mathbf{B}$ velocity profiles consistent with experimental data from Charge-Exchange Recombination spectroscopy (CER) and DBS.

Experiments and infinite-n ballooning mode stability calculations confirm that the barrier cannot expand inward [3], in contrast to typical PT H-mode pedestal formation dynamics where the pedestal width can reach $\sim 15\rho_i$. Plasmas with strong NT therefore do not approach the peeling-ballooning limit, remaining ELM-free even when the heating power P_{aux} is much above the predicted L-H power threshold [from the 2008 ITPA (Martin) scaling]. The absence of ELMs at strongly negative triangularity reduces divertor peak heat loads and potentially eases core-edge integration issues for future NT burning plasmas.

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MCF 1 - Turbulence and transport I

O 009 - Effect of the magnetic geometry on Trapped Electron Modes instability: comparison between theory and gyrokinetic simulations

De Gianni Ludovica¹, Peter Donnel¹, Garbet Xavier¹, Sarazin Yanick¹, Bigué Roméo², Dif-Pradalier Guilhem¹, Grandgirard Virginie¹, Obrejan Kevin¹, Protais Matthieu¹

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ABSTRACT TEXT

Experiments on the TCV [1] and DIII-D [2] tokamaks have shown that negative triangularity (NT) reduces the turbulent transport. Trapped Electron Modes (TEM) are thought to play an important role in this process. However, a comprehensive understanding of the underlying physics remains elusive, which calls into question the viability of NT regimes for fusion-grade plasmas. To identify the key mechanisms for the stabilization of TEM at NT, a linear stability model has been recently derived [3]. In this contribution, this model is extended by incorporating a simplified model for ions without accounting for their resonant response, so that ITG modes are excluded. This extension enables a qualitative agreement of the model with gyrokinetic simulations performed with GYSELA [4] and GENE [5] in the linear regime.

A detailed analysis of the analytical model shows that both Finite Larmor Radius effects and the fraction of trapped particles are detrimental for linear stabilization of TEMs by NT. On the other hand, NT is stabilized only when the poloidal localization of the linear modes — ballooning character — is accounted for, highlighting the key role of “Finite Mode Width” effects. A key quantity for understanding this effect is the precession frequency, the growth rate in the fluid limit scaling like its square root. The ballooning of the instability gives more weight to deeply trapped electrons, whose precession frequency is lower for NT than for positive triangularity (PT).

Another key finding is that all quantities entering the dispersion relation are sensitive to the chosen parametrisation of the flux surface (Culham or Miller), highlighting the importance of flux surface details in the context of TEMs. This is a crucial point to take into account when comparing results obtained either by theory or gyrokinetic codes. This sensitivity may also partially account for the observed variations in experimental results due to the top/down asymmetry of triangularity.

Finally, nonlinear GYSELA simulations allow one to quantify the departure with respect to linear predictions. In particular, the electric and diamagnetic components of the Reynolds stress, which drive the zonal flows, will be shown to exhibit significant differences in NT and PT configurations.

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MCF 1 - Turbulence and transport I

O 010 - Dependencies of the transition into regimes of suppressed anomalous impurity transport in W7-X and implications for stellarator reactors

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ABSTRACT TEXT

In view of feasible reactor operation regimes, the transport of impurities needs to be governed by a trade-off between low impurity confinement of helium ash and small inward transport of edge sourced impurities. Therefore, the identification, understanding, and prediction of reactor scenarios of compatible impurity transport is crucial on the path to self-sustained fusion burn.

The optimization of the W7-X stellarator with respect to neoclassical transport led to dominant anomalous transport in the energy [1], particle [2], and impurity [3,4] transport channels. Despite this optimization, specific scenarios of dominant neoclassical and suppressed anomalous transport in the impurity channel have been identified [5,6].

In these, impurity density profiles are strongly peaked, arising from dominant neoclassical convection. Accordingly, we find the peaking strength to be governed by the neoclassically predicted linear scaling with impurity charge and to only weakly dependent on magnetic field topology. We show that the observed inward transport is incompatible with sufficient helium ash removal in a reactor scenario. This demands for the identification of parameters governing the transition into regimes of suppressed anomalous impurity transport.

Across various experimental scenarios, the transition into the neoclassically dominated regime is found to be governed by a critical a/Ln_e of unity. The threshold value is found to be universal across magnetic configurations and independent on field strength, causing impurity accumulation to appear across a significant range of the W7-X parameter space. Gradients of other parameters are found not to play a critical role. With W7-X plasmas of high confined energy currently relying on the formation of a density gradient above this threshold [7], an interlinkage of high stored energy and central impurity accumulation is identified. This stresses the importance of the findings in view of a potential stellarator type reactor, calling for the development of active control schemes enhancing anomalous impurity transport at will or configurations of core electron root confinement [8].

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MCF 1 - Turbulence and transport I

O 011 - Relevance of stochastic transport in spherical tokamaks

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ABSTRACT TEXT

Stochastic perturbations of the magnetic field can have a strong influence on the cross-field transport in high β tokamak plasmas. They can be a prevailing source of electron heat transport at high β and low collisionality conditions accessible in spherical tokamaks (STs). Although, stochasticity is a subject far from being completely understood, various reduced models have been developed that are able to capture the essential physics. By implementing different models [1, 2, 3] in the JINTRAC integrated modelling tool [4], the impact of stochastic magnetic fields on electron transport has been studied in the MAST/MAST-U STs as a function of collisionality. Reduced stochastic models have been adopted in a complementary way, together with the TGLF transport code, to provide a complete description of the transport channels in spherical tokamaks. These simulations have demonstrated good agreement with MAST/MAST-U experiments. The analysis of heat conduction coefficients shows a trend in which the impact of stochasticity on the transport becomes more apparent as the ratio of collisional mean free path to parallel correlation length of the magnetic field is increased. This trend could be very useful in the assessment or qualification of the role of stochasticity in tokamak scenarios. The impact of temperature and density gradients on stochastic energy transport has been also investigated. Thus, this work [5] improves our understanding of transport due to stochastic magnetic perturbations, which in turn informs predictions of energy confinement in future large tokamaks including ITER and STEP. Implications of these findings for future devices will be discussed.

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O 012 - Acceleration of unstable particles in laser-plasma accelerators using structured light

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ABSTRACT TEXT

Plasma-based accelerators routinely achieve accelerating fields of 10–100 GV/m. Typically, plasma wakefield structures accelerate electrons, since the accelerating structure typically moves near the speed of light [1,2]. In contrast, heavier particles such as muons [3] and pions, with lifetimes in the particles' frame ranging from microseconds to nanoseconds, would greatly benefit from these extremely high accelerating gradients. However, these particles are not easily trapped in the plasma accelerating structure due to the significant difference between their velocity and the group velocity of the driver.

To address this challenge, we propose to utilize advanced techniques to control the group velocity of wave packets by shaping their spatio-temporal spectrum [4,5,6]. These innovations enable the creation of pulses with variable and subluminal group velocities suitable for driving wakes for slower particles. We simulate the full-scale acceleration of non-relativistic particles to relativistic speeds using this approach with the PIC code OSIRIS [7]. Combining such pulses with a tailored plasma density profile prolongs the dephasing-length of non-relativistic particles until they reach relativistic speeds. Our method unlocks the potential to exploit high plasma accelerating fields for non-relativistic and unstable particles, enabling applications such as acceleration of cooled muons for injection into subsequent accelerator stages and enhancing muon yield through pion acceleration and decay.

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BPIF 1 - Laser and particle beam interactions with plasmas (LPI) 1

O 013 - Nanofoams in action: a versatile tool for laser-plasma interaction experiments

Alessandro Maffini¹, Kevin Ambrogioni¹, David Dellasega¹, Marta Galbiati², Maria Sole Galli de Magistris¹, Francesco Gatti¹, Matteo Iaccarino¹, Claudia Mallimaci¹, Francesco Mirani¹, Davide Orecchia¹, Valeria Russo¹, Davide Vavassori¹, Matteo Passoni¹

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ABSTRACT TEXT

Nanostructured low-density materials, also known as nanofoams, represent a novel target concept for high-intensity laser matter interaction experiments.

Thanks to its capability of producing nanofoams with controlled composition, morphology, thickness and density, Pulsed Laser Deposition (PLD) has emerged as an ideal tool to fabricate nanofoam targets for different laser-matter interaction studies [1].

Here, we review our most recent results in terms of nanofoam synthesis with PLD [2, 3] and discuss some relevant applications of these advanced materials, both on theoretical and experimental side. Indeed, nanofoam usage embraces the fields of laser-driven acceleration of ions [4,5] and generation of secondary particles including neutrons, positrons, radionuclides [6,7], and high-energy photons [8,9]. In all these contexts, PLD foams can be a key tool to set up and enhance the energy conversion from laser to particles. Likewise, nanofoams enable improved ablation efficiency in targets for Inertial Confinement Fusion [10] and alpha particle sources via in-target proton-boron fusion reactions [11]

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BPIF 1 - Laser and particle beam interactions with plasmas (LPI) 1

O 014 - Photon acceleration of high-intensity vector vortex beams into the extreme ultraviolet

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ABSTRACT TEXT

Extreme ultraviolet (XUV) light sources allow for the probing of bound electron dynamics on attosecond scales, interrogation of high-energy-density matter, and access to novel regimes of strong-field quantum electrodynamics. Despite the importance of these applications, coherent XUV sources remain relatively rare, and those that do exist are limited in their peak intensity and spatio-polarization structure. Here, we demonstrate that photon acceleration of an optical vector vortex pulse in the moving density gradient of an electron beam–driven plasma wave can produce a high-intensity, tunable-wavelength XUV pulse with the same vector vortex structure as the original pulse. Quasi-3D, boosted-frame particle-in-cell simulations show the transition of optical vector vortex pulses with 800-nm wavelengths and intensities below 10^{18} W/cm² to XUV vector vortex pulses with 36-nm wavelengths and intensities exceeding 10^{20} W/cm² in a tailored density profile of length 1.2 cm. The XUV pulses have sub-femtosecond durations and nearly flat phase fronts. The production of such high-quality, high-intensity XUV vector vortex pulses could expand the utility of XUV light as a diagnostic and driver of novel light–matter interactions.

BPIF 1 - Laser and particle beam interactions with plasmas (LPI) 1

O 015 - Visualizing Plasmons and Ultrafast Kinetic Instabilities in Laser-Driven Solids using X-ray Scattering

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ABSTRACT TEXT

Ultra-intense lasers that ionize and accelerate electrons in solids to near the speed of light can lead to kinetic instabilities that alter the laser absorption and subsequent electron transport, isochoric heating, and ion acceleration. These instabilities can be difficult to characterize, but a novel approach using X-ray scattering at keV photon energies allows for their visualization with femtosecond temporal resolution on the few nanometer mesoscale.

The scattering signal can be predicted from Particle-in-cell simulations. We present here combined experimental and synthetic results from laser-driven flat silicon membranes that show development of periodic structures in the plasma electron density. Our Particle-in-cell simulations confirm that the observed signals are due to an oblique two-stream filamentation instability.

These findings provide new insight into ultra-fast instability and heating processes in solids under extreme conditions at the nanometer level with possible implications for laser particle acceleration, inertial confinement fusion, and laboratory astrophysics.

O 016 - Multi-stage simulations of nanowire ablation and proton acceleration in petawatt laser interactions

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ABSTRACT TEXT

The interactions of ultra-intense lasers with nanowires received a lot of attention as they show potential to increase the laser light absorption [1]. This leads to an increased yield in the production of accelerated particles for a variety of applications or generate ultrahigh pressure conditions for the studies of matter in extreme condition [2]. These kinds of experiments are sensitive to the laser pedestal, especially for multi-petawatt laser systems, even if the contrast is significantly high. The target ablates at a few picoseconds before the main pulse arrives. During the ablation, a shock wave is generated and propagates into the target, or the nanowire will undergo implosion at the tip until the wire structure is significantly damaged [3]. Here, we determine the time where the target begins to ablate using the ablation mechanism in the long pulse regime. We use the measured laser temporal profile of a 1 PW laser system at ELI-NP for this estimation. We then apply the ablation time as the starting point of the radiation hydrodynamic simulation. After that, the simulation is followed by the particle-in-cell simulation to appropriately account for the collisionless absorption. We begin the simulation by using the flat target and compare the accelerated proton cutoff energy to the experimental results. The experiments were performed at the E5 experimental area in ELI-NP with a 1 PW Ti-Sapphire laser system, focusing a 14 J laser pulse of 25 fs duration on a 4 μm FWHM spot. We discuss the effects present in the combined 3D simulations and their correlation with the experimental results. These understandings offer physical insight into the interaction of a nanowire array with a high-power laser pulse. These works were supported by Contract No. PN23210105 funded by the Romanian Ministry of Research, Innovation and Digitalization and of the Extreme Light Infrastructure Nuclear Physics Phase II, a project co-financed by the Romanian Government and the European Union through the European Regional Development Fund and the Competitiveness Operational Program (Grant No. 1/07.07.2016, COP, ID 1334).

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BPIF 1 - Laser and particle beam interactions with plasmas (LPI) 1

O 017 - A novel hybrid-target injector for high-charge laser-driven electron acceleration: understanding the injection process

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ABSTRACT TEXT

Typically, laser-driven electron sources do not accelerate enough charge for most of the envisaged applications, especially if high energies and high beam quality (low divergence, small energy spread...) are also required. To address this issue, at CEA, we have devised a novel “hybrid” laser-driven electron source consisting of a gas-jet coupled to a plasma mirror. The key idea is that, during the reflection on the high-density plasma mirror, the laser is able to extract a substantial amount of charge, which is subsequently trapped in the accelerating structure formed in the gas jet.

In 2022 we validated the “hybrid injector” concept with proof-of-principle experiments at the Laboratoire d'Optique Appliquée facility (LOA, France), and with large-scale numerical simulations carried out with the Particle-In-Cell code WarpX (a work [1] describing these results as well as the technical innovations realized in the WarpX code was awarded the Gordon Bell prize in 2022).

A new series of experiments was performed in 2023 with a 40TW laser power at LOA, and in 2024 at the PW-class facility Apollon (France). These experiments demonstrated the interest of the “hybrid injector” concept. We notably showed that, with a laser power of 40 TW, the spectral density of charge, per unit angle (100pC at 300MeV, a few% energy spread, mrad divergence) is among the best results reported in the literature for comparable laser powers.

In this contribution, we will focus on the outcome of a recent numerical simulation campaign, carried out in order to fully elucidate the injection process of the electrons extracted from the solid target. All the numerical simulations presented in this contribution are based on the Particle-In-Cell code WarpX.

WarpX is an open source, advanced electromagnetic and electrostatic Particle-In-Cell code, hosted by the High Performance Computing Foundation (HPSF). It supports several features including Perfectly-Matched Layers (PML), mesh refinement, and the boosted-frame technique. WarpX is a highly-parallel and highly-optimized code, which can run on GPUs and multi-core CPUs, and includes load balancing capabilities.

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O 018 - Process control in low pressure capacitive radio frequency plasmas based on kinetic simulations

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ABSTRACT TEXT

This work focus on the topic of process control in low-pressure radio-frequency (RF) capacitively coupled plasmas (CCPs), which is critical for semiconductor manufacturing such as high-aspect-ratio etching. Three key control mechanisms, i.e. voltage waveform tailoring (VWT), electrode surface customization, and magnetic field application, are systematically explored based on Particle-In-Cell/Monte Carlo collision (PIC/MCC) simulations to advance plasma dynamics understanding and enable precision control.

The effects of VWT are studied in geometrically asymmetric discharges. A constructive/destructive superposition of the geometrical and electrical asymmetries is found to affect the plasma density and charged particle distribution functions through modifying the direct current self-bias voltage and the sheath dynamics. By adjusting the low-frequency component of dual-frequency waveforms, energetic electron fluxes at the wafer are enhanced through minimized sheath collapse duration. Peaks-waveforms (via harmonic superposition) and square waveforms (via reduced duty cycles) are shown to promote high-energy electron bombardment, offering a pathway to neutralize dielectric etch feature charges and avoid profile distortion [1–4].

Electrode surface customization is studied to improve the plasma uniformity above the wafer by tailoring the counter (grounded) electrode. Embedding trenches enhances electron bounce-resonance heating, while radial material variations alter secondary electron emission and reflection probabilities. Both methods demonstrate localized control over electron power absorption and plasma density, enabling uniformity optimization above the wafer [5,6].

A study of magnetized CCPs is performed at high frequency (60 MHz) conditions, where a magnetically induced attenuation of the self-excitation of the plasma series resonance (PSR) is observed for the first time, which in contrast to lower frequency, leads to a reduction of the plasma density with a low magnetic field being applied to the discharge [7].

Overall, several new concepts for parameter control of CCPs are discovered computationally with high potential for knowledge based improvement of plasma processing applications in semiconductor manufacturing and other fields.

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07/07/2025, 16:45–18:35, Room: Zeta 1

LDTP 1 - Plasma Processing & Sustainability

O 019 - Production of reactive species in non-equilibrium hydrogen plasmas

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ABSTRACT TEXT

Non-equilibrium hydrogen plasmas are of significant interest for basic plasma physics and applications including plasma-enabled materials processing. Obtaining enhanced spatial control of reactive species production, including that for negative ions and atomic hydrogen, is critical. In this study, we investigate their production in the surface and the bulk of radio-frequency (rf) driven plasmas at low pressure. Mass spectrometry and photoemission yield spectroscopy are applied to investigate the surface production of negative ions from doped diamond, and laser spectroscopy enables the spatially resolved measurement of atomic hydrogen. Fluid-kinetic simulations are used to study the impact of spatial gradients in the rf power deposition on the formation of reactive species. The results are expected to be of interest for increasing our understanding of reactive-species production, and its application in the context of plasma technologies.

LDTP 1 - Plasma Processing & Sustainability

O 020 - ExB plasmas generated by e-beams and non-thermal electrons for materials processing and aerospace applications

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ABSTRACT TEXT

There is a growing interest in the use of low temperature magnetized plasmas generated by electron beams and non-thermal electrons for processing of materials at atomic scale with applications to microelectronics and quantum systems.[1–3] For these applications, the plasma (density $\sim 10^9\text{--}10^{10}\text{ cm}^{-3}$ and electron temperature $\sim 0.1\text{--}0.5\text{ eV}$) is typically generated by injecting an energetic ($10^2\text{--}10^4\text{ eV}$) electrons into a low pressure ($1\text{--}10\text{ s mtorr}$) background gas along the applied magnetic field ($\sim 10\text{--}100\text{ Gauss}$). The magnetic field helps to confine the plasma and separate the plasma regions with energetic electrons in the injected region and colder electrons at the plasma periphery. These partially ionized and partially magnetized plasmas can be subject to a number of instabilities including beam-plasma, [4] and gradient drift instabilities [5] which may, for example, alter the propagation of energetic electrons along the reactor and ion heating,[6] respectively. For soft processing applications, these effects may be unwanted as they can cause plasma non-uniformities and enhance ion-induced damage to substrates. In this talk, we will discuss the effect of the electron energy distribution function of injected electrons on plasma generation and these instabilities. Special attention will be devoted to mitigation of these instabilities and control of plasma kinetics using active boundaries. [7,8]

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O 021 - Hydrogen production via combined dry reforming of ethanol with steam using 915 MHz microwave plasma at atmospheric pressure

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ABSTRACT TEXT

The growing demand for sustainable, clean energy sources has spurred research into efficient hydrogen production methods. Currently, steam methane reforming (SMR) is the dominant industrial process for hydrogen production. Although SMR is cost-effective on a large scale, it relies heavily on fossil fuels and contributes significantly to CO₂ emissions. Furthermore, SMR requires centralised facilities, which incur additional transportation and storage costs. These drawbacks underscore the need for alternative, decentralised, and sustainable hydrogen production technologies. It is therefore essential to develop methods that not only operate at large scales but are also adaptable to small-scale, localised production near end users. One promising approach is the conversion of ethanol by microwave plasma, which enables hydrogen generation at atmospheric pressure.

This work investigates the efficiency of hydrogen production from ethanol–water mixtures using a 915 MHz microwave plasma in a dry reforming process. The primary objective is to determine the influence of the ethanol-to-water ratio on the reforming process and to identify the optimal conditions for maximising hydrogen yield. A metal-cylinder-based nozzleless microwave plasma source (MPS), supplied via a waveguide, was employed in the experiments. Tests were conducted using carbon dioxide as the carrier gas at volumetric flow rates of 2700 NL/h and 3900 NL/h. The ethanol-to-water ratio was varied under the following conditions: pure ethanol, 3:1, 1:1, and 1:3 (v/v), with a microwave power of up to 5 kW. The mass flow rate of the ethanol–water vapour mixture introduced into the MPS ranged from 0.4 to 2.4 kg/h. Preliminary results yielded a hydrogen production rate of 25.6 g H₂/h and an energy yield of 5.1 g H₂/kWh. Ongoing research is focused on optimising the operating conditions of the MPS to further improve hydrogen production efficiency.

To gain deeper insight into the conversion mechanisms of ethanol in the plasma, this work combines hydrogen production measurements with plasma diagnostics. Optical emission spectroscopy was utilised as non-invasive method for determining key plasma parameters, particularly the vibrational and rotational temperatures of the molecules present. By correlating these plasma parameters with the observed hydrogen production efficiency, the study provides valuable information on reaction kinetics and energy distribution within the plasma.

LDTP 1 - Plasma Processing & Sustainability

O 022 - Complex dynamics in laser-produced high-entropy plasma: advances in controlling thin film growth with plasma diagnostic

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ABSTRACT TEXT

High-entropy materials (HEMs), represent a groundbreaking class of multi-principal element materials that enable the exploration of diverse and variable properties within a single multielement system. Generating HEA thin-film by means of plasma-based technologies provide unique opportunities for scalability by tailoring microstructure, morphology, and functional properties by understanding the plasma environment.

In this work we report on the dynamics of laser produced high-entropy plasma are investigated by angle resolved electrical and the space and time resolved optical emission spectroscopy. The results showed a complex dynamic of a multi element plasma with selective acceleration and angular separation angular splitting of the plasma based on the nature of the ions and their kinetic energy. The nature of the expansion environment (Ar, O₂, N₂) of the high entropy plasma shows acceleration up to keV in O₂ and N₂, while the inert atmospheres confine the dynamics in the 50–800 eV kinetic range. The time resolved electrical investigation showed a modulation of the electron temperature at high pressure, signaling potential gas phase chemical reaction, while optical emission spectroscopy revealed different electron excitation temperatures for each of the composing element of the plasma which can indicate differential oxidation or nitridation processes.

Complementary thin films were fabricated using pulsed laser deposition under various atmospheres (up to 100 Pa), substrate temperatures (500 °C), and variable fluences. Morphological and structural investigations were completed using several surface analysis techniques such as AFM, SEM, XRD, XPS and far infrared spectroscopy. It is shown that by controlling ion dynamics during the growth process the thin films parameters can be systematically tuned to achieve a diverse range of microstructures, from amorphous and nanocrystalline to mixed-phase morphologies.

Plasma characterization provided further insight into fundamental of laser-high entropy matter interaction, linking the resulting properties of the thin films with the fundamental aspect of property of the plasma such as electron temperature, plasma potential or Debye length. This work highlights the potential of high-entropy alloy and oxide thin films for advanced applications, including microwave absorption, where their tunable structural and optical characteristics play a crucial role.

ACKNOWLEDGEMENT

This work was supported by the NATO grant SPS MYP G6153.

BSAP 1 - Astrophysical plasmas: High-energy astrophysics

O 023 - Investigating sources of coherent radio emissions from neutron star magnetospheres by particle-in-cell kinetic simulations

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ABSTRACT TEXT

Coherent radio waves of pulsars and fast radio bursts bring us information about relativistic extremely-magnetized pair plasmas in neutron star magnetospheres because the waves originate at plasma kinetic micro-scales. Though various radio emission mechanisms have been proposed in the last decades for their interpretation. However, many lack the inclusion of self-consistent wave-wave and particle-wave interactions and first-principle based modeling on their observable properties such as the luminosity spectrum, its polarization and directivity. Hence, particle-in-cell kinetic simulations that self-consistently include the necessary effects are an excellent tool for the plasma and radio emission diagnostics.

We investigated the pulsar radio waves formed pair cascades in neutron star polar cap regions. We studied a range of magnetic dipole inclination angles and magnetospheric currents to reveal how radio emissions can operate for various structures of pulsar magnetospheres.

We found that the pair creation events produce intensive Poynting flux originating in an electric gap region close to the star surface. The Poynting flux escapes the polar cap along open field lines where the plasma density is low, and the flux may propagate without significant absorption. The radiation is strongly linearly polarized. Moreover, the produced pulsar radio beam does not have a cone structure; instead, the radiation mostly escapes along those open magnetic field lines in which no pair creation occurs.

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07/07/2025, 16:45–18:35, Room: Zeta 2

BSAP 1 - Astrophysical plasmas: High-energy astrophysics

O 024 - Pevatrons and ultra-high energy cosmic rays as messengers of extreme astrophysical plasma

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ABSTRACT TEXT

The acceleration of charged particles in astrophysical plasma leads to amazing phenomena that we can observe with the most sensitive telescopes and cosmic-ray detectors. Recent detections of galactic sources accelerating particles up to pevatron energies (10^{15} eV) and beyond are pushing the boundaries of our understanding of the non-thermal Universe. In addition, ultra-high-energy cosmic rays (UHECRs) with even higher energies of $\sim 10^{18} - 10^{20}$ eV arrive on Earth from outside of the Galaxy. Their origin remains unknown, and identifying the sources of UHECRs is one of the most pressing problems in Astrophysics.

Accelerating particles to such extreme energies remains a very challenging problem also from a theoretical point of view. The maximum energy that particles can achieve is constrained by a very robust upper limit called the Hillas energy. Reaching this limit is only possible in certain sources, under extreme conditions in the plasma. In this talk we will introduce these extreme accelerators. We will review the most efficient acceleration mechanisms capable of accelerating galactic Pevatrons and extragalactic UHECRs. We will also discuss how laser-plasma experiments are opening the door to new means for studying cosmic ray physics.

O 025 - Topology as a cornerstone feature of the magnetic fields

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ABSTRACT TEXT

Remote observations of narrow (~ 100 s km width, ~ 1000 s km length) braided solar coronal magnetic fields, with seemingly analogous structures on a huge astrophysical scale (~ 100 – 1000 AU) of Herbig- Haro objects and on tiny scale (~ 100 cm) in laboratory experiments, together with *in situ* interplanetary measurements of (i) intermittent fluxes of energetic solar particles due to flaring magnetic field as well as (ii) recently observed sustained small-scale magnetic fields reversals in the solar wind - open a venue for a modern topological interpretation of magnetized plasma. The standard description of magnetic fields as a set of simple (distorted) field lines is generalized to strongly spatially structured forms. We apply Braid and Knot Theory to various physical configurations and construct new characteristics of those topological magnetic structures, deducing their topological invariants, constraining their evolution and stability and delineating the relaxation path to magnetized equilibria. The 3-dimensional interconnection between the mathematical braids and knots are applied to the topologically non-trivial magnetized structures from solar corona to the interplanetary medium, to astrophysical and laboratory domains. The heliospheric analysis results in conjectures regarding (i) braids' stability under oscillations and successive appearance and decay of magnetic loops, (ii) reconfiguration of braided structures into magnetic knotted configurations, (iii) their large-scale expansion into the solar wind resulting in the intermittent observation of solar flare ions and (iv) emission of small-scale compound magnetic knots in the solar wind resulting in switchback structures. These conclusions may help in shedding light on the formation and existence of numerous topological structures over a broad range of magnetized configurations and over huge expanse of space.

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BSAP 1 - Astrophysical plasmas: High-energy astrophysics

O 026 - PIC and PIC-MHD Simulations of Electron-Positron induced streaming Instability

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ABSTRACT TEXT

Observations show evidence for TeV Halos surrounding certain pulsars, indicating the presence of extended slow diffusion zones where electron-positron pairs interact with the thermal gas. One possible explanation for the presence of such diffusive regions is that the turbulence is self-induced by the electron-positron pairs that come streaming out of the pulsar-wind nebula.

We explore this possibility by means of 1D-3V PIC and PIC-MHD simulations that follow the evolution of thermal gas as it interacts with an electron-positron beam. We find that the linear phase of the instability agrees well with analytical predictions. In the non-linear phase, we determine that the intensity of saturated waves is consistent with a momentum exchange between a decelerating beam and growing magnetic waves. A unique aspect of the instability is that the waves are non-symmetric. The left-handed circular polarized waves are strongly dampened when entering the ion-cyclotron branch. By contrast, right-handed waves are dampened at smaller wavelengths when entering the Whistler branch. As a result, the electrons and positrons begin to behave differently in the turbulent environment. The positrons can maintain a final drift velocity in excess of the ambient Alfvén speed whereas the drift of electrons can drop below the Alfvén speed.

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BSAP 1 - Astrophysical plasmas: High-energy astrophysics

O 027 - Evolution of an electrostatic collisionless shock created by a blast shell and formation of a mixing layer in Particle-In-Cell simulations

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ABSTRACT TEXT

Large thermal pressure gradients in collisionless plasma generate a strong thermoelectric field that accelerates ions from the dense plasma toward the dilute (ambient) plasma [1]. In a fluid picture, a contact discontinuity separates the accelerated ions of the dense plasma from the ambient ions. The ambient ions near this discontinuity are also accelerated. If their relative speed exceeds the sound speed, a forward shock forms, separating the accelerated ambient ions from those at rest [2]. However, in collisionless unmagnetized plasma, no stable contact discontinuity exists [3]. The ion-acoustic wave mediating the forward shock exhibits properties that depend on the electron-to-ion temperature ratio and is susceptible to Landau damping [4], potentially reflecting upstream ions. Even in a one-dimensional geometry—representative of the early expansion phase of the collisionless plasma—and for a subcritical shock speed, this fluid picture remains too simplistic.

We present results from one-dimensional simulations using the PIC code SMILEI, where protons from a dense plasma are accelerated to speeds sufficient to drive an ion-acoustic shock in the dilute ambient plasma. We examine how the electron-to-proton temperature ratio and the magnitude of the thermal pressure change influence the shock structure and the mechanisms leading to the formation of a mixing layer. This layer, which separates the protons of the dense and dilute plasma, effectively replaces the contact discontinuity. Finally, we connect our simulation results to experimental observations of shocks generated by the ablation of solid targets with intense laser pulses [5].

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Plenary Session 3

O 028 - Interplay of electromagnetic turbulence, global MHD modes, fast particles, and Alfvénic instabilities in fusion plasmas

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ABSTRACT TEXT

There are a number of experiments worldwide dedicated to producing burning plasmas in the foreseeable future. Energetic particles will be abundant in these plasmas. The “meso-scale” dynamics of the energetic particles will introduce new synergies and couplings across various length and time scales. Turbulence and zonal structures cannot then be considered separately from fast particles and Alfvénic modes, as was usually done until now. The collisionless nature of reactor relevant plasmas, together with the crucial role played by wave-particle resonant interactions, make it necessary to address all these phenomena in phase space simultaneously. In addition, MHD-type instabilities, such as kink or tearing instabilities, will affect the dynamics and transport in phase space, making the overall plasma dynamics a multi-scale nonlinear problem. Its constituents as well as the links between the scales generally become both global and kinetic. Global nonlinear gyrokinetics is the optimal inclusive description to address this problem within a single framework. In this talk, I will show groundbreaking gyrokinetic simulations [1,2] of multiscale fusion plasma dynamics in a variety of fields. The results include fast-frequency-changing “chirping” Alfvénic modes, beat-wave-driven zonal flows generated by Toroidal Alfvén Eigenmodes in JET plasmas [3], linear stability and turbulence in high-beta plasma regimes, novel electromagnetic modes in realistic ITER plasmas, nonlinear dynamics of islands generated by tokamak tearing instabilities [4], a new paradigm of nonlinear excitation of Alfvénic modes by the ambient turbulence in Wendelstein 7-X [5], and nonlinear interchange instabilities in HELIAS stellarator plasmas in deeply MHD-unstable regimes [6].

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Plenary Session 3

O 029 - Jumping out of the thermal bath at interplanetary shocks in Solar Cycle 25

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ABSTRACT TEXT

Interplanetary (IP) shock waves propagate in the heliosphere due to solar activity phenomena. IP shocks are important sites of energy conversion and particle acceleration in the Heliosphere and can be observed *in-situ* utilizing spacecraft measurements, thus providing one of the missing links to remote astrophysical environments, and an excellent “natural laboratory” to test several mechanisms of energy conversion which are still under debate.

From this point of view, a large fleet of existing heliospheric observers provide an unparalleled opportunity to gain insights about IP shocks, effectively triggering a “new golden era” for investigating the role of IP shocks in the overall energetics of the heliosphere.

A crucial component of such fleet is Solar Orbiter, yielding direct measurements at different locations in the inner heliosphere with unprecedented time and energy resolution in the suprathermal (usually above 50 keV) energy range, thereby opening a new observational window for studying how particles are accelerated out of the thermal bath.

First, I will present the statistical properties and general trends of Solar Orbiter IP shocks up until the solar maximum of cycle 25. With particular attention to the link between shock parameters and particle acceleration efficiency.

I will then focus on specific cases where Solar Orbiter and other observers (e.g., Parker Solar Probe, Wind) elucidated previously unknown aspects of energetic particle production, relevant for both heliospheric and astrophysical systems.

Plenary Session 3

O 030 - Ion motion and self-modulation suppression in a plasma wakefield accelerator

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ABSTRACT TEXT

Beam-driven plasma wakefield accelerators rely on the interaction between a particle bunch and a plasma to generate ultra-high fields ($\sim$ GV/m), typically used for accelerating charged particles. When the driver length exceeds the plasma wavelength required to achieve such high fields, transverse wakefields modulate the driver, forming a train of microbunches that resonantly drive the wakefields. This process, known as self-modulation, is essential for experiments such as AWAKE at CERN, which employs long proton bunches as wakefield drivers due to their high energy content and their ability to accelerate charged particles to very high energies in a single plasma stage. We describe AWAKE and highlight the most significant experimental results obtained so far: control of the self-modulation process and the acceleration of externally injected electrons. A particular focus is placed on measurements conducted with plasmas of varying ion masses, which show that significant ion motion suppresses self-modulation. This suppression is characterized by a distinct experimental signature: the emergence of a bunch tail. For the first time, we study the onset and conditions under which ion motion occurs within a single wakefield excitation, examining the effects of varying wakefield amplitudes and ion masses. These measurements confirm the inverse relationship between ion motion and ion mass. Additionally, we demonstrate that plasma density gradients—both positive and negative—can suppress self-modulation, in agreement with theoretical predictions. Multiple diagnostics reveal this suppression and the asymmetries between positive and negative gradients. Finally, we outline the potential applications of this acceleration scheme in particle physics.

08/07/2025, 11:15–13:05, Room: Alfa

MCF 2 - Burning plasmas and reactor operation

O 031 - The SPARC and ARC tokamaks: Predictive results and open physics questions on the path to a commercial fusion power plant

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ABSTRACT TEXT

Commonwealth Fusion Systems and its partners are in the late stages of building the SPARC tokamak [1], aiming for net energy in 2027, and are in the early stages of designing the ARC fusion power plant, aiming for operation in the early 2030s. To design SPARC and prepare for operations, a large body of computational and empirical predictive work has been completed. This work, combined with SPARC's new parameter space ($B_t = 12.2\text{T}$, $I_p = 8.7\text{ MA}$, $Q = 11$, $P_{fus} = 140\text{ MW}$) and robust early diagnostic set [2], means that SPARC will provide a wellspring of opportunity to validate predictions, ranging from gyrokinetic predictions of core performance, to detachment onset and stability, to alpha particle dynamics [3].

Simultaneously, CFS and its partners have begun predictive physics work for the ARC power plant design ($P_{e,net} = 400\text{ MW}$), with the understanding that there remain significant uncertainties in these predictions. This talk will summarize a number of early results of the physics analysis of ARC.

CFS works closely with university and national lab partners around the world on both SPARC and ARC. This talk will describe how the unique capabilities and strengths of these partners combine to accelerate the path to commercial fusion energy.

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MCF 2 - Burning plasmas and reactor operation

O 032 - The Tokamak Exhaust Designer: a new tool for enhanced divertor control on MAST-U

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ABSTRACT TEXT

Exhaust physics experiments are the flagship of the MAST-U research programme, facilitated by an extensive poloidal field (PF) coilset and baffled divertor chambers [1]. A key enabler thereof is robust, flexible, intuitive control over the divertor magnetic geometry. This contribution describes the development, implementation, and testing of a new scenario development tool, the Tokamak Exhaust Designer (TED), and its exploitation to accelerate the creation and control of a wide range of divertor magnetic geometries throughout the 2024/5 campaign.

The method implemented in TED is based on vacuum spherical harmonic (SH) constraints [2]; by retaining the vacuum field over the core plasma chamber—expanded as four SH basis functions—as the PF currents change, the confined plasma shape is held constant. Combining these SH constraints with ones on the magnetic geometry (separatrix position, flux expansion, field angle, etc) at points in the divertor chamber greatly simplifies the design of new exhaust geometries for a given core plasma.

Packaged into an intuitive, user-friendly tool, we demonstrate how this approach has revolutionised the magnetic control of the MAST-U divertor. Examples are given of using feed-forward currents to create a wide array of geometries, including super-X, X-point target, and X-divertor, in just one plasma shot, with operators able to quickly calculate the PF currents required inter-shot. We also show how TED expedites the design of new feedback control actuators for specific divertor properties, such as strike point location or degree of closure, in the face of complex geometry constraints, and how it can be used to avoid operational limits and reduce coil current demands.

Beyond maximising the exploitation of present-day experimental devices, we also discuss prospects for applying this approach to simplify the challenging problems faced by future machines, including the design of PF coilsets, optimal control algorithms, and extension to conventional aspect ratio tokamaks.

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MCF 2 - Burning plasmas and reactor operation

O 033 - High-fidelity physics Integrated Modeling in support of ITER and burning plasma research

Francesca Poli¹, Paulo Abreu¹, Maksim Dubrov¹, Olivier Hoenen¹, Sun-Hee Kim¹, Florian Koechl¹, Simon Pinches¹, Guillermo Suarez Lopez¹, Romain Futtersack², Elina Militello Asp², Rui Coelho³, David Coster⁴, Thomas Jonsson⁵, Par Strand⁶, Dmytro Yadykin⁶

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ABSTRACT TEXT

Following the recent decision to replace the first wall material with tungsten and change the Heating and Current Drive power and mix, the ITER Organization is working with the international community to prepare an updated ITER Research Plan [1]. Operation with a tungsten first wall demands understanding the physics of startup on a metal wall, the impact of tungsten on plasma performance and stability, access to burn, sputtering effects from the antenna, and the consequences of a metal wall on disruptions and on current quench duration [2]. Integrated modeling is critical to the preparation of the ITER Research Plan, to minimize risks and to support the design of controllable plasma pulses. Scenario evaluation has achieved an advanced level of predictive capability including free-boundary magnetic equilibrium and core-edge-SOL integration. Whilst open questions remain, the ITER Organization is taking a comprehensive approach—leveraging the advances made by the international community—to deliver a fully integrated simulation framework for data analysis and predictions that includes a High-Fidelity Plasma Simulator, based on JINTRAC and DINA, and on the European Transport Simulator [3,4,5]. This talk discusses specific examples of scenario development in support of the ITER Research Plan, from the Start of Research Operation to high-performance fusion operation in the DT-1 phase. These simulations evolve the plasma discharge including the limited phase, transient phases, to assess entry and exit from H-mode with reduced tungsten accumulation, and divertor heat loads in dynamic conditions. The examples will be used to highlight the advances in theory and modeling, as applied to self-consistent simulations of tokamak plasma discharges, but also the gaps that remain to gain confidence in predictions for burning plasmas. The use of synthetic diagnostics is being recognized as an important component of a simulator, for validation of physics models, for extensive assessment of the data analysis chain, and for design of controllable discharges. Finally, the role of the international community in validating models in the ITER Modeling and Analysis Suite (IMAS) environment, to support operation on existing devices, and prepare for operation in future devices, including ITER, is highlighted.

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MCF 2 - Burning plasmas and reactor operation

O 034 - Experimental validation of momentum transport theory in the core of the ASDEX Upgrade tokamak

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ABSTRACT TEXT

This work employs the established momentum transport analysis at ASDEX Upgrade to investigate the parametric variations of the momentum transport coefficients [1] in mainly ion temperature gradient mode dominated H-mode plasmas. Experimental results are compared to a comprehensive database of gyrokinetic calculations. Generally, good agreement between predicted and measured diffusive and convective transport coefficients is found. The Prandtl number correlates strongly with the magnetically trapped particle fraction. The pinch number depends most dominantly on the logarithmic density gradient and magnetic shear, consistent with the theoretical predictions of the Coriolis pinch [2]. The intrinsic torque from residual stress in the inner core is small, scales with the local logarithmic density gradient, and the data suggest a possible sign reversal. In the outer core, the intrinsic torque is always co-current directed and scales with the pressure gradient. Both trends are consistent with prior experimental findings [3–5]. They suggest that different mechanisms contribute to residual stress generation in the inner and outer core, with profile shearing effects dominating the inner core [6, 7]. Towards the edge, most likely, effects from ExB-shearing become more influential via the diamagnetic term in the Er force balance [8]. These results offer the first comprehensive picture of this transport channel in the core plasma and contribute to validating the corresponding theoretical understanding. The derived scaling laws construct a reduced momentum transport model validated against an additional dataset. The successful reproduction of experimental data demonstrates that the reduced model captures the essential contributions to momentum transport in the core plasma. This validation opens avenues for various applications, including integrated modeling approaches and real-time control, and will provide a foundation for predictions of rotation profiles in future reactors.

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MCF 2 - Burning plasmas and reactor operation

O 035 - Long pulse achievements in the WEST tokamak

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ABSTRACT TEXT

The WEST superconducting tokamak, featuring full tungsten (W) environment and actively cooled ITER-grade divertor, provides valuable insights for the operation of future magnetic fusion devices [1]. In recent campaigns, a strong effort has been placed on long duration plasma scenarios (well beyond 100 s), relevant for plasma-wall interaction phenomena and far above the plasma current diffusion timescale ($\sim 1\text{--}2$ s). Such long discharges are made possible by the use Lower Hybrid Current Drive (LHCD), supplemented by bootstrap current with a fraction reaching $\sim 20\%$. The long pulse scenario development in WEST, supported by integrated modelling [2], has now resulted in a world record long tokamak plasma discharge of 1337 s (~ 22 minutes), with injected energy of 2.6 GJ. The long pulse scenarios are performed with feedback-controlled plasma current sustained by LHCD in order to achieve close to or full non-inductive current drive (loop voltage of 0–3 mV). Several discharges of > 500 s have been obtained, featuring $T_{e0} \sim 3.5$ keV, $\beta_p \sim 2$ and $H_{98y2} \sim 1$ in L-mode regime.

In the course of the long pulse developments, new challenges related to operation in full metallic environments, thus directly relevant to next-step fusion devices, have appeared. Firstly, the ohmic plasma current ramp-up phase in full W environment has high radiative fraction ($> 60\%$) and is prone to the triggering of resistive MHD modes. This requires optimization of the plasma current waveform and early nitrogen injection [3]. Secondly, unforeseen radiative events due to the detachment of W-rich flakes from redeposited layers on the divertor, but also the spontaneous triggering of internal transport barriers, can cause MHD limits.

Ongoing developments in WEST are now targeted at reaching long pulse scenarios in the X-point radiator regime [4]. The results obtained show good prospects for extending this divertor-preserving regime, crucial for fusion power plant operation, towards long durations with core performance comparable or better than that obtained in attached divertor regime.

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MCF 2 - Burning plasmas and reactor operation

O 036 - Magnetic configuration effects on pellet fuelling in stellarators

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ABSTRACT TEXT

Efficient fuelling is an important factor for the viability of fusion reactors, particularly in stellarators where core particle depletion can be a significant challenge [1], despite the recent indications that the risk may be lower [2]. While cryogenic pellet injection offers deeper particle deposition in both tokamaks and stellarators, its behaviour in the latter remains less understood. The advantage of High Field Side injection, namely inward plasmoid drift [3], is not so evident [4, 5], unlike in tokamaks where it is well-established.

This study investigates the effect of the magnetic configuration, including the iota profile and the magnetic well, on pellet ablation and particle deposition in the TJ-II and the W7-X stellarators. Besides, experimental results from ablation light and plasma profiles are compared with HPI2 simulations [6–8], which uses a VMEC equilibrium as input. This ensures that differences in magnetic configuration are addressed, albeit in a simplified way, as the gradB is averaged along the plasmoid parallel length. Moreover, these findings are discussed in relation to those from other diagnostics, such as fast cameras [9].

This study demonstrates the key role of the magnetic configuration in determining pellet fuelling in stellarators, thereby emphasising the necessity for a thorough consideration of magnetic configuration effects when designing fuelling systems for future stellarator reactors. This conclusion is supported by both simulations and experiments, although differences in the experimental post-injection profiles are sometimes of the order of the measurement uncertainties.

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O 037 - Electromagnetic QED cascades: How close are we to getting showers, avalanches and pair plasmas in the laboratory?

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ABSTRACT TEXT

Several flagship experiments on multi-petawatt laser facilities and accelerators worldwide explore the possibility of creating electromagnetic (EM) cascades as a pathway to generating pair plasmas in the laboratory [1]. These cascades are initiated when high-energy electrons, positrons, or γ photons interact with intense EM fields. In background EM fields, such as those near neutron stars, black holes, or at the focus of ultra-intense lasers, cascades develop via nonlinear Compton scattering and Breit-Wheeler pair production. In matter, cascades arise from bremsstrahlung radiation and Bethe-Heitler pair production driven by strong nuclear fields.

Electromagnetic showers, a specific type of cascade, have been observed in both strong background fields [2] and matter [3], though with limited yields. These showers draw energy from the seed particle beam—such as electron beams from accelerators or laser wakefields—or from intense γ -photon flashes [4]. The first part of this talk will review recent analytical models [5] that describe shower dynamics. Emphasis will be placed on strategies to enhance shower multiplicity (i.e., number of pairs produced per seed particle) and on the feasibility of achieving a pair plasma state through showers in either background fields or matter.

Electromagnetic avalanches, while not yet realized experimentally, offer a promising route to dense pair plasmas due to their exponential growth of electron-positron pairs. Unlike showers, avalanches extract energy directly from the background field and require specific EM field configurations to sustain re-acceleration of particles. The second part of this talk will leverage recent theoretical advances [6] to evaluate the conditions needed to trigger avalanches at multi-petawatt laser facilities. Particular attention will be given to determining the minimum laser intensity required for avalanche development and how parameters such as pulse duration and polarization influence this threshold.

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08/07/2025, 11:15–13:15, Room: Beta

BPIF 2 - Ultra-high intensity laser-matter interaction & high-field physics (QED) 1

O 038 - QED cascades in extreme focusing

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ABSTRACT TEXT

We investigate the onset and development of the electron-positron cascade, seeded by tenuous gas electrons, during a collision of two tightly focused laser pulses. The results reveal that the laser pulse polarization plays a critical role in reaching cascade pair production. Contrary to traditionally considered linear or circular polarization, we utilize radially polarized laser beams which provide a restoring force that is acting in the opposite direction to the one in which the seed electrons have been previously ejected. Therefore this feature guarantees the cascade seeding even if the seed electrons were previously expelled from the center of the focal plane. As a consequence, the laser power required for a cascade development is 100x (80x) lower compared to the case of circular (linear) polarization of tightly focused laser pulses. In other words, the threshold intensity for the onset of the electron-positron cascade is two orders of magnitude lower than that in the case of circular or linear polarization.

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08/07/2025, 11:15–13:15, Room: Beta

BPIF 2 - Ultra-high intensity laser-matter interaction & high-field physics (QED) 1

O 039 - Electromagnetic showers in matter: towards e^-e^+ pair plasmas

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ABSTRACT TEXT

When high-energy leptons (electrons, positrons) or photons interact with a sufficiently thick layer of matter, copious emissions of photons (via Bremsstrahlung) and electron-positron pair production (via the Bethe-Heitler process) give rise to so-called electromagnetic showers (EMS). Such showers open the path to relativistic electron-positron pair plasmas in the laboratory [1,2] thus offering new opportunities for laboratory astrophysics [3].

In the first part of this talk, I will briefly discuss how the work [4] can be used to derive a set of equations, solutions of the kinetic equations, that describes the kinetic structure of EMS in matter. I will show how the shower multiplicity scales with the source (seed particle energy) and target (material, thickness) parameters. Our predictions will be shown to be in excellent agreement with GEANT4 simulations, and our results discussed in the context of previous works [5].

In the second part of the talk, using both our new analytical model and GEANT4 simulations to account for all relevant effects (Coulomb collisions, ionization, photo-electric effect, etc), I will present a comprehensive study of the density, characteristic size, and angular divergence of electron-positron jets produced by EMS as they emerge at the back-side of the target. This will provide us with clear guidelines for the realization of pair plasmas in the laboratory, which I shall put in the context of recent experimental achievements [1,6].

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BPIF 2 - Ultra-high intensity laser-matter interaction & high-field physics (QED) 1

O 040 - Challenges and perspectives of efficient gamma-ray production in near-critical targets with PW-level high-intensity lasers

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ABSTRACT TEXT

Laser facilities operating at multi-petawatt power and approaching peak intensities of 10^{22} – 10^{23} W/cm² are open to user access world-wide [1]. According to theoretical studies and particle-in-cell simulations, remarkable results are expected in these facilities where short focal can deliver pulses with relativistic field strength, $a_0 \gg 1$, on near-critical or overdense targets creating dense, relativistic, and potentially quantum plasmas. The expected results foresee the enabling of efficient super-ponderomotive acceleration of electrons [2], high-energy emission of gammas with brightness above 10^{21} photons/(s mrad² mm² 0.1%BW) in hundreds of MeV through the process of Non-linear Inverse Compton Scattering (NICS) [3,4], and therefore the opening of the exploration of strong-field quantum electrodynamics. However, users of those facilities need to face several non-idealities that make it challenging to achieve the predicted results. The difficulties range from the control of crucial laser parameters such as the temporal and spatial contrast of the pulse [5], to the design and handling of suitable targets [6] and diagnostics [7].

The present contribution addresses these topics by combining theoretical and numerical studies with the experimental results achieved during a 2024 campaign at Apollon 1PW [8]. Specifically, we address the characterization of the Apollon prepulse effect on near-critical targets, the modelling and detection of gamma-ray emission in this context considering both NICS and bremsstrahlung contribution, and the design of a routine for the data analysis of scintillators signals acquired during the campaign. Leveraging these results, we propose solutions at the target and setup level to the aforementioned challenges with the support of proof-of-concept hydrodynamic and particle-in-cell simulations. Our contribution finally details the application of these solutions to the design of a planned experiment at Apollon 3PW in the next year.

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08/07/2025, 11:15–13:15, Room: Beta

BPIF 2 - Ultra-high intensity laser-matter interaction & high-field physics (QED) 1

O 041 - Ion acceleration using high order PW helical beams at ELI-NP

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¹ ELI-NP, Laser driven experiments, Magurele, Romania

ABSTRACT TEXT

Helical laser beams, featuring orbital angular momentum (OAM) and a characteristic doughnut-shaped intensity profile have recently gained significant attention in high-power laser applications. Their unique properties open up new possibilities in laser-plasma interactions, enabling novel physical phenomena at extreme intensities. We present the latest experimental results on ion acceleration using high-order Petawatt (PW) helical laser beams at ELI-NP, covering a wide range of laser and target configurations. We also discuss complementary particle-in-cell (PIC) simulations and how they correlate with our experimental observations to further elucidate the underlying acceleration mechanisms.

08/07/2025, 11:15–13:05, Room: Zeta 1

LDTP 2 - Liquids, Agricultural and Biomedical Applications

O 042 - Chemical reactivity induced in liquids by non-equilibrium atmospheric plasma

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ABSTRACT TEXT

The plasma-liquid interactions involves a complex interplay of physical and chemical processes occurring at the interface between a plasma and a liquid medium. These interactions give rise to the generation, transport, and transformation of various reactive species, leading to a wide range of chemical reactions and dynamic phenomena. The complex processes of plasmas contacting liquid water that need to be considered include gas phase chemistry, multiphase species transport, mass and heat transfer, interfacial reactions, and liquid phase chemistry. A distinction is made between the bulk liquid and the interfacial region, the latter being the location where many important processes involving short-lived species occur. Configurations of the plasma contacting the liquid significantly affects the underlying hydrodynamics as well as other properties of the plasma and the interface that affect interfacial transport. The type and quantity of the reactive species formed by discharge plasma in the liquid depend on the nature and the composition of the working gas and also on the physical-chemical properties of the liquid in the case of contact with plasma. When these species come into contact with the liquid surface, they can react at or penetrate through the plasma-gas/liquid interface and dissolve into the bulk liquid, and can undergo various chemical reactions in the liquid. In this talk processes of reactive species at the plasma-liquid interface and their coupled chemical reactions in the liquid phase will be presented.

O 043 - Possibilities for upscaling atmospheric pressure plasma systems for treatment of liquid samples

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ABSTRACT TEXT

In recent years there has been a development of different applications of plasma treated liquids (PTL). In many different applications that were investigated at laboratory level so far, fundamental reactions and chemistry behind the plasma-liquid interaction have been recognized pointing the way towards possible industrial applications [1,2]. However, further steps regarding scaling-up of the plasma systems are ambiguous due to the complexity of the system and the interaction with the liquid target. The scaling-up in principle is anticipated for the volume of the produced PTL, but it can be also considered regarding maximizing through output of the liquid and minimizing the treatment time. As each application and plasma system requires specific approach, in this study we focused on investigation of the system that could be used for agricultural applications – for decontamination of pesticide polluted water and treatment of pure water for plant growth. In that context, we will present results on design and optimization of a multi-pin atmospheric pressure plasma jet operating with Ar as a working gas. The pin-type electrodes are supplied with high-frequency sine wave signal enabling creation of streamers that can be brought in contact with water surface. Detailed discharge diagnostics including optical emission spectroscopy, plasma imaging and electrical characterisation of the system operating in contact with water will be presented in order to compare the differences between the scaled-up system and the one pin jet. Special attention will be devoted to the stability of plasma operation and the properties of PTL. We will also present the results of dependence of physical and chemical properties of the treated pure and polluted water with respect to increase of the sample volume up to 0.5 l and with adding a sample recirculation system. Conclusions drawn from the scale up process regarding general influence of several key parameters of the plasma system, properties of the PTL and liquid decontamination will be presented.

ACKNOWLEDGEMENT

This work was supported by MSTDI Republic of Serbia grant 451-03-68/2024-14/200024, the Science Fund of the Republic of Serbia, grant No. 3114/2021 — Project APPerTain-BIOM and grant No.14916/2024 — Project PoWeRCAP-EGARDEN.

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O 044 - Role of Streamers and Bubbles in the Plasma Assisted Production of Hydrogen

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ABSTRACT TEXT

Hydrogen production in small “on-board” generators can allow cleaner and more efficient combustion engines. Experiments with nanosecond pulses at an average power of about 10 W in water solutions with 35% alcohol revealed very efficient production of the synthesis gas (H_2 + CO) with about 65% of H_2 . This corresponds to the production efficiency of less than 10 kWh/kg H_2 . The methanol-based electrolytes proved about 25% higher production efficiency than the ethanol-based ones and the energy consumption as low as about 4.5 kWh/kg H_2 . The process optimizations for maximum production of hydrogen gas in all electrolytes revealed importance of intense streamers which can produce gas nanobubbles. In the presentation most of these important observations and findings will be described and explained.

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O 045 - Low-Temperature Plasma Diagnostic in Dielectric Capillaries for Laser Wakefield Acceleration

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ABSTRACT TEXT

Capillary systems are essential components of laser-plasma accelerators (LPAs), particularly for generating very high-energy electron (VHEE) beams. These structures enable precise energy control, improved beam quality, and enhanced acceleration gradients by guiding and confining laser pulses and plasmas over extended distances. Accurate diagnostics of plasma density and temperature within the capillary are crucial for optimizing plasma conditions and achieving efficient acceleration.

This study examines gas-filled plasma-discharge capillaries for laser wakefield acceleration (LWFA). A high-voltage discharge pre-ionizes the gas before the laser pulse, enhancing plasma formation, enabling precise density control, sustaining laser intensity over multiple Rayleigh lengths, and improving energy stability and coupling.

To characterize the plasma in dielectric capillary discharge waveguides, we utilize various spectroscopic diagnostics, including Balmer line emission analysis, to track the spatial and temporal evolution of plasma density and temperature along the capillary's longitudinal axis. These measurements offer insights into plasma uniformity and stability, essential for optimizing waveguide performance in LWFA applications.

To complement the experimental findings, we also present simulations of capillary discharge dynamics using COMSOL Multiphysics. Plasma density is evaluated as a function of applied voltage and pressure, enabling the analysis of plasma behavior under different discharge conditions. A comparison with experimental data confirms the model's accuracy in predicting plasma characteristics and underscores its potential for optimizing capillary discharge parameters.

At the I-LUCE facility (INFN-Laser induced Radiation Production) in Catania, Italy, a capillary-based laser-plasma acceleration system is being developed to produce high-quality electron beams tailored for VHEE and FLASH radiotherapy (FLASH-RT) applications. The system is designed to optimize electron acceleration by varying capillary parameters such as length, diameter, and channel shape.

O 046 - Nitric oxide diagnostics in plasma heated gas using laser absorption spectroscopy

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ABSTRACT TEXT

Accurate and real-time detection of nitric oxide (NO) in plasma-assisted combustion systems is critical for optimizing burner performance and reducing NO_x emissions. This work presents the development of a tunable diode laser absorption spectroscopy (TDLA) diagnostic for NO quantification in plasma heated gas relevant to plasma burner environments. A tunable diode laser operating near 5060 nm is directed through an experimental setup, including beam splitters, lenses, photodetectors and a 25 cm long cell (absorbing path) subsequently filled with different gas seeded with NO. Room-temperature tests revealed that the low absorption signal and high noise floor make it challenging to detect NO reliably in these conditions. However, the chosen NO transitions become significantly stronger at high temperatures (up to a few thousands kelvin) typical of plasma-assisted combustion. Future experiments will therefore be conducted at these elevated temperatures using the setup in [1], which can withstand such conditions. In this configuration, the plasma burner is embedded in a 50 cm long diameter chamber whose circular base has a 12.5 cm diameter. The resulting NO quantitative diagnostics in plasma heated gases will be confirmed by independent measurements using Fourier transform infrared spectroscopy (FTIR). Additionally, the presence of water vapor (H₂O), a common combustion byproduct, introduces critical spectral interference, highlighting the importance of careful line selection and identification, and interference correction in real combustion environments, which is very valuable for the combustion community. By referencing HITRAN/HITEMP databases [2], [3], absorption coefficients are to be identified for prospective high-temperature measurements. These advancements in sensor design set the stage for accurate, in-situ quantification of NO under realistic plasma burner conditions, offering a promising avenue for real-time emissions monitoring, improved burner design, and sustainable energy production.

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O 047 - Experimental characterization of stimulated Raman side-scattering in the context of the direct-irradiation approach to Inertial Fusion Energy

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ABSTRACT TEXT

Thermonuclear fusion ignition has been demonstrated at the National Ignition Facility, using an Indirect-Drive approach, confirming the potential of fusion as a commercial source of energy. However, due to its higher energy coupling between the laser drivers and the target, Direct-Drive approach is the implosion scheme considered for Inertial Fusion Energy.

It was recently observed that such approach will be prone to stimulated Raman side-scattering (side-SRS). Due to the complexity to characterize this instability experimentally, its impact on the implosion is not properly understood yet. Indeed, side-SRS involves a particular geometry scattering light perpendicularly to the local density gradient. Therefore, the scattered light is strongly affected by the refraction on its way out of the plasma. This leads to a wavelength dependent emission profile, over a very broad volume. Usual diagnostic methods have a limited angular coverage and thus cannot accurately measure this instability.

To solve these limitations, a new fibre-based diagnostic method has been specifically developed and implemented on several facilities. It enabled us to characterize side-SRS in multiple regimes and greatly improved our understanding of this instability. Our methodology and the results gathered so far will be presented during this talk.

O 048 - Laser-driven Electromagnetic Pulses for the manipulation of charged particle beams

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ABSTRACT TEXT

The low-frequency content, in the radiofrequency-microwave range, of transient electromagnetic emissions caused by intense laser-matter interactions, is known as “Electromagnetic Pulses” (EMPs) [1]. Having intensities up to the MV/m order, a main research activity has been devoted to their mitigation. Nevertheless, there are several promising studies aiming at exploiting the mechanisms at the base of the generation of such intense fields. They include the production of kT transient magnetic fields [2] and of traveling waves for particle acceleration and focusing [3]. A new application has been recently proposed [4] for creating large-intensity (MV/m and beyond) transient electric fields over large volumes and with specific spatial distributions, for many applications such as: particle acceleration, medicine, biology, electromagnetic compatibility, material science, aerospace, electronics, sensors. We show here the unique and very promising features provided by these EMP technologies for the management and the conditioning of accelerated particle beams, produced by either conventional particle accelerators or laser-plasma interaction schemes.

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O 049 - Effect of spectral bandwidth on the stimulated scattering of a spatially smoothed laser beam in plasma

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ABSTRACT TEXT

Stimulated laser scattering on plasma waves in a corona is the major obstacle for efficient laser energy deposition on inertial confinement fusion (ICF). Optical laser beam smoothing techniques such as random phase plate (RPP), crossed polarizations, induced spatial incoherence (ISI), and smoothing by spectral dispersion (SSD) proved not sufficient for mitigation of parametric instabilities, and attention is shifted to the assessment of the potential of large spectral bandwidth of a few percent or more. Experimental data are very limited, and the theory and simulations are of prime importance. However, numerical simulations deliver contradicting results in clear disagreement with established theories.

Here, we report the results of studies of spatial amplification of the forward and backward scattering of a broadband spatially smoothed laser beam in plasmas relevant to ICF. A recently developed statistical theory of parametric instabilities [1] is applied to the stimulated Brillouin scattering (SBS) and criteria of the mitigation of forward and backward scattering are obtained for laser beams smoothed with RPP, ISI, and SSD. The analytical results are confirmed with dedicated numerical simulations using a paraxial electromagnetic code and agree with the experiment [2]. By contrast, numerical simulations using a particle-in-cell code demonstrate that increasing laser bandwidth has little effect on stimulated Raman scattering (SRS), but increase the reflectivity and hot electron generation [3]. This effect is attributed to the electron trapping in the SRS-driven plasma wave and broadening of the plasma resonance beyond the laser bandwidth. Theoretical analysis and relation to experiments will also be discussed.

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BPIF 3 - Laser and particle beam interactions with plasmas (LPI) 2

O 050 - Experimental study of laser plasma instabilities driven by 527 nm laser pulses with narrowband and broadband spectra

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ABSTRACT TEXT

One of the challenges for commercially viable inertial confinement fusion (ICF) are laser plasma instabilities (LPI). During coupling of the laser light with the produced plasma, various processes result in both the reflection and scattering of a significant amount of energy, and acceleration of electrons to high energies. These “hot” electrons then pre-heat the inside of the fusion target before the shock front arrives and reduces compression efficiency. Consequently, the presence of LPI requires higher initial laser energy to reach the same compression conditions, and should thus be mitigated.

One approach is increasing the spectral bandwidth of the laser pulses. Resulting in a reduction of coherence length, increased bandwidths are predicted to deny LPI the time to fully develop, with an appreciable effect expected for a FWHM of $\Delta\lambda/\lambda \approx 1\%$ and higher [1, 2]. However, the exact changes with increasing bandwidth are hard to predict, partially due to the interaction between different types of LPI [3]. Experimental research into the effect is still very limited, and of great interest to the ICF community. Thanks to a recent upgrade, the PHELIX laser at the GSI Helmholtz Centre for Heavy Ion Research can now deliver 2ω pulses with variable bandwidths of up to about 0.5%. This enables the option to test the theoretical predictions.

We present a study of LPI with 2-ns laser pulses at a central wavelength of 527 nm. This includes results for pulses with monochromatic bandwidths from experiments with the L4n laser at ELI – Beamlines [4] and PHELIX. We also report on preliminary results of a study directly comparing LPI at narrow (0.03%) and the aforementioned broad bandwidths after the upgrade of PHELIX.

The intensities during these experiments lie in the regimes of 10^{13} to 10^{15} W/cm². Our study focuses on two plasmon decay and stimulated Brillouin and Raman scattering in back- and side-scatter directions. Additionally, electron spectra were measured at several angles in front of and behind the target. This was done indirectly via the X-ray bremsstrahlung they produced and directly via magnetic electron spectrometers. Both show increased signal with broadband pulses, indicating that the hot electron population is altered.

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BPIF 3 - Laser and particle beam interactions with plasmas (LPI) 2

O 051 - A comprehensive study of laser-plasma experiment between sub-relativistic and relativistic intensities

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ABSTRACT TEXT

An intensive investigation and comparative study of laser-plasma experiments between sub-relativistic and relativistic intensities were carried out at the Prague Asterix Laser System (PALS). The iodine laser at PALS (wavelength 1.315 μm , pulse duration ~ 350 ps) delivers energy up to 600 J to produce plasma using 10 μm thick copper and tantalum targets. The focal spot of the focused beam interacting with the target was characterized and the peak intensity exceeds 10^{18} W/cm². The hot electron energy distribution was measured by multi-channel electron spectrometer at different angular directions, x-ray emission spectrum by bremsstrahlung spectrometers and hot electron distribution by Cu K-alpha diagnostic. Thomson parabola, CR-39 differential absorption spectrometers, and ion collectors were employed to measure accelerated proton and ion energy spectra. The maximum proton energy of 4.5 MeV was observed at the highest laser intensity. The electron density distributions in plasma plume at different time delays were measured by three-frame interferometry using probe beam provided by the femtosecond Ti:Sa laser. The experimental study of pre-plasma generation and its interaction with the main pulse is complemented with numerical simulations using hydrodynamic codes PALE and FLASH. The results are crucial for understanding the laser self-focusing, filamentation, and generation of energetic particles. The preliminary data from the experiment reveals insightful information about the characteristics of energetic particles, radiation, plasma dynamics and relevant physics associated with sub-relativistic and relativistic intensities using kilo-Joule nanosecond class laser. These findings have numerous applications in inertial confinement fusion, laboratory astrophysics, electromagnetic pulse generation, radiation sources and high energy density physics.

MCF 3 - Divertor physics and power exhaust

O 052 - Divertor Tokamak Test Facility Physics Basis

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ABSTRACT TEXT

We present the physics basis of the Divertor Tokamak Test facility (DTT), elaborated with the help of 130 scientists in the DTT Research Plan. DTT will have relevant dimensionless parameters as close as possible to those typical of ITER & DEMO-class reactors.

The talk will summarize DTT power exhaust strategy, plasma scenarios, transport and MHD, the physics of heating, current drive and fueling and energy particles behavior.

We show that DTT is instrumental to pin down the crucial scaling of λ_q , as DTT can reach a fully integrated scenario where high core performance with low pedestal collisionality and high density goes with edge parameters relevant for the next generations of fusion devices.

Based on extensive simulations, we will present how DTT addresses key issues as:

- (a) the compatibility of good core performance with tolerable exhaust conditions. The activities for the development and assessment of baseline and advanced scenarios for various divertor configurations, at nominal field and current, will be presented. The available divertor magnetic configurations in DTT, feasible even within the same discharge, are in priority order: Single Null, X divertor and Negative Triangularity.
- (b) the achievement of efficient ion heating in future reactors where electrons will be heated.
- (c) the scaling of energy confinement with dominant electron heating, no torque injection and significant fast ion population and
- (d) the possibility of efficient plasma operation at high density.
- (e) the study of Detached regimes optimization and control by impurity seeding in various scenarios.
- (f) Energetic Particle physics studies with reactor relevant dimensionless parameters.

Like ITER, DTT will have 27 internal active coils, which will support the development of small/no ELMs scenarios and their control. We explain how DTT will address the development of the science and technology for off-normal events control. In particular, DTT will be equipped with a SPI Disruption Mitigation System similar to that of ITER.

International acceleration in fusion makes DTT even more relevant: in a scenario where SPARC may produce proof of principle D-T plasmas and ITER starts its operation, accessing reactor relevant plasma exhaust regimes in DTT will be fundamental for the first generation of reactors.

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MCF 3 - Divertor physics and power exhaust

O 053 - Power exhaust and detachment in LSN with varying outer leg length using multi-species turbulence simulations and experiments designed for validation

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ABSTRACT TEXT

We present the TCV-X23 experimental scenario, developed to validate tokamak turbulence simulations, and compare experimental profiles to fluid plasma and kinetic neutrals simulations performed with the GBS code [1]. TCV-X23 features a lower single null configuration with low toroidal magnetic field and a long outer divertor leg, extending the TCV-X21 database [2] to higher-density regimes relevant to plasma detachment. Experiments were performed at low and high upstream plasma densities and in both toroidal field directions, with comprehensive edge diagnostics including a divertor reciprocating probe array, spectroscopy, and gas puff imaging. The resulting database will be made open and widely available for validating fluid turbulence codes targeting high-dissipative regimes, detachment mechanisms, and their interaction with turbulence. Using the GBS code, we simulate the dynamics of three fluid species (electrons, D⁺, D₂⁺) coupled with two kinetic neutral species (D and D₂). Simulations with longer divertor legs and higher densities show increased atomic neutral densities from D₂ dissociation, reducing target ion flux and inducing detachment. Simulations suggest that the interaction between neutral dynamics and turbulence reduces divertor fluctuations during detachment, while simulated and measured profiles show increased mid-plane turbulent fluxes and larger SOL widths at higher densities. These findings highlight the importance of neutral-turbulence interplay and demonstrate GBS's ability to replicate trends observed in high-density plasmas.

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MCF 3 - Divertor physics and power exhaust

O 054 - EIRENE Interpretation of Divertor Deuterium Emission in DIII-D constrained by 2D Divertor Thomson Scattering and Langmuir Probe Measurements

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ABSTRACT TEXT

EIRENE simulations of deuterium emission across the DIII-D low-field side (LFS) divertor target predict the measured Lyman and Balmer series emission in both attached and detached divertor conditions when constrained by the measured 2D Divertor Thomson Scattering (DTS) electron temperature (T_e) and (n_e), and Langmuir probe (LP) ion current density. In detached conditions, EIRENE also predicts negligibly low molecular Fulcher band emission in the divertor, consistent with spectroscopic measurements. Hence, for measured ion flux to the divertor target and plasma conditions, and disregarding ELMs and other transients, the combination of plasma recycling models, the applied AMJUEL atomic and molecular rates, and neutral particles and photon transport model in EIRENE reproduces the measured deuterium emission within the uncertainty of the measurements and simulation setup. These studies separate the validation of neutral particle transport, and atomic and molecular physics, from coupled edge fluid code EDGE2D-EIRENE predictions which fail to reproduce the measured hydrogenic emission and imply an order of magnitude lower molecular and atomic densities than when constrained by DTS and LP measurements for detached conditions.

For detached plasmas, only constrained EIRENE simulations reproduce the measured Balmer- γ emission, implying a strongly (three-body, electron-ion) recombining plasma adjacent to the LFS target plate. These simulations also predict the measured radial profile of line-integrated Lyman- α emission composed of peaks at the X-point driven by direct excitation of deuterium atoms, and at the target plate driven by recombination. These findings are a result of T_e being below 1 eV poloidally from the target plate to halfway up to the X-point, with n_e peaking at $4 \times 10^{20} \text{ m}^{-3}$ in a similar extent of the leg. Including Lyman- α and Lyman- β opacity in the simulations reduces Lyman- α emission by a factor of 2 and increases Balmer- α emission by 20% in the vicinity of the LFS strike point. In contrast, EDGE2D-EIRENE predicts lower n_e , peaking in the vicinity of the strike point only, resulting in Lyman and Balmer emission predominantly produced by excitation only. These studies indicate that recombination plays a more dominant role in the onset of detachment than currently predicted by edge fluid codes.

ACKNOWLEDGEMENT

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MCF 3 - Divertor physics and power exhaust

O 055 - Addressing the power exhaust challenge with double-null configurations

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ABSTRACT TEXT

Power exhaust poses a major design constraint for future tokamaks. This multi-machine study explores the Double-Null (DN) geometry as a potential solution to reduce heat and particle loads on plasma-facing components. We present experimental investigations of power sharing between divertor targets in DN configurations, conducted on the MAST-U, TCV, and WEST tokamaks across attached and detached plasma regimes. Our results show that in DN, power is predominantly distributed between the two outer divertor legs (>88%), consistent with previous studies. This enhanced inner/outer asymmetry, compared to Single-Null (SN) configurations, arises from ballooned radial transport and magnetic disconnection between the inboard and outboard sides. These findings are further supported by 2D SOLEDGE transport simulations, incorporating a ballooned diffusion model and drift effects in WEST geometry. Additionally, experiments on TCV reveal that reducing triangularity stabilizes resistive ballooning modes and significantly balances the deposited inner/outer power ratio by an order of magnitude. A previously proposed reduced model for power sharing in L-mode and attached plasmas has been refined to quantify the effects of ballooned radial transport and drifts, achieving good agreement with experimental measurements. To further mitigate peak heat loads, we have also investigated DN operation in highly radiative scenarios. Our results indicate that, compared to SN, DN achieves lower detachment thresholds in density on TCV (by 20%-25%) or nitrogen seeding rate on WEST (by 66%), leading to reduced core contamination and improved confinement while maintaining comparable reductions in power deposition. Pronounced detachment of both divertors is experimentally demonstrated across all devices. MAST-U's strongly baffled divertors help decouple the two chambers while WEST's experiments highlight the control of a single radiation front during several tens of seconds. Overall, these findings show that DN offers significant benefits for power exhaust, making it a relatively mature alternative divertor configuration for future fusion power plants.

MCF 3 - Divertor physics and power exhaust

O 056 - X-point target radiator regime in tokamak divertor plasmas

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ABSTRACT TEXT

Fusion plasma regimes featuring an X-point radiator (XPR) [1] are promising candidates to address the significant power exhaust challenges in reactor-scale tokamaks. In this work, we present the experimental observation of a new type of X-point radiator, the XPTR (X-point target radiator) [2], which forms at a secondary X-point embedded along the divertor leg well separated from the confined plasma, in an alternative divertor configuration known as the “X-point target” (XPT) [3]. Experiments are conducted on the TCV tokamak, where a detailed two-dimensional structure of the XPTR is revealed through a combination of high-resolution spectral imaging, bolometry, in situ Langmuir probe and Thomson scattering measurements. Access to divertor detachment is strongly facilitated with >5x heat flux reduction compared to the conventional single-null, together with the formation of a radiative zone near the secondary X-point. The sensitivity of the radiation front (radiator) position to upstream density variations is reduced by >5x near the secondary X-point, suggesting a broad operational space of detachment that remains well below the threshold for radiative collapse. Overall, the XPTR scenario demonstrates TCV’s most favorable exhaust performance to date, which can be accessed in nitrogen-seeded high-power conditions where a conventional divertor fails to detach. Its basic physics is modeled by extending the XPR schematic [4] to the divertor scrape-off layer, confirming X-point radiation as a fundamental feature arising from the coupling between magnetic geometry and radiative processes, regardless of whether the field lines are closed or open. The XPTR offers many compelling benefits in view of a reactor and its possible incorporation in the forthcoming SPARC reactor [5] and ARC pilot plant, including access to a robust state of divertor detachment with reduced impurity injection, control requirements, and without risking confinement degradation due to excessive radiative edge cooling of the confined plasma.

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MCF 3 - Divertor physics and power exhaust

O 057 - X-point radiation and up-down asymmetry in detached plasmas of Wendelstein 7-X

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ABSTRACT TEXT

The Wendelstein 7-X (W7-X) stellarator explores the island divertor concept, which leverages intrinsic magnetic island chains to form a three-dimensional (3D) scrape-off layer (SOL). Stable plasma detachment is routinely achieved in the standard magnetic configuration ($\iota = 5/5$) through radiation predominantly from intrinsic carbon impurities. Throughout the detachment regime, the radiation zone remains edge-localized (with a peak at normalized radii $r/a \geq 1.0$), minimizing core plasma degradation. During the initial detachment phase, as the radiative loss fraction (f_{rad}) increases (typically 0.6–0.9) either by raising plasma density at fixed heating power or reducing heating power at fixed density, the radiation zones shift both radially and poloidally toward the X-points of the magnetic islands. This shift produces distinct multi-X-point radiation (multi-XPR) patterns. Despite the symmetric magnetic topology, these patterns exhibit an up-down asymmetry, where a dominant radiation zone appears near an upper X-point in the forward-field direction. This up-down asymmetry reverses upon changing the field direction, suggesting drift effects, with $\mathbf{E} \times \mathbf{B}$ drift possibly playing a key role. In highly radiative regimes ($f_{rad} \approx 0.9$ –1), the radiation zones shift to the last closed flux surface (LCFS), and the up-down asymmetry almost vanishes, resulting in intense radiation on the inboard side.

This study investigates carbon impurity radiation dynamics in the detachment regime, focusing on the pronounced up-down asymmetry in the multi-XPR structure during the initial detachment phase. This effect is not captured by 3D modeling with EMC3-Eirene, which predicts poloidal but not up-down asymmetry due to the absence of drifts. Bolometer tomography reveals these asymmetries, while visible video diagnostics confirm that the multi-XPR structure follows the helical field periodicity. The observed asymmetry near X-points in magnetically equivalent island regions is associated with impurity density variations, primarily driven by poloidal $\mathbf{E} \times \mathbf{B}$ drift with opposing velocity directions (toward or away from the LCFS). Following the radiation zone shifting, temperature and density variations in the island SOL additionally influence the asymmetry degree.

O 058 - Recent implosions experiments in the compressive regime at the Laser MegaJoule facility

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ABSTRACT TEXT

We propose here to present the last ICF hohlraum experimental campaign which was carried out in 2024 on the LMJ laser facility. The objective was to compare two hohlraum shapes, a cylinder and an elliptic shaped hohlraum (rugby). The cylinders exhibited the lowest backscatter levels, lower than 3 % of the laser energy. But achieving a symmetric implosion requires cone fraction, thus to reduce the inner laser power on LMJ where the number of inner beams and the number of outer beams are the same. Less cone fraction is required in a rugby hohlraum but, on the other hand, higher levels of Brillouin scattering were measured, nearly 10 % of the laser energy. 2D and 3D calculations are shown which try to match the measured hot spot shapes. Finally, we present our future designs for the next years, as more energy and beams will be available. We show how trade-offs must be made between the irradiation symmetry on the capsule and the deleterious effects of laser plasma interaction which could become a main concern with the laser energy increase.

BPIF 4 - Inertial Confinement Fusion

O 059 - Implosion and illumination designs for laser driven fusion energy

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ABSTRACT TEXT

To achieve laser driven nuclear fusion, a pellet of hydrogen isotopes is imploded in reaction to an expanding plasma, ablated by the laser. The implosion is subject to hydrodynamic instabilities, while laser-plasma instabilities (LPI) occur in the expanding plasma. These instabilities are two of the greatest challenges faced when designing suitable implosions for laser fusion experiments. Each instability can be evaluated numerically but requires expensive computations that can become prohibitive on the timescales required by the implosion. A new methodology employs temporally discretised evaluations and simple physics based approximations to enable fast and accurate illumination design of experiments at existing laser facilities [1].

Major breakthroughs in laser fusion experiments have led to significant public and private funding around the world [2]. Within France, the Taranis project led by Genf is aiming to create a laser fusion reactor to produce electrical energy. In order to achieve the necessary implosion stability, a reactor would require hundreds or thousands of laser beams, each with carefully selected parameters. The enormous parameter space and the expense of numerical evaluation is a significant challenge for design of future facilities.

This talk presents a new methodology for creating and evaluating the drive configuration of beams for future laser facilities. A state-of-the-art ray-tracing tool [3] is employed alongside automated optimization to create novel illumination geometries while considering the impact of the LPI cross-beam energy transfer, beam spot shapes, bandwidth and wavelength. This technology is a critical step towards fusion energy, furthermore it creates opportunity for designing a greater variety of experiments at current facilities, and evaluating LPI thought too computationally expensive for prior methods.

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BPIF 4 - Inertial Confinement Fusion

O 060 - First demonstration of improved yield with reduced adiabat and increased compression in high-performance implosions on the National Ignition Facility

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ABSTRACT TEXT

After decades of research, indirect-drive inertial confinement fusion (ICF) experiments at the National Ignition Facility (NIF) have achieved a significant milestone by demonstrating target gains exceeding one [1]. Using up to 2.2 MJ of laser energy, target gains of ~ 2.4 and energy yields of ~ 5 MJ have been achieved to date. However, a major challenge is to improve performance further as future applications necessitate much higher target gains, $G > 15$. One approach to achieving improved implosion performance is to pursue increased fuel compression via a lowered implosion adiabat, although historically this approach has not resulted in increased performance. Experiments have been performed testing a reduced adiabat by introducing small changes to the drive laser pulse shape and the resulting shock timing for an existing, and well-studied implosion design at 1.9 MJ laser drive with near-ignition performance (experiment N210808) [2]. Experiments using the updated design demonstrate, for the very first time, increased compression and fusion yield in ICF implosions on the NIF by using a lower fuel adiabat, and increased compression with a reduced adiabat in high-density carbon ablaters. Compared to the previously best-performing experiment with a laser energy of 1.9 MJ, these experiments exhibit increases of up to 80% and 14% in nuclear fusion yield and fuel compression, respectively, and with repeatable performance. Further, it is the only implosion design to have achieved a target gain exceeding one with a laser energy of less than 2 MJ. These findings highlight the efficacy of reduced adiabat designs in achieving higher compression and fusion yields, offering a promising pathway for future ICF applications. This work not only addresses a long-standing question in ICF but also paves the way for achieving higher target gains with optimized implosion strategies. This work was performed under the auspices of the U.S. Department of Energy by LLNS, LLC, under Contract No. DE-AC52-07NA27344. LLNL-ABS-872331.

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BPIF 4 - Inertial Confinement Fusion

O 061 - Strongly magnetized cylindrical implosions in inertial confinement fusion experiments

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ABSTRACT TEXT

An initial background magnetic field (seed B-field) applied to inertial confinement fusion (ICF) experiments can be amplified to 10^4 – 10^5 T by the target compression. Such strong compressed B-fields may improve ICF performance since they lead to a better confinement of electrons and alpha particles, reduction of electron thermal conduction losses and increase of self-sustained fusion reactions yield. The result is a hotter core that ignites at lower densities and with slower implosions that are less susceptible to hydrodynamic instabilities. The use of cylindrical targets with a seed B-field aligned along its axis allows an axially symmetric implosion since the B-field is everywhere perpendicular to the radial compression. Experiments on the OMEGA laser facility (United States) showed that a 30 T seed B-field increases the core temperature by 50% and reduces its density by a factor of ~ 2 , which is consistent with a 10 kT compressed B-field at stagnation [1]. We are now extending such magnetized implosions to mega-joule-scale laser facilities, such as the National Ignition Facility (NIF, United States) and the Laser MegaJoule (LMJ, France). We will present the first results obtained at NIF, which exhibit a more symmetric compression, reduced instability growth and 3 times higher neutron yield for the magnetized implosions using a 16.5 T seed B-field than for the non-magnetized ones. We will also discuss the modeling of a related experiment at LMJ (scheduled for 2027) which should result in a 3 times higher compression ratio.

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BPIF 4 - Inertial Confinement Fusion

O 062 - 3D rad-hydro modelling on the NIF: effect of low-mode asymmetries on capsule implosions and use of foams for symmetry control*

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ABSTRACT TEXT

Cryogenic implosions at the National Ignition Facility (NIF) using high-density-carbon (HDC) ablaters during the 2019–2020 period showed asymmetric assembly of the fuel areal density as measured from a suite of nuclear diagnostics. Since the main objective of hot-spot ignition relies on maximal conversion of shell kinetic energy into hot-spot internal energy, these asymmetries are an indication of an appreciable loss mechanism. Using 3D rad-hydro integrated hohlraum simulations a set of hypotheses, inherent quad-to-quad variations, hohlraum features and capsule layer non-concentricity, were systematically studied to ascertain their impact and to determine possible mitigation strategies [1]. This work suggested that implosions could benefit from modifications to the hohlraum diagnostic window configuration (used to assess hot-spot symmetry) as well as stricter capsule manufacturing tolerances. Among other factors, these improvements played a role in the successful N210808 shot [2], first experiment exceeding the “Lawson-like” ignition criterion. Follow-up experiments (N221204, N240210) demonstrated further improvement in performance reaching fusion energy production > 2 larger than the laser energy delivered to the target. The performance improvement of implosions at the NIF ushers in a new frontier in high-energy density (HED) physics allowing for probing of conditions relevant to astrophysical phenomena. For the current indirect-drive NIF configuration, however, the use of this new capability, such as diagnosing material properties at extreme conditions, requires the removal of beams (used as back-lighters), introducing an inherent drive asymmetry onto the primary implosion that may lead to significant yield degradation. 3D computer simulations are used to assess the magnitude and impact of quad-removal on an igniting implosion and to assess possible compensation strategies. Moreover, as we push toward higher performance implosions, control of additional low-mode asymmetries, currently mitigated using plasma processes, i.e., cross-beam energy transfer, may need to be supplemented by target modifications. Simulations suggest that strategically-placed aerogel foam disks within the hohlraum substantially improve symmetry control. Simulations and initial experimental results will be shown.

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MCF 4 - Advances in 3D systems

O 063 - Piecewise omnigenous fields: a radically new family of optimized magnetic fields for stellarator reactors

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ABSTRACT TEXT

In omnigenous stellarator magnetic fields, charged particles are perfectly confined in the absence of collisions and turbulence, as in an axisymmetric tokamak. Consequently, the magnetic configuration is optimized to be close to omnigenity in any candidate for a stellarator fusion reactor. However, omnigenity imposes stringent constraints on the spatial variation of the magnetic field strength B [1]. In particular, the contours of constant B on the flux-surface must close either toroidally, poloidally or helically. In a stellarator, these topological constraints on the B contours sometimes lead to complicated plasma coils [2].

In this talk, a new notion of optimized magnetic fields, named *piecewise omnigenous stellarators* [3], will be presented. We will revisit the physical picture behind standard omnigenity, and then we will prove that piecewise omnigenous fields can also give exceedingly small collisional transport without satisfying the aforementioned topological constraints.

Piecewise omnigenous fields radically broaden the space of accessible reactor-relevant magnetic configurations [4]. We will show that, besides small collisional transport of the bulk plasma, these configurations may exhibit favourable properties regarding alpha-particle confinement, bootstrap current, impurity control, turbulent transport or coil simplicity.

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MCF 4 - Advances in 3D systems

O 064 - 3D plasma-wall interaction simulations: Advances and challenges for ITER and Wendelstein 7-X

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ABSTRACT TEXT

Plasma-wall interaction (PWI) is one of the key issues for realizing magnetic fusion energy (MFE), as it determines wall lifetime, retention and radiation by impurities. Tungsten (W) as the primary plasma-facing material has the focus of PWI studies in support of ITER and other future MFE reactors. Due to being a high-Z material, W accumulation in the core plasma can lead to significant radiative power loss resulting in low plasma performance and ultimately plasma collapse. While W has a high sputtering threshold for main plasma hydrogen isotopes, it can be sputtered by (seeding) impurities or energetic charge-exchange neutrals (CXN). W erosion and possible transport to and accumulation in the core plasma needs accurate predictions by tools like the Monte-Carlo code ERO2.0. This code allows global erosion-redeposition and impurity transport simulations in 3D. Such non-axisymmetric treatment is indispensable to consider complex non-axisymmetric geometries as given in stellarators or created by resonant magnetic perturbations (RMPs), as well as effects like magnetic shadowing on shaped plasma-facing components.

In this contribution, we provide an overview of recent and ongoing modelling activities with ERO2.0 in support of ITER and Wendelstein 7-X (W7-X) in view of the planned transition from low-Z to high-Z wall material in both devices. Predictive ERO2.0 modelling for ITER has been performed using plasma backgrounds simulated by the code suite OEDGE (including SOLPS and an extended grid via onion-skin model and EIRENE) under the assumption of a beryllium (Be) main chamber. We provide a summary of these results such as gross erosion and net fluxes in main chamber and divertor, together with a perspective on how modelling can predict changes in erosion and impurity transport coming with the transition to a full-W wall. In a similar way, we review the prior interpretative ERO2.0 modelling of carbon (C) erosion in W7-X using EMC3-EIRENE C-seeded plasma backgrounds and its validation using spectroscopy and post-mortem analysis data. We discuss how predictive modelling can help predict a possible future operation of W7-X with all plasma-facing components replaced by W, with respect to impact on divertor lifetime and radiation losses.

MCF 4 - Advances in 3D systems

O 065 - Efficient single-stage optimization of islands in finite- β stellarators

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ABSTRACT TEXT

We present single-stage optimizations of islands in finite- β stellarators [1]. Stellarator optimization is traditionally performed in a two-stage process; in the first stage, an optimal equilibrium is calculated which balances a set of competing constraints, and in the second stage a set of coils is found that supports the equilibrium. Stage one generally utilizes a stellarator representation that enforces the condition that flux surfaces in the plasma are nested—a condition which is often desirable but not guaranteed. Furthermore, generating the coils after optimization introduces a mismatch, and this error is increased if manufacturing or accessibility constraints need to be included. We demonstrate a fully single-stage optimization scheme that directly varies the coils to optimize islands in the divertor region of finite- β island-containing equilibria. To achieve this we use the *simsopt* [2] framework to control and remove islands in Multi-region Relaxed MHD (MRxMHD) equilibria represented by the free-boundary Stepped Pressure Equilibrium Code (SPEC) [3]. We build upon previous work where islands were removed from quasisymmetric vacuum fields [4], and from finite- β equilibria without coils [5], to achieve this direct-from-coils optimization where the degrees of freedom are the coil parametrization. We furthermore demonstrate a dimensionality reduction scheme which computes the variations of the coils that affect the plasma using a singular value decomposition. Using these variations as degrees-of-freedom both improves the quality of the achieved optimum and reduces the computational cost of the optimization. This method can be used to control the size and location of islands in the divertor region of stellarators and design devices that leave adequate space between the coils and divertor components.

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MCF 4 - Advances in 3D systems

O 066 - Systematic study of CXRS ion flow measurements in W7-X stellarator towards a validation of neoclassical theory

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ABSTRACT TEXT

A rigorous and detailed study of ion velocity measurements in the Wendelstein 7-X (W7-X) stellarator is presented, exploring a broad range of magnetic configurations and operational conditions. The model integrates the complex 3D geometry of the W7-X stellarator, the magnetic configuration computed with the Variational Moments Equilibrium Code (VMEC), and the precise geometry of the Charge Exchange Recombination Spectroscopy (CXRS) diagnostic's viewing lines [1], ensuring a high-fidelity reconstruction of the plasma flow parameters. Utilising an extended forward model specifically designed for the CXRS diagnostic, this work goes beyond previous CXRS flow studies at W7-X by addressing row-dependent detector wavelength drifts. The work achieves a high level of agreement between experimental results and neoclassical flow predictions that has not been reported before in literature.

A distinguishing feature of this analysis is the consideration of all relevant flow components, including the EXB, Pfirsch-Schlüter (PS), and net parallel ($V_{||}$) contributions [2]. The study also incorporates critical corrections for fine structure effects, ion excited state lifetime, and cross-section distortions, which are of particular importance in W7-X due to the inherently low plasma flow velocities. These velocities require a wavelength measurement precision of at least one-tenth of a pixel, reflecting the extraordinary diagnostic sensitivity achieved in this research. Our results reveal that the derived flow profiles are both statistically robust and consistent across different emission lines. Furthermore, the inferred radial electric field (E_r) closely aligns with independent Doppler Reflectometry measurements in overlapping radial regions, providing a robust validation of the experimental approach. So far, no clear configuration-dependent variations in ion flow were detected in the magnetic configurations explored with this experimental accuracy.

This work sets a new benchmark in the validation of neoclassical transport theory in stellarators, as a product of integrating sophisticated modeling, precise diagnostics, and detailed error analysis. By achieving an unmatched level of agreement between experimental data and theoretical predictions, this study establishes a foundation for further advancements in the understanding and optimization of plasma behavior in complex, three-dimensional magnetic confinement devices.

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MCF 4 - Advances in 3D systems

O 068 - Geometry landscape for zonal flow activation in turbulent plasmas

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ABSTRACT TEXT

Magnetically confined plasmas are often characterized by the spontaneous emergence of large-scale coherent structures in microscopic turbulence, which is one of the most notable physical phenomena in these systems. Particularly, the nonlinear excitation of zonal flows and its significant impact on the turbulent transport are key discoveries from both theory and experiments for the plasma turbulence. Then, how can we “activate” or “enhance” such nonlinear structures? The zonal-flow dynamics in general non-axisymmetric three-dimensional magnetic fields is yet to be fully clarified, but the diversity of the magnetic geometries in stellarators strongly motivates us to explore capabilities of enhancing the zonal-flow formation.

This study will present recent progress on the geometry-induced activation of the zonal flows and/or vortex structures in the context of stellarator optimizations with a novel nonlinear turbulence proxy model[1,2]. A key geometric factor is the local geodesic curvature which is associated with the linear zonal flow response[1]. Optimal confinement geometries are explored by using mathematical optimization and/or Markov chain Monte Carlo stochastic sampling with the above extended nonlinear proxy model. The nonlinear gyrokinetic simulations for the optimal geometry revealed a significant enhancement of the zonal-flow generation, leading to the transport suppression with less stiffness on the temperature gradient. We also discuss a landscape approach for investigating the stability, robustness, and the mutual distances in local optima of magnetic geometry to activate the nonlinear dynamics[3].

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O 069 - Magnetic field amplification induced by cosmic-ray pressure at non-relativistic shocks

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ABSTRACT TEXT

Non-thermal emission at radio, X-rays and gamma rays from different types of objects suggests the presence of a higher-than-expected magnetic field in the sources. On the other hand, reaching the energies required via diffusive shock acceleration also demands for an amplification of the local magnetic field. A connection between particle acceleration and magnetic field amplification in astrophysical shocks appears to exist, beyond field compression. While cosmic-ray streaming instabilities can efficiently amplify magnetic fluctuations in the shock precursor, it is not clear whether this can guarantee an efficient confinement of cosmic rays of the highest energies. An alternative process for the amplification of fields at larger scales has been suggested, which relies on the turbulent dynamo powered by the pressure of the accelerated cosmic rays interacting with the density inhomogeneities of the interstellar medium. We have explored this mechanism numerically, firstly using purely magnetohydrodynamics, and more recently employing a modified technique of Particle-In-Cell-Magnetohydrodynamic. With this technique, the particles are evolved using the relativistic guiding center equations extended with stochastic terms for representing the particles' spatial diffusion, generated by the subgrid fields. In this talk I would introduce the ideas behind the amplification process and our most recent numerical results.

08/07/2025, 16:45–18:35, Room: Zeta 2

BSAP 2 - Astrophysical plasmas: Cosmic rays

O 070 - Cosmic-ray transport and acceleration in astrophysical plasmas

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ABSTRACT TEXT

Despite more than a hundred years research on cosmic rays (CRs) their origin is still not completely clear. Which sources can accelerate CRs to the observed extremely high energies? How do they propagate from their sources to Earth? To find answers on those, among the most intriguing questions in astroparticle and plasma physics, we will follow a cosmic ray from its origin, e.g., accelerated at a shock wave of a supernova remnant, on its path through ambient photon and hadronic targets where it is continuously deflected by turbulent magnetic fields down to Earth.

I will show multi-messenger models for the different stages of a cosmic ray's life cycle to illustrate the current research status. All models use our new simulation framework, based on stochastic differential equations to describe the ensemble averaged cosmic-ray propagation. The simulations can be compared and tuned to observations of cosmic rays and neutral secondary particles, photons and neutrinos. I will discuss these models in the light of recent observations of ultra-high energy gamma-ray sources (PeVatrons) and the observation of the Galactic disc in neutrinos.

O 071 - On the width of a collisionless shock and the index of the cosmic rays it accelerates

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ABSTRACT TEXT

Despite being studied for many years, the structure of collisionless shocks is still not fully determined. Such shocks are known to be accelerators of cosmic rays, which, in turn, modify the shock structure. The shock width λ is known to be connected to the cosmic rays (CRs) spectral index, a . Here, we use an instability analysis to derive the shock width in the presence of CRs. We obtain an analytical expression connecting the shock width to the CRs index and to the fraction of upstream particles that are accelerated. We find that when this fraction becomes larger than $\sim 30\%$, a new instability becomes dominant. The shock undergoes a transition where its width increases by a factor ~ 8 – 10 , and the CRs acceleration effectively ends. Our analysis is valid for strong, non-relativistic and unmagnetized shocks. We discuss the implication of these results to the expected range of CRs spectra and flux observed, and on the structure of non-relativistic collisionless shocks [1,2].

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O 072 - Sapphire++ – MHD: A finite element MHD code for astrophysical plasmas with energetic particles

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ABSTRACT TEXT

We present Sapphire++ (<https://sapphirepp.org>) [1], an open-source code developed to simulate astrophysical fluids as well as the propagation and acceleration of energetic particles including self-consistent feedback.

The evolution of astrophysical plasmas is often driven by cosmic-ray (CRs) currents. Both around energetic sources, such as supernova remnants (SNR) and on galactic scales, CRs play a vital role in the driving turbulence and winds. Capturing these effects in simulations of large systems is a challenging multi-scale problem, as one needs to capture physical phenomena occurring on vastly different scales. In some scenarios, like the escape of CRs from sources (e.g. SNR), characteristic quantities can vary by many orders of magnitude.

To address these open questions, we developed Sapphire++. It combines and couples the simulation of the plasma with energetic CRs. We use a pseudo-spectral method to solve the Vlasov-Fokker-Planck (VFP) equation for the high energy component. Utilising a decomposition of the distribution function into spherical harmonics, the dimensionality of the problem is reduced allowing for efficient multi-scale simulations. The thermal plasma is modelled using the magnetohydrodynamics (MHD) equations, and likewise solved using a discontinuous Galerkin finite element (DG-FE) method. We highlight, that coupling these two modules, VFP and MHD, enables self-consistent simulations.

We showcase the code's validity using the well-studied process of diffusive shock acceleration, presenting a number of novel findings previously unidentified, but with far-reaching implications...

The MHD module is verified against and compared to existing codes in terms of accuracy and performance.

Finally, we present results for a combined MHD and CR simulation, in the example of CR current driven instabilities.

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O 073 - PIC Simulation of Oblique Whistler Waves from Gradient Drift Instability at a Low-Beta Subcritical Perpendicular Shock

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ABSTRACT TEXT

Subcritical perpendicular shocks in plasma with beta close to 1 form a thin transition layer, enabling precise measurements of its structure. These shocks compress the incoming upstream plasma and amplify its magnetic field B_0 . The plasma density and magnetic field amplitude reach their peak values in the overshoot layer and converge to their downstream values behind it.

We use PIC simulations, which resolve the x-y plane, to examine the stability of the overshoot layer that propagates along x. We have previously considered the cases where B_0 was aligned with y or z. In the first case [1], we observed stable oscillations of the overshoot layer at a frequency close to the lower-hybrid frequency. In the second case [2], perturbations of the overshoot layer did not oscillate. A gradient drift instability led to the growth of lower-hybrid waves that were strong enough to perturb the overshoot layer.

We present results from a PIC simulation in which the upstream B_0 is perpendicular to x, tilted at 45 degrees relative to z, and has the same amplitude as in [1, 2]. Stable oscillations of the deformed overshoot layer are observed, though they have a lower frequency than in [1] due to the weaker component of B_0 along y, which reduces the magnetic tension of the deformed field lines. An initially planar overshoot layer does not remain planar, consistent with observations in [2]. The electric current from electrons drifting orthogonally to B_0 has a component along the unresolved z direction, which changes the range of wavevectors available to instabilities. Oblique Whistler waves grow at a rate similar to that of the lower-hybrid waves in [2].

Oblique Whistler waves commonly appear ahead of (quasi-)perpendicular shocks [3], where they originate from a Modified Two-Stream Instability (MTSI) driven by the shock-reflected ion beam. In our simulation, they are driven by a gradient-drift instability near the overshoot, which causes the overshoot layer to oscillate. We discuss how this drift instability may explain the shock boundary oscillations observed at Earth's bow shock [4], which have previously been attributed to a nonuniform upstream plasma [5] that deforms the shock's overshoot.

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Plenary Session 4

O 074 - Routes to high-performance operation in Wendelstein 7-X (W7-X): turbulence suppression with shaping of the density profile

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ABSTRACT TEXT

Steep density gradients lead to improved plasma performance in the neoclassically optimized stellarator W7-X. This improvement, which is evident in the global energy confinement time as well as in the ion temperature, can be explained by a strong reduction of the ITG turbulence. Experimentally, such conditions can be achieved with several methods, for instance, with moderate electron cyclotron resonance heating (ECRH) after fresh wall conditioning, dominant heating with neutral beam injection (NBI) and injection of cryogenic hydrogen pellets. The duration of the improved phase is determined by the plasma stability and by the ability to sustain the steep density gradient, i.e. by the particle transport. We present an extensive overview of relevant experiments from recent campaigns, and discuss the potential of these methods for the long pulse operation. In particular, it is shown that a fine balance of the NBI and ECRH heating allows to maintain the beneficial turbulence suppression for several seconds. The plasma parameters achieved in these experiments can be compared with present day tokamaks.

Analysis of a wide experimental database, that covers plasmas with densities up to $1.8 \cdot 10^{20} \text{ m}^{-3}$, ECRH powers up to 8 MW and NBI powers up to 6 MW, shows that transport in W7-X is determined mainly by the ion scale turbulence. Because of this, in gas fuelled plasmas with a strong electron heating, the density profile is usually flat and the ion temperature is limited to about 1.6 keV. However, if the normalized density gradient a/L_n is raised sufficiently, e.g. due to the pellet fuelling, the anomalous heat diffusivity is reduced by about a factor of four. In such conditions, the ion temperature can reach values of up to 3.5 keV with the same level of electron heating. In addition, the characteristics of the impurity transport also change dramatically. These experimental observations are supported with gyro-kinetic simulations. It is worth noting that the turbulent transport gains importance in W7-X due to the successful reduction of the neoclassical transport, which shows that optimization and control of the turbulence will be important also for the future stellarator reactor.

Plenary Session 4

O 075 - Application of Non-Thermal Plasma for the Treatment of Selected Types of Foods and Conditioning of Biological Material

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ABSTRACT TEXT

Non-thermal atmospheric pressure plasma (APP) is gaining recognition as an alternative to traditional thermal and chemical-based methods in food preservation, agriculture, and medicine. This study investigates its role in enhancing food safety, promoting seed germination, and modifying biological materials including dental enamel's and preosteoblasts' properties. In the food industry, APP generated in the glide-arc reactor (GAD) was applied to bakery products and fresh juices to evaluate its effects on nutritional value and microbial reduction during storage. The combination of cold atmospheric plasma and sumac powder (*Rhus coriaria* L.) significantly improved the microbiological stability and extended the shelf life of fresh carrot juice. Juice treated with CAP and enriched with 3% sumac powder remained microbially safe for up to 72 hours, while also retaining elevated levels of polyphenols (34.36 mg/100 ml) and carotenoids (3.49 mg/100 g more than control samples), demonstrating its potential for preserving thermolabile foods. In agriculture, APP was used to treat *Lavatera thuringiaca* L., onion, radish and other types of seeds via GAD, surface discharge type reactor or dielectric barrier discharge (DBD) plasma jet. For the last case, pre-sowing plasma exposure improved germination capacity (from 36.25% in control seeds to 61.5% after 2 minutes and 65% after 5 minutes) and germination energy (from 30% to 55.5% and 56% for 2- and 5-minute treatments, respectively). In medicine, APP was investigated for its impact on primary teeth enamel using a DBD plasma jet for exposure durations of 5, 10, and 20 minutes. Plasma treatment influenced enamel characteristics such as color, wettability, surface roughness, and elemental composition. While brief exposure enhanced whitening and wettability, prolonged treatment led to irreversible enamel damage, suggesting its potential use for plasma-assisted whitening or pre-treatment before dental procedures. Non-thermal plasma can be an interesting solution for solving certain problems in agriculture, food preservation, and medicine as a standalone technology or providing a superposition treatment effects in combination with other treatment techniques. However, further optimization of plasma treatment parameters, especially, in the terms of treatment time, volume and correlation with other factors impacting the treatment is necessary to maximize plasma benefits across different applications.

Plenary Session 4

O 076 - The physics of gaseous diffractive optics for high-power lasers

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ABSTRACT TEXT

High-power lasers have applications ranging from particle acceleration to controlled thermonuclear fusion. Using large-scale optical elements is required in order to sustain the extreme fluences of these lasers, which puts limits on the maximum laser intensities that can be generated. A new approach to this problem consists in creating diffractive optical elements made of gas instead of solid, capable of sustaining fluences two to three orders of magnitude greater than solids. To create such a gas optics, a low-energy, spatially-modulated deep UV imprint laser beam is absorbed by a small fraction of ozone introduced in the gas; the UV absorption dissociates the ozone molecules, leading to localized heating of the surrounding gas via collisions and subsequent chemical reactions. The resulting gas heating launches mixed acoustic/entropy waves in the gas, which imprint refractive index modulations—thus turning the gas into a diffractive optics.

We will present a comprehensive physical description of these gas optics, as well as new experimental results showing stable diffraction efficiencies above 95% and providing a detailed characterization of these novel optical elements. These results show excellent agreement with our new integrated simulations tools, combining the chemistry, nonlinear hydrodynamics and wave optics involved in the process.

The high performance of gaseous optics, their high optics damage threshold and their transient nature (microsecond lifetimes, can be re-created at high repetition rate) make them well suited for a broad range of applications, including as final optics for future inertial fusion energy facilities.

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, and funded by the LDRD Program at LLNL under Project Tracking Code No. 24-ERD-001.

O 078 - Development of a high-current, high fusion performance scenario on JET: physics insights and operational challenges

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ABSTRACT TEXT

Since the installation of a Be-W first wall on JET a scenario development programme has taken place to realize a high-current scenario, with $q_{95} \sim 3$, $\beta_N \sim 1.8$ and capable of delivering high fusion performance for 5 s in the D-T campaigns in 2021 and 2023.

The JET baseline scenario was realized in D-T at 3.5 MA in 2021 (DTE2 campaign), but, despite achieving transitorily $P_{\text{fusion}} \sim 8$ MW, it could not be sustained for more than 3 s. Analysis and modelling showed that this was due to two main factors: the improved particle confinement in D-T resulted in higher densities for the same plasma current leading to higher levels of radiated power and lower margin above the L-H threshold with respect to D, and the compound ELMs to flush the W was more difficult to induce in D-T for the same gas throughput as in D.

The results of the analysis suggested running the scenario at 3 MA and with increased fuelling to sustain it for 5 s with less concern for the fusion performance. These modifications allowed to run the scenario for 5 s until the programmed end of the discharge. The 5 s 3 MA baseline plasma produced 18 MJ of fusion energy over 5 s with ~ 30 MW of additional power, a modest performance compared to the record fusion power obtained in DTE2, but provided valuable insight into critical aspects of operation at high current in a W environment such as margin above L-H threshold, W transport in the plasma core, pedestal and SOL and details of the heat and particle sources. Many of these points are potentially relevant for bigger machines such as ITER.

In this paper we revisit the analysis of the 3.5 MA unsustained version of the baseline scenario and present the new results obtained at 3 MA in DTE3. We also review recent simulations showing how available transport models applied to core and core-SOL can explain phenomena ranging from fusion performance, impurity transport and control of the fuelling mix. Finally, we discuss open questions and improvements to our present modelling capabilities required to extrapolate the results to a power plant.

MCF 5 - Tokamak scenarios I (challenges)

O 079 - Role of plasmoid drift in the efficiency and reliability of shattered pellet injection

Mengdi Kong¹, Eric Nardon², Daniele Bonfiglio³, Matthias Hoelzl⁴, Di Hu⁵, Stefan Jachmich⁶, Umar Sheikh¹, Weikang Tang⁴, Grant Bodner⁷, Nicholas Eidietis⁷, Roman Samulyak⁸

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ABSTRACT TEXT

Shattered pellet injection (SPI) is the primary strategy for the disruption mitigation system (DMS) in future large tokamaks including ITER to prevent disruption-induced damage [1]. Among this, deuterium (D2) SPI was envisaged to address runaway electron (RE) avoidance in ITER via a strong dilution cooling before the thermal quench [2]. However, our recent interpretative modelling of D2 SPI into a JET H-mode plasma using the 3D non-linear MHD code JOREK demonstrates that the $\mathbf{E} \times \mathbf{B}$ drift of the ablation plasmoid towards the tokamak low field side (LFS) could substantially limit the core density rise needed for RE avoidance, where $\mathbf{E}$ and $\mathbf{B}$ refer to the electric and magnetic field, respectively [3]. This limits the effectiveness of the LFS D2 SPI strategy. To clarify the fundamental process affecting plasmoid drift, we performed further 3D MHD modelling with a simplified setup in JOREK and reached quantitative agreement with existing plasmoid drift theory [4]. To overcome the limited efficiency of D2 SPI in RE avoidance of future tokamaks, a plausible alternative is to use a so-called trace neon SPI scheme, where a small percentage of impurities (typically neon) is added to the hydrogen-isotope SPI. This is envisaged to reduce the pressure imbalance of the plasmoid via stronger local radiation of impurities, thus suppressing plasmoid drift and improving core density rise [5]. Experiments with trace neon SPI were conducted in the final experimental campaigns on JET and provide a valuable comparison for the simulations. JOREK modelling is on-going to examine this scheme, which is crucial for developing injection schemes for the ITER DMS. In this work, we will discuss the role of plasmoid drift in the efficiency and viability of SPI (including trace neon SPI) in disruption mitigation, combining theory, numerical modelling and experimental analyses achieved so far.

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MCF 5 - Tokamak scenarios I (challenges)

O 080 - Validation of tungsten erosion and transport simulations in tokamaks

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ABSTRACT TEXT

Predictive simulations of tungsten (W) erosion and transport in Joint European Torus (JET) plasmas are demonstrated to align with the experimentally inferred W density in the main plasma, within the modelling uncertainties arising from the accuracy and coverage of the measured deuterium plasma conditions [1]. The plasma scenarios investigated include a steady-state L-mode plasma as well as time-dependent simulations of type-I ELMy H-mode plasmas in JET with heating power up to 34 MW.

The ERO2.0 code [2] is employed to model W erosion and edge transport, and the JINTRAC [3] suite of codes is used to simulate W transport from the pedestal top to the core plasma. The neoclassical cross-field transport of W is predicted by the FACIT [4] code in the ERO2.0 simulation domain and by NEO [5] within JINTRAC. Turbulent transport is predicted by a surrogate model trained on QualiKiz simulations [6], with transport coefficients adjusted in the pedestal to reproduce the measured electron density and temperature gradients.

Several upgrades to the physics models were newly implemented in ERO2.0, applied for the first time and validated in this study: 1) Non-Maxwellian energy distributions for charge-exchange neutrals imported from kinetic EIRENE simulations. 2) The centrifugal effect inducing poloidal W asymmetries due to plasma rotation. 3) Spatially non-uniform anomalous cross-field transport coefficients. 4) Time-dependent plasma conditions representing a cycle consisting of pre-ELM, ELM, and post-ELM phases. 5) A model describing the flushing of W from the confined plasma by ELMs based on the measured time evolution of the plasma stored energy. All of these upgrades were crucial in achieving code-experiment agreement on the W density profiles in the H-mode scenarios.

The predicted neoclassical ion temperature screening of W reduces the W density in the plasma via outward convection near the pedestal top during the pre-ELM phase of the JET hybrid scenario [7], consistent with statistical analysis of the experimentally observed screening of W [8] and highly relevant to ITER [9]. In higher-collisionality JET H-mode scenarios, strong inward convection of W is predicted during the inter-ELM phase, followed by outward flushing and increased W erosion due to the ELM crash.

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MCF 5 - Tokamak scenarios I (challenges)

O 081 - Full-discharge simulations of TCV using the Fenix flight simulator

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ABSTRACT TEXT

Tokamak flight simulators aim to simulate the entire tokamak plant (including the controllers, observers, and actuators) over a full discharge, using as only inputs the signals going into the tokamak. Such simulations are an important final test to check if the planned discharge will achieve the intended schedule. In addition, they can also be used to design experiments and test different controllers. In this contribution, we show full-discharge simulations for TCV with the Fenix flight simulator, which was originally developed for AUG [1,2].

We demonstrate the workflow of the coupling between the ASTRA-based Fenix flight simulator, the FGE free boundary equilibrium code of the MEQ suite [3] that is widely used for TCV operation and analysis, and the TCV magnetic controller [4]. In particular, the recently developed magnetic shape controller is added to the framework (in addition to the usual RZIp-hybrid controller).

Using these tools, we simulate a number of TCV discharges, focusing on the dynamic phases, which are typically complex phases in terms of control requirements and are usually not studied as extensively in first-principle simulations. For a TCV ITER baseline discharge, we show that Fenix is capable of simulating the ramp-up phase with the transition from a limited to a diverted equilibrium, the L-H transition provoked by NBI heating, and the flattop phase following it. Furthermore, cases are studied in which the triangularity is scanned during the discharge. In general, adequate matches of both equilibrium and kinetic profiles are found between simulation and experimental data obtained from kinetic equilibrium reconstruction. These results provide the necessary confidence to use Fenix for preparing future discharges and for testing different control strategies on TCV.

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MCF 5 - Tokamak scenarios I (challenges)

O 082 - Time evolved current drive modelling of solenoid-free microwave start-up in tokamaks

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ABSTRACT TEXT

Understanding the solenoid-free start-up of tokamaks is critical to successful power plant design. Start-up involves the plasma ionisation, initiation of a plasma current and current drive until closed flux surfaces are formed and the plasma is confined. This phase is different to the flat-top due to the open field lines, additional current drive mechanisms, inclusion of ionisation physics and low densities and temperatures. At present, most experimental tokamaks start-up with a central solenoid. However, solenoid-free microwave start-up has significant advantages for power plants as the microwaves can be used for current drive over the duration of the pulse and the technology is relatively robust to the harsh conditions. This is particularly attractive for spherical tokamaks like STEP with limited space in the centre column for a shielded solenoid.

Nevertheless, start-up is not well understood. Previous work has interpreted experimental results to propose potential mechanisms for the formation of closed flux surfaces [1]. However, there is currently no way to predict the time evolution of the current drive and plasma parameters. We have developed a novel Fokker-Planck solver Start-Up Modelling of Microwaves In Tokamaks (SUMMIT) to simulate microwave start-up in time. SUMMIT accounts for the changing field structure from open field lines, along which many particles are lost, to closed flux surfaces as well as microwave diffusion, collisional diffusion, plasma back emf and particle sources due to ionisation. This enables the interaction and relative importance of different current drive mechanisms and plasma parameters to be explored as the plasma evolves. Detailed comparisons with microwave start-up experiments performed on MAST [2] have shown remarkable agreement and explained results not fully understood at the time. In particular, the lost particles are found to play a crucial role in the current drive. This new understanding can be used to inform the design of future experiments and power plants.

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MCF 5 - Tokamak scenarios I (challenges)

O 083 - Thermal quench induced heat fluxes on ASDEX Upgrade

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ABSTRACT TEXT

Unmitigated disruptions pose a risk for tokamak operation. This holds for many scenarios on current day devices and will affect all larger machines currently in the planning or building phase. Therefore, disruptions must be avoided or sufficiently mitigated. While some aspects have been studied extensively, the divertor heat fluxes have received less attention. During the thermal quench (TQ), most of the plasma thermal energy is lost via radiation or conducted to the divertor. The resulting heat-flux does not lead to long-term operational consequences for present day devices however, this does not hold for next step devices.

Previous work has established estimations for the TQ duration, the energy fraction conducted to the divertor, and the area subjected to the peak heat-flux [1]. However, extrapolation to future devices requires a multi-machine scaling, which is incomplete. In particular, the time scale of energy deposition in the divertor, which is different from the core collapse time, needs further investigation.

The TQ peak energy fluence (determined by peak heat flux, deposition time and affected area) is of interest, as it determines the possibility to melt plasma facing components, which in turn constrains the required efficiency in terms of radiated energy fraction of a mitigation system. An infrared diagnostic system, that measures the divertor temperature has been operating at ASDEX Upgrade (AUG) for the last three decades. With this system the TQ fluence can be determined. While most disruptions in AUG are mitigated, a sufficient amount of unmitigated cases is available.

A database of unmitigated TQ phases has been constructed including a variety of different scenarios. This allows the investigation of the TQ dependence on various parameters, such as stored energy, pressure, impurity concentration, and pedestal height. The database includes AUG operation with both carbon and tungsten plasma facing components, allowing the study of the effect of wall material. A TQ fluence model is under development following the principles used in the [2] ELM fluence model.

Comparable infrared systems are available in other devices such as JET. Towards a multi-machine database, efforts are ongoing to include this data.

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O 084 - Direct Imaging of Wakefields Generated by Structured Light

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ABSTRACT TEXT

Since their inception [1], laser-wakefield accelerators (LWFAs) have shown their capability to produce high-quality, monoenergetic electron beams [2–4]. Yet, the push toward higher electron energies and more efficient accelerators is constrained by several limitations. Foremost among these are the dephasing and diffraction limits [5,6]. A promising strategy to address these issues involves using structured light to modulate the on-axis propagation velocity in LWFAs [7–11]. By pairing the diffraction-resistant properties of Bessel beams with spatio-temporal pulse shaping, this approach offers an unprecedented combination of extended acceleration lengths and strong acceleration gradients [10–11]. Here we present the first experimental observation of wakefields driven by such structured beams. Spatio-temporally tailored pulses are directed through a specialized focusing mirror to form a quasi-Bessel beam, and the resulting wakefield is directly probed using femtosecond relativistic electron microscopy [12–13]. Simulations corroborate the experimental data, offering novel insights into this underexplored regime. We show an experimental demonstration of the ability to modify the on-axis propagation velocity of the wakefield [14]. We track the wakefield’s evolution throughout the focal region and examine how specific spatio-temporal manipulations influence both its structure and propagation velocity. Finally, we present the first results using such wakefields to accelerate electrons [15]. These findings establish a foundation for harnessing structured-light-based strategies to overcome dephasing in LWFA.

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O 085 - Highly efficient laser wakefield accelerator and gamma/neutron sources

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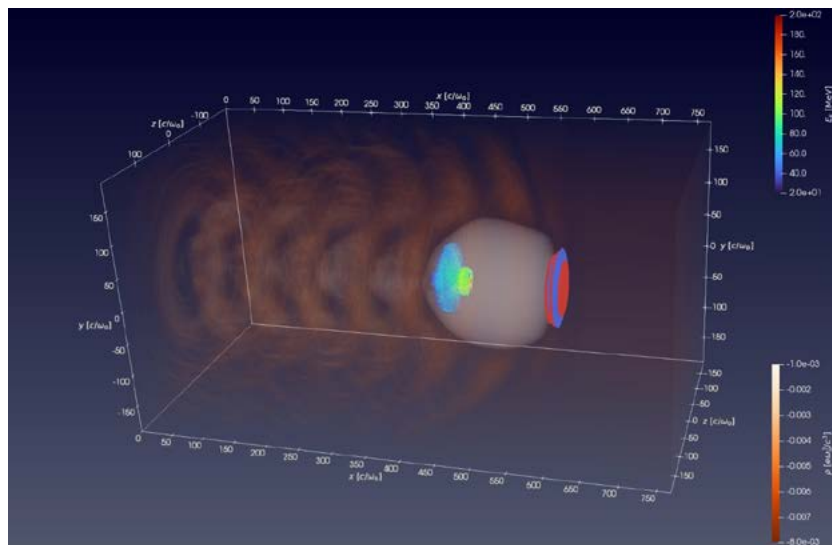
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ABSTRACT TEXT

Recent advancements in ultrashort, few-cycle laser pulses, enabled by thin film compression, have achieved 100 TW-class peak power at 10 Hz repetition rates. We explore the potential of these pulses for highly efficient laser wakefield acceleration of electrons. Numerical simulations predict the generation of nC-class electron bunches with energies exceeding hundreds of MeV, achieving over 50% energy transfer from the laser pulse to electrons above 15 MeV [1]. In this regime, a rapidly depleting pulse drives a strong cavitated wakefield. The self-steepening of the pulse continuously extends the plasma bubble, sustaining massive self-injection and resulting in exceptionally high-charge electron beams.

This approach shows promise for applications such as Bremsstrahlung emission and tertiary particle generation. Up to 30% of the laser energy can be converted into hard X-rays (>10 keV) due to the high efficiency of radiation losses from electrons exceeding 100 MeV, surpassing collisional losses. These X-rays can facilitate neutron production via photonuclear reactions, with simulations indicating the release of 8×10^8 fast neutrons from a 1.5 cm-thick lead converter [2]. Considering the potential high repetition rate operation, this scheme represents a major advancement toward applications like fast neutron resonance radiography and fast neutron activation.



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O 086 - Radiative betatron losses drive phase-space shaping and hollow beam formation in wakefield acceleration

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ABSTRACT TEXT

We investigate the role of extreme betatron oscillations in wakefield-accelerated beams, where betatron losses become a dominant factor in beam dynamics. In high-density plasmas within the bubble (or blowout) regime, relativistic beam particles radiate photons with energies comparable to their initial kinetic energy and at rates comparable to their acceleration. The radiated power scales with the square of the oscillation amplitude, leading to nonlinear cooling that varies across phase space. Similar to synchrotron radiation in magnetic fields [1,2], this cooling modifies the beam's kinetic properties, reshaping its momentum and spatial distribution and driving the formation of hollow beams with pitch-angle anisotropies. We derive characteristic timescales for this process and confirm our findings through Particle-in-Cell simulations using OSIRIS [3,4]. This mechanism fundamentally alters beam dynamics, constraining acceleration energy gains at high densities while also enabling hollow beams that can drive coherent radiation processes [5].

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BPIF 5 - Laser-plasma acceleration of particles and plasma-based radiation sources 1

O 087 - Self-modulated laser wakefield acceleration of μC -level relativistic electron beams at the LMJ-PETAL facility

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ABSTRACT TEXT

This work presents the results of an underdense laser-plasma acceleration campaign carried out at the LMJ-PETAL laser facility in 2023. The goal of the campaign was to generate and characterize relativistic electron beams in the self-modulated regime of laser wakefield acceleration (SMLWFA). We focused the PETAL laser beam (700 fs, 360 J) onto the edge of a newly commissioned supersonic helium jet using two different nozzle designs (4 mm and 10 mm diameter, and peak pressures around 50 bars) with initial electron densities in the 10^{18} – 10^{19} cm^{-3} range for a total of 5 laser shots. The accelerated electron spectra, measured with the SESAME charged-particle spectrometer, displayed 2-temperature distributions with energies beyond 150 MeV. The beam charges and spatial profiles were also characterized with a radiographic cassette held near the target chamber center (TCC) comprising an Imaging Plate (IP) stack as well as nuclear activation pellets. The electronic charges carried by the beams are shown to be on the order of a few 100 nC, with a single shot presenting a record-breaking total charge exceeding 1 μC . The beam properties show good agreement with large-scale 3D particle-in-cell simulations performed with the CALDER code. These results open the way towards applications of high-charge relativistic electron beams such as the production of secondary particle sources, the radiography of high energy density environments and inertial confinement fusion experiments.

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O 088 - A new facility dedicated to laser-plasma accelerator based very-high-energy-electron radiotherapy

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ABSTRACT TEXT

The notion of utilizing very high energy electrons (VHEE) in the 200MeV range for treating deep-seated cancerous tumors has recently gained traction in the particle accelerator community. As a result, numerous technical advances aimed at developing medically sound conventional and non-conventional electron accelerators have emerged. Since late 2022, the European Innovation Council has been funding eBeam4Therapy, a project with the goal of optimizing VHEE beam performances for radiotherapy applications. This involves characterizing the 3D dose deposition, improving and scaling down each component of the machine, and ultimately building a laser-plasma accelerator that demonstrates technical feasibility while being economically competitive. In this discussion, we will explore the novelty of the project, the physics of electron acceleration at its heart, and the interaction between VHEE and tissues.

BPIF 5 - Laser-plasma acceleration of particles and plasma-based radiation sources 1

O 089 - Laser-driven radiation sources for cultural heritage: laser-driven PIXE and XRF on historical and archaeological artifacts

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ABSTRACT TEXT

Non-destructive elemental analysis techniques such as Particle Induced X-Ray Emission (PIXE), and X-Ray Fluorescence Spectroscopy (XRF) are widely employed across multiple scientific disciplines due to their unparalleled sensitivity trace elements. PIXE, particularly effective for low-Z materials, enables trace element detection at the parts-per-billion level [1], making it an effective instrument for provenance studies in archaeology and material characterization in artwork conservation [2]. However, its reliance on electrostatic accelerators limits its portability and in situ applications, which are often required in Cultural Heritage (CH) research. In contrast, XRF is more effective for high-Z materials and is commonly used in portable setups [3]. Despite this, XRF alone lacks the ability to analyse low-Z elements as effectively as PIXE. Only few instruments combine PIXE and XRF into a single measurement system, maximizing their complementary strengths.

Laser-driven accelerators based on solid targets can offer a promising alternative by enabling compact and potentially portable PIXE-XRF setups [4,5]. When an ultra-fast (~ 10 fs), high-intensity ($>10^{18}$ W/cm²) laser interacts with thin ($\sim \mu\text{m}$) solid targets, it generates a mixed radiation field, which includes characteristic X-rays, high-energy electrons, and accelerated ions with a broad quasi-exponential energy spectrum. This approach enhances versatility and potential portability.

In this contribution, we present a proof-of-principle experiment demonstrating laser-driven PIXE-XRF in air on CH materials. Using the ELIMAIA beamline (ELI Beamlines), driven by the HALPS laser, and a CCD camera in single photon counting mode, we analysed certified reference materials and CH artifacts (medieval bronzes, iron age ceramics). Accelerated protons and X-rays from target were brought in air through a versatile setup based on a proton magnetic spectrometer [6] and were fully characterised, to allow for quantitative analyses. These results lay the foundation for the development of laser-based accelerators tailored for CH studies, suggesting that, with further optimisation, this approach could achieve elemental sensitivity comparable to conventional sources while maintaining the inherent compactness and versatility of laser-driven systems.

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LDP3 - Dusty and strongly coupled plasmas

O 090 - Annihilation gamma spectra of magnetically confined positrons scattering, forming positronium, and cooling

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ABSTRACT TEXT

The 511-keV line is the strongest gamma-ray line from outside the solar system and its interpretation could provide insight into the makeup of interstellar clouds in which energetic positrons slow down and eventually annihilate [1]. It is crucial to study systems where positrons undergo numerous collisions with neutrals to accurately interpret the gamma spectra, given that the cross-sections are energy dependent and collisional cross-sections are significantly larger than those of annihilation [2]. This study utilizes positrons confined to the closed dipole field of a permanent magnet trap to measure positron collisions with gas [3], as opposed to traditional transient positron beams. An array of 21 gamma detectors situated in re-entrant ports 1 cm from the confinement volume detects 10^4 gammas per shot [4]. Processing on FPGAs timestamps and records the energy of each detection [5]. The time and energy spectra of annihilation indicate a transition in confinement losses from charge exchange mediated positronium formation and decay to collisional transport to the walls. When CF_4 , a molecular gas, is introduced into the confinement volume, the transition time shifts earlier, suggesting positronium formation is cut off by inelastic scattering cooling positrons below the charge-exchange threshold. Positrons are injected into the trap with negligible perpendicular energy and confined by an electrostatic bias on the magnet case. Collisions with neutrals scatter positron pitch angles into magnetic confinement. The evolution of the parallel and perpendicular energy distribution can be inferred by ramping the magnet bias down to negative potentials and detecting the fraction of positrons reaching its surface and annihilating. Elastic and inelastic scattering rates are determined from the evolution of the energy distribution as a function of the hold time. This work paves the way for exploring the interactions of confined positrons and electrons, a diagnostic need of the APEX (A Positron Electron eXperiment) collaboration and its aim of producing magnetically confined positron-electron pair plasma in a levitating dipole and an optimized stellarator [6].

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O 091 - Plasma surface interaction at objects with floating potential

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ABSTRACT TEXT

A plasma as an ionized gas has markedly different properties than a normal gas. Especially the free electrons and ions can be used to trigger and enhance chemical reactions. Therefore, low-temperature plasmas are a working horse of material processing. From etching via deposition to catalytic reactions a huge variety of processes are subject of research or already used in applications [1]. For most of them the plasma surface interaction is strongly influenced by the plasma sheath region, which has significantly different properties than the plasma bulk region. To study the chemical processes in such plasmas is not trivial. The standard approach uses ex-situ diagnostics, i.e. the treated surface is extracted from the plasma device and transferred to a diagnostic device. This approach has some limitations: the surface might change during this process and to resolve the chemical processes temporally is difficult. However, for spherical dust grains it is possible to realize an in-situ Mie-scattering diagnostic which is powerful enough to give detailed information on chemical reaction at the surface and surface modifications. Starting with a brief introduction of the diagnostic itself, this contribution will discuss the surface modification as well as its prospect/impact on low temperature and astrophysical plasmas as well as basic physics [2].

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O 092 - Modelling the evaporation of vacuum arc macroparticles by a beam of energetic electrons

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ABSTRACT TEXT

Arc erosion plasma sources are widely used in modern science and industry. Due to the high deposition rate, they are very productive tools for the synthesis of various functional and protective coatings, for modifying the surface properties of structural and decorative materials. However, the presence of macroparticles from cathode material in the plasma prevents the use of arc erosion sources in applications requiring high-quality coatings, especially those requiring low defect density and low roughness at the nanometer level. In principle, macroparticles can be removed using suitable filters. Their use, however, leads to significant losses of the plasma flow followed by a decrease in the deposition rate, which compromises one of the unique features of these sources, namely their high deposition rate.

A filter concept that evaporates macroparticles without removing their mass from the plasma flow would improve the quality of the coating and increase the deposition rate. That is why alternative concepts to remove macroparticles are of interest. One way to achieve this is to use an electron beam to evaporate the macroparticles.

Here, we discuss an approach using energetic (keV) electrons injected into the arc plasma. They introduce additional energy into the plasma which promotes evaporation of the macroparticles and may eventually lead to complete destruction of macroparticles. By solving a self-consistent system of equations for the energy balance, the ion and electron currents to and from a macroparticle, and the macroparticle mass balance, it is shown that favorable conditions for the evaporation of macroparticles may exist. It is shown that the main parameters influencing the macroparticle evaporation rate are the plasma density as well as the density and energy of the electron beam. It has been shown that macroparticles with a radius of 1 μm or less may completely evaporate during the time about 2 ms if the energy of the electron beam is in the range of 3 to 5 keV and the beam-to-plasma density ratio is greater than 0.01.

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O 093 - Phase separation and scaling laws in binary strongly coupled plasma

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ABSTRACT TEXT

Phase separation is the process by which a homogeneous mixture separates into its constituent components, occurring across various varieties of systems with different lengths and time scales. A common everyday example is the separation of the oil and vinegar mixture. This phenomenon is also observed in binary systems of strongly coupled plasmas, where Coulomb interaction energy dominates over thermal energy. Due to this strong coupling, particles tend to arrange into more ordered structures, leading to phase transitions and intermediate states.

This talk presents an investigation of phase separation in a binary strongly coupled plasma (BSCP) using two-dimensional classical molecular dynamics (MD) simulations [1]. The focus is in the liquid-liquid regime, where particles interact via a screened Coulomb potential (Debye-Hückel potential). Notably, the screening differs between like and unlike species, driving phase separation. MD simulations offer valuable insights into particle-to-system scale dynamics, making them a powerful tool for modeling such plasmas.

We examine the effects of coupling strength and screening parameters on domain growth in both equal (critical mixture) and unequal number density (off-critical mixture) cases. During phase separation, domain growth follows a time-dependent power law, with an exponent factor b characterizing the coarsening mechanism. We demonstrate that the exponent factor is $\frac{1}{2}$ for the equal number density and $\frac{1}{3}$ for the unequal number density case. Our findings reveal that the viscoelastic nature of the plasma modifies the scaling law compared to binary mixtures of viscous fluids, particularly in the unequal number density case [2].

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LDTP 3 - Dusty and strongly coupled plasmas

O 094 - Study of re-deposition dynamics of thin film in rear ablation geometry

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ABSTRACT TEXT

Laser matter interaction has been the subject of considerable research interest due to its diverse applications and the basic scientific interest owing to the large density and its gradients [1]. The processes of melting, evaporation, and the formation of plasma and its dynamics during laser matter interactions have been extensively investigated using variety of methods [2]. The ablation or material removal process largely depends on the ablation geometry and ambience. In addition to the melting process the possibility of re-deposition is significantly high when the background pressure is high. In this study, we present an innovative pump-probe based experimental setup for investigating the process of melting, re-deposition and the plasma plume dynamics, during the rear ablation geometry of a thin film coated on a glass substrate. In this configuration, the probe laser is separated into a transmission and reflection of probe based on the transmission and reflection properties of the matter (plasma/molten surface) under investigation. The ambient conditions influence the formation of plasma as well as the dynamics of the plume, thereby modulating the transmission and reflection of the probe laser. The results show that a portion of the ablated material is getting deposited on the spot of ablation. The study offers valuable insights into the laser-based ablation of thin film coatings, which will have implications for the in situ cleaning of viewports on large experimental facilities, such as tokamak and other systems, coating units, pulsed laser deposition (PLD), laser-induced forward transfer (LIFT), laser surface structuring, and so forth. Furthermore, the results are indicative of inverse bremsstrahlung absorption of the probe pulse in the plasma plume, providing deeper insights into the underlying mechanisms [3]. Relevant experimental configurations and results will be discussed in detail.

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BSAP 3 - Fundamental plasmas

O 095 - Universal fluctuation spectrum of Vlasov–Poisson turbulence

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ABSTRACT TEXT

The ‘thermal’ fluctuation spectrum of the electric field arising due to particle noise in a quiescent Vlasov–Poisson plasma was derived in the 1960s. Here, we derive a universal fluctuation spectrum of the electric field, at Debye and sub-Debye scales, for a turbulent Vlasov–Poisson plasma. This spectrum arises from what is likely to be the ‘final cascade’—a universal regime to be encountered at the extreme small-scale end of any turbulent cascade in a nearly collisionless plasma. The cascaded invariant is C_2 , the quadratic Casimir invariant of the particle distribution function. C_2 cascades to small scales in both position and velocity space via both linear and nonlinear phase mixing, in such a way that the time scales associated with the two processes are ‘critically balanced’ at every scale. We construct a scaling theory of the fluctuation spectrum of C_2 in (k, s) space—and hence of the electric field in k space—in arbitrary dimensions, where k and s are the spatial and velocity wavenumbers, respectively. The electric-field spectrum is sufficiently steep for the nonlinear mixing to be controlled by the largest-scale electric fluctuations, and so the C_2 cascade resembles the Batchelor cascade of a passive scalar, albeit in the kinetic phase space. The conclusions of our theory are corroborated by direct numerical simulations of a forced 1D-1V plasma. We predict that the cascade is ultimately terminated at the (spatial) wavenumber where the turbulent electric-field spectrum gives way to the fluctuation spectrum associated with discrete particle noise; this transition scale is set by the amplitude of the turbulent electric fields and the plasma parameter. The characteristic time scale for this small-scale cutoff to be reached is the dynamical time of phase-space mixing times a logarithmic factor in the plasma parameter—this is the first concrete demonstration of this property of Vlasov–Poisson turbulence, analogous to how fluid turbulence dissipates energy at a rate (nearly) independent of molecular diffusion. In the presence of the phase-space cascade at Debye and sub-Debye scales—a scenario that may be ubiquitous—standard collisional plasma theory ceases to be valid. This calls for the development of new collision operators suited to such turbulent environments.

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BSAP 3 - Fundamental plasmas

O 096 - Data-driven modelling of collisional kinetic plasma dynamics

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ABSTRACT TEXT

Computational plasma physics has seen significant advances in the ability to model nonlinear plasma dynamics from first principles. However, capturing the complex multi-scale dynamics of plasmas, especially in non-equilibrium and strongly coupled regimes, remains challenging. This talk will highlight recent work that explores the potential of combining machine learning algorithms with traditional plasma kinetic simulation frameworks to address these challenges.

The first part of the talk will focus on integrating Graph Neural Networks (GNNs) as surrogate models for kinetic plasma simulators [1]. We demonstrate that GNNs can accurately replicate the dynamics of a one-dimensional plasma for arbitrary degrees of collisionality, and generalize effectively to conditions well beyond their training data. We also show that GNNs can implicitly learn a computationally efficient collisional operator in 1D. In the second part, we discuss the use of self-consistent electromagnetic Particle-in-Cell (PIC) simulations that resolve the inter-particle fields that mediate collisional interactions to guide the development of data-driven, collisional operators [2]. These data-driven operators can shed light on the nature of collisions in strongly coupled regimes and, in the future, elucidate how collisional operators are modified in far-from-thermodynamic-equilibrium conditions.

We conclude with a discussion on the possible directions for higher-dimensional surrogate models of kinetic plasma dynamics and the opportunities presented by existing high-fidelity data from state-of-the-art kinetic simulators.

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O 097 - Universal equilibria, phase-space structure of collisionless plasma systems, and turbulence in non-Maxwellian plasmas

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ABSTRACT TEXT

A fundamental tenet of thermodynamics is that chaotic systems will relax to maximum-entropy states. In plasmas, the chaos is conventionally provided by interparticle collisions and the universal maximum-entropy equilibrium is a Maxwellian distribution. However, in collisionless plasmas, relaxation via collective turbulent dynamics can push the system towards a non-Maxwellian equilibrium long before collisional effects take over. Like collisional plasmas, this collisionless relaxation can be described by an effective ‘collision integral’ which maximises the entropy of the system, reaching maximum entropy distributions which we derive. These maximum entropy states preserve certain short-time collisionless invariants—associated with the incompressibility of phase space—which endows the system with a partial ‘memory’ of its prior conditions. We will argue theoretically and show numerically that this memory is broken by a turbulent cascade to small scales in phase space, which breaks the precise conservation of phase volume. The equilibria are still determined by the short-time collisionless invariants, but the invariants themselves are driven to a universal form by the nature of the turbulence. We apply this theory to the case of beam-driven instabilities in one-dimensional electrostatic plasmas, where sufficiently strong turbulence causes the distribution function of particle energies to first rapidly become Maxwellian, then subsequently develop a power-law tail, with exponent -2 .

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BSAP 3 - Fundamental plasmas

O 098 - Phase-space electron-hole dynamics in 1D-1V kinetic plasma

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ABSTRACT TEXT

Single electron-hole dynamics are investigated through kinetic Vlasov-Maxwell simulations of a one-dimensional plasma composed of two species, electrons and protons, with a reduced mass ratio. This investigation is not merely of theoretical curiosity but critical for the understanding of a wide range of natural phenomena, such as those in space and astrophysical plasmas [1,2], such as those observed in the Earth's magnetosphere [3,4] or magnetic reconnection events [5,6] where collision-less plasmas prevail.

The electron-hole's acceleration and growth-rate of phasetrophy is methodically investigated through parameter scans as a function of different plasma and electron-hole parameters, such as the electron mean velocity $v_{0,e}$, initial hole velocity v_h , electric potential amplitude ϕ_0 , and gradients of the distribution functions $\partial_v f_{0,e}(v_h)$ and $\partial_v f_{0,i}(v_h)$.

A first study shows two different regimes of positive exponential increase for the electron-holes phasetrophy growth-rate at both positive and negative gradients from both sides of the electron distribution function. A linear increase of the electron-hole's phasetrophy growth-rate is measured as a function of both ion and electron equilibrium distribution functions. And finally, two power laws are measured for low-amplitude and high-amplitude regimes as a function of the electric potential amplitude. Moreover, a qualitative agreement between measurements of phasetrophy growth-rate and an effective gradient, which considers the variations and effects of the electron distribution function gradients over the electron-hole's width, is also observed.

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O 099 - Quantum numerical scheme for multidimensional transport equations

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ABSTRACT TEXT

Simulating complex physical phenomena appearing, for example, in nonlinear dynamical systems and plasma dynamics, is computationally demanding on classical computers, due to high memory requirements and long simulation times. Quantum computing presents a promising alternative for solving partial differential equations (PDEs), offering potential advantages in memory efficiency and computational speed.

This work introduces a quantum numerical scheme for solving multidimensional transport equations with position- and time-dependent coefficients. The approach consists of three main steps: initialization, evolution, and measurement. Initialization is performed through a quantum state preparation protocol, while the evolution step utilizes product formula methods after discretizing space and time. The evolution is implemented through a combination of quantum Fourier transform and diagonal unitaries. The quantum state preparation and the diagonal unitaries can be efficiently implemented on digital quantum computers using sparse Walsh series. A detailed analysis of space discretization errors and product formula approximations is provided, alongside numerical simulations. This approach is relevant for solving the Vlasov equation with external electromagnetic fields or for simulating non-linear dynamical systems via their associated Liouville equation.

Plenary Session 5

O 101 - Insights from JET high fusion power scenario in the final D-T campaign

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ABSTRACT TEXT

Thermonuclear fusion is achieved by heating 50/50 D/T mixture to high temperatures. However, it is also possible to achieve significant fusion power by selectively heating minority fuel component in hot plasma composed mainly of the other fuel species. In that case, the minority species will have a non-Maxwellian distribution function with significant fraction of ions reaching energies where the maximum of the D-T reaction cross section occurs.

That approach has been implemented at JET and led to the record fusion energy output of 69MJ in the final DT experiments(DTE3). It was achieved by injecting deuterium neutral beams (D-NBI) into tritium plasmas with ion cyclotron resonance heating (ICRH) tuned to be absorbed by deuterium ions[1]. The properties of such plasmas are different from a conventional thermonuclear reactor. The plasma composition must remain tritium-rich to maximize the number of beam-target reactions, i.e. deuterium injected by D-NBI must be efficiently removed from the plasma core after thermalisation. Intense NBI heating causes large density gradients and plasma rotation which are unfavourable conditions if high-Z impurities are present.

Accumulation of high-Z impurities was the main factor limiting fusion performance in DTE2 (2021)[2]. Further experiments were made in DTE3 with the goal to achieve stationary plasmas with higher fusion power. The goal was partially accomplished by substantially increasing the ICRH power, but the best performing discharge still suffered from gradual accumulation of impurities. At some point during the discharges, a region of improved confinement—internal transport barrier (ITB)—was formed transiently. Usually this is considered beneficial for fusion plasmas, but in beam-target scenario it can amplify the inward impurity convection which ultimately leads to plasma degradation. That effect was an unintentional consequence of the specific plasma current profile tailoring and likely could be avoided if JET was equipped with current-drive capabilities.

While the beam-target driven fusion cannot be a solution for efficient fusion power generation, its potential to create high neutron fluences in relatively compact volumetric neutron source (VNS) devices might play a key role on the roadmap to development of commercial reactors[3]. Various physics aspects of such machines have been successfully proven at JET in its final years of operations.

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Plenary Session 5

O 102 - Quantum computing for plasma simulations: Opportunities and challenges

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ABSTRACT TEXT

Modern plasma physics and its applications in astrophysics and fusion energy sciences has come to rely heavily on state-of-the-art computation. Many of the key discoveries of the last couple of decades have been driven by advanced numerical simulations performed in the world's leading supercomputers, and the expectation is that further significant progress is tightly coupled to algorithmic advances and hardware improvements. On the other hand, the simulations that can be performed in today's, and near future, computational platforms often remain orders of magnitude smaller than required by the parameters of the environments that they are trying to simulate. Inevitably, a computational paradigm shift is necessary if we are to perform realistic simulations of many of the problems that drive research in this field. Quantum computers have the potential to offer up-to-exponential speed-ups for at least some types of applications. However, it is unclear how one might develop efficient quantum algorithms for the typically highly nonlinear problems that plasma physics and its applications deal with. This talk aims to explore initial ideas along these lines, as well as share some reflections on what is necessary for plasma physics to benefit from the advent of this novel computational platform.

Plenary Session 5

O 103 - Plasma electrification: A promising route for sustainable production of fuels and chemicals

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ABSTRACT TEXT

The conversion of inert molecules with strong chemical bonds, such as CO₂, CH₄, and N₂, into value-added synthetic fuels and platform chemicals has attracted significant attention. However, activating these molecules remains a great challenge due to their thermodynamic stability, which necessitates substantial energy input. Non-thermal plasma (NTP) has emerged as a promising technology for gas conversion under ambient conditions, offering a pathway to overcome these challenges. The integration of NTP with heterogeneous catalysis holds great potential for achieving synergistic effects, as the interaction between plasma and catalysts can activate catalysts at low temperatures, enhance their activity and stability, and significantly improve conversion, selectivity, and yield of desired products. Additionally, this approach can enhance the overall energy efficiency of the process. A notable advantage of plasma-based processes is their ability to be instantaneously switched on and off, providing exceptional flexibility for decentralized fuel and chemical production. This feature is particularly advantageous when coupled with renewable energy sources, especially intermittent ones. This presentation will explore the challenges and opportunities in plasma-catalytic gas conversion for fuel and chemical synthesis, focusing on key chemical processes such as CH₄ activation, CO₂ conversion, and nitrogen fixation. The discussion will highlight the potential of this technology to drive sustainable and efficient fuel production in the future.

MCF 6 - Tokamak scenarios II (no-ELM regimes)

O 104 - Building a path towards a negative triangularity fusion reactor with gyrokinetic simulations and experiments on TCV

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ABSTRACT TEXT

Since the first experiments on the TCV tokamak [1], many advances have been made in the study of Negative Triangularity (NT) plasmas. It is now well established that NT plasmas close access to H-mode [2,3], creating the most robust ELM-free scenario known, while greatly stabilizing turbulent transport to achieve H-mode-like performance [4–8]. These features make NT an attractive alternative to fusion power plant (FPP) concepts based on the Positive Triangularity (PT) H-mode scenario. However, the conceptualization of an NT FPP is still at an early stage and some important questions remain unanswered.

In this talk, we will show important new results obtained within the EUROfusion's WPTE-RT-02 and TSVV-02 that answer some of these open questions. Using gyrokinetic simulations, we show how plasma parameters such as elongation, aspect ratio, magnetic shear, plasma beta and collisionality affect the beneficial impact of NT on confinement. By systematically analyzing these factors, we gain valuable insights into how NT can be optimized to enhance performance in fusion devices. Furthermore, we will present a simple but effective model that explains the role of triangularity (and shaping in general) in influencing turbulent transport. Specifically, we will apply this model to Ion Temperature Gradient (ITG) modes, Trapped Electron Modes (TEM), and Micro-Tearing Modes (MTM).

On the experimental side, we will show TCV results that explore the feasibility of different NT scenarios for DTT, a next-generation tokamak currently under construction in Italy. The experimental results show that NT scenarios can achieve similar performance to PT H-mode plasmas and highlight the importance of the plasma edge in sustaining these results. Lastly, we will present a study that explores whether reducing the external heating of NT plasmas provides a path to increase the power multiplication Q of future fusion reactors. Using a simple zero-dimensional model based on observations from the NT TCV database and experiments on DIII-D [3,6], we find that NT plasmas with only Ohmic heating can outperform externally heated plasmas in machines with high magnetic field and/or large fusion gain.

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MCF 6 - Tokamak scenarios II (no-ELM regimes)

O 105 - Characterization of edge modes in different confinement regimes

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ABSTRACT TEXT

For future reactors based on the tokamak concept, it is necessary to establish high-confinement modes without type-I edge localized modes (ELMs). Several natural ELM-free operation scenarios like the enhanced α high-confinement mode (EDA H-mode), the quasi-continuous exhaust regime (QCE), the intermediate phase (I-phase) or the improved energy confinement mode (I- mode) have been studied in ASDEX Upgrade. Each regime exhibits characteristic edge fluctuations that are responsible for the ELM stabilization in their respective improved energy confinement regime [1]. The key to extrapolating scenarios for large machines such as ITER is to understand the physical nature of these edge modes. For the first time, a quantitative analysis of the edge modes in four different ELM-free regimes has been carried out using a newly installed thermal helium beam (THB) diagnostic [2]. The THB diagnostic routinely provides key mode characteristics like phase velocity, wavenumber and radial localization from electron density and temperature fluctuations. A large database of mode properties in different plasma regimes makes it possible to identify trends and thus the characteristics of the modes. Additionally, quantitative comparisons of the experimental mode properties with simulations are now possible. In particular, simulations with the gyrokinetic code GENE strongly support the experimental findings of resistive and kinetic ballooning modes at the edge in EDA H-modes and QCE scenarios.

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O 106 - Observation of sheared turbulence structure during edge-localized mode suppression with lower hybrid waves on EAST tokamak

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ABSTRACT TEXT

Edge-localized modes (ELMs) could lead to high transient heat loads on the divertor plates, posing critical challenges for the safety of the first wall materials. Similar as external coils, lower hybrid wave (LHW) is an alternative method to generate resonant magnetic perturbation (RMP) and control ELMs. Recently, stable ELM suppression has been successfully demonstrated on the EAST tokamak by using LHW modulation. First, the spatial structure of HCFs induced by LHW is measured by a newly developed DEP diagnostic. A density threshold is discovered to generate considerable LHW HCFs, which is the key dependence of HCFs on plasma parameters. Based on these experimental results, a fine 3D HCFs model is reconstructed by the field line tracing, and the magnetic topology induced by HCFs is analyzed by the MAPS code. The radial magnetic field perturbation calculated by the HCFs model matches that measured by pick-up coils, and the divertor heat flux footprint estimated by the field-line diffusion model is consistent with that of Langmuir probe, demonstrating the validity and accuracy of the HCFs model. When ELM is suppressed, the normalized radial magnetic field perturbation has very good resonant features with the resonant surfaces at the plasma edge. Edge magnetic islands are created by the HCFs, and a stochastic region is formed in the pedestal region. During ELM suppression, the pedestal density decreases significantly, leading to a slightly smaller electron pressure gradient, which shifts the pedestal plasma from the stability boundary of the P-B mode to a stable operational regime. Edge broadband turbulence is enhanced greatly and an ECM is observed in the pedestal region during ELM suppression, which could drive outward cross-field transport. Furthermore, the spatial structure of the ECM measured by GPI is intensively sheared in pedestal, and the turbulence radial velocity also decreases strongly in this region, which agrees with the poloidal structure of local magnetic topology, indicating the existence of magnetic islands or stochastic region, which is a key feature of the physical theory of ELM control with RMPs. This research provides a promising and economical technique to control ELM events in ITER and other fusion reactors.

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MCF 6 - Tokamak scenarios II (no-ELM regimes)

O 107 - A high-confinement, no-ELM regime in JET: the EDA H-mode

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ABSTRACT TEXT

This work presents the achievement of the EDA H-mode in the Joint European Torus (JET) with the beryllium-tungsten wall for the first time, an important milestone in addressing the critical challenge of transient heat loads in fusion reactors. The EDA H-mode is a high-confinement regime without edge localized modes (ELMs) that exhibits several desirable properties for a reactor. Its observation in metallic-walled devices was previously restricted to only Alcator C-Mod [1] and ASDEX Upgrade (AUG) [2], highlighting the relevance of its extension to JET, the world's largest non-carbon tokamak.

The experiments were performed in deuterium, with a toroidal magnetic field of 2.8 T and a plasma current of 1.5 MA. The EDA regime was accessed and sustained by combining ion cyclotron resonance heating, strong plasma shaping, and sufficient fueling. Compared to AUG plasmas with the same heating method, EDA H-modes at JET feature lower pedestal collisionality and higher core temperature at a similar LH-normalized power, $P/P_{LH} \sim 2$. Additional noteworthy qualities include no-torque operation at a high Greenwald fraction with no impurity accumulation despite the absence of ELMs. The plasma edge instead exhibits the main EDA signature, a benign quasi-coherent mode that likely regulates pedestal transport.

In addition to characterizing the EDA H-mode in JET, research directions and implications for upcoming devices are discussed. This is particularly relevant to the full-tungsten ITER and SPARC, which predominantly feature wave-based external heating methods. Overall, the EDA H-mode is a promising regime that could become a key no-ELM scenario in future reactors.

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MCF 6 - Tokamak scenarios II (no-ELM regimes)

O 108 - Progress in the understanding of edge transport in the QCE regime on TCV

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ABSTRACT TEXT

The Quasi-Continuous Exhaust (QCE) regime is an ELM free regime usually achieved with large separatrix density and high plasma shaping. It is believed that the avoidance of Type-I ELMs is the result of an increased turbulent transport by ballooning modes close to the separatrix. To better characterize the transport from the pedestal outwards, measurements of turbulence have been conducted with a set of complementary diagnostics in terms of spatial coverage and measured physical quantities. A standard QCE plasma, obtained with $I_p = 170$ kA, $B_t = 1.4$ T, $q_{95} = 4.7$, $d = 0.5$, $k = 1.5$ and $P_{NBI} = 1.3$ MW [1] was diagnosed with the short pulse reflectometer (SPR) [2], the thermal helium beam (THB) [3], the Doppler Backscattering diagnostic (DBS) [4] and the Gas Puff Imaging (GPI) [5]. The first two (reflectometry) diagnostics (SPR and DBS), provide density fluctuations measurements at different scales from near-SOL to the mid-pedestal with X-mode, and from mid-pedestal to inside the plasma with O-mode. The THB and GPI use the same He beam to probe the SOL up to just inside the separatrix. Enforcing agreement with TS permits extraction of SOL densities profiles at ~ 300 kHz from SPR. Filaments appearing as weakly coherent modes (~ 40 – 60 kHz) are observed close to the separatrix with the DBS (in line with previous results on AUG), the THB and the GPI. Located at different toroidal/poloidal locations, time delays between the DBS and THB/GPI could allow mode characterization. Broadband turbulence is observed in the SOL (THB, DBS) and blob dynamics is further quantified in the SOL with GPI: blobs propagate in the radial direction with velocities up to 1500 km/s. Inside the separatrix, structures propagate in the poloidal direction with velocities consistent between DBS and GPI measurements.

In addition, we will discuss the recent progress made to achieve a QCE regime at $q_{95} < 4$ benefiting from a shot preparation based on FBT-RAPTOR coupling for kinetic equilibrium prediction (KEP) [6].

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O 110 - High-intensity laser-driven collisionless electrostatic shock formation and ion acceleration in a multicomponent plasma

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ABSTRACT TEXT

Shock waves in space, such as supernova remnants and the earth's bow shock, are collisionless shocks generated in collisionless plasmas. These shocks are one of the most promising candidates for the sources of cosmic rays and energetic particles. Thanks to the development of high-power lasers, a new method of studying high-energy astrophysics, such as the formation and evolution of collisionless shocks, in the laboratory, Laser Astrophysics, is emerging. Recently, high-intensity laser-driven collisionless electrostatic shock ion acceleration has drawn attention [1–5]. In this scheme, upstream ions of the shock are reflected and accelerated by the shock potential.

This talk investigates collisionless electrostatic shock ion acceleration in a near-critical-density multi-component plasma. The shocks are driven by a high-intensity picosecond duration laser pulse, and we will present results from both 2D particle-in-cell (PIC) simulations [1–4] and experiments [5]. PIC simulations reveal the excitation and identification of the electrostatic two-stream instability associated with a collisionless shock [2,4] and its effect on ion acceleration [2,3]. The experiments show that protons are the only accelerated ions when a multi-component plasma is driven by a laser with the modest normalized vector potential of $a_0 \sim 2$ [5]. These results of PIC simulations and experiments imply that collisionless electrostatic shocks accelerate selectively only protons.

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BSAP 4 - Laboratory Astrophysics

O 111 - Formation of differentially rotating free-boundary plasmas with x-ray driven plasma flows at the MAGPIE facility

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ABSTRACT TEXT

We will present results obtained using a newly developed experimental platform, fielded on the MAGPIE pulsed-power generator, which uses soft x-rays generated by wire array z-pinch implosions to ablate between 4 and 8 planar or wedge-shaped targets, creating converging plasma flows with non-zero angular momentum. This results in the formation of a stable, hollow, differentially rotating cylinder of plasma which is sustained by the ram pressure of the converging flows. Using measurements including Thomson scattering, interferometry, optical self-emission spectroscopy, and fast gated cameras, we characterise the plasma parameters and rotation of this plasma. By changing the material of the ablating targets, we can investigate radiative effects. The large Reynolds ($Re \sim 10^5$) and magnetic Reynolds ($Rem \sim 20$) numbers, and the possibility to add an axial or cusp B-field, allows a direct test of the effects of magnetic fields on the structure and stability of the rotating plasma. This is relevant to the physics of astrophysical rotating plasmas such as protoplanetary disks and could help improve our understanding of mechanisms such as angular momentum transport in these systems.

O 112 - Simulations and Experiments of Shocks in Weakly Collisional Plasmas

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ABSTRACT TEXT

Simulations and Experiments of Shocks in Weakly Collisional Plasmas

Collisional shocks play a fundamental role in both astrophysical environments and laboratory experiments. The classical fluid structure consists of an ion compression shock embedded within a thermal shock, which is divided into a thermal precursor (ahead of the ion shock) and a relaxation layer (behind the ion shock). This structure serves as a playground for non-thermal effects to emerge [1,2], particularly within the thermal precursor, where fast-moving ions (non-thermal ions) can counter-stream against the bulk flow.

Their propagation depends on the size of the precursor, as they can move through this region with few collisions with the hot plasma. Such kinetic effects modify the shock structure and, under certain conditions, can drive instabilities.

Using high-energy-density laser experiments at the LULI2000 facility, we achieved time-resolved measurements of shock profiles with unprecedented detail. Diagnostics, including Thomson scattering, allowed us to probe ion and electron temperatures and densities across the different regions of the shock structure.

Complementary state-of-the-art MHD and fully kinetic simulations (PIC) are presented to interpret the experimental data and provide insight into the underlying physical mechanisms. FLASH [3], an extended-MHD code, is used to simulate large-scale plasma dynamics under experimentally relevant conditions, guiding the experiments and analyzing the data. Smilei [4], a fully kinetic particle-in-cell code, is used to investigate the mechanisms responsible for generating non-thermal ions through 1D simulations of shock formation and its evolution toward a steady-state condition.

This combined experimental and numerical approach allows us to explore the interplay between fluid and kinetic effects in shocks in weakly collisional plasmas and to investigate the conditions under which kinetic processes arise and influence shock structure.

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BSAP 4 - Laboratory Astrophysics

O 113 - Study of magnetic field compression in plasma for laboratory astrophysics

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ABSTRACT TEXT

Compression of magnetic fields are an active area of research in astrophysics [1]. Indeed, this mechanism of particle acceleration takes place at different scales of the Universe, such as within interactions between solar wind and planetary magnetospheres, interactions between supernova remnants or even between galaxies magnetic fields.

The mechanism of compression occurs when magnetized HED plasmas collide in a parallel configuration. Then, a rise of the temperature and density gradients is observed in the colliding zone, leading to an increasing value of the magnetic field localized in this zone. This mechanism has been studied using the high-power laser facility LULI2000 (École Polytechnique). We used simultaneously two nano-second long lasers to ionize two opposite targets. The laser irradiation generates on each target a plasma within which a toroidal magnetic field is embedded [2] via the Biermann battery effect. As the two plasmas collide, compression ensues.

Diagnostics such as proton radiography [3], interferometry, Thomson scattering and optical pyrometry have been used to characterize the plasmas. Measurements were performed at several times and permitted to evaluate the plasma parameters as well as the temporal evolution. Thus, we can deduce the electron density map and the local ion and electron temperatures.

Our experimental results are supported by numerical simulations that model the whole evolution of the set-up. Simulations with the code FLASH [4] are conducted to reproduce the expanding plasmas and the magnetic field evolution, in order to investigate the ideal MHD effects on compression. Besides modeling the evolution of the setup, the FLASH simulations will constitute a base for PIC simulations using the code SMILEI [5]. These will be made to complete the hydrodynamical model brought by FLASH and provide a study of kinetic effects during the compression as well as assess the limits of MHD modeling. This theoretical work will enable us to support our experimental results and will constitute a complete study of the mechanism.

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O 114 - Axisymmetric eigenmodes driven by positive energy gradients in the alpha particle distribution function in JET D-T plasmas

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ABSTRACT TEXT

During the third deuterium-tritium (DTE3) campaign at JET, alpha particle-driven instabilities were observed within the toroidal Alfvén eigenmode frequency range. The modes were excited at the start of high-performance hybrid pulses during rapid increases in injected beam power and before the onset of ion cyclotron resonance heating. The magnetic probe signals were sufficiently strong for the toroidal mode numbers (n) to be determined. The instabilities included an axisymmetric mode ($n=0$), which suggests that they were driven by positive energy gradients rather than radial gradients, which typically drive instabilities in this frequency range. The absence of these eigenmodes in pure deuterium reference pulses provides strong evidence that fusion-born alpha particles were responsible for destabilising them.

Simulations using the TRANSP and LOCUST codes show the formation of large positive energy gradients in the alpha particle distribution function, resulting in a bump-on-tail distribution. The bump was created by an increase in beam power from 8 MW to 21 MW, which enhanced the beam-thermal fusion rate. Alpha particles slowed down to resonant energies within 150 ms, driving the modes sufficiently strongly to overcome damping from thermal particles and beam ions, which was computed using the CASTOR and HALO codes. These results suggest that similar modes could be excited during transient events including sawtooth crashes in future burning plasmas.

MCF 7 - Fast particles

O 115 - Microturbulence is suppressed when Alfvén eigenmodes are excited

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ABSTRACT TEXT

Compelling evidence that ion temperature gradient (ITG) turbulence can decrease in response to an increase in Alfvén eigenmode (AE) activity has been obtained in neutral-beam heated DIII-D discharges. The effect is observed in many discharges, with up to ~50% reductions in turbulence for a single toroidal AE and nearly complete suppression in plasmas with multiple AEs that have identical toroidal mode numbers. Reductions in turbulence with increased AE activity occur on both short (~1 ms) and long (~100 ms) timescales. When the turbulence is locally suppressed, the electron and ion temperature increase ~30%. Beam emission spectroscopy (BES) and Doppler backscattering (DBS) diagnostics simultaneously measure the AEs and turbulence. In contrast to the AE dependence, in the cases explored, changes in toroidal rotation and fast-ion dilution have weaker impact on the turbulence. Although the cause of the AE-turbulence correlation is still under investigation, preliminary evidence that theoretically predicted AE-driven zonal flows cause the reductions in turbulence has been obtained. Because they ultimately determine alpha and thermal transport, understanding the interactions that set AE and turbulence amplitudes is essential for accurate predictions of reactor performance.

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MCF 7 - Fast particles

O 116 - Electromagnetic instabilities in global gyrokinetics and their interaction with energetic particles

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ABSTRACT TEXT

Turbulence in present-day tokamaks is often characterized by low beta regimes where mostly electrostatic (ES) instabilities such as the Ion Temperature Gradient (ITG) modes dominate. In a simplified picture, as the bulk-plasma beta increases, such modes are stabilized, until electromagnetic (EM) modes such as the Kinetic Ballooning Mode (KBM) become unstable. A more complex picture emerges when including energetic particles (EPs), which may stabilize ITGs, but can also drive large-scale Alfvén eigenmodes.

In this work, we investigate the nature of the transition from ES to EM instabilities with help from linear and nonlinear simulations using the non-linear global EM gyrokinetic particle-in-cell code ORB5. We show in simplified geometry a detailed linear picture with the help of advanced diagnostics: the transition from ballooning high- n ES modes (ITG), to flute-like low- n Alfvénic modes (Alfvénic ITGs); showing that the simple ITG-KBM picture needs to be extended to capture a shift to low- n and increased importance of rational surfaces (making it an inherently global problem). We demonstrate that some of these properties (low- n , rational surfaces) survive from the linear picture into the nonlinear phase. We also show how the effect of EP beta complicates the picture, and how this decouples between EP density and EP temperature.

Finally, we show that such EM flute-like modes have been found in gyrokinetic studies of experimental cases, for existing machines and for ITER scenario predictions.

MCF 7 - Fast particles

O 117 - Simulation-driven first experimental observation of shear Alfvén wave caused by ion cyclotron resonance heating in stellarator plasmas

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ABSTRACT TEXT

Interactions between shear Alfvén waves (SAWs) and energetic particles (EPs) are crucial to the performance of burning plasmas. The incompressible shear Alfvén waves can be destabilized by EPs produced by fusion reactions and auxiliary heating sources such as neutral beam injection (NBI) and/or radio-frequency wave heating, which can drive large EP transport that degrades plasma confinement and threatens vacuum vessel integrity. SAWs have been routinely observed in tokamaks for NBI and ion-cyclotron-range-of-frequency (ICRF) heating since the 1990s. However, in stellarators, only beam-induced SAWs are documented, while the ICRF-induced SAW has not been observed over the past decades.

Here, we report the first self-consistent simulation, as well as the first experimental observation, of an ICRF-induced SAW in a stellarator plasma. An extended kinetic-MHD hybrid code MEGA is employed for simulating minority ion heating in LHD. A SAW during on-axis ICRF heating in LHD is numerically predicted. The prediction is demonstrated by an LHD experiment, where the observed SAW shows good agreement in the mode frequency and spatial profile. The extraordinary acceleration of localized trapped particles (LTPs) by ICRF waves and the unique wave-particle interactions lead to the destabilization of SAW. The LTPs can be accelerated up to energies well above 1 MeV by ICRF waves even in a high minority ion ratio of 10% and are well-confined in the MeV energy range with an effective tail temperature over 300 keV. The MeV LTPs can resonate with the SAW via drift motions in the poloidal direction, which is different from the conventional toroidal precession drift resonance of trapped fast ions in tokamaks and stellarators and is analogous to the one in exciting ultra-low-frequency waves in the Earth's magnetosphere. The findings provide valuable insights into how EPs with localized trapped orbits, particularly fusion-born MeV alphas, interact with SAWs in advanced stellarators.

MCF 7 - Fast particles

O 118 - Spatial structure of NBI-driven shear Alfvén waves in the TJ-II stellarator: modeling vs. experimental results

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ABSTRACT TEXT

Shear Alfvén waves destabilized by NBI are quite common in TJ-II plasmas and provide a good testing ground for model validation purposes in non-axisymmetric configurations. In order to obtain a set of well-characterized Alfvén perturbations, a series of experiments have been carried out on plasmas with combined ECRH and NBI heating using three different magnetic configurations. In these experiments, changes in the plasma current of only a few kA, which can be produced using ECCD, allows us to investigate different spectra of waves while keeping thermal plasma parameters and fast ion pressure almost constant. To characterize the spatial structure of Alfvén instabilities we use three arrays of Mirnov coils, poloidally and helically distributed, which give information on mode periodicity and polarization [1], and one heavy ion beam probe (HIBP), which measures the radial profile of the perturbed potential [2]. The interpretation of mode number measurements is performed with the aid of a synthetic Mirnov coils diagnostic [3]. We then set out the slowing down simulations, providing fast ion density profiles and NBCD calculations [4]. An estimate of the ECCD is also included in the calculation of the rotational transform profiles. Finally, mode frequencies and numbers as well as radial structure of the wave potential are compared to the results of simulations carried out with the FAR3d gyro-fluid code [5].

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O 120 - Multi-GeV electron bunches obtained via direct laser acceleration for high-energy photon and pair production

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ABSTRACT TEXT

Direct Laser Acceleration (DLA) is a promising mechanism for accelerating electrons to multi-GeV energies with total charges exceeding 100 nC using multi-petawatt lasers. Gas targets have been shown to enhance the electron energy spectrum cut-off while simultaneously improving energy transfer efficiency, reaching over 10% [1,2]. If optimal laser focusing strategy is applied, it can result in the production of well-collimated electron beams (with divergences of tens of milliradians) and enable the formation of high-density electron bunches approaching the critical plasma density. The unique properties of DLA-accelerated electrons open new possibilities for various laser-plasma interaction regimes.

First, we examine the radiation emitted by electrons accelerated in an optimally focused multi-petawatt laser beams. The combination of high gas densities ($\sim 10^{19} \text{ cm}^{-3}$), large accelerated charge, and multi-GeV energies produces a bright, collimated gamma-ray source with synchrotron-like spectra with critical frequencies at tens of MeV. The small source size and ultrashort electron bunch duration enable gamma-ray brilliances on the order of $10^{22} \text{ photons/mm}^2\text{mrad}^2\text{s} \cdot 0.1\% \text{BW}$ at critical frequencies [3].

DLA electrons can also serve as an efficient source of secondary particles. When interacting with high-Z materials, they generate gamma rays via bremsstrahlung, which can subsequently produce electron-positron pairs through the Bethe-Heitler process. GEANT4 simulations indicate that neutral electron-positron plasmas can be generated after interaction with centimeter-scale converters. Additionally, if the initial electron energy is sufficiently high, a significant number of muons can be produced in a single laser shot.

Finally, the unique properties of DLA-accelerated electron bunches enable efficient gamma-ray generation in head-on collisions with counter-propagating laser pulses. A plasma mirror placed in the laser path can reflect the partially depleted laser. Facilitating high intensity of laser pulses used for the direct laser acceleration, electrons interacting with the reflected pulse undergo Compton scattering in a regime with quantum parameters (χ) exceeding unity. This single-laser scheme provides a promising avenue for probing strong-field quantum electrodynamics (QED) at existing laser facilities.

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BPIF 6 - Ultra-high intensity laser-matter interaction & high-field physics (QED) 2

O 121 - On measuring stimulated photon-photon scattering using multiple ultraintense lasers

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ABSTRACT TEXT

We present designs for an experiment using a multipetawatt facility to measure stimulated photon–photon scattering (SPPS), providing a first direct measurement of the nonlinearity of the quantum electrodynamic (QED) vacuum. SPPS is a prediction of strong-field QED for the response of the vacuum to intense electromagnetic fields, in which virtual electron–positron pairs mediate scattering between photons. The scattering is a fourth-order QED process and has never been directly observed due to its low cross section. The proposed experiments will test the hypothesis that the Euler–Heisenberg Lagrangian accurately predicts the nonlinear vacuum response to intense electromagnetic fields, and has the potential to bound beyond-the-standard model physics in a new regime. Preliminary simulations using a realistically temporally- and spatially-shaped laser model predict a three-beam interaction using two 25-PW beams, one of which is split, will produce a detectable signal of >1000 scattered photons per shot. We present predicted results for proposed experimental configurations of the NSF OPAL facility, including realistic laser-focusing geometries with and without second-harmonic conversion of two input beams. From these predictions, we derive requirements for the laser facility, including experimental geometry, beam polarization, co-timing, and co-pointing. The results confirm that beam cotiming better than the pulse duration and copointing better than the shortest laser wavelength are needed to robustly scatter photons on a per-shot basis. Requirements and potential technologies for the detector system are also discussed. Finally, we assess the bounds that a successful execution of this experiment may place on beyond-the-standard-model physics, in particular the mass scale of Born-Infeld nonlinear electrodynamics. This material is based upon work supported by the Department of Energy [National Nuclear Security Administration] University of Rochester “National Inertial Confinement Fusion Program” under Award Number DE-NA0004144 and Department of Energy under Award Number DE-SC0020431.

O 122 - Predictive tool for Nonlinear Compton and Radiation Reaction scattering experiments

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ABSTRACT TEXT

Advancements in all-optical experimental setups, such as increased repetition rates and enhanced control in the accelerator and scattering stages, are enabling studies with greater statistical significance in strong-field quantum electrodynamics (SFQED).

Future experiments will allow more accurate testing of theoretical models and the development of novel high-energy particle and radiation sources. The ability to extract more comprehensive information from experimental data is then essential for refining our understanding of SFQED phenomena. Rather than relying on isolated diagnostics, analyzing correlated energy-angle distributions of both electrons and emitted photons within the same interaction event provides a more accurate and complete comparison with theoretical predictions. Specifically, reliably identifying and separating from the background signal signatures of radiation reaction on the electron beam after collision with an intense laser is one of the current main challenges of the field.

To facilitate this, we have developed a computational framework to model expected outcomes in strong-field QED scattering experiments [1]. The approach enhances our ability to interpret complex experimental data, particularly in scenarios where multiple physical effects could influence the observed distributions.

We validate this new tool through comparisons with particle-in-cell simulations incorporating Monte Carlo methods and existing theoretical predictions. The model is applied across a broad range of interaction conditions, including variations in laser focusing, electron beam divergence, and different collision geometries, such as head-on, oblique, and perpendicular configurations. These comparisons provide insights into the influence of key experimental factors on the observed radiation and particle distributions.

Finally, we discuss the application of this method to recent experimental data and its potential role in shaping upcoming experimental campaigns [2]. By improving the accuracy of data interpretation and comparison with theoretical models, this approach contributes to ongoing efforts to deepen our understanding of strong-field QED phenomena in high-intensity laser experiments.

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O 123 - Self-aligned Compton photon source from multi-GeV LWFA electron beam

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ABSTRACT TEXT

The multi-PW HPLS and Apollon lasers from The Extreme Light Infrastructure — Nuclear Physics (ELI-NP) and LULI have successfully been commissioned and used to increase the incoming photon energies by nine orders of magnitude, from eV to GeV energy range in a robust self-aligned scheme with 100% laser beam collision rate. At ELI-NP the 10 PW laser beam, with central wavelength of 810 nm and pulse duration of 25 fs, was focused to about 60 μm spot size at FWHM, achieving a peak intensity on target of $\sim 1 \times 10^{20} \text{ W cm}^{-2}$ or a normalized vector potential $a_0 \sim 7$. Using a gas-jet target 60 mm long and a gas mixture of Helium doped with 2% Nitrogen, we were able to accelerate electrons via LWFA to 6 GeV and beyond. The electron beam from the LPA is deviated by an 80 cm long dipole magnet and detected with a Lanex screen coupled to an ANDOR Camera. Employing an all-optical setup, we have built a self-aligned Compton scattering source by combining the LPA with a plasma mirror. The plasma mirror consisted of a 250 μm -thick Mylar foil that can be moved along the propagation axis. The laser pulse, ahead of the electron beam, is back-reflected towards the electrons, and the collision results in the emission of high-energy Compton photons. The normalized vector potential of the reflected laser pulse, a_{0r} , was about 5, making the Compton scattering occur in the nonlinear regime with the emission of a broadband radiation spectrum. A matrix of LYSO scintillators was used to detect the Compton photons. From the profile of the photon energy deposition and the detector response, gamma-ray photon spectra were reconstructed, giving synchrotron spectra parametrized by a critical photon energy $\hbar\omega_c$ up to 0.55 GeV. We have observed a clear deviation from the classical $\gamma^2 a_0$ scaling, entering then into a moderate quantum regime with a $\chi \simeq 0.3$ where the quantum nature of the interaction cannot be neglected.

10/07/2025, 11:15–13:05, Room: Zeta 2

BPIF 6 - Ultra-high intensity laser-matter interaction & high-field physics (QED) 2

O 124 - Coherently enhanced radiation friction

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ABSTRACT TEXT

Radiation spectrum of a dense bunch of charged particles in a laser pulse is coherently enhanced at low frequencies. We analytically derive the main features (spectral range and shape, angular spread) of the coherently enhanced radiation of particles randomly distributed in a cylindrical bunch colliding head on with a pulsed plane wave with a Gaussian envelope [1,2].

For a dense bunch in a course of scattering particles can lose a substantial energy due to radiation. We identified that in such conditions coherent radiation friction mostly originates from forward and backward scattered radiation and developed a model, which predicts the dependence of the average momentum loss of the particles on all the relevant parameters of the bunch and laser pulse.

Three-dimensional PIC simulations demonstrate high accuracy of our models for both radiation and radiation friction. Our findings demonstrate that observation of radiation friction with dense bunches is feasible at lower particle energies and laser intensities than commonly accepted.

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BPIF 6 - Ultra-high intensity laser-matter interaction & high-field physics (QED) 2

O 125 - Laser-Plasma Accelerators for Strong-Field QED Studies

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ABSTRACT TEXT

Cutting-edge high-power laser facilities are beginning to enable groundbreaking investigations into quantum electrodynamics (QED) within the nonperturbative regime, where electromagnetic fields approach or exceed the so-called critical “Schwinger” field of QED [1]. In this extreme domain, phenomena such as Breit-Wheeler pair production, vacuum birefringence, and quantum radiation reaction are expected to occur—effects that have yet to be observed in a controlled laboratory environment. Achieving these field strengths requires laser intensities on the order of $I_s = 2.3 \times 10^{29}$ W/cm², far surpassing the current record of 10^{23} W/cm² [2]. A practical pathway toward accessing this regime involves leveraging Compton scattering between ultra-relativistic electron beams and ultra-intense laser pulses, providing a platform to probe strong-field QED effects. Recent advancements in laser-plasma accelerators, particularly laser wakefield acceleration (LWFA) [3], have opened new avenues for all-optical strong-field QED experiments, with several groups worldwide, including CoReLS/GIST, actively pursuing this approach.

In our recent work, we conducted experiments on nonlinear Compton scattering in strong laser fields, where a multi-GeV electron interacts with hundreds of laser photons simultaneously. Utilizing LWFA, we generated an ultra-relativistic electron beam, which we collided with a laser pulse at an intensity parameter $a_0 = 14$ and an incidence angle of 30° , achieving a quantum nonlinearity parameter $\chi = 0.46$. This interaction produced high-energy gamma rays via multiphoton Compton scattering, with photon energies extending up to 700 MeV—well beyond the linear Compton scattering threshold—confirming the onset of the strongly nonlinear regime [4]. Our measured gamma-ray spectra showed excellent agreement with both QED-PIC simulations and analytic models, validating the theoretical framework. These results not only demonstrate nonlinear Compton scattering under strong-field conditions but also pave the way for future studies of more complex processes, including nonlinear Breit-Wheeler pair production, as higher laser intensities and electron energies become attainable.

This work was supported by the Institute for Basic Science grant (IBS-R038-D1).

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MCF 8 - H-mode pedestal

O 126 - Radial Impurity Transport in the Pedestal of reactor-relevant Tokamak Operation Regimes

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ABSTRACT TEXT

A key challenge on the way to a tokamak fusion reactor is the combination of high confinement in the plasma core with a manageable power exhaust. Tailored distributions of impurities play a crucial role to achieve sufficient radiative cooling of the plasma edge while avoiding excessive fuel dilution and radiation losses in the core. This requires well controlled radial impurity transport, especially in the core-edge connecting region of the pedestal. The plasma edge physics of reactor-relevant operation regimes deviate from the standard high-confinement mode (H-mode) since large (type-I) edge localized modes (ELMs) need to be prevented. However, the altered pedestal impurity dynamics remain largely unexplored due to the experimental difficulties posed by the steep gradients.

We present a comprehensive experimental study of radial impurity transport in the pedestal of reactor-relevant tokamak operation regimes. A novel framework has been developed to disentangle flux surface-averaged diffusion and convection profiles with high radial resolution based on the stationary balance of multiple impurity charge state densities. The high-dimensional inverse problem is solved with Bayesian sampling for thorough uncertainty quantification, accounting for non-Gaussian error statistics. It relies on data that has been acquired with a customized charge-exchange spectroscopy diagnostic setup at ASDEX Upgrade. Dedicated discharges have been performed to compare the neon transport in promising confinement regimes to inter-ELM phases of type-I ELMy H-modes and to the low confinement mode (L-mode). Neoclassical transport modeling is used to separate collisional and turbulent contributions to the inferred transport coefficients, providing insights into the underlying physical mechanisms. Our analyses confirm previous findings of predominantly neoclassical impurity transport between large ELMs, while the ELMs act as additional diffusion [1]. We show that the small ELMs of the quasi-continuous exhaust (QCE) regime also contribute significant turbulent diffusion, and moreover present first results for the ELM-free enhanced D α (EDA) H-mode, and for ELM-suppression with resonant magnetic perturbations (RMPs).

Our study facilitates predictions of impurity behavior in future devices with different kinetic profiles, to which impurity densities cannot be easily scaled. We thus provide a key ingredient for assessing reactor scenarios with respect to their core-edge integration.

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MCF 8 - H-mode pedestal

O 127 - 'Density cliff' formation near the separatrix of high density H-modes at JET and its role for the H-mode density limit

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ABSTRACT TEXT

For a tokamak fusion reactor, high plasma density will be key to maximise fusion performance and to meet the requirements for power exhaust. Density ramp experiments in H-mode on JET, designed to take advantage of the recent improvements to the FM-CW reflectometer diagnostic [1], have revealed that at sufficiently high densities the radial profile shape of the density pedestal departs from the established tanh-paradigm. A local steepening (the 'density cliff') develops over an extremely narrow area of 1–2 mm (compared to 2 cm pedestal width), which is too narrow to be resolvable by the Thomson Scattering or Li-beam diagnostics. The cliff always develops first near the pedestal top, hence well inside of the separatrix. As the density increases further, the cliff location gradually drifts outboards and remains in the vicinity of the separatrix (to within a few mm) until the H-mode Density Limit (HDL) is reached. At the HDL, the density cliff collapses on a timescale of 10–20 ms, while the density profile gradients further inboards (in the confined region) or further outboards (including the density shoulder in the SOL) remain unaffected on this timescale. This observation provides direct evidence that the HDL is indeed triggered due to instability in a very localised (mm-) region near the separatrix, as previously proposed. Detailed evaluation of edge density and temperature profiles reveals good agreement between HDL onset and theoretical predictions by the Generalised Heuristic Drift model [2]. Alternatively, the same profiles reveal that ideal ballooning MHD instability near the separatrix could also be responsible for triggering the HDL, which was in fact the assumption behind the original Heuristic Drift model [3]. This is because the cliff's very steep density gradient also drives locally the pressure gradient near the separatrix up to critical levels.

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MCF 8 - H-mode pedestal

O 128 - Experimental characterization of ELM precursor oscillations on MAST-U and comparison with ELITE simulations

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ABSTRACT TEXT

Understanding alternatives to Type-I ELM operation regimes is a key research focus for operating fusion devices. While Type-I ELMs in H-mode is a standard scenario, the energy released by Type-I ELMs is unacceptably high for future reactors. The peeling–ballooning instability model is the established theory of Type-I ELMs and has successfully reproduced experimental observations, including pedestal stability limits and ELM onset.

Experimental studies have shown that various types of ELMs are often preceded by coherent oscillations, known as ELM precursors [1],[2]. The lifetime of these modes varies, but they have been shown to exhibit nonlinear behaviour preceding the ELM crash [2].

The turbulence imaging beam emission spectroscopy (BES) diagnostic on MAST-U has been upgraded, featuring an 8×8 pixel array, ~2 cm spatial resolution, and 500 kHz analogue bandwidth for characterizing edge plasma instabilities. Signal quality has been significantly improved in 2024. MAST-U BES serves as a unique diagnostic tool for analysing the temporal and spatial evolution of density variations simultaneously before and during various types of ELMs. Its two-dimensional measurements not only reveal poloidal wavelengths directly but also enable the measurement of poloidal velocities of precursor modes.

This study presents a detailed characterization and analysis of precursors to Type I, tentatively identified Type-II, and Type-III ELMs on MAST-U. Type-I ELM experimental results are also compared with ELITE simulations [3]. The precursor wave propagates in the counter-current (electron diamagnetic) direction, and velocity modulation of the mode is observed in Type-I, Type-II, and Type-III ELMs [2]. Type-II ELM pedestals are characterized by the continuous presence of a pedestal-localized mode, whose amplitude is modulated synchronously with pedestal flattening and small α peaks, indicating increased transport. Interestingly, simultaneous velocity modulation has also been detected in Type-II ELMs.

Experimental observations consistently show the presence of counter-rotating modes. The interaction of these modes with flow shear, which stabilizes the H-mode pedestal, may be key to understanding the ELM crash.

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MCF 8 - H-mode pedestal

O 129 - Detection and characterization of intra-ELM modes in Type-I ELMy scenarios at TCV using the Thermal Helium Beam diagnostic

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ABSTRACT TEXT

One of the fundamental regimes for the foreseen experiments in ITER is the H-mode. This regime is characterized by the presence of Edge Localized Modes (ELMs), which cause large transient power loads on plasma-facing components. A better understanding of these phenomena is crucial to achieve more controllable scenarios. ELMs are often preceded by coherent oscillations, the study of which could lead to a better description of their onset. This work aims to examine the intra-ELM modes observed in Type-I ELMy H-mode shots at TCV. The primarily used diagnostic is the Thermal Helium Beam (THB), a spectroscopic device widely used in tokamaks for measuring electron density (n_e) and temperature (T_e) profiles in the plasma boundary region. Thanks to its MHz time resolution, the THB is not only able to detect these fluctuations but also to characterize them in terms of T_e and n_e . In the selected dataset a common pattern of intra-ELM modes was observed with a frequency range of 30–90 kHz, spatially located a few centimeters inside the separatrix. By exploiting the THB capabilities, these fluctuations are identified mostly as electron density oscillations, with no evident temperature structure. In the SOL region, no coherent fluctuations were detected, but only turbulent filaments, that show no correlation with the inner mode. The obtained results are compared with other diagnostics, and with previous works on intra-ELM modes in other machines.

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O 130 - A gyrokinetic analysis of turbulent transport in the pedestal region of the MAST-U tokamak

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ABSTRACT TEXT

Turbulence is the dominant form of confinement reducing transport occurring in tokamaks and understanding and reducing turbulence is key to the successful operation of a commercial fusion reactor. In tokamaks with sufficient heating power input, we observe the formation of an edge transport barrier in which turbulence is suppressed and pressure gradients increase, known as the pedestal. This is the high confinement mode (H-mode) of operation and the properties of this pedestal are key to tokamak performance. This work aims to increase our understanding of the conditions required to access H-Mode, how the plasma pedestal height and width evolves over time and why. A linear local gyrokinetic study is performed for a MAST-U equilibrium immediately before and after the transition to H-mode, and in an established pedestal. Analysis is performed using $\hat{s}$ - α diagrams to map the stability of the plasma edge, where $\hat{s}$ is the magnetic shear and α is the normalised pressure gradient; this provides insight into why the equilibrium sits at the α value it does and what instabilities drive the turbulence limiting this value. In conventional models of the pedestal the pressure gradient is often thought to be limited by the Kinetic Ballooning Mode (KBM). Here we explore the extent to which the plasma can access to the second stable region of the KBM at high α and low $\hat{s}$. The boundary of the highly unstable KBM is shown to closely follow that of the ideal ballooning mode at the second stable boundary whilst extending slightly beyond the first stable boundary. However, a less unstable mode is found to partially block access as it extends to far lower shear at lower α . This mode, with an onset close to the equilibrium shear and pressure gradient at the H-mode transition, could limit the pressure gradients at early times until the equilibrium shear drops sufficiently low, thereby acting as a barrier to higher α which is passed during the transition. This methodology could lead to greater understanding of how to access and optimise pedestal performance.

MCF 8 - H-mode pedestal

O 131 - Pedestal density prediction for tokamaks

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ABSTRACT TEXT

While the H-mode pedestal pressure has been successfully predicted for many tokamaks using the EPED model [1–4], the prediction of the pedestal density has lacked a validated model and is taken as an input in EPED. In this work, we show that a relatively simple model that combines a neutral particle (both thermal and charge-exchanged) source, the plasma particle flux from the core and a diffusive transport model in the pedestal region, is able to predict the density pedestal height for several tokamaks. The transport model combines particle transport that is proportional to the heat transport, which itself consists of kinetic ballooning mode transport that is triggered above a set normalised pressure gradient and neoclassical transport. With the same assumption for the plasma particle transport in the pedestal for each device, the model predicts the density pedestals for JET, AUG, MAST-U accurately and the initial tests of the model on an H-mode density scan in Alcator C-Mod show promising agreement as well, both by using the experimental temperature profile and by predicting the temperature along with the density using the EPED model. We predict the pedestals for ITER and show that, assuming stiff core heat transport, the fusion power is strongly dependent on the predicted pedestal density, which in turn is sensitive to the separatrix density. However, the neutral particle density at the plasma edge plays only a small role. We also predict the density pedestal for the JT-60SA tokamak and STEP fusion reactor and show the main dependencies of the prediction.

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O 132 - An internally consistent model for high energy density material properties

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ABSTRACT TEXT

High energy density (HED) plasma systems such as giant planets, stars, and inertial confinement fusion (ICF) targets span an enormous range of material conditions, traversing extreme temperatures, densities, and pressures. Predictive hydrodynamic simulations of these plasma systems rely on atomic-scale models to generate and tabulate constitutive data such as equations of state (EOS), transport coefficients, and opacities. The HED community has developed a wide variety of models that can accurately calculate subsets of the needed data, but very few of these models can produce all required properties. Tables based on multiple models for different properties and/or different regimes are likely to have internal inconsistencies. In this talk, we describe an average-atom model based on Kohn-Sham density functional theory (KS-DFT) that can predict a wide range of plasma properties, including detailed opacity and emissivity spectra with self-consistent line shapes. The predictions of the model are compared against benchmark-quality models such as time-dependent multi-center DFT and state-of-the-art collisional-radiative kinetics model. We then explore the impact of adopting these internally consistent constitutive data sets on the performance of magneto-inertial fusion targets.

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O 133 - X-ray spectroscopic diagnosis of core conditions in highly magnetized cylindrical implosions

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ABSTRACT TEXT

Applying a controlled external magnetic field to inertial confinement fusion implosions has proven effective in reducing thermal losses and increasing fusion yields. Cylindrical implosions provide a well-suited platform for studying magnetized phenomena in high-energy-density plasmas [1]. In this context, accurate diagnosis of plasma conditions is crucial for validating magneto-hydrodynamics (MHD) models and advancing our understanding of magnetized transport physics. This work illustrates the use of X-ray spectroscopy to characterize the core conditions in magnetized cylindrical implosions conducted at OMEGA and, more recently, at NIF. Space- and time-integrated Ar K-shell spectra from OMEGA experiments exhibit highly reproducible and distinctive features, both with and without an applied magnetic field. A multizone spectroscopic model successfully fits the experimental spectra. The analysis reveals a 50% increase in core temperature at half-mass density when a 30 T seed B-field is applied. Additionally, the methodology demonstrates potential for extracting a coarse-grained radial profile of core conditions at stagnation, supporting the formation of a hotter central spot in the magnetized scenario. These observations align well with synthetic spectra obtained by post-processing extended-MHD simulations, including detailed atomic-kinetics and Stark-broadened line shapes. This agreement provides strong evidence that the core conditions at peak compression are consistent with a 10 kT compressed magnetic field [2]. To further assess the large temperature gradients predicted by simulations, a dual-dopant (Ar and Kr) spectroscopy approach is proposed [3]. While Ar K-shell emission is sensitive to temperatures in the range of ~600–2500 eV, Kr K-shell emission probes higher-temperature regions, where Ar is nearly fully ionized. The simultaneous observation of both Ar and Kr emission offers a means of spatially resolving temperature gradients across the core, from colder outer regions to the hotter central zone.

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O 134 - From X-ray phase contrast imaging to coherent diffraction for inverse problem solving in laser-driven experiments

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ABSTRACT TEXT

Recent major advances in condensed matter and high-energy density physics have been achieved by highly-resolved X-ray radiography [1–3]. The development of phase contrast imaging and coherent diffraction has highlighted refraction and diffraction effects in the probed object [4–9], thus improving the quality of the raw image while encoding more information in the radiograph. However, quantitative interpretation of the data remains difficult, and differs from the processing carried out for standard absorption contrast measurements particularly due to the presence of non-local effects [10]. Here, we introduce a wave-based approach that covers all these measurement regimes in the context of laser-driven experiments, and present several numerical approaches for determining certain physical properties of interest using phase reconstruction algorithms. In particular, we have applied these methods to a 1D hydrodynamic simulation of the interaction between an intense laser beam and a solid target, in order to follow precisely the propagation of a shock-wave through a low-Z material. In the diffraction regime, the developed numerical schemes have enabled us to retrieve some physical quantities, like optical properties or electron density. The emergence of new X-ray sources perfectly coherent makes these new approaches a promising alternative for the study of matter under extreme conditions, such as equation-of-state measurements, shock-wave propagations, hydrodynamic instabilities or turbulences.

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O 135 - Characterizing shock dynamics in foams with Talbot interferometry

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ABSTRACT TEXT

Proper description of Matter in Extreme Conditions (MEC) requires deep understanding of plasma processes. High-resolution characterization of High Energy Density (HED) plasma dynamics is crucial to improving models and predictions. However, accurate diagnostic probing of laser-target interactions in lab-astro and fusion-relevant experiments is challenging due to short time scales, high densities and density gradients involved within a μm -scaled volume. In this context, the use of coherent X-ray sources such as those generated at the LCLS constitutes an extremely powerful tool given their spatial and temporal coherence, short pulse durations and high photon energies. The combination of these light sources with Talbot interferometry, a grating-based phase imaging method, translates in a diagnostic which is highly sensitive to density gradients and can easily probe transparent media with μm resolution. We present results from an experiment in which low-density foams (20–500 mg/cc) were laser-irradiated ($\sim 60\text{J}$, 10 ns, $\sim 10^{13}\text{Wcm}^{-2}$) at the LCLS-MEC beamline. The evolution of the laser-generated shocks was characterized using 2D Talbot X-ray interferometry and the data were unraveled with the TNT code [1]. The shock velocity was measured from the Talbot images and compared with VISAR measurements, finding a systematic underestimation of the shock velocity by the latter, consistent with a deceleration of the shock after the laser is turned off. The use of interferometry permitted to obtain absolute measurements of the phase shift induced by the plasma and therefore extract 2D maps of the electron areal density of the shocked foams with submicron resolution. The data are in good agreement with hydrodynamic simulations, providing insights on the different mechanisms for shock formation and evolution.

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O 136 - Relaxation pathways in X-ray Free Electron Laser heated Iron

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ABSTRACT TEXT

Over the past two decades, X-ray free-electron lasers (XFELs) have made significant progress, achieving peak brightness in the XUV and X-ray regions that were previously only attainable in the optical and infrared ranges. This advancement has opened new possibilities in high-energy density science. It enables the creation of solid-density plasmas with larger volumes, greater uniformity, and well-defined properties, including temperature and density. XFEL heating proceeds through photoionization and thermalisation, and as such initially creates a non-thermal electron distribution. This gives a new platform to create well defined plasma states with tailored electron distributions.

In the last years, several experiments have been focus in the creation of solid density plasmas of mid-Z materials, especially transition metals. Since collisional models have been proven to be a successful method to understand the time resolved atomic kinetics, we have adapted the non-thermal collisional radiative model BigBarT [1–3] in order to simulate arbitrary elements.

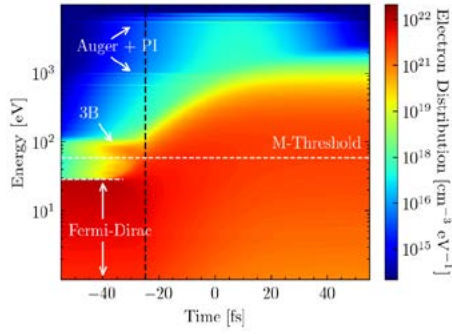


Fig. 1: Electronic distribution temporal evolution of an Iron XFEL produced plasma, for a 30 fs FWHM pulse at 10^{18} W/cm² and a pump energy of 8100 eV.

We investigate the effects of inelastic thermalization in iron under intense X-ray irradiation using the atomic model BigBarT, suited for the self-consistent evolution of the electron continuum, including degeneracy effects [5]. A typical evolution of the distribution function is showed in Fig. 1. Our study focuses particularly on collisional M-shell ionization, which we identify as the most efficient relaxation process of non-thermal electrons (Fig. 2). This greater efficiency could impact the transport of high-energy electrons in dense plasmas and raises the question of whether atomic processes should be included in kinetic models. Moreover, comparison of calculated spectra with data could be used to refine collisional cross sections, that are otherwise difficult to compute due to their proximity to the continuum and the associated plasma screening effects.

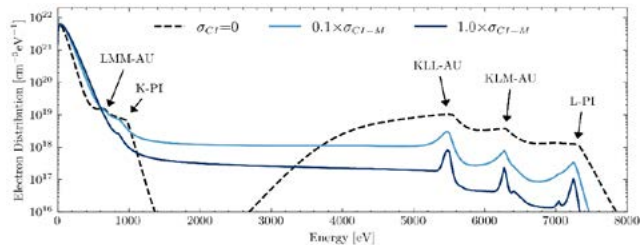


Fig. 2: Electron distributions at the pulse peak (60 fs) for varying collisional ionization cross sections of the M-shell. The dotted line represents the scenario without collisional ionization under the same conditions, 30 fs FWHM pulse at 10^{18} W/cm² and a pump energy of 8100 eV.

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O 137 - From non-thermal plasma to cultural heritage: Tailored Atomic Oxygen Generation for non-contact cleaning sensitive works of art

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ABSTRACT TEXT

Aerospace engineering and science's contribution to multiple game-changing technologies that have become essential to society is difficult to underestimate: from LASIK eye-tracking technology to insulin pumps, scratch-resistant lenses, and many others. Non-thermal generation of atomic oxygen (AO) in space simulators of NASA and ESA has found a contribution not only in tests of satellites but also in cultural heritage areas (CH) due to the possibility of oxidizing organic materials in a very controlled way. Here, the concept of the tailored AO process and recent experimental results on the treatment of CH objects are presented. The approach is based on a groundbreaking non-contact cleaning technology that uses RF plasma-generated AO at atmospheric pressure to remove problematic carbon-based contaminants. Those include environmental pollution and fire-born soot from challenging cultural heritage surfaces in an entirely non-mechanical, solvent and liquid-free manner, without waste. The process of AO generation is investigated by ps- and ns-TALIF spectroscopy as a function of the operational parameters of the plasma source. The effect of gas mixture composition, input power, and RF harmonics on oxygen dissociation and gas heating are analysed and optimized for the need for contactless cleaning of materials. The optimal O₂ admixing at 0.15 vol.% is determined based on the 2D mapping of AO in the effluent by ps-TALIF method. It is revealed that the presence of second harmonics and, more specifically, phase shift between harmonics, can strongly enhance AO production with no increase of the gas heating. The proposed method of atomic oxygen generation empowers CH conservators in diverse specializations with a new technology that resonates with the urgent need to refine cleaning methodologies and gain treatment readiness for fire damage.

LTDP 4 - Computational Plasmas and Diagnostic Development

O 138 - Plasmas for in-situ resource utilisation on Mars

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ABSTRACT TEXT

Low-temperature plasmas are emerging as a versatile technology for space applications, including waste gasification, nutrient recovery, regolith reduction for oxygen recovery and space agriculture [1]. In this context, in-situ resource utilization (ISRU) plays a crucial role in reducing reliance on Earth, lowering mission costs, and simplifying system design. A key area of research is plasma CO₂ decomposition directly from the Martian atmosphere, which generates oxygen and carbon monoxide, valuable for life support and fuel production [2]. In addition, by mixing the produced O₂ with Martian atmospheric N₂, fertilizers for future agriculture can also be synthesized [3].

Plasma technologies exhibit several advantages over traditional CO₂ electrolysis. They can operate directly with the ambient Martian gas mixture and pressure, eliminating the need for compression and potentially reducing system weight and power consumption; Plasma systems are highly adaptable, capable of processing various feedstocks and produce different compounds. Plasma-membrane systems offer the potential for high performance regarding specific energy consumption and oxygen production per kg of equipment sent to Mars. Finally, plasma sources are inherently reliable, durable and scalable. However, CO₂ dissociation is energetically costly and product separation remains challenging. One promising approach is leveraging the synergy between low-temperature plasmas and ion-conducting membranes [2].

This work presents recent advances in plasma-based ISRU for Mars, integrating modeling efforts to unravel the complex plasma-chemistry dynamics in Martian conditions with fundamental studies on ion transport across separation membranes. These theoretical insights are complemented by dedicated experimental campaigns aimed at refining models and deepening our understanding of plasma-driven processes in extraterrestrial environments.

This work was supported by the Portuguese FCT—Fundação para a Ciência e a Tecnologia, under funding to IPFN (DOI: 10.54499/UIDB/50010/2020, 10.54499/UIDP/50010/2020, and 10.54499/LA/P/0061/2020), and to project PTDC/FIS-PLA/1616/2021 (DOI: 10.54499/PTDC/FISPLA/1616/2021).

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O 140 - Global plasma model of a Microwave Electrothermal Thruster (MET) for self-consistent performance calculations

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ABSTRACT TEXT

Over the last decades, space propulsion systems have played a crucial role in the space market. Among them, electric propulsion (EP) technologies attracted significant interest due to their higher specific impulse compared to chemical thrusters, resulting in better propellant mass economy [1]. Although many EP thrusters are very mature, their lifetime is reduced by the erosion caused by plasma fluxes impinging on electrodes and grids. Electrodeless plasma thrusters avoid this issue by using electromagnetic interactions to energize the propellant, without direct material contact [2].

The Microwave Electrothermal Thruster (MET) is an electrodeless device that heats a gaseous propellant using microwaves and a free-floating plasma. The plasma absorbs the wave energy and transfers it to the propellant, without material contact. MET offers several advantages: scalability, compatibility with different propellants, reduced erosion and extended lifetime [3].

MET design and optimization can be addressed using electromagnetic and plasma fluid numerical models. The former approach enables analysing the cavity dimensions and plasma influence on microwave fields. The latter enables the study of plasma discharge, propellant heating, and heat transfer to the cavity wall under various operating conditions. Both approaches are computationally demanding [4]. Conversely, global models describe the time evolution of volume-averaged densities and temperatures, with a reduced computational effort. They are widely used to study complex discharges, and to investigate how external parameters (e.g., input power, mass flow rate) impact on the plasma behaviour [5].

This study develops self-consistent MET global plasma models for atomic gases, predicting the plasma species densities, temperatures, and thruster performance. Two equations modelling the heavy species heating and the wall heat transfer are included to estimate the gas and the wall temperatures, contrary to state-of-the-art models [5]. Input powers from to kW and specific energies from to MJ/kg are explored.

Results show electron densities of 10^{16} – 10^{19} m⁻³, electron temperature around 1 eV, thrust efficiency decreasing with increasing specific energy, and wall temperatures reaching 1000 K. The developed models prove to be powerful and fast tools to estimate the MET plasma parameters and propulsive performance, as well as their scaling with operating conditions, thereby assessing the best operational settings.

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LTDP 4 - Computational Plasmas and Diagnostic Development

O 141 - Numerical design and experimental characterization of an innovative ‘plasma-shaped’ cavity realized in AM for ECR Ion Sources

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ABSTRACT TEXT

Among the possible ways to improve the performance Electron Cyclotron Resonance (ECR) ion sources, the redesign of the plasma chamber and microwave injection system play a key role. The proposed innovative chamber design named IRIS (Innovative Resonator Ion Source) is derived from the typical six-branches-star density iso-surfaces of ECR ion sources plasmas, emulating the electron distribution as dictated by the confining B-minimum configuration. Its novel microwave launching system consists of a slotted waveguide that smoothly matches the cavity walls. Both the chamber and its microwave injection system have been designed using CST-Studio-Suite with the objective of increasing the power absorption into the plasma core, thereby maximizing the on-axis electric field. Particle-In-Cell simulations have confirmed the higher in-plasma energy deposition expected for IRIS compared to a conventional cylindrical cavity. The cooling system design has been performed via COMSOL Multiphysics, combining the RF, heat-transfer and structural mechanics modules. The final prototype has been realized in Additive Manufacturing (AM) via Selective Laser Melting (SLM) technology, post-processed via Plasma Electropolishing (PEP), and eventually characterized in terms of S-parameters and on-axis electric field measurement using a bead-pull technique. Experimental measurements and tests have been performed and results are presented, paving the way to routine operations in future ECR ion sources.

O 142 - Relativistic plasma dynamics around astrophysical compact objects

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ABSTRACT TEXT

The time-variable (in particular pulsed-) emission from black holes and neutron stars holds key information on the nature of curved spacetime and ultra dense nuclear matter. However, due to the complex plasma dynamics at play, the interpretation of the observed signals is difficult. I will present some recent work on modeling general relativistic magnetohydrodynamic processes around black holes and accreting neutron stars. I will first discuss the dynamics of strongly perturbed black hole magnetospheres as they can occur for example during binary neutron star merger events. The simulations have revealed a brief ‘black-hole pulsar’ phase, followed by an intriguing alignment of the magnetic moment and black hole spin which can uniquely imprint the high energy emission of the current sheet. I will further discuss the transient dynamics of multipolar black hole magnetospheres. Switching gears, I will then discuss our recent 3D simulations of accreting neutron stars with oblique magnetospheres, focusing on the questions of jet formation and pulsed emission. The obtained X-ray pulse profiles are consistent in amplitude and harmonic content with the observations of AMXPs, however they also exhibit significant and rapid variability in hotspot temperature and shape due to the turbulent accretion flow.

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BSAP 5 - Astrophysical plasmas: Compact objects

O 143 - Fully kinetic simulations of magnetorotational turbulence in astrophysical compact-object accretion flows

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ABSTRACT TEXT

We present recent advances in first-principles simulations of black hole accretion. Using a localized approach, we perform shearing-box simulations of ion-electron plasma in black-hole accretion disks, where collisionless turbulence, angular-momentum transport, and nonthermal particle acceleration are captured self-consistently. Our simulations focus on the nonlinear development of the magnetorotational instability, which feeds off the central object's gravitational energy and provides a powerful driver for disk turbulence. For the first time, our simulations include vertical density stratification, showing a complex disk dynamics hinting at the formation of a magnetized corona. Moreover, we present the first ion-electron simulations with realistic proton-to-electron mass ratio, where a two-temperature state naturally emerges and the particle species are heated unequally. These results have important implications for global modeling using, e.g., magnetohydrodynamics with subgrid-heating prescriptions.

O 144 - A visual approach to MHD accretion disk instabilities

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ABSTRACT TEXT

Accretion disks around black holes have long been theorised to be turbulent in order for steady accretion flows to occur. The most likely source of this turbulence is an instability driven by a weak magnetic field and rotation flow shear: the Magneto-Rotational Instability (MRI) [1]. Many authors have focused on how this fast-growing, axisymmetric instability appears in a WKB analysis of local, Cartesian boxes moving with the background flow. Non-axisymmetric versions of the MRI, on the other hand, require a fully global approach, taking into account the curvature and radial variation of a cylindrical disk. The full Fourier spectrum of waves and instabilities accessible to a given disk equilibrium can then be determined using magnetohydrodynamic (MHD) spectroscopy [2]. Recently, rigorous MHD spectroscopy identified a new type of ultra-localised, non-axisymmetric instability in global, thin, cylindrical disks: the Super-Alfvénic Rotational Instability (SARI) [3]. For these SARIs, a densely packed 2D region in complex eigenfrequency space contains modes that are corotating at various radii in the disk, each one localised between two Alfvénic resonances and hence insensitive to the radial boundaries [4].

In this work, we revisit the basic mechanism behind both the MRI and the SARI through visualising the Fourier eigenmodes in time and 3D space using the Legolas code (<https://legolas.science/>), which calculates the Fourier spectrum of waves and instabilities for any given 3D (non-)ideal (M)HD equilibrium with variation in one dimension. We highlight how both instabilities operate through an imbalance of centrifugal, Coriolis, and magnetic tension forces, and how the polarization of the velocity and magnetic field perturbations differs importantly between these axisymmetric and non-axisymmetric modes. In particular, the SARI polarization results in deformations of the magnetic field lines that can lead to intricate structures even in the linear regime because of the associated phase shifts. We furthermore consider disks with various equilibrium magnetic fields on top of which many linear (non-)axisymmetric modes are superimposed, and determine how the resulting (linear) stresses differ. Finally, we confirm some of these properties using the finite-volume code MPI-AMRVAC (<https://amrvac.org/>) and follow the new SARI modes as they interact and evolve into the non-linear regime.

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Plenary Session 6

O 145 - Laboratory experiments at accelerator and laser facilities to probe high-energy astrophysical processes

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ABSTRACT TEXT

We will give an overview of laboratory astrophysics experiments at accelerator and laser facilities, focusing on high-energy processes related to the transport and diffusion of cosmic rays and ultra-relativistic particles.

We will show how laser experiments performed at the Omega and NIF laser facilities can shed light on our understanding of how cosmic rays are deflected by the stochastic, spatially intermittent intergalactic magnetic field. We will discuss measurements of energetic charged-particle propagation through a laser-produced magnetized plasma with these properties, and characterize the diffusive transport of the particles experimentally. The results show that the transport is diffusive and that, for the regime of interest for the highest energy cosmic rays, the diffusion coefficient is unaffected by the spatial intermittency of the magnetic field.

Moreover, relativistic electron-positron plasmas are ubiquitous in extreme astrophysical environments such as black-hole and neutron-star magnetospheres, where accretion-powered jets and pulsar winds are expected to be sites of particle acceleration. So far, our experimental inability to produce large yields of positrons in quasi-neutral beams has restricted the understanding of electron-positron pair plasmas to simple numerical and analytical studies, which are rather limited.

We will present the first experimental results confirming the generation of high-density, quasi-neutral, relativistic electron-positron pair beams using the 440 GeV/c beam at CERN's Super Proton Synchrotron accelerator. We show that the characteristic scales necessary for collective plasma behaviour, such as the Debye length and the collisionless skin depth, are exceeded by the measured size of the produced pair beams. In the first application of this experimental platform, the stability of the pair beam is studied as it propagates through a meter-length plasma, analogous to TeV γ -ray induced pair cascades in the intergalactic medium.

We conclude by discussing how these experiments can provide fundamental insights on beams of energetic particles interacting with the background plasma, and possibly explaining the observed lack of reprocessed GeV emission from TeV blazars.

Plenary Session 6

O 146 - Exhaust control in the WEST tokamak, in preparation of ITER tungsten divertor operation

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ABSTRACT TEXT

The operational lifetime of the first tungsten divertor of ITER must be at least 10 years. To anticipate this challenge, an ITER-grade divertor has been deployed in the WEST tokamak. In attached divertor conditions ($T_e \sim 20$ eV) and with target heat loads up to 10 MW/m² steady-state, an unprecedented particle fluence of 1027 p/m² (corresponding to a few high performance ITER pulses) was reached in two campaigns (11 h of plasma). Unmitigated tungsten erosion leads to the formation of tens of micrometre thick fragile deposits [1]; with detrimental consequences on infra-red wall surveillance, transient radiative events from flake emission, and potential fuel retention. ITER shall anticipate this and consider the need to control the divertor plasma below 5 eV from start of research operation.

Such an operation with controlled cold target conditions was demonstrated in WEST using nitrogen injection in Deuterium plasmas. Upon sufficient seeding, the divertor plasma eventually transitions within microseconds into a stable, dense and cold ($T_e < 3$ eV at target) regime featuring an X-Point Radiator (XPR) [2], with strongly mitigated heat loads and tungsten erosion. Nonetheless, a finite ion flux is maintained on both divertor targets. Main scrape-off layer profiles are weakly impacted by the XPR appearance in the divertor, and core confinement is improved through a combination of ion dilution effects and reduced tungsten contamination.

XPR scenarios in WEST have been found to be highly repeatable, real-time controllable, stable over multiple tens of seconds and over a wide range of operational parameters. The possibility of using a simple interferometry signal (line-integrated density) as a reliable control scheme for such XPR regimes was demonstrated in WEST for the first time, opening new sensor and control perspectives for next step fusion plants [3]. After seeding is stopped, the XPR remains in the plasma over a pumping time scale (~ 5 s in WEST), enabling plasma ramp down at low disruptivity and control of nitrogen legacy without cleaning technics. This represents the scenario for future high fluence campaigns at WEST, reproducing ITER divertor particle loads to investigate residual tungsten migration in a cold divertor regime.

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Plenary Session 6

O 147 - Advancing the Energy Frontier of Plasma-Based Proton Acceleration with Petawatt Lasers

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ABSTRACT TEXT

Laser-driven plasma accelerators can produce pulsed multi-MeV ion beams with high peak currents by irradiating solid targets with ultra-intense laser pulses. This innovative concept has gained significant attention as a compact and energy-efficient alternative to conventional accelerators, with applications in radiotherapy, neutron generation, and fast ignition for inertial confinement fusion. However, maturing plasma accelerators from complex physics experiments into turnkey particle sources requires advances in beam quality, robustness, and high-repetition-rate scalability.

A promising path toward this goal is the relativistically induced transparency (RIT) regime, where ion acceleration is enhanced by precisely synchronizing the laser pulse arrival with the onset of target transparency. In a series of experiments using two state-of-the-art petawatt laser systems, DRACO-PW (Dresden, Germany) and J-KAREN-P (Kyoto, Japan), we systematically investigated laser and target parameters to identify optimal conditions for plasma acceleration [1]. Our results demonstrate the immense potential of the RIT regime by reaching record proton energies of up to 150 MeV with just 22 J of laser energy [2]. The generated proton beam featured a high-energy, low-divergence component that was both spectrally and spatially distinct. Target transparency emerged as a simple yet powerful control parameter, highly sensitive to subtle laser–target variations.

Start-to-end simulations validate these results, elucidating the role of preceding laser light in pre-expanding the target along with the detailed acceleration dynamics during the main pulse interaction. Rather than optimizing a single acceleration stage, we tailored the plasma density so that the laser triggers a cascade of acceleration mechanisms, greatly enhancing energy transfer and acceleration efficiency. The insights into the role of the ultrashort pulse duration and the temporal contrast of the laser represent a significant step forward in understanding and controlling plasma-based ion acceleration in this regime, as confirmed by the successful reproduction of experimental results at two independent facilities.

Enabled by innovative laser diagnostics, advanced operation techniques, and hybrid simulation approaches, these advances mark a significant step toward next-generation laser-driven plasma accelerators, paving the way for their integration into scientific, industrial, and medical applications.

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MCF 9 - Turbulence and transport II

O 148 - Parametric decay instabilities in fusion plasmas: Consequences and new possibilities

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ABSTRACT TEXT

Electron cyclotron heating by high-power microwave beams is a key method for plasma heating in tokamaks and stellarators. Under some conditions, these beams engage in nonlinear three-wave interactions, known as parametric decay instabilities (PDIs), where energy is transferred from the main beam to two downshifted waves. PDIs are well documented to occur during fundamental electron Bernstein wave heating, with observations in multiple devices. However, PDIs were overlooked in the more common second-harmonic electron cyclotron heating until recently, when nonlinear scattering was observed. This has been attributed to a class of PDIs that involves wave trapping in density fluctuations. Here we provide an overview of recent experimental and theoretical advances in PDI research. We report direct observations of PDIs at the devices ASDEX Upgrade, TCV, Wendelstein 7-X, and NORTH and show that the occurrence of PDIs is correlated with density fluctuations in the scrape-off layer caused by ELMs and blobs as well as density fluctuations in the plasma core due to NTMs. We outline the consequences of PDI occurrence, which could include a decrease in the heating efficiency and an associated fast-ion production. Additionally, we discuss possible schemes for exploiting PDIs, including controlled energy transfer to selected plasma waves and potential diagnostic techniques for density fluctuations.

MCF 9 - Turbulence and transport II

O 149 - 3D turbulence simulations in detached conditions and their implications for the mean-field modelling of divertor regimes

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ABSTRACT TEXT

Magnetic fusion reactors will operate in detached divertor regime. 2D mean-field fluid edge plasma codes are still the main work-horses for the preparation of this operation. These tools rely on a gradient-diffusion description of anomalous transport, with diffusion coefficients usually tuned to match experimental scaling laws for the Scrape-Off-Layer (SOL) width. However, these have been derived for attached sheath-limited plasmas and it is unclear how anomalous transport responds to divertor regimes, although evidence exists of a widening of the SOL in high density regimes.

In this contribution, we present the results of 3D edge plasma turbulence simulations obtained in relevant detached divertor conditions and discuss their implications for mean-field models. The SOLEDGE3X fluid edge plasma code is used for that purpose, coupled to a self-consistent recycling model based on fluid neutrals. A set of simulations in a TCV long divertor leg geometry was run, covering a range of density regimes from attached to fully detached at the outer target.

Turbulence properties, such as fluctuation levels and intermittency, are found to be impacted by divertor conditions in a complex fashion depending on the location. The resulting time-averaged density and temperature profiles show significant flattening in the SOL beyond an inflexion point reminiscent of experimental density shoulders. In all cases, heat flux profiles exhibit 2 separate decay lengths in the near (l_{near}) and far SOL (l_{far}), with $l_{\text{near}} < l_{\text{far}}$. Detachment is associated with an increase by $\sim 30\%$ of l_{near} and a 4-fold increase of l_{far} .

Mean-field transport coefficients reconstructed from turbulent fluxes are strongly non-homogeneous, with a ballooning structure and a complex pattern in the divertor. Divertor detachment results in a 5-fold increase of the particle perpendicular diffusion coefficient everywhere in the SOL. In the detached case, the anomalous perpendicular heat conduction is found negative in the outer divertor leg, due to a local reversal of the temperature gradient but no reversal of the conductive part of the turbulent heat flux. This raises fundamental questions concerning the validity of the gradient-diffusion approach in high density regimes. We finally explore several options to improve the gradient-diffusion approach and make it compatible with the observed phenomenology.

MCF 9 - Turbulence and transport II

O 150 - Confinement transitions and large-scale mode activity in magnetic configurations with internal islands in the Wendelstein 7-X stellarator

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ABSTRACT TEXT

In experiments with stationary magnetic islands inside the LCFS of the W7-X stellarator, the position and size of these islands can have a significant impact on plasma performance: the diamagnetic energy can change by up to 25 % upon small island modifications. Confinement transitions are accompanied by the appearance and disappearance of intermittent global mode activity, superficially resembling H-mode and ELMs in tokamaks.

Previous experiments primarily varied the position of a 5/5 island chain inside the LCFS by modifying the iota profile [1]. Here, we focus on auxiliary “control coils” (originally designed to control divertor heat loads) to further modify resonant magnetic islands inside the LCFS. Carefully designed experiments with a slowly increasing island size in stationary plasmas (constant heating and radiated power, constant density) show that at a certain threshold, confinement degrades by 20% and the mode activity entirely stops. Reducing the island size in the same plasma, we recover the better confinement and the mode activity reappears.

This behaviour is observed in different magnetic configurations (e.g. different iota shear / radial axis shift) with configuration-dependent control coil thresholds.

The mode activity associated with improved confinement scenarios (only appearing with large islands inside the LCFS) manifests as intermittent, global bursts. In each crash event, several % of diamagnetic energy can be lost and ejected via the scrape-off layer as measured by reciprocating Langmuir probes. In the core, the crash has a poloidal mode number $m = 1$ as shown by Mirnov coils and soft X-ray tomography. After each crash, the X-ray emission profile is steepened, with an inversion radius well inside of the island chain ($r/a = 0.6$). This observation implies a steeper density profile, which is known to be beneficial for confinement in W7-X as it reduces ITG turbulence (the major energy loss mechanism in W7-X [2]). This is mirrored by strongly reduced broadband turbulence and Alfvénic activity in the quiescent phases between crashes, allowing the diamagnetic energy to recover after the crash.

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MCF 9 - Turbulence and transport II

O 151 - Integrated PIC-fluid modeling of the melting experiments of the WEST tokamak monoblocks

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ABSTRACT TEXT

During the WEST 2024 C9 experimental campaign, a set of experiments was carried out to characterize the physical damage on divertor monoblocks exposed to a parallel energy flux (a set of similar experiments are described in [1,2]). This was achieved by grooving a monoblock of a given plasma facing unit (PFU) thus exposing the monoblock of the following PFU along the toroidal direction. Two experiments were completed: a preparatory one featuring a parallel heat flux lower than the minimum required for melting (approx. 75 MW/m²), and a melting one with parallel heat fluxes higher than 100 MW/m². Experimentally measured data consisted in the temperature evolution along the monoblock (measured from IR thermography), parallel heat flux and ion current density, and post-damage observations.

To better understand the experiments, it was essential to model accurately the plasma-material interaction, accounting for effects such as local electric currents reaching the monoblock, magnetic and Debye sheaths forming close to the wall, finite ion Larmor radius effects, thermionic and secondary electron emission, and plasma particles collisions with recycled neutrals. This was achieved by combining axisymmetric scrape-off layer (SOL) fluid codes like SOLPS-ITER and SOLEDGE with the kinetic particle-in-cell code DESPICCO [3]. With the former codes, the relevant plasma conditions at the exposed monoblock location were identified for both experiments, while the latter code was used to model the last millimetres of the plasma-wall interaction consistently, including the above-mentioned effects and assuming the correct toroidal shaping of the monoblocks, as already done in a past study for DTT [4]. These PIC simulations cover the plane containing the toroidal and normal-to-wall directions, thus permitting to evaluate correctly the effects of monoblock shadowing and bevelling.

In this work, we will first present the results of the SOL codes, whose transport parameters were tuned to minimize the discrepancy between simulations and the available experimental data. Secondly, regarding the PIC code results, the heat flux and sputtering profiles and their spatially smoothed distribution (due to ion gyromotion effects) along the monoblock surface, as well as the local ion impact distribution functions, will be shown, with a direct comparison against any available experimental data.

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MCF 9 - Turbulence and transport II

O 152 - Towards continual learning surrogates for transport solvers

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ABSTRACT TEXT

Through a continual learning approach, surrogates of computationally demanding physics models can likely be continually improved within integrated modelling workflows. Surrogate models have become ubiquitous for emulating quasilinear models of tokamak core turbulence [1–3] in efforts to speed up transport solvers. Typically, the surrogate models are valid only within the database that was used in fitting the model, such as a database derived from a set of transport simulations of selected DIII-D discharges [1] or data representing selected experimental profiles at JET [3]. Ultimately, due to the high input parameter dimensionality, it is unlikely that any static collection of data used for fitting a surrogate model will span the domain of all possible use cases for the surrogate model, even for a single device.

In this work, we seek to develop a continual learning strategy for adapting surrogate models to new domains. A surrogate model of TGLF [4] has been fit on a data distribution representing AUG L-mode plasmas. The surrogate model has been implemented into the ASTRA transport solver [5] and can reproduce the heat transport channel in a selected L-mode plasma. Ongoing work is devoted to implementing the continual learning strategy to reproduce a database of AUG L-mode plasmas. Whenever the surrogate’s predicted variance exceeds a threshold, the full quasilinear model is evaluated instead and the new simulations are added into the surrogate model training data distribution, followed by re-training of the surrogate model. It was observed in a synthetic test that the surrogate model exhibits continually decreasing prediction error when applied within an integrated modelling workflow. This approach will be demonstrated through the modelling of an AUG heating ramp [6].

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O 153 - First experiments on alternative divertor configurations in ASDEX Upgrade

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ABSTRACT TEXT

Power exhaust is one of the major challenges for the development of a fusion power plant. An efficient divertor design, combining a high radiative fraction, detachment and helium exhaust is required. Alternative divertor configurations (ADC) such as Snowflake or X-Divertor have been proposed, aiming to outperform conventional single null divertors. In a major two year long effort, ASDEX Upgrade has been equipped with a new upper divertor enabling the study of those configurations. The divertor includes two in-vessel divertor coils and a charcoal coated cryo pump capable of pumping helium. The plasma facing components are toroidally symmetric allowing operation in both helicities with a total injected energy of up to 110 MJ. In order to observe the divertor conditions the new upper divertor is equipped with an extensive set of diagnostics. With its size and high auxiliary heating power ASDEX Upgrade is now capable to study these configurations at reactor relevant Scrape-Off Layer (SOL) heat fluxes in an all tungsten environment. This contribution presents the first ADC experiments conducted with the new upper divertor in ASDEX Upgrade. It has been commissioned and scenario development up to 800 kA of plasma current has been completed. The different envisioned ADC configurations, such as X-Divertor with a large poloidal flux expansion and Snowflake with an additional X-Point in the divertor region, have been achieved. H-Mode discharges with an auxiliary heating power of up to 20 MW were achieved so far. Significant changes of the divertor conditions are observed in the different configurations. These changes of the heat load distribution onto the divertor plasma facing components together with the changes in the temperature and density distribution in the divertor volume are compared to modeling. Both attached and detached conditions have been achieved using both unseeded and nitrogen seeded discharges. The X-Point Radiator (XPR) regime has been achieved in the upper divertor, including the same feedback control capabilities that are already present in the lower divertor.

BPIF 8 - Laser-plasma acceleration of particles and plasma-based radiation sources 2

O 154 - Single-Shot, All-Optical Measurements of Laser-Produced Plasmas

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ABSTRACT TEXT

High-intensity ($>10^{18}$ W/cm²), short-pulse (<10 fs) laser systems are generating significant interest worldwide due to their numerous applications in science, technology, medicine and industry. These lasers are capable of generating secondary sources of electrons, ions, protons, neutrons, and x-rays, some of which may be used as a heating spark in fast ignition, and/or for multi-modal radiography, cancer treatment, and more.

At the heart of these applications is the laser-plasma that is initially produced by the high-intensity laser's interaction with the target matter. These plasmas range widely in spatial scales from microns to millimeters and their dynamics can evolve on femtosecond to nanosecond timescales. Due to the sensitivity with which the plasma properties depend on the incident laser system, and the downstream effects of this initial plasma on the subsequent secondary sources and physics applications, diagnostics that capture a robust picture of their temporal and spatial evolution on a single shot must be developed for and demonstrated on high-intensity, high-energy laser systems [1].

Studies of high-intensity-laser plasmas to-date have been limited by either temporal or spatial resolution, relying on scanning one variable, such as time or delay, to take a complete measurement. Such measurements that use multiple laser shots to form a complete measurement cannot reliably distinguish between changes due to shot-to-shot variations and changes due to the variable being scanned. To address this problem, this work discusses the development and implementation of single-shot diagnostics for laser-produced plasmas [2].

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BPIF 8 - Laser-plasma acceleration of particles and plasma-based radiation sources 2

O 155 - 11B-p fusion reaction with energetic- nanosecond- lasers: in-target and pitcher-catcher schemes for applications in inertial confinement fusion schemes

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ABSTRACT TEXT

The $11\text{B}(p, \alpha)2\alpha$ fusion reaction, wherein low-energy protons (p) fuse with a boron-11 (11B) nucleus to yield three alpha particles (α), emerges as a promising avenue for clean and efficient energy production. Recent experimental efforts worldwide have demonstrated the feasibility of triggering p- 11B fusion through advanced laser-plasma interaction schemes. Although energetically less favourable compared to the conventional D- 3He fusion reaction, p- 11B fusion offers several compelling advantages: both reactants are naturally abundant; the reaction is effectively neutron-free, significantly reducing material activation around the fusion site; and it holds potential for diverse applications beyond inertial fusion energy plants, such as compact alpha particle sources and medical applications, including superficial tumour irradiation and radioisotope production. However, several critical challenges persist. Chief among these are the characterization of the fusion cross-section under plasma conditions, accurate determination of the stopping power within plasma environments, and the optimization of laser-target interaction geometries. Traditional beam-target methodologies for cross-section measurement are not directly transferable to plasma-based reactions due to the complex dynamics involved. Furthermore, experimental observations have revealed post-acceleration of emitted alpha particles, attributed to transient electric fields generated within the plasma, adding a layer of complexity to the reaction dynamics. A comprehensive understanding of the p- 11B fusion mechanism in plasma remains an open scientific question, best addressed through meticulously designed laser-matter interaction experiments. In this context, experiments conducted at the Prague Asterix Laser System (PALS) facility in Czech Republic, offer a unique investigative platform, utilizing high-energy, sub-nanosecond laser pulses to probe the fusion process. This study marks the first thorough comparison of two experimental configurations, the “in-target” and “pitcher-catcher” schemes, under identical conditions within the same laser shot. This approach enables a direct assessment of each method’s efficacy in facilitating fusion. In the in-target scheme, the intense laser pulse generates a longitudinal ponderomotive force, creating an electrostatic field that accelerates protons from the target’s front surface, enabling direct interactions with boron ions within the same target. Conversely, the pitcher-catcher configuration employs a primary target to generate energetic protons, which subsequently impinge on a secondary 11B -enriched target.

O 156 - ELIMAIA beamline: a user-oriented platform for repetition-rate ion acceleration and applications

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ABSTRACT TEXT

We present the ELIMAIA laser-plasma Ion Accelerator, capable of achieving relativistic intensities up to $5 \cdot 10^{21}$ W/cm², powered by the high repetition-rate, high peak-power L3-HAPLS laser at the ELI Beamlines user facility. Using thin targets of various compositions (e.g., Al, Au, Ni, Ti, Pd) and thicknesses (1.5–10 μ m), we investigated and optimized the efficiency of the accelerator. Under optimal conditions, a peak proton energy exceeding 40 MeV with a flux of $\sim 10^{11}$ protons/sr/shot was achieved.

The Ion Accelerator demonstrated excellent reliability and shot-to-shot stability, operating at a repetition rate of 0.5 Hz for tens of consecutive shots. This performance is supported by integrated systems for on-shot target positioning, data acquisition, and analysis, ensuring the beam-line is a robust platform for user experiments.

We also highlight the successful commissioning of the ELIMED section, which enables the capture, selection, and transport of laser-driven ions in air for multidisciplinary applications. Notably, we conducted the first-ever in-vitro experiment at ELI Beamlines, irradiating foreskin cells using a proton beam with energy specifically selected through the ELIMED section of the ELIMAIA beamline.

BPIF 8 - Laser-plasma acceleration of particles and plasma-based radiation sources 2

O 157 - Ion acceleration by super-intense laser interaction with optically shaped gaseous targets in the near critical density plasma regime

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ABSTRACT TEXT

Near-critical density (NCD) target profiles are considered as a promising alternative to conventional, over-dense, foil targets for high repetition rate, debris-free laser-driven ion acceleration. State-of-the-art simulations predict ion acceleration to energies of up to hundreds of MeV in the NCD regime. However, this regime remains experimentally challenging for intense, fs laser systems due to the precise control over the target profile peak density and density gradients required, with only scarce experimental demonstrations of ion acceleration in the NCD regime achieved so far.

Here, we present for first time, experimental validation of our previous simulations¹ of a novel method of under-dense gaseous profile optical shaping into NCD gaseous profiles as high rep rate targets for laser-driven ion acceleration. Ion acceleration experiments are conducted using the 45 TW, fs laser system *Zeus*, hosted at the Institute of Plasma Physics and Lasers (IPPL).

The scheme employs dual, intersecting laser-generated, counterpropagating blast waves that compress the gaseous medium, upon their shock front's collision, forming steep density gradient slabs of a few microns scale length. The compression of the target is maintained over several ns, mitigating laser synchronization issues.

3D HydroDynamic (HD) simulations are performed to optimize the target density profile optical shaping, along with exploiting the effects of the inherent Amplified Spontaneous Emission (ASE) of the accelerating laser pulse. Matching of simulation to experimental results is achieved using an 'in-house' developed synthetic optical probing algorithm.

The super-intense laser-NCD target interaction is investigated using 3D Particle-In-Cell simulations. The simulations reveal the generation of multi kTesla, azimuthal magnetic fields, strongly suggesting that Magnetic Vortex Acceleration is the dominant underlying acceleration mechanism. Measurements of multi-MeV ions energy spectra and high-dose electron emission are presented.

ACKNOWLEDGMENTS

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O 158 - Quasi-monochromatic carbon ion beams using the “peeler” acceleration scheme

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ABSTRACT TEXT

We present the generation of quasi-monochromatic carbon ion bunches from laser-solid interaction. The employed scheme is an extension of the “peeler” acceleration, originally proposed for proton acceleration[1]. This scheme involves irradiating a narrow (sub-micron) side of a tape target, which results in the generation of a surface plasma wave and the subsequent acceleration of the high peak energy, quasi-monochromatic, and low divergence proton bunch by the electrostatic field induced at the target rear. Nevertheless, the energy spectrum of higher Z (such as carbon) ion bunches is still thermal-like.

We propose a method to generate quasi-monochromatic carbon ion beams by placing a mass-limited carbon structure at the rear of the target. Using 3D particle-in-cell simulations, we show that a quasi-monochromatic carbon bunch can thus be obtained. For a characteristic case designed for PW-class laser pulses, the structure size is a few hundred nanometers along all dimensions and its density is decreased to about 5% that of graphite. Hence, all its particles experience a homogeneous accelerating field. As a result, 1e8 carbon ions with peak energy ~110 MeV/u, with a divergence of 20 degrees in the vertical plane and ~1 degree in the horizontal plane can be obtained.

Such parameters, together with the low duration of the beam and in combination with the versatility of high power laser facilities, shall make this scheme attractive for practical applications such as heavy ion therapy, higher resolution diagnostics of extreme plasma states, ion fusion studies, and nuclear physics.

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BPIF 8 - Laser-plasma acceleration of particles and plasma-based radiation sources 2

O 159 - A high yield, continuously operating fast neutron source driven by a table-top 10 Hz laser

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ABSTRACT TEXT

Neutrons are vital diagnostic tools in research and industry, thanks to their deep penetration and direct interaction with nuclei. Laser-driven neutron sources have gained interest over the past two decades for their compact size, lower cost, ultrashort pulse durations, and less demanding radiation safety requirements, compared to reactors, spallation sources, and accelerators. Advances in laser and target technology have further enabled high-flux neutron generation. While most studies use pet-watt (PW) lasers with joule-scale pulses and low repetition rates, high-repetition, few-cycle laser pulses with tens of watts of average power offer a promising quasi-continuous alternative [1]. In this paper we introduce a femtosecond-laser-based neutron source, the first of its kind, which is capable of operating for several hours per day, and ready for applications.

Deuterons were accelerated to MeV energies using 12 fs, 23 mJ laser pulses at a 10 Hz repetition rate (SEA laser, ELI-ALPS) interacting with a 450 nm thick liquid heavy water leaf (pitcher). The accelerated deuterons with a cutoff energy around 1 MeV hit the secondary target (catcher) made of compressed deuterated polyethylene. Fast neutrons are then generated from the induced the ${}^2\text{H}+{}^2\text{H}$ fusion reaction. Neutron spectra and spatial distribution were measured using a time-of-flight (TOF) system. The eight detectors were positioned around the target chamber, each angle and distance carefully measured with an optical tracking system. In addition, calibrated bubble detectors placed in the target chamber provided a robust measurement that is inherently insensitive to electromagnetic pulses and gamma radiation.

During five days of experimental time, the deuteron acceleration worked several hours per day, with a stability of cutoff energy better than 10%. The record laser-to-neutron conversion rate of 7.8×10^5 neutron/J was achieved by optimized acceleration of deuteron ions from a heavy water liquid sheet. The generated neutrons have a slightly beam-like distribution parallel with the accelerated deuteron beam. In this direction, kinetic energy peaks around 3 MeV. The daily neutron yield is 1.8×10^5 n/s, with a short term stability of 4%, and a daily stability of 7%.

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MCF 10 - MHD

O 160 - 3D non-linear MHD simulations of the flux pumping dynamo for sawtooth control at realistic experimental parameters

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ABSTRACT TEXT

Sawtooth control and improving plasma confinement are crucial for long-pulse tokamak discharges in the next generation of reactor-scale tokamaks [1]. In this context, the flux pumping in the hybrid scenario potentially offers a self-regulating and robust solution to address these needs [2]. Experimentally, flux pumping has been verified in various tokamaks, and the anomalous redistribution mechanism of plasma current has been identified [2–4]. Theoretically, basic properties of flux pumping have been qualitatively analyzed through nonlinear magnetohydrodynamic (MHD) simulations [5,6]. Nevertheless, quantitative modeling and a precise understanding of flux pumping are needed to assess its feasibility in ITER and DEMO.

This work takes an important step in studying flux pumping and the hybrid scenario achieved in ASDEX Upgrade (AUG) [2] at realistic parameters and experimental conditions with 3D nonlinear full MHD simulations in JOREK [7]. Long timescale simulations verify the validity of 1/1 core MHD instability induced dynamo effect in maintaining flux pumping. During the initial saturation stage of the ideal 1/1 quasi-interchange mode (on a timescale of milliseconds), the central safety factor (q_0) and MHD dynamo term oscillate together, reaching appropriate values due to the self-regulating behavior of the core plasma. On the longer resistive diffusion timescale of seconds, the stable negative MHD dynamo continuously redistributes core current and pressure. As a result, q_0 is maintained close to unity due to the low-shear current density and pressure profiles in the plasma core, and the system enters a sawtooth-free and quasi-stationary helical state. The final saturated mode exhibits combined characteristics of the 1/1 quasi-interchange mode and the 1/1 tearing mode. The obtained dynamo loop voltage is of the order of mV/m and closely matches experimental observations in AUG, resolving prior overestimations [2,6].

Meanwhile, we scan critical parameters, including the current source, plasma beta, viscosity, resistivity, etc., to determine operating windows of flux pumping in AUG and support the development of a fast predictive surrogate model [8]. Further efforts aim to extend the MHD model and address JET experiments.

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MCF 10 - MHD

O 161 - Magnetic topology dynamics during reconnection events in RFX-mod

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ABSTRACT TEXT

Magnetic reconnection is a self-organized phenomenon of redistribution of currents in a plasma, which changes dramatically the topology of the magnetic field. It is found in disparate environments, such as the magnetosphere, the solar corona and, last but not least, toroidally confined plasmas for nuclear fusion research. The study of reconnection in a laboratory is of paramount importance for comparison with space plasmas, where measurements are more difficult to perform, and also of practical importance, since reconnection sustains the magnetic field but is also responsible for fast particle losses, causing plasma-wall interaction (PWI) and deterioration of confinement.

This paper is devoted to the study of particle orbits during a reconnection event in the RFX-mod device. The PWI patterns are measured via a fast camera looking at the graphite-covered inner wall, and compared with detailed simulations of particle motion in the 3D magnetic topology, performed with the Hamiltonian, guiding center ORBIT. The inclusion of an electrostatic potential is shown to be a fundamental ingredient for explaining non-Maxwellian energy distributions, the fast, non-diffusive drop of electron temperature and the ion acceleration, which are features of reconnection in the laboratory. Our results can be extrapolated also to other environments, such as the solar corona, where ion acceleration is a distinct feature of reconnection events.

MCF 10 - MHD

O 162 - Linear extended MHD in ASDEX Upgrade and Wendelstein 7-X

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ABSTRACT TEXT

Magnetohydrodynamic instabilities such as (peeling-)ballooning, (double-)tearing and kink modes impose operational limits in both stellarators and tokamaks. For this reason, it is important to understand the physics affecting the behaviour of these instabilities in order to extrapolate their onset to future fusion reactors. While flow-free ideal or resistive MHD is capable of predicting the existence of significant MHD instabilities, their precise onset and hence the true operational limit that these instabilities impose requires considering additional physics.

In this work, we show the effects of resistivity, parallel and gyro-viscosity, toroidal and neoclassical (ExB and ion diamag. drift, Pfirsch-Schlüter and parallel) flows and heat conductivity on growth rate and frequencies of (peeling-)ballooning and kink modes in ASDEX Upgrade and (double-)tearing modes in Wendelstein 7-X. The stability analysis is performed using the linear extended MHD code CASTOR3D [1,2], where recently heat conductivity and neoclassical flows were implemented into the system of MHD equations. Parallel flows, being part of the neoclassical flows, impact the growth rate of instabilities similarly to toroidal flows while having almost no effect on the mode frequency. It is shown that resistivity, gyro-viscosity and flow physics significantly affect growth rates and frequencies of MHD instabilities [3–5] while the effect of heat conductivity and parallel viscosity is relatively small. Finally, we demonstrate that the frequencies of experimentally observed inter-ELM modes at ASDEX Upgrade [3] are in good agreement with the frequencies of predicted MHD instabilities if extended MHD effects are taken into account.

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MCF 10 - MHD

O 163 - JOEREK simulations of radiation collapses and their magnetic signatures in ITER start-up limiter plasmas

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ABSTRACT TEXT

Disruptions in high energy tokamaks like ITER can reduce in-vessel component lifetime or potentially require maintenance periods, making the effectiveness of the Disruption Mitigation System (DMS) crucial for operation. Successful disruption mitigation relies on an early detection by various diagnostic systems, with magnetic diagnostics being a particularly important example. In this work, 3D JOEREK non-linear MHD disruption simulations are performed in order to provide examples of synthetic magnetic diagnostic data which can then be used to assess the detection functions and avoidance strategies for disruption handling.

The first disruptions that will be encountered in ITER will occur during the very early stages of the Start of Research Operation (SRO) when first plasmas are attempted and current ramp-up in limiter configuration on the tungsten (W) inner wall is performed before the X-point transition (at $I_p \sim 3$ MA). The presence of low Z impurities in these early plasmas, coupled with the use of W, will lead to conditions in which disruptive radiative collapse is likely [1]. Despite the low stored energy in these plasmas, thermal (TQ) and current (CQ) quench heat loads on the SRO temporary W first wall require assessment.

To provide realistic estimates of these heat loads and as a first test of a newly developed synthetic magnetic diagnostic workflow (Curr2Mag), non-axisymmetric simulations of radiation collapses induced by the presence of edge (e.g. Ne, O) and core (W) radiating impurities in ITER limiter plasmas are being performed for the first time with JOEREK. Using typical, mildly elongated limiter configurations (in the range 1–3 MA) extracted from DINA code scenario simulations, a fixed impurity content is imposed to induce a radiation collapse. Synthetic signals for the ITER magnetic probes and flux loops are obtained with Curr2Mag, which calculates the signals based on the 3D plasma, wall and coil currents. Heat loads on the shaped 3D first wall panels at the TQ and CQ are used to assess expected spatial and temporal surface temperatures and to provide averaged heat flux widths suitable as input to engineering design studies.

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MCF 10 - MHD

O 164 - Resonant Layer Responses to Non-Axisymmetric Magnetic Perturbations in Two-Fluid, Drift-MHD Regimes

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ABSTRACT TEXT

A tokamak responds strongly to non-axisymmetric, resonant magnetic perturbations (hereafter will be referred to as RMP for brevity) through a narrow layer across a rational surface as seen in magnetic reconnection and braking. RMP is a promising scheme to ensure stable and high-performance operations in tokamaks [1, 2, 3, 4] such as to correct intrinsic error fields, mitigate and suppress ELMs in H-mode plasmas and runaway electrons during tokamak disruptions. Therefore, in-depth understanding of resonant layer responses is of great importance in exploring the fidelity of the fusion reactors. The perturbed responses can be characterized by the single parameter defined as the discontinuity in the magnetic field normal to the resonant surface. The physically represents the shielding currents that form across the resonant layer. Inherent complexity in the responses necessitates adopting the two-fluid drift-MHD model in the complete form: The only inclusion of electron viscosity changes a power coefficient of the field penetration thresholds from $1/4$, $1/4$ [5] to 1 , $5/8$ [6] in the HRI and SCI regimes, respectively. In this work, we explore the complex responses in the two-fluid drift-MHD regimes by employing the code, Slab-Layer (SLAYER) [7]. To deal with an intrinsic numerical stiffness, the Riccati transformation method aiming at solving the stiff ordinary differential system with the higher order is adapted to impose the asymptotic boundary conditions [8]. This work particularly focused on the responses of the resonant layers under an effect of the parallel flow, since its role has not been identified. It's unveiled that the parallel flow response gives rise to the ion shielding current and shifts the zero-crossing condition of for $E \times B$ rotation. The shifting mechanism is clearly distinct with the neoclassical toroidal viscosity since it's the outcome of inner layer. The four field solutions are fully reconstructed in configuration space, which quantified the dominant balancing in the governing equations and clarified which physics plays a key role in the response. A quasi-linear analysis of the force balance reveals that the ion shielding current influences the field penetration threshold. Thereafter, we extended the analysis to the full drift-MHD regimes.

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MCF 10 - MHD

O 165 - Alfvén Mode Excitation by ITG Turbulence

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ABSTRACT TEXT

Throughout all operational phases (2018–2024) of the optimized stellarator Wendelstein 7-X in Greifswald, Germany, a rich spectrum of MHD activity has been observed. In the vast majority of experimental programs, despite the absence of energetic particle sources, broadband and discharge-lasting Alfvénic fluctuations occur. The fluctuations resemble those of Alfvénic activity in tokamak experiments during ohmic plasma scenarios (at the TFTR, ASDEX Upgrade and TCV tokamaks [3]). At the Wendelstein 7-X stellarator, the magnetic fluctuation measurements reveal the excitation of Alfvén eigenmodes (AEs) in electron cyclotron resonance heated plasmas, even in the absence of a conventional fast-particle driving source. This work presents an explanation for the excitation of AE via ion temperature gradient (ITG) turbulence [1] with an extensive experimental description of the phenomena. The detected AEs (Mirnov-measurements) in the range $50 < f < 450$ kHz are consistent with ellipticity, toroidicity, and non-circularity-induced AEs [1, 2]. Density fluctuations (Phase Contrast Imaging measurements) indicated dominant ITG turbulence in these plasmas [4]. The amplitudes of AEs and density fluctuations show a correlation for different magnetic field configurations. Moreover, in turbulence-reduced regimes, caused by peaking of the density profile via pellet injection, a reduction in the AE amplitude is found. Non-linear gyrokinetic simulations using the EUTERPE [5] code revealed simultaneous excitation of zonal flow activity and generation of AEs driven by ITG turbulence.

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BSAP 6 - Space plasmas

O 167 - Turbulence and preferential heating in astrophysical plasmas

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ABSTRACT TEXT

Astrophysical plasmas are typically collisionless, meaning they can deviate significantly from local thermodynamic equilibrium. This allows different particle species, such as protons and electrons, to sustain distinct temperatures. Observations suggest that turbulence plays a crucial role in transferring energy from large, energy-containing scales to small kinetic scales, where it is ultimately converted into plasma internal energy (heating). However, a key open question remains: how does turbulence partition energy between protons and electrons? Does it favor one species, or does it distribute energy evenly? This question is central to several major open problems, including the heating of the solar corona and the luminosity of accretion disks around black holes. Over the past two decades, significant theoretical and numerical efforts have been made to predict the proton-to-electron heating ratio. However, direct, extensive in-situ measurements remain scarce. Using data from NASA's Magnetospheric Multiscale (MMS) mission in the Earth's magnetosheath, we analyze how turbulence drives plasma heating through the pressure-strain interaction. We identify the scales at which heating becomes effective and explore how energy is partitioned between protons and electrons as a function of the plasma parameters. Our findings deepen our understanding of the interplay between turbulence and plasma heating, with implications for interpreting remote-sensing observations of astrophysical plasmas.

BSAP 6 - Space plasmas

O 168 - Quasi-periodic pulsations in solar and stellar flares: automated detection and insights into electric current systems in coronal plasmas

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ABSTRACT TEXT

Flares are driven by the release of free magnetic energy stored in electric currents, both on small scales near magnetic X-points and larger scales in flux ropes, current sheets, or loops. While the standard flare model describes this energy release, it does not account for quasi-periodic pulsations (QPP), which are frequently observed in solar and stellar flare light curves. These oscillatory patterns carry crucial but underexplored information about flare initiation, evolution, and the surrounding plasma environment. In this talk, we discuss simultaneous multi-wavelength observations of QPP in stellar superflares, in soft X-rays (SXR) with XMM-Newton and in white light (WL) with Kepler spacecraft. The detected SXR and WL oscillation periods and their correlation suggest a link to electric current oscillations in the flare loop, providing the first explicit seismological evidence in favour of the equivalent LCR-contour model of a flare loop, at least in the extreme conditions of stellar superflares. However, detecting QPP is challenging due to their intrinsically non-stationary nature, contamination by noise, and the rapidly increasing volume of flare observations. To enable large-scale identification of such events, we developed a fully convolutional network (FCN) to classify flare light curves based on the presence of exponentially decaying harmonic QPP. Trained on synthetic data and tested on Kepler flare observations, the FCN demonstrated high accuracy and successfully identified QPP in a large flare catalogue. This automated approach offers a promising solution for the preliminary sifting of QPP events in real flare data, providing insights into their properties and underlying physical mechanisms. The FCN is accessible through a user-friendly browser-based application, making it a useful tool for future observational studies.

BSAP 6 - Space plasmas

O 169 - Spectrum of high-altitude blue auroral emissions observed with hyperspectral camera for auroral imaging (HySCAI) during astronomical twilight

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ABSTRACT TEXT

The hyperspectral camera for auroral imaging (HySCAI), which can provide a two-dimensional (2D) aurora image with full spectrum, was developed to study auroral physics. HySCAI consists of an all-sky lens, monitor camera, galvanometer scanner, grating spectrograph, and electron-multiplying charge-coupled device (EM-CCD). The galvanometer scanner can scan a slit image of the spectrograph on the all-sky image plane in the direction perpendicular to the slit. HySCAI has two gratings; one is 500 grooves/mm for a wide spectral coverage of 400–800 nm with a spectral resolution (FWHM) of 2.1 nm, and the other is 1500 grooves/mm for a higher spectral resolution of 0.73 nm with a narrower spectral coverage of 123 nm. This system has been installed at the KEOPS (Kiruna Esrange Optical Platform Site) of the SSC (Swedish Space Corporation) in Kiruna, Sweden [1, 2].

A quantitative measurements of aurora emission during the astronomical twilight are difficult using the all-sky camera equipped with a band-pass filter, because of the contamination of background emission due to sunlight. In contrast, the HySCAI gives the precise aurora emission intensity by subtracting the background of the spectrum. The spectrum of high-altitude blue auroral emissions has been observed with HySCAI during morning astronomical twilight. Auroral resonance scattering of N_2^+ 1NG (0, 1) (427.8 nm) emission starts to increase from the east (03:07:22 UTC), and then the increase of this resonance scattering emission extends to the magnetic zenith (03:43:22 UTC). The volume emission rate is evaluated from the rise in resonance scattering emission (time derivative of emission intensity). The volume emission rate of N_2^+ (427.8 nm) becomes maximum when the shadow height of the sunlight becomes 200 km, although the GLOW model [3] predicted the peak altitude of N_2^+ (427.8 nm) of 120 km. The higher altitude of the resonance scattering emission peak observed with HySCAI supports the idea that upflowing N_2^+ ions are responsible for the sunlit aurora, although we cannot rule out another possible mechanism: N_2^+ is produced by the charge exchange of O^+ .

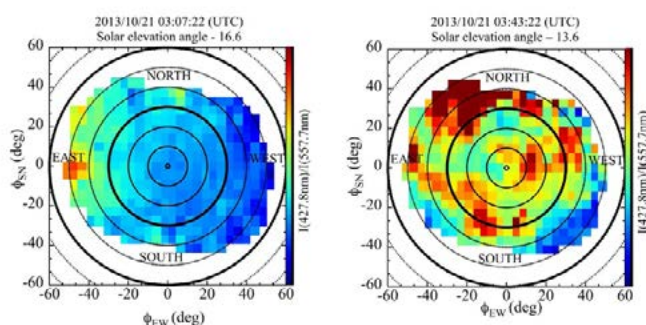
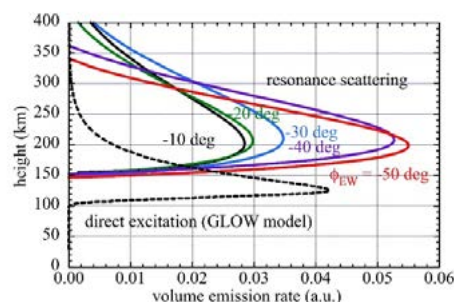


Image of N_2^+ (427.8 nm) emission normalized by OI (557.7 nm) emission.



Volume emission rate of N_2^+ (427.8 nm) as a function of shadow height of the sunlight.

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O 171 - Wave conversion and heating in a two-fluid partially ionized atmosphere

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ABSTRACT TEXT

The solar chromosphere is a highly dynamic layer governed by magnetic forces. Both models and observations face challenges in analysis and interpretation. For example, the mechanism that heats the chromosphere remains to be determined. Chromospheric plasma temperatures range between 4000 K and 9000 K, so it contains a significant amount of neutral particles. Charged and neutral components move as a whole for phenomena operating at timescales significantly larger than collision times between them. However, if the characteristic timescales become comparable or smaller than collision times, charges and neutrals may decouple and rise plasma temperature by means of frictional heating. Here, we investigate wave dissipation via charge-neutral collisions as a heating mechanism in a two-fluid model. We focus on the propagation of magneto-acoustic waves in two distinct 2D setups containing an acoustic-to-magnetic (or vice versa) conversion region. In the first scenario, we examine a vertically stratified atmosphere with a uniform magnetic field. Acoustic waves are launched from the bottom of the atmosphere at various angles relative to the magnetic field. In the second scenario, we maintain the same thermodynamic conditions but introduce a potential magnetic field, which allows for the existence of a magnetic null point. In this case, a driver generates a vertically propagating acoustic wave from the bottom of the atmosphere, positioned directly below the magnetic null point. Moreover, we perform comparative analysis for two distinct atmospheres: a Holmul model representing a cool atmosphere in radiative equilibrium and a hot chromosphere represented by a VAL3C model. We also modify the ionization fraction of the atmosphere to explore its effect on the heating mechanism. In those conditions, we investigate how fast and slow waves are affected by collisional interaction. A preliminary result shows that slow shocks can produce at the upper layers differences in velocity between charges and neutrals comparable to those produced by fast waves at lower layers.

Poster Presentations

Poster Session BPIF 1

1 P 001 - Spectroscopic characterization of directly-driven spherical implosions using artificial neural networks

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ABSTRACT TEXT

The analysis of emission or absorption spectra, which typically involves the comparison of experimental data with spectroscopic models, stands as a key diagnosis tool of hot and dense plasmas. Traditional model-independent search algorithms rely on χ^2 minimization over a broad set of theoretically motivated synthetic spectra computed across a wide range of temperature and density conditions. However, these approaches can be computationally expensive, particularly when multi-zone spatially resolved analyses are required.

In this work, we present a new approach for the characterization of directly-driven imploding spherical targets using an artificial neural network (ANN) model trained on Ar K-shell synthetic spectra. The training dataset covers temperatures from 0.5 to 5 keV and electron densities from $1e22$ to $1e25$ cm⁻³, with a uniform random noise added in order to mimic the experimental data noise. First results for the analysis of uniform plasmas show good agreement between predicted and test conditions with minimal computational cost even at relatively high noise-to-signal ratio. We further discuss the impact of the added noise level in the predicted conditions across different temperature and density regimes as well as the extension of our ANN model to multizone analysis. Finally, in the context of Ar-doped spherical implosion experiments performed at the OMEGA laser facility, we compare the core conditions inferred from χ^2 minimization search algorithms with those obtained using our ANN-based approach.

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Poster Session BPIF 1

1 P 002 - Design of compact Thomson parabola spectrometer with high energy resolution

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ABSTRACT TEXT

We present the design and development of a compact high-resolution Thomson parabola ion spectrometer capable of characterising the energy spectra of low-Z ion species in multi-MeV energy range which is suitable especially for the proton-boron fusion. Within this study we also analysed the fringe effects of both magnetic and electric field and their influence on the energy resolution of various charge-to-mass ratio ion states with emphasis on the differentiation of alpha particle traces and heavier ion traces. Different ion energy ranges can be probed using an electromagnet setup with a variable field strength from 0–0.6 T, a variable electric field with intensity corresponding to applied voltage in the range 0–20 kV, and a variable drift-space. Thomson parabola spectrometer was designed in SIMION software taking in account the resolution of microchannel plate given by channel diameter and the number of amplification stages. Our Thomson parabola spectrometer will be located at PALS facility (Prague) equipped with kJ-class sub-nanosecond laser system and therefore it has to be resistant to electromagnetic pulses which are generated during the laser-plasma interaction and can disrupt the resolution of ion traces.

Poster Session BPIF 1

1 P 003 - Probing the density evolution of borane plasma by a multi-frame interferometer

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ABSTRACT TEXT

The Mach-Zehnder interferometer is a simple and widely used interferometer for studying fluid flow, heat transfer, plasma temperature, density distribution, etc. Its key advantage lies in its two distinct arms, which can be extended as needed while ensuring the object is probed only once. Furthermore, the fringe spacing and orientation are controlled by varying the angle between the beams leaving the interferometer. These features make the Mach-Zehnder interferometer ideal for the multi-framing device.

This work presents the design and experimental validation of a multi-frame Mach-Zehnder interferometer. Laser pulses with different colours and polarizations are introduced into the interferometer setup. This approach enables single-shot monitoring of dynamic phenomena, such as plasma evolution. The further advantage of this interferometer is its easy alignment procedure, as the probe beams travel co-propagating in one arm without the need for spatial separation of arms probing the object at different angles as in current few-frame interferometers. In addition, the delay between individual frames can cover the range from femtoseconds to nanoseconds depending on the desired temporal scale of the probed object or phenomenon.

We demonstrate the experimental application of the multi-frame Mach-Zehnder interferometer for electron density measurements of hot dense plasma produced by a sub-nanosecond kilojoule laser pulse at the PALS facility in Prague.

Poster Session BPIF 1

1 P 004 - Foam-based targets for stable laser-driven fusion energy

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ABSTRACT TEXT

In laser-driven fusion, target stability is crucial for achieving efficient compression and ignition. Hydrodynamic instabilities, seeded by laser and target inhomogeneities are amplified during target acceleration, pose significant challenges to achieving uniform compression. Polymer foams offer a promising solution by modifying plasma conditions and smoothing perturbations at the ablation front.

A decade of experiments at the National Ignition Facility (NIF) has demonstrated that inertial confinement fusion (ICF) is a viable pathway to energy production, with recent experiments exceeding the ignition threshold [1]. However, no ignition-scale laser facility is currently configured for direct-drive fusion. In this context, the **Taranis project in France**, led by **GenF**, is advancing laser fusion reactor designs that require highly stable and easily manufacturable targets. Foam-based targets present a promising approach by reducing imprint and improving implosion robustness [2,3].

In this work, we use high-fidelity 2D hydrodynamic FLASH [4] simulations to assess the role of CH-based foams in mitigating imprint and stabilizing implosions. The simulations capture key plasma properties, including laser energy deposition, density evolution, and perturbation growth. We analyse the effects of foam density, thickness, and pore size on imprint suppression and instability control.

By leveraging numerical modeling, we provide insights into optimal foam configurations for direct-drive implosions in the multi-kJ regime. These findings contribute to the design of advanced targets for laser fusion experiments and future inertial confinement fusion reactors.

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Poster Session BPIF 1

1 P 005 - Surrogate modelling of electron acceleration in near-critical density QED plasmas at ultra-high intensities

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ABSTRACT TEXT

When an intense laser pulse interacts with a plasma target, its propagation and energy absorption depend strongly on the plasma density relative to the critical density. In the non-relativistic regime, three general cases arise: (i) for sub-critical densities, the laser propagates through the target; (ii) for over-critical densities, the laser penetrates the plasma within a characteristic skin depth which is typically very small; and (iii) for near-critical, the laser propagates into the dense target, but its propagation is strongly modified by the plasma. In this last case the mechanisms governing electron acceleration are not well understood. This is important as at ultra-high intensities the electrons in the plasma become ultra-relativistic and even solid target can become near-critical. At these intensities strong-field QED effects also become important, further complicating the situation.

In this work, we compare fully kinetic simulations performed with EPOCH to theoretical predictions of electron dynamics at ultra-high intensities. Due to the computational expense of simulating these interactions over a wide parameter space, we employ surrogate modelling techniques to extrapolate trends and construct a reduced model of the system. Since these models leverage Gaussian processes, they inherently provide uncertainty quantification, allowing us to extract error bars on predicted results. This approach enables efficient exploration of the parameter space and provides deeper insight into the fundamental physics of laser-driven electron acceleration in near-critical density plasmas.

Poster Session BPIF 1

1 P 006 - Quantum-accelerated simulation of electron-positron pair production in Extreme Laser-Plasma interactions

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ABSTRACT TEXT

The imminent deployment of next-generation petawatt lasers, such as at ELI L4 and Apollon, brings many novel opportunities to study strong field quantum electrodynamics in intense laser-plasma interaction. An example of SFQED processes in this regime is electron-positron pair creation. An accurate study of pair yield is paramount to enable efficient experiment design. Estimating the number of pairs produced in such processes is usually done with Monte Carlo simulations; However, these simulations can often be computationally expensive. In this project, we perform Quantum Monte Carlo Integration, using Quantum Amplitude Estimation, to estimate the number of produced electron-positron pairs in extreme laser-plasma interactions. We prepare the initial particle distribution and the quantum circuit to calculate the expected pair-production probability. We implement Iterative Quantum Amplitude Estimation using the Qiskit framework. Initial simulations of pairs were produced and compared well with classical simulations. Furthermore, we discuss the continuation of this model by investigating scalings, including more pair-production processes and improvements in accuracy.

Poster Session BPIF 1

1 P 007 - Equation of motion of uniformly accelerating charged particles including radiation reaction effect

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ABSTRACT TEXT

The intense laser-matter interactions are expected to be generate various quantum beams such as positrons and neutrons [1]. In these analyses, trajectories of charged particles need to be evaluated including radiation reaction effect. The Lorentz-Abraham-Dirac (LAD) equation is widely known as a candidate of the equation of motion of charged particles including the radiation reaction effect[2]. It is known, however, the solutions of the LAD equation suffer from problems known as a ran-away solution and violation of causality. Alternative equations are proposed such as the Landau-Lifshitz, the Mo-Papas, the Ford-O'Connell equations, and others.

In order to clarify the differences of these proposed equations, we compared the solution of LAD equation and those of the Landau-Lifshitz, the Mo-Papas, and the Ford-O'Connell equations [6]. Solutions under a static magnetic field and a rotating electric field using each equations are obtained, and the parameters such as the Lorentz factor, radiation loss rate, the Lorentz invariant quantum parameter are compared. It is shown that the Lorentz factors and radiation loss rates evaluated by using those equations show quite similar behaviour and the relative differences are less than 10^{-6} in the regime where classical radiation reactions are applicable. In this paper, we consider an alternative equation of motion, especially paying attention to the uniformly accelerating charged particle, where radiation reaction force in the LAD equation diminishes. We evaluate the self-force on the uniformly accelerating particle using nonlinear electrodynamics.

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Poster Session BPIF 1

1 P 008 - Amplifying strong field signatures with flying focus pulses

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ABSTRACT TEXT

Strong field signatures in laser-particle interactions accumulate with interaction time. This can be leveraged with “Flying Focus” (FF) laser pulses where the moving focal point of a FF forms an intensity peak that can travel at any velocity, over distances much longer than a Rayleigh range [1,2]. Specifically, particle beams can propagate with the laser focus, so that the particles stay in the region of peak field intensity for prolonged interaction times. Using FF pulses, we demonstrated that radiation energy loss accumulation, and accumulation of phase shift induced by vacuum birefringence enable experimental access to strong field effects at orders of magnitude lower laser powers and intensities than in conventional fixed-focus setups, while still achieving comparable response [3,4]. Even more importantly, in the quantum regime of the laser-electron interaction the energy loss and photon yield scale more favourably with the interaction time than the laser intensity. In this regime, FF pulses provide an outright advantage over fixed-focus pulses, with simulations of 10 GeV electrons colliding with 10 J pulses predicting 5× increase in the yield of 1–20 MeV photons [5].

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Poster Session BPIF 1

1 P 009 - Modeling and theoretical description of extreme laser-matter interaction

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ABSTRACT TEXT

Extreme environments are naturally found throughout the Universe, e.g. in the vicinity of compact objects such as neutron stars. Describing plasma in extreme conditions requires not only the study of kinetic plasma dynamics, but also accounting for additional particle generation (e.g. electron-positron pairs), as well as radiative processes that give rise to gamma-rays, which are invisible for the simulation grid. The radiation emission and pair generation affect the energy redistribution among different particle species, and can affect particle properties such as spin. More recently (and in the near future), with the access to ultra-high laser intensities, it is/will be possible to re-create some aspects of these extreme conditions in laboratory. Numerical developments coupling plasma physics methods with all necessary high-field phenomena are critical to predict, interpret and plan the experiments of the future. I will report on the recent advances on modeling capabilities of OSIRIS-QED, and dedicated diagnostics that are specially developed for studying the ultra-high-field phenomena. Case studies will be presented, showing the most recent physics results obtained by the team using the OSIRIS framework.

Poster Session BSAP 1

1 P 010 - Investigating the competition between kinetic plasma instabilities in Earth's magnetosheath using the semi-implicit Particle-In-Cell method

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ABSTRACT TEXT

Thermal anisotropies, different temperatures in the parallel vs perpendicular direction with respect to the ambient magnetic field, are common in collisionless plasma such as solar wind and magnetospheric plasmas. A sufficiently large ratio of perpendicular to parallel temperature with respect to the ambient magnetic field causes cyclotron and mirror instabilities to grow. It has been suggested that a plethora of variable factors: an anisotropic electron distribution (Ahmadi et. al., 2016), a concentration of helium ions (Remya et. al., 2013) and the parallel proton beta (Gary, 1992) can affect the relative growth rate of these two instabilities. Together, these contributing factors may help to explain why observations of proton instabilities in Earth's Magnetosheath show the growth of unstable mirror modes (Kaufmann et al., 1970) in regions where linear theory predicts cyclotron instabilities will possess the higher growth rate. By leveraging multidimensional kinetic simulations with the Energy Conserving Semi-Implicit Method (Gonzalez-Herrero et al., 2018), this work examines the behaviour of the proton mirror and cyclotron instabilities under the effect of the aforementioned contributing factors with the goal of identifying under which parameter space the proton mirror instability may dominate.

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Poster Session BSAP 1

1 P 011 - Nonlinear modulation of dispersive fast magnetosonic waves in an inhomogeneous rotating solar low- β magnetoplasma

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ABSTRACT TEXT

We study the modulation of fast magnetosonic waves (MSWs) in rotating inhomogeneous low- β magnetoplasmas with the effects of gravitation and the Coriolis force. By employing the standard multiple-scale reductive perturbation technique (RPT), we derive a nonlinear Schrödinger (NLS) equation that governs the evolution of slowly varying MSW envelopes. The fast MSW becomes dispersive by the effects of the Coriolis force in the fluid motion, and the magnetic field and density inhomogeneity effects favor the Jeans instability in self-gravitating plasmas in a larger domain of the wave number (k , below the Jeans critical wave number, k_j) than homogeneous plasmas. The relative influence of the Jeans frequency (ω_j , associated with the gravitational force) and the angular frequency (Ω_c , relating to the Coriolis force) on the Jeans carrier MSW mode and the modulational instability (MI) of the MSW envelope is studied. We show that the MSW envelope (corresponding to the unstable carrier Jeans mode with $\omega_j > 2\Omega_c$ and $k < k_j$) is always unstable against the plane wave perturbation with no cut-offs for growth rates. In contrast, the stable Jeans mode with $\omega_j > 2\Omega_c$ but $k > k_j$ manifests either modulational stability or MI having a finite growth rate before being cut off. We find an enhancement of the MI growth rate by the influence of magnetic field or density inhomogeneity. The case with constant gravity force (other than the self-gravity) perpendicular to the magnetic field is also briefly discussed to show that the fast magnetosonic carrier mode is always unstable, giving MI of slowly varying envelopes with no cut-offs for the growth rates. Possible applications of MI in solar plasmas, such as those in the X-ray corona, are also briefly discussed.

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Poster Session BSAP 1

1 P 013 - The use of imaging plates for proton radiography in laser-driven experiments

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ABSTRACT TEXT

A new detector design has been fielded on the Omega-60 laser facility using a DHe-3 backlighter capsule to radiograph a magnetized experiment. DHe-3 capsules produce a low flux ($\sim 10^8$ yield in 4π) of protons requiring detectors with close-to single-particle sensitivity to be employed. The new detector stack consisted of both imaging plate (IP) and CR-39 to detect 14.7 MeV protons where, historically, only CR-39 has been used. IP is sensitive to significant contributions in signal from both x-rays and protons so additional filtering has to be added to attenuate the x-rays. The signals and features observed from a single shot are detected by both IP and CR-39, giving confirmation that it is protons creating the signatures on the IP. A large benefit to this new stack design is that IP can be scanned and processed on much faster timescales than CR-39 allowing for prompt shot feedback.

Results from recent experiments investigating magnetised, collisionless shocks as well as plasmas being driven out into hohlraum-like gas fills have utilized this detector and results from these platforms will be presented. Electromagnetic field structures are produced in these experiments from the modification of background magnetic fields (collisionless shocks)

Poster Session LDTP 1

1 P 014 - Modeling of the ion dynamics in a bounded low-temperature plasma with moment methods

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ABSTRACT TEXT

In several low-temperature plasma applications, such as electric propulsion and plasma etching, the ions are out-of-equilibrium due to their diluted nature, the presence of strong gradients and strong electric field. Classical fluid models are therefore not well-suited to describe their dynamics due to the often non-Maxwellian velocity distribution functions (VDF) of the ions, and one usually has to rely on kinetic models. However, the latter are computationally very expensive, especially at higher pressures, and are therefore not well-suited to be applied to large systems.

In this study, we investigate moment methods as an alternative approach to model the ion dynamics in a low-temperature plasma. We address the two main modelling challenges, namely the moment closure and the collisions. For that, we implemented four of the most common five-moment models (Grad, HyQMOM, EQMOM and maximum entropy) [Pichard 2023] with a finite-volume discretization in a one-dimensional simulation [Alvarez 2020] and compared the results with a similar particle-in-cell (PIC) simulation [Lequette 2024]. We also consider a proper description of the collisions based on the integration of the Boltzmann collision term with several forms of VDF. We ran these simulations for several pressure regimes and assessed the accuracy of the moment models to describe the macroscopic behavior of the ions (by considering some moment profiles) and their ability to reconstruct a VDF (from the simulated moments) similar to the ones obtained from the PIC simulations.

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Poster Session LDTP 1

1 P 015 - Study on power efficiency for hydrogen production by methane decomposition using AC plasma

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ABSTRACT TEXT

In recent years, the technology to produce turquoise hydrogen by thermal decomposition of methane has been attracting attention. Various types of plasma are proposed for the methane pyrolysis. Plasma can be only used or a catalyst used with plasma for hydrogen production. Low- or high-temperature plasma can be used, and CCP or ICP configuration can be also suggested. Each plasma technology has its own advantages and disadvantages, and some technologies are close to commercialization for hydrogen production. However, it is not yet clear which method can secure economic feasibility and productivity [1–2].

This study focuses on preliminary experiments to determine whether energy optimization and economic feasibility for hydrogen production are possible using a laboratory-scale plasma system. Plasma working at AC frequency was applied to ensure that the plasma process is suitable for hydrogen production, and various parameters were optimized. In addition, computational analysis and optimization of operating variables to minimize electrical energy consumed in the methane decomposition process are discussed.

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Poster Session LDTP 1

1 P 016 - A fully coupled Pressure-Based Method for the Electron Fluid Model in Hall-Effect Thrusters

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ABSTRACT TEXT

The Hall-Effect Thruster is an electrostatic thruster that typically features an annular discharge channel. A radial magnetic field within the channel reduces electron mobility and induces the formation of a localized axial electric field near the channel exit. The ions are accelerated by this electric field, thereby generating thrust. A plasma model that effectively simulates this sequence of processes is the 2D axisymmetric hybrid model, where ions and neutrals are represented as macroparticles, while electrons are modeled as a fluid. This numerical approach has been widely employed in Hall-Effect Thruster plasma simulations^[1,2]. Conventionally, fully-2D hybrid models that utilize a magnetic field-aligned mesh to solve the electron fluid equations employ a segregated solution algorithm, where the electron momentum equation is approximated using the generalized Ohm's law under the assumption of inertialess electrons^[3,4]. However, this approach requires multiple iterative computations to achieve convergence of the equation residuals. Additionally, a numerical method capable of solving the electron momentum equation in a more general form is necessary to account for electron inertia. This study presents the derivation of a fully coupled pressure-based method for solving the electron flow governing equations in a fully-2D method by formulating them into a single sparse matrix. Furthermore, a comparative analysis with simulations incorporating electron inertia is conducted to investigate the influence of electron inertia on plasma response.

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Poster Session LDTP 1

1 P 017 - Optical emission spectroscopy of tungsten cathodic arc plasma at different argon and nitrogen pressure

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ABSTRACT TEXT

The vacuum-arc discharge has numerous applications in both physics and applied technologies [1]. The vacuum-arc deposition method is commonly utilized in the industry to modify material surfaces and apply functional coatings. The optical spectrum of tungsten plasma was mainly investigated in the high vacuum region and also in various gases at pressures close to atmospheric pressure [2, 3]. Although the medium vacuum range is used for coating applications. Therefore, studies of the optical spectrum of tungsten cathodic arc at these pressures are of interest. The optical emission spectroscopy is a non-contact method that can be used over a wide range of temperatures, plasma densities, and neutral gas pressures. This is important in studying metallic plasmas both in vacuum and in neutral and reactive gas environments.

The optical emission spectrum of steady-state tungsten cathodic arc discharge plasma in an industrial commercial “Bulat-6” installation [4] at different argon and nitrogen pressure was investigated. The gas pressure range in the experiments was from 0.05 Pa to 5 Pa. A vacuum cathodic arc source with a magnetic stabilization field and tungsten cathode (diameter 60 mm) was used in the experiments. The arc current was $I_a = 130$ A. The plasma lines spectrum was registered by optical emission spectrometer in the spectral range from 214 to 673 nm. The ions charge state and plasma elemental composition were determined through the optical emission spectroscopy. The spectral line intensities of excited tungsten atoms and ions, as well as molecules and molecular nitrogen ions and argon from pressure were analyzed.

The obtained dependences of electron temperature, charge composition of metal and gas ions, and the ratio of neutral particles to charged particles as a function of nitrogen or argon pressure can be useful to explain the synthesis of tungsten-based coatings and to understand the processes of interelectrode plasma of vacuum arcs with tungsten cathodes.

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Poster Session LDTP 1

1 P 018 - Numerical and experimental investigation of an atmospheric pressure DC corona discharge

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ABSTRACT TEXT

Ionic propulsion in the atmosphere is an emerging topic that is gaining significant momentum within the scientific community. This is due to its potential for low-cost, high-durability propulsion systems based on the electro-hydrodynamic (EHD) force produced by different types of discharges (i.e. corona, DBD). The characterization of these discharges plays a crucial role in the understanding and in the improvement of the ionic thrusters performances and, consequently, in optimizing propulsion systems. In this work, a concentric wire-cylinder corona discharge in atmospheric-pressure air is studied through comparison between experimental results and numerical simulations. The discharge is simulated using a 1D code in cylindrical coordinates, developed in MATLAB, which solves the time-dependent drift-diffusion-reaction equation using the finite volume method. Two different reaction schemes were used for the corona discharge simulations: one from Parent et al. [1], which includes $e, N_2, N_2^+, O_2, O_2^+, O_2^-$, and another from Kozhevnikov et al. [2], in which O_4^+ , N and O are added. A campaign of experimental measurements is performed on a wire-cylinder corona reactor, with the same geometrical characteristics of the simulated device. The V-I characteristics obtained from the simulations are in good agreement with both the phenomenological model proposed by Monrolin et al. [3] and the current measurements performed on the laboratory device, across a wide range of voltage values. Interestingly, it is found that both studied reaction schemes yield an accurate V-I characteristic, despite showing significant differences in the species spatial distribution once the discharge has reached steady state—to be discussed in the full version of this manuscript. This finding should be taken into account when such numerical approaches are used to evaluate EHD thrust for propulsion applications.

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Poster Session LDTP 1

1 P 019 - Plasma synthesis of nanogold for SERS detection of trace explosives

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ABSTRACT TEXT

Nanogold is a promising material for enhancing surface-enhanced Raman scattering (SERS), enabling the detection of hazardous analytes at very low concentrations. This study introduces a straightforward, single-step plasma synthesis approach that leverages plasma–liquid redox chemistry to regulate both the size and yield of Au nanoparticles. Within five minutes, a low-temperature argon plasma reduces an Au³⁺ precursor, producing primarily spherical Au particles measuring approximately 20 nm at 0.025 mM and up to 90 nm at 1.0 mM, alongside plate-like structures found at concentrations from 0.25 to 1.0 mM.

The improved SERS signals correlate with UV–Vis absorption and reflectance spectra, attributable to synergistic plasmonic hotspots arising from sphere–sphere, plate–sphere, and plate–plate nanogold interactions. When combined with gold-plated CPU grid pin arrays, this mixture facilitates the trace detection of both aromatic (TNT, TNB, TNP) and aliphatic (RDX, PETN, HMX) explosives.

The results reveal that the more stable aliphatic analytes, with their lower vapor pressures (10^{-8} – 10^{-11} atm), produce smaller signal fluctuations (relative standard deviation, RSD ~6–10%) than the more volatile (10^{-5} atm) aromatic analytes (RSD ~12–17%) at comparable analyte levels. The calculated limits of detection (LoD) were approximately 2–6 nM for aromatic explosives and around 0.6–0.9 nM for aliphatic counterparts. Finally, it is demonstrated that the diminished performance of aromatic explosives under identical sensing conditions influences SERS–PCA separation, which can be enhanced either through a machine learning approach (PCA with k-NN classification) or by focusing on the specific NO₂ fingerprint region.

Poster Session MCF 1 - L

1 P 020 - Preliminary results from magnetic measurement by using hall sensors in the KSTAR tokamak

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ABSTRACT TEXT

The linear integrating drift was typically observed in the signal of the inductive magnetic sensor for a plasma control during a plasma discharge with a time of less than ~20 sec in the KSTAR tokamak, and it was easily compensated by using linear fit on the baseline of the signal. However, it was found that there was the nonlinear integrating drift in the signal of the magnetic sensor for a long-pulsed plasma with a duration of longer than 30 s. The nonlinear drift was clearly observed in the sensor located at the outer midplane (OMP) side, which was mostly caused by the heat-up of the sensor itself due to the radiation from plasma because the sensor was opened to the plasma at the OMP side [1]. Thus, there was an activity for finding a method for compensating the nonlinear drift in the sensor signal during a long-pulsed plasma. In parallel with the activity, we tried to apply the method by using hall sensor for the magnetic measurement in the KSTAR. Considerable progress on the research and development of the hall sensors have been carried out in the IPP CAS for applying them to the magnetic measurements in the future machines such as the ITER and DEMO [2, 3]. Several hall sensors were provided by the IPP CAS as the international collaboration, so the performance test of the hall sensors was carried out during the experimental campaign in the KSTAR. Which is thought as the first step for applying the hall sensor to the magnetic measurement during a long pulsed plasma for resolving the nonlinear drift issue. In this work, the issue of the nonlinear drift in the magnetic measurement by using the inductive sensor for the long-pulsed plasma will be described, and the preliminary results from the performance test of the hall sensor during vacuum and plasma shots in the KSTAR will be presented.

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Poster Session MCF 1 - L

1 P 021 - Tungsten content quantification in Wendelstein 7-X plasmas

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ABSTRACT TEXT

Tungsten has emerged as one of the most promising materials for first-wall components in nuclear fusion devices. Erosion of the first wall can in principle lead to heavy contamination of the plasma, where high-Z elements like tungsten dilute the main fuel and may cause radiative plasma collapse if concentrations exceed critical levels. To investigate the influence of intrinsic tungsten sources on the plasma, a small fraction of the Wendelstein 7-X (W7-X) stellarator's inner wall is made from, or coated with, tungsten. This includes some baffle and heat shield tiles, while the largest part of the first wall remains carbon based.

To monitor the tungsten content in W7-X plasmas, spectroscopic systems are used: UV spectroscopy at the edge, VUV and X-ray spectroscopy in the core. This contribution focuses on tungsten measurements made by VUV spectroscopy using the High Efficiency XUV Overview Spectrometer (HEXOS) installed at W7-X.

The most prominent tungsten feature in the VUV spectral range is the so-called tungsten quasi-continuum, referring to an unresolved transition array in the 4...7 nm wavelength region. In the latest W7-X campaign, the quasi-continuum was "calibrated" by injecting impurity pellets containing known tungsten quantities into steady-state plasmas at varying densities and temperatures. Based on the known amount of W atoms injected with the impurity pellet, combined with the increase of total radiated power as measured by bolometry, a lookup-table like dataset of the quasi-continuum signal for given tungsten concentrations in different plasma conditions was created.

Using this dataset, the tungsten content in W7-X plasmas – with a focus on the intrinsic background concentration – is estimated for large parts of the latest experimental campaigns. A closer look is taken on selected discharges with increased tungsten content, and their potential implications for increasing the number of tungsten first wall components in W7-X are discussed.

Poster Session MCF 1 - L

1 P 022 - Utilizing ECE for precise measurement of the Shafranov shift and plasma equilibrium assessment

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ABSTRACT TEXT

Electron Cyclotron Emission (ECE), sensitive to the local magnetic field, can be used as a plasma equilibrium diagnostic tool in conjunction with electron temperature (T_e) diagnostics such as Thomson scattering. Even without full T_e profile inference from ECE, the center of the emission spectrum displays the on-axis magnetic field and its reduction by the diamagnetic effect, hence the plasma pressure and the Shafranov shift. Initial estimates of the Shafranov shift using this method have indicated that it is possible to detect variations in plasma equilibrium on the order of millimeters. Hence, the optimization of the W7-X stellarator to minimize Shafranov shift for better plasma confinement and stability can be explored for various magnetic configurations and pressure profiles. A practical application of this diagnostic tool lies in its ability to facilitate the rapid adjustment of the on-axis magnetic field, which is crucial for accurate plasma profile mapping.

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Poster Session MCF 1 - L

1 P 023 - Fast visible imaging of X-point radiator regime in WEST

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ABSTRACT TEXT

The divertor in next-generation fusion devices like ITER and DEMO must withstand years of quasicontinuous operation. To ensure this, steady-state heat fluxes on the target must remain below 10 MW/m², and target temperatures must stay below 5 eV under active control. The development of actively cooled scenarios has been studied on the WEST tokamak, which features a full tungsten, ITER-grade divertor. A stable radiative X-point (X-point radiator, XPR[1,2]) is formed through nitrogen seeding, where neutral impurities interact with the plasma. A visible camera operating at 10 kfps monitors the XPR with spectral filters to isolate radiation contributions from nitrogen and deuterium atomic lines. Tomographic inversion of camera images reconstructs 2D poloidal maps, providing insights into high- and low-field side asymmetry, poloidal drifts, and the localization of neutral deuterium and nitrogen. However, wall reflections interfere with the inversion process, requiring a reflection model in the transfer matrix calculation[3]. This is challenging since wall elements reflect light differently, and their optical properties can change over the course of an experimental campaign. Using ray tracing and the Cook-Torrance model, we generate geometry matrices that account for reflections, and calculate local reflection indices by combining real and synthetic images. We analyze videos of a detached plasma in limiter configuration, where emissive regions are far from walls. By cropping images to exclude walls, we obtain a poloidal emissivity map with minimal reflection interference. A geometry matrix with uniform wall reflectivity generates a synthetic image with this emissivity map, which is compared to real data to estimate local reflection coefficients. This inferred reflection model is subsequently applied to other experimental scenarios featuring Xpoint radiator. In particular we investigate the detailed dynamics of XPR formation, with microsecond range change in LFS/HFS radiation distribution. The influence of magnetic topology (upper vs lower single null) is also explored, with strong differences in dynamics and final states. Finally, confrontation to absolutely calibrated visible spectroscopy and high fidelity plasma modelling with SOLEDGE are envisaged.

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Poster Session MCF 1 - L

1 P 024 - Magnetic measurement under the environment with lower tungsten divertor in KSTAR tokamak

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ABSTRACT TEXT

The drift characteristics of the magnetic sensor signals in the magnetic measurement, which are important for better plasma control, are investigated after the graphite tiles as the plasma facing components were upgraded to the tungsten mon-blocks at the lower divertor for the long-pulsed operation with high heated plasma in the KSTAR tokamak. Here, the sensor signals processed through a low-pass filter are supplied to the plasma control system (PCS), and then they are stored in the data acquisition system (DAQ) [1]. For long-pulse plasma operation of up to 100s, the magnitude of the drift should be within a certain value required in the PCS. In addition, the locations of some Mirnov coils (MCs) for the MHD study were changed and the halo current monitors (HCMs) for the disruption study were newly installed during the procedure for the divertor upgrade [2].

In this work, the result from the experimental investigation of the drift characteristics of magnetic sensors after the divertor upgrade will be presented and the technical details of MCs and HCMs will be described.

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Poster Session MCF 1 - L

1 P 025 - Design of a hybrid polychromator for Thomson scattering diagnostic system on KSTAR

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ABSTRACT TEXT

Impurities in fusion plasmas degrade optimal plasma conditions by causing fuel dilution, which reduces fusion efficiency, and radiative power loss, which depends on the ionization state. The effective ion charge (Z_{eff}) is a key metric for quantifying impurity content in the plasma [1–5]. In KSTAR, which uses tungsten as its inner wall material like ITER [6], a small amount of impurity generated from plasma-wall interaction can significantly increase Z_{eff} , necessitating research on impurity generation, behavior, and accurate measurement. Recently, the toroidal visible bremsstrahlung (TVB) array in KSTAR has been upgraded to measure Z_{eff} profiles by detecting visible bremsstrahlung radiation, combined with electron temperature (T_e) and electron density (n_e) profiles from Thomson scattering (TS) diagnostics system [7]. TS system measures scattered signals along the laser beam path, with collection optics aligned accordingly. The filter polychromator in TS diagnostics detects wavelengths from 800 nm to 1064 nm, as the light source operates at 1064 nm. By modifying this polychromator, visible bremsstrahlung signals can be acquired along the identical line of sight and at the same timing as TS measurements. Building on previous projects [8,9], this study will enhance Z_{eff} measurement accuracy by extending bremsstrahlung continuum detection beyond the conventional 523 nm region. The hybrid polychromator is designed with two spectral regions:

- Thomson scattering region: Uses interference filters and avalanche photodiodes (APD), functioning as a conventional TS polychromator, covering 800 nm–1064 nm.
- Bremsstrahlung region: Uses interference filters and photomultiplier tubes (PMT), optimized for high-sensitivity bremsstrahlung continuum detection. Filters have narrow bandwidths, with central wavelengths selected to avoid line emissions based on visible spectrometer measurements.

A long-pass dichroic mirror with a 700 nm cut-on wavelength separates the two regions, allowing independent detection of TS and bremsstrahlung signals. Absolute calibration of the visible bremsstrahlung channels, essential for Z_{eff} calculation, is achieved using a calibrated integrating sphere. This research will improve Z_{eff} measurement accuracy and provide complementary data to the TVB array, contributing to a better understanding of impurity characterization.

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Poster Session MCF 1 - L

1 P 026 - Preliminary design of a Mirror-Type Thomson Scattering System in KSTAR

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ABSTRACT TEXT

The Thomson scattering diagnostic system in KSTAR has been designed as a tangential type and is currently in operation. This system collects Thomson scattering signals using lenses and transmits them to a polychromator via optical fibers. The transmitted signals are processed using a QDC (Charge to Digital Converter) digitizer and a 5 GS/s digitizer to calculate the electron temperature (T_e) and electron density (n_e) in the core and edge regions[1][2].

The newly designed Thomson system aims to enhance spatial measurement resolution in the plasma edge region and to cross-validate the calculated results by implementing a back-scattering-type Thomson scattering system. In KSTAR, T_e values can currently only be cross-verified using the Electron Cyclotron Emission (ECE) diagnostic, making additional cross-validation diagnostics particularly important. Unlike the existing Thomson system, the new system collects backscattered Thomson signals in the laser incident direction using a parabolic mirror and transmits these signals to the polychromator via optical fibers. The advantages of this method include reduced weight compared to a lens-based collection system and the ability to measure Thomson signals independently of the polarization of scattered light. In this presentation, we introduce the optical design for collecting back-scattered signals using a parabolic mirror and discuss the efficiency of the system through simulations.

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Poster Session MCF 1 - L

1 P 027 - Characterization of magnetic fluctuations in Reversed-Field Pinch plasmas

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ABSTRACT TEXT

The spectral properties of electromagnetic turbulence at the plasma edge of the RFX-mod device are experimentally characterized, in particular with respect to the role of the magnetic equilibrium, which in the reversed-field pinch configuration is parametrized by the reversal of the toroidal magnetic field at the edge. RFX-mod is a Reversed-Field Pinch (RFP) device that can operate in regimes with plasma current up to 2 MA. The measurements are obtained from sets of high-frequency in-vessel arrays of magnetic probes, covering the full toroidal and poloidal angles of the torus. High plasma current discharges are investigated, as in these conditions a spontaneous transition from an axisymmetric to a helical equilibrium (the Quasi-Single Helicity regime) is experimentally observed in RFP. This transition is induced by the growth of the most internally resonant resistive kink mode, which in RFX-mod is characterized by $m = 1$ and $n = 7$, being m and n the poloidal and toroidal mode numbers, respectively. The analysis is mainly devoted to the study of the magnetic fluctuations during reconnection phenomena, which cyclically occur in RFP plasmas. Reconnections are associated with a rapid reduction of the amplitude of the dominant mode, as well as of the equilibrium toroidal magnetic field at the edge. The evolution of magnetic fluctuations before, during, and after reconnection events is analysed and the presence of different kinds of instabilities is observed. Moreover, an analysis of the electromagnetic fluctuations, excluding the reconnection events phases, is carried out. We describe how the magnetic equilibrium affects the spectral properties of the fluctuations. The results of this analysis will provide useful indications on the typical electromagnetic phenomena to be further investigated in the RFX-mod2 device. This is the upgraded version of RFX-mod, whose new diagnostic systems will include a much larger number (>1700) of in-vessel magnetic coils.

Poster Session MCF 1 - L

1 P 028 - Investigation of possible solutions for the Grad-Shafranov equation by using Bayesian inference

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ABSTRACT TEXT

Many novel frameworks for equilibrium reconstruction of fusion plasmas have been developed over the years. Many of these have been successfully applied to large-scale magnetic fusion experiments that are equipped with advanced diagnostics. However, there are cases where equilibrium reconstruction needs to be performed with limited diagnostics. For example, due to the consideration of blanket coverage and radiation environments, commercial fusion reactors are required to operate with reduced diagnostic capabilities. When the diagnostics are not informative, an equilibrium that is consistent with the MHD force balance and limited data may not be uniquely determined. In selecting an equilibrium reconstruction algorithm, it is important to know how well data constrain possible solutions for an equilibrium.

In this contribution, we present a Bayesian-based analysis framework that characterizes the whole solution space of the Grad-Shafranov equation for a given axisymmetric plasma and a diagnostic setup. To consider all possible solutions, we first apply a Gaussian process tomography to the observations that are given by linear combinations of toroidal current elements and analytically calculate the current profile in the form of a probability distribution. Then, we further constrain the solution space by incorporating the MHD force balance condition into the likelihood. The posterior distribution that describes MHD equilibria is numerically calculated by the Markov chain Monte Carlo sampling.

We have applied this inference framework to the geometry of the PLATO tokamak and shown that the flux surface locations can be determined relatively well only from 16 pick-up coils, 4 flux loops, and a diamagnetic loop. On the other hand, the toroidal current density is inferred with limited success, and the inferences of the safety factor and pressure profiles are difficult. The characterization of possible choices of equilibria realized by this approach will help to optimize the equilibrium reconstruction schemes.

Poster Session MCF 1 - L

1 P 029 - Mirnov coil-based plasma state classification with deep learning methods

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ABSTRACT TEXT

In this work, we present a new methodology for plasma state classification using deep learning: Optimal Autoencoder System for Instability Study (OASIS), an autoencoder that efficiently compresses high-time-resolution Mirnov coil signals into latent vectors. The latent vectors are projected onto a three-dimensional space using Uniform Manifold Approximation and Projection (UMAP) [1], clustering Mirnov coil data with similar physical characteristics and enabling the automatic classification of L- and H-modes.

The classification of L-mode and H-mode is essential for establishing and controlling stable operational strategies in tokamak plasmas. In particular, the H-L back transition can lead to disruptions, making its classification even more important [2]. Plasma state classification has been studied across various devices using different deep learning models. Automating event detection via deep learning enables high-accuracy detection of tokamak events without human intervention, facilitating the analysis of extensive datasets accumulated over years of experiments and improving plasma scenario control and stability.

For the plasma state classification, typically, line-averaged electron density and $D\alpha$ signals have been utilised [3], with some studies also incorporating plasma current and diamagnetic loop signals [4–6]. Given that most conventional diagnostics, including the interferometer used for line-averaged density measurements, are expected to face challenges due to high neutron fluence and radiation in fusion reactors [7], maximising the extraction of physical insights from the remaining operational tools is essential. Building on this, this work introduces a deep learning methodology that determines plasma states using only Mirnov coil signals, demonstrating their potential as a key diagnostic in environments with limited diagnostic availability.

To validate this approach, we developed OASIS to extract meaningful features from Mirnov coil signals and tested its effectiveness in plasma state classification using UMAP. OASIS compresses the cross-power and cross-phase spectra, obtained via fast Fourier transform of signals from two toroidal Mirnov coils in KSTAR [8], into a compact latent representation. This preserves essential instability-related information while enabling efficient classification. Applying OASIS to KSTAR data demonstrated its high accuracy in distinguishing between L- and H-modes. This approach introduces a method for diagnosing plasma states using magnetic diagnostics, even in reactor-relevant environments where diagnostics are limited.

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Poster Session MCF 1 - L

1 P 030 - Full Data Streaming Infra-Red Video Bolometer (IRVB) of Korea Superconducting Tokamak Advanced Research (KSTAR)

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ABSTRACT TEXT

The plasma radiation is regarded as the most fundamental measurement for power balance [1], boundary physics [2], impurity transport [3], and disruptions [4]. InfraRed Video Bolometer (IRVB) is used for these measurements with a simple pin-hole camera and an IR camera, providing robustness against electromagnetic noise and structural simplicity.

Since 2023, the KSTAR lower divertor has been using tungsten plasma-facing components (PFCs), making real-time control a crucial issue. Consequently, KSTAR IRVB has been reconfigured for in-situ data streaming diagnostics. This reconfiguration faced challenges not only in the speed of analysis but also in the fact that the camera did not support streaming acquisition. As a result, the control program for the now obsolete camera model was redeveloped to support streaming. The analysis process was optimized for speed with GPU-based computations. By leveraging advanced parallel processing techniques, the data analysis efficiency was significantly improved.

In KSTAR, real-time data is handled using reflective memory (RFM); however, due to the limited capacity of RFM, only the representative values of sampled zones were recorded. To meet the demand for the entire profile data, a real-time data streaming service using Data Distribution Service (DDS) was established in parallel. DDS offers higher performance, better scalability, and stronger security measures. Considering the single profile's entire size of 40,000 bytes, the latency of DDS is estimated to be around 200 microseconds [5], which is acceptable given the IRVB's streaming frame rate of approximately 30 fps (33 ms). This infrastructure allows for comprehensive data collection and real-time analysis, enhancing the operational capabilities of KSTAR. The details of the full data streaming IRVB system will be presented.

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Poster Session MCF 1 - L

1 P 031 - Upgrade of APD and amplifier circuit in the polychromator of the KSTAR Thomson scattering diagnostic system

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ABSTRACT TEXT

Thomson scattering (TS) diagnostic system plays a crucial role in nuclear fusion research by providing electron temperature and density profiles. The polychromators of the TS system on KSTAR have been equipped with a five-channel combination of an interference filter, an avalanche photodiode (APD), and an amplifier circuit, to detect the extremely weak scattered signals [1]. Recently, the need for improvement of the polychromator on KSTAR TS system has emerged. First, as part of its ongoing upgrades, KSTAR recently changed the divertor tile materials from carbon to tungsten [2], which unexpectedly led to an increase in stray light intensity detected by the TS system. While the stray light does not affect TS signal measurement channels, it poses a challenge for absolute calibration using Rayleigh scattering, since the characteristic time of the current amplifier circuit in the polychromator is longer than the time interval between the scattered signal and the stray light signal. Second, the polychromators currently use APDs without temperature-bias voltage compensation, so the sensitivity could be highly dependent on temperature changes, potentially leading to unstable measurements during long-time operation. Finally, the existing circuit has a fixed gain, preventing optimization for the bit resolution of the fast digitizer currently in use [3]. To address these issues, improvements have been planned for both the APDs and amplifiers in the polychromator. The upgrade focuses on replacing the electronic components, independent of the optical components such as filters. The APDs will be replaced with new models, along with a dedicated high-voltage (HV) power supply module and amplifier circuit. The HV module compensates for temperature-dependent APD gain fluctuations using feedback from the temperature sensor embedded in each APD. In addition, the amplifier is designed to have a short characteristic time, allowing clear separation between scattered signal and stray light signal. These improvements are expected to enhance the reliability of the TS system and its analysis results.

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Poster Session MCF 1 - L

1 P 032 - Radial measurements of core hydrogen isotope ratios in ASDEX Upgrade

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ABSTRACT TEXT

The ability to measure and control fuel-ion ratios in the plasma core is relevant for optimizing the power output of future fusion reactors. However, few diagnostic techniques are able to provide localized core measurements of hydrogen isotope ratios for this purpose. Here we present the first proof-of-principle measurements of radially resolved H/D ratios in the core ($\rho \approx 0.05\text{--}0.4$) of ASDEX Upgrade using collective Thomson scattering (CTS). The measurements were conducted in pure Ohmic/ECRH-heated H-mode discharges, using edge fuelling at ratios of up to $H/(H+D) \approx 0.5$. We obtained CTS spectra using a novel combination of 8-bit and 14-bit fast digitizers, and with H/D ratios extracted from the data using both Bayesian inference and inversion based on artificial neural networks. We compare our results to line-integrated measurements from the plasma edge based on optical spectroscopy, while also outlining possible extensions of this work to hydrogen/helium radial transport studies and to possible implications for an ITER/DEMO fuel-ion diagnostic.

Poster Session MCF 1 - L

1 P 034 - Off-axis neutron camera design for the MAST Upgrade

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ABSTRACT TEXT

Neutron diagnostics play a crucial role in studying fast ion confinement in fusion plasmas, particularly in devices like MAST Upgrade, where neutron emission is dominated by beam-thermal nuclear reactions. To support investigations into fast ion behaviour and the effects of off-axis Neutral Beam Injection (NBI), a dedicated multi-channel, collimated neutron flux monitor is being designed for measuring neutron emissivity off-axis.

This paper presents the design of the off-axis neutron camera, detailing its mechanical structure, collimation system, detector selection, and expected performance. The camera is optimized to provide spatially resolved neutron flux measurements in the region where the off-axis NBI deposits fast ions, complementing existing on-axis neutron diagnostics on MAST Upgrade. The proposed design achieves a statistical accuracy of 10% with a time resolution of 10 ms in off-axis NBI scenarios. The off-axis neutron camera diagnostic will be commissioned and installed during an upcoming experimental break and is expected to provide valuable insights into fast ion behaviour, contributing to improved understanding of plasma heating and confinement.

Poster Session MCF 1 - L

1 P 035 - Development of an Integrated Data Analysis Platform for the VEST Tokamak

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ABSTRACT TEXT

Recent advancements in magnetic confinement fusion research underscore the need for standardised data infrastructures to effectively manage and analyse the rapidly growing volume of experimental and computational data. The ITER project has led the way with the Integrated Modelling and Analysis Suite (IMAS), which employs a standardised Interface Data Structure (IDS) that promotes consistency, interoperability, and collaborative research [1,2]. Complementary efforts within the U.S. AtoM project, such as OMFIT and OMAS, provide robust Python-based frameworks for multi-code integration and advanced data analysis, marking a significant shift towards a unified fusion data ecosystem [3,4,5]. Building on these initiatives, we have developed an integrated data analysis platform tailored for the VEST tokamak at Seoul National University and affiliated institutions in Korea. By leveraging Highly Scalable Data Service (HSDS), a REST API-based web service for HDF5 data stores, the system supports distributed processing and efficient high-volume remote data handling [6]. This direct compatibility facilitates code sharing, reduces maintenance overhead, and extends data exchange capabilities across diverse experimental and computational data. The platform modularises various analysis workflows, including (a) post-processing of diagnostic data, (b) generation of machine-specific axisymmetric electromagnetic geometries, and (c) calculation of vessel eddy currents. Additionally, this framework also provides Python wrappers and routines for established modelling codes, including EFIT (for magnetic equilibrium reconstruction) [7], CHEASE (for refined equilibrium solution) [8], and GPEC (for stability and 3D plasma response evaluation) [9]. This architecture simplifies tasks such as visualisation, signal processing, profile fitting, parametric scanning, and statistical evaluations, providing a robust environment for iterative, multi-step analyses. The library also seamlessly integrates with the IMAS and OMFIT ecosystems using the IDS data structure, offering a familiar interface for integrated workflows. It is distributed as an open-source pip package, enabling collaborative development and supporting both research and educational pursuits. Future developments will focus on achieving machine-independent data analysis workflows, promoting data accumulation under FAIR principles, and accelerating data-driven research in magnetic confinement fusion [10,11].

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Poster Session MCF 1 - T

1 P 036 - MHD instabilities in benign termination of runaway electron beams in the JET tokamak

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ABSTRACT TEXT

Mitigation schemes for plasma disruptions will be essential for future large plasma current tokamaks such as ITER or commercial FPPs, as they can impose significant thermal and mechanical loads on tokamak components. A promising solution to mitigate the resulting runaway electron (RE) beams is the low-Z benign termination scheme. The scheme relies on the injection of neutral particles, either via Shattered Pellet Injection (SPI) or Massive Gas Injection (MGI), to recombine the plasma bulk, resulting in a low-density and low temperature companion plasma. Access to a low safety factor edge allows the rapid growth of an MHD instability that deconfines the REs, increases the RE deposition wetted area, and terminates the RE beam. Along with the successful demonstration of this technique in the DIII-D [1–3], TCV and AUG tokamaks [4], foundational experiments were performed in the JET tokamak [5,6]. In most of these experiments it was observed that there are lower and upper limits of injected materials for which mitigation is successful and benign. Recent experiments on the JET tokamak reached higher pre-disruptive plasma currents than on the other machines and have revealed challenges in setting correct and benign injection values. Furthermore, in contrast to the other tokamaks, the terminating MHD event occurs on JET at higher edge safety factors. Understanding and modeling these JET experiments is critical for reactor-relevant extrapolation of these concepts. This work addresses this issue through a systematic and empirical analysis of magnetic sensor data from a large database of benign termination experiments from the JET tokamak. The focus of this analysis is on the nature and modeling of the terminating MHD event. This will include experimental data analysis, synthetic equilibrium modeling with TokaMaker [7], and stability modeling with GPEC [8] or MARS-F [9]. Starting points of the investigation are the MHD growth rates, their modeling and dependencies. Another focus is on changes in the MHD mode structure with changing companion plasma density, which will be part of a comparison to data from the DIII-D tokamak in the future.

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Poster Session MCF 1 - T

1 P 037 - Intrinsic momentum transport driven by magnetic topology in tokamak plasmas

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ABSTRACT TEXT

We demonstrate that magnetic topology breaks a symmetry of the local gyrokinetic model, enabling turbulence to drive intrinsic momentum flux in large devices. This occurs when magnetic shear is zero and the safety factor q is close to (but not exactly) a rational number. Tokamaks with such q profiles will spontaneously rotate. Nonlinear gyrokinetic simulations indicate this mechanism is significantly stronger than all other drives of intrinsic rotation. It also generates an intrinsic electric current that pulls q towards rational values [1,2], potentially aiding non-inductive current drive. Lastly, irrespective of momentum transport, near-rational values of q display dramatically reduced turbulence [3]. We believe these sharp changes in the turbulent transport of heat, momentum, and current are key to the formation of ITBs, but they also represent a challenge for plasma control systems.

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Poster Session MCF 1 - T

1 P 038 - Dynamics of zonal structures and ion temperature gradient modes in the presence of energetic particles

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ABSTRACT TEXT

Ion temperature gradient modes (ITGs) develop in tokamak plasmas due to the presence of spatial gradients of temperature (the core being hotter than the edge). Turbulence then forms due to the nonlinear interaction of ITGs. Zonal (i.e. axisymmetric) structures (ZSs) take an important role in the nonlinear dynamics of turbulence. The nonlinear dynamics of turbulence and ZSs is affected by energetic, i.e. suprathermal, particles (EP). EPs can be found in present tokamak plasmas because of external heating mechanisms, and in burning plasmas due to the nuclear fusion reactions.

Global instabilities, like Alfvén modes (AMs), can also linearly and nonlinearly interact with EPs, turbulence and ZSs. As AMs can have an important role as mediators among EPs, ZSs and turbulence, the problem is intrinsically multiscale, and a global treatment must be used. In this paper, we investigate the dynamics of ZSs and ITGs, in the presence of EPs, by means of numerical simulations with the global gyrokinetic particle-in-cell code ORB5. ORB5 is able to treat both microscale turbulence and macro-scale modes, as well as mesoscale ZSs, in the presence of EPs, thanks to its multi-species global electromagnetic capabilities.

Two regimes are considered here: the regime where AMs are linearly unstable, and the regime where AMs are linearly stable. In both cases, a reduction of turbulence has been found. In the former case, this can happen due to the forced-driven zonal flows, or to the modification of the temperature profiles by the AMs. In the latter case, this can be due to resonance effect, dilution effect and others mechanisms. These regimes are discussed, and the effect of EPs with temperature characteristic of burning plasmas, is shown.

Poster Session MCF 1 - T

1 P 039 - Non-gyrokinetic high-frequency mode instability for tokamak edge like gradients

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ABSTRACT TEXT

The stability analysis of gyrokinetic slab ion temperature gradient (ITG) modes is well-established and results in temperature and density gradient stability thresholds that depend on the parallel and perpendicular wavenumbers. In a recent PRL [1], using 6D turbulence simulations with a specially optimized code that resolves the Larmor orbits, we found potentially significant non-gyrokinetic instabilities for steep, but not unrealistic, gradients in the tokamak edge with simplified slab geometry. These instabilities may be classified as unstable ion-Bernstein waves (IBW). To understand these phenomena, we extended the ITG analysis to high-frequency non-gyrokinetic modes. This extension requires modifying the zero-frequency gyrokinetic polarization using the Gordeyev function, as well as providing rigorous estimates of the magnitudes of the infinite sums appearing in the dispersion relation. Similar to the ITG modes, we derive a threshold criterion for the instability. However, unlike gyrokinetic ITGs, the non-gyrokinetic modes require only the presence of a temperature gradient and not a particularly high ratio of temperature to density gradients. In contrast, gyrokinetic ITGs are suppressed when the density gradient is too large relative to the temperature gradient (the η_i criterion). Interestingly, the IBW growth rate tends to increase with the density gradient. It is likely that including additional physics (e.g., magnetic curvature or interactions with kinetic electrons) will significantly amplify the drive of similar non-gyrokinetic instabilities, potentially leading to an expansion of the field of strongly magnetized plasma turbulence.

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Poster Session MCF 1 - T

1 P 040 - Transport model surrogates via Gaussian process regression with neural network kernels

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ABSTRACT TEXT

Neural network (NN) surrogate models have been widely developed to rapidly simulate the behavior of large-scale turbulent transport models [1]. Training highly reproducible NN surrogate models requires extensive datasets, inevitably leading to larger NN models and longer computation times. Furthermore, NN surrogate models cannot evaluate prediction uncertainty. When unintentionally predicting outside the training data range, NN surrogate models will output solutions with potentially low accuracy, which may be used regardless of their reliability. To address these challenges, we explored surrogate model construction using Gaussian Process (GP) regression (GPR). In contrast to NN models suited for large-scale data, GPR non-parametrically estimates unknown functions based on observed data distributions and can evaluate uncertainties. It particularly excels at high-accuracy predictions with small-scale datasets.

Kernel selection in GPR is crucial for appropriately representing data structures. Recently, Neural Network kernels approximating infinite-width NN behavior based on the central limit theorem have been proposed [2]. Neural Network Gaussian Processes (NNGP), combining deep learning flexibility with GP probabilistic interpretation, possess the capability to capture complex, nonlinear, and high-dimensional data patterns.

We attempted to construct surrogate models using NN kernels that could match or exceed NN model performance. Our in-house GPR library, `dgpr`, supports various common kernels, including NN kernels and kernel composition, and is written with the aid of JAX, enabling automatic differentiation and GPU utilization. We have benchmarked `dgpr` against `GPy`, a popular GPR library, across multiple cases and found good agreement.

The GP-based surrogate model trained by `dgpr` works better than the NN surrogate model for the heat flux prediction on multiple datasets generated by the transport code GOTRESS [1] with the TGLF transport model. Especially, the results demonstrate that NNGP provides superior predictions. We will also introduce predictions using other kernels and methods for reducing the required amount of training data.

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Poster Session MCF 1 - T

1 P 041 - Self-consistent gyrokinetic simulations of magnetic islands in tokamaks

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ABSTRACT TEXT

The evolution of magnetic islands in tokamak plasmas are investigated employing gyrokinetic simulations performed with the particle-in-cell code ORB5 in the collisionless limit. Both linearly unstable tearing modes and turbulence-driven magnetic islands are investigated. Linear simulations confirm the expected trends of the growth rate with respect to e.g. electron mass and plasma beta. At higher values of beta, the tearing mode is suppressed and a mode with the same helicity but with twisting parity, coupled with the neighbouring poloidal harmonics, is destabilized. It is shown that strongly driven modes can produce turbulence even in the case of flat background pressure profiles through Kelvin-Helmholtz unstable flows around the island separatrix. This can lead to a strong reduction of the island size. In the presence of pressure gradients, magnetic islands are in general driven nonlinearly by fast-growing microinstabilities, until decoupling occurs when the island size is comparable to the eddy size, confirming previous gyrokinetic studies in toroidal geometry. After decoupling from the turbulence, further growth can occur even in the absence of a linear drive through the coalescence of small scales into larger ones, as observed also in recent fluid simulations. Magnetic islands are found to rotate in the electron diamagnetic direction in the linear phase, unless only ion temperature gradients are present. At the end of the exponential-growth phase, the rotation stops and flips usually to ion diamagnetic direction. The influence of the island on density and temperature profiles is discussed.

Poster Session MCF 1 - T

1 P 042 - Energy balance for ion temperature gradient driven modes in 6D kinetic Vlasov simulations

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ABSTRACT TEXT

We have developed an advanced and scalable semi-Lagrangian solver tailored for the 6D kinetic Vlasov system. This solver incorporates a highly efficient scheme to address the $\mathbf{v} \times \mathbf{B}$ acceleration resulting from the strong background magnetic field [1, 6] which allows us to simulate the excitation of plasma waves and turbulence with frequencies extending beyond the cyclotron frequency without being limited by gradient strength or fluctuation levels [5]. The solver has undergone rigorous testing in the low-frequency regime, consistently providing accurate results for dispersion relations and energy fluxes in linear and non-linear scenarios [4]. Given the significant influence of edge turbulence on the confinement properties of magnetically confined plasmas, having a tool that precisely captures turbulent transport is crucial. Despite the high computational costs, considering 6D kinetic effects becomes indispensable for a comprehensive understanding of edge physics.

Previous research [3, 5] has demonstrated that the fully kinetic system displays behaviours beyond gyrokinetics in scenarios with large density and temperature gradients, akin to the edge of a tokamak during transition phases. Having a full understanding of all energy transport channels is crucial. This contribution showcases an innovative description of the particle and energy fluxes of the 6D kinetic Vlasov system. Our new approach offers significant advantages, allowing us to discern various contributions to the energy flux and allows for identifying individual gyrokinetic and nongyrokinetic contributions of the energy flux while minimizing inherent gyrooscillations in energy and particle fluxes [2].

Simulating increasingly complex and accurate physical models has become possible with the increased computational capabilities in recent years. Gyrokinetic theory was introduced in the 1960s and 1970s to describe plasmas more accurately than fluid models while eliminating the complexity of the fast gyration of the particles around the magnetic field in 6D kinetic models. Although current gyrokinetic simulations show fair agreement with experimental results in core physics, crucial assumptions made in the derivation make it unreliable in regimes with higher fluctuations and stronger gradients, such as the tokamak edge.

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Poster Session MCF 1 - T

1 P 043 - Measurements of the intrinsic torque driven by up-down asymmetric L-mode plasmas in TCV

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Previous studies have examined the effect of intrinsic rotation driven by up–down asymmetries in the equilibrium of Ohmic TCV plasmas[1]. In this work, we quantify this effect in neutral beam (NB)-heated L-mode plasmas. We utilize the TCV counter-balanced NB system to produce plasmas with near-zero rotation by slowly ramping the injected torque to induce rotation direction reversal mid-discharge. Near-zero rotation minimizes momentum transport effects, and externally applied torque approximately balances the intrinsic torque, allowing its estimation.

The experiments were conducted with a counter-clockwise (top view) plasma current, $j = -233$ kA, and with both co- and counter-clockwise toroidal magnetic fields, $b = \pm 1.44$ T. The study includes both positively and negatively up–down asymmetric plasma shapes, $s^\pm$, as in [1]. The three discharges obtained can be summarised with the sign combinations $s^-b^-j^-$, $s^+b^-j^-$ and $s^-b^+j^-$.

All discharges exhibit sawtooth instability with a frequency of approximately 190 Hz with inversion radius at $\rho_{\text{tor}} \sim 0.35$, with little visible effect outside. It is also noted that, despite good engineering matches, differences exist in the resulting q_{95} , plasma volume and in kinetic profiles, necessitating careful analysis. Future experiments aim to improve these matches.

We find that near the plasma edge, where up–down asymmetry is significant, the toroidal velocity gradient, $v'_\phi = -dv_\phi/dr$, is more positive, with $\sigma_s \sigma_j \sigma_b > 0$, in agreement with theory and earlier Ohmic plasma experiments[1].

This study further analyses these discharges, leveraging the methodology developed earlier[2,3] to quantify the intrinsic torque in these plasmas. Additionally, we assess turbulence characteristics in these plasmas and compare against gyrokinetic GENE calculations of intrinsic torque[4].

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Poster Session MCF 1 - T

1 P 044 - Turbulence Regulation and Zonal Flow Dynamics in Magnetically Confined Plasmas

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ABSTRACT TEXT

The dynamical interplay between turbulent particle transport (Γ) and Reynolds stress (R) during the formation of zonal flows are explored on the basis of the density-potential coupling in drift-wave turbulence. This study provides insights into the interplay of these phenomena, which are critical for understanding transport regulation during the formation of transport barriers in magnetically confined plasmas.

In drift-wave turbulence, a temporal anti-correlation between particle transport and Reynolds stress was observed. This phenomenon is reflected in a strong correlation and anti-correlation of the temporal density-potential cross-phase with Γ and R , respectively (Sarkis et al., Phys. Rev. E, 2025). Langmuir probe measurements at the TJ-K stellarator reveals a degradation within the dynamical relationship between the turbulent fluxes and the density-potential coupling during the formation of zonal flows. The occurrence of zonal flows appears to break the established correlation, and the cross-phase is found to be varying independently from Γ . The constant level of the turbulent transport is found to be sustained through the density-potential cross-amplitude obtained by the wavenumber integrated cross-power spectrum.

Temporally resolving the bicoherence of density and potential fluctuations establishes a link between density and the large-scale zonal potential, offering insight into the observed decorrelation. This is further elucidated through the energy transfer analysis where density fluctuations are observed to couple with zonal flows, transferring energy to smaller scale potential structures that are representative of GAM's.

Bicoherence and energy transfer provide details on the transport regulation through zonal flows, as they enlighten the maintained particle transport level in terms of the dynamically evolving coupling between density and potential fluctuations.

Poster Session MCF 1 - T

1 P 045 - A collisional 6-moment gyro-fluid model

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ABSTRACT TEXT

We present a 6-moment collisional gyro-fluid model. The moments consist of density, parallel velocity, perpendicular temperature, parallel temperature, parallel flux of perpendicular heat and parallel flux of parallel heat. The collisional closure of particle collisions and plasma-neutral interactions is presented in the long wavelength limit following previous work in [Wiesenberger2022]. Following [Scott2021] we setup intra-particle collisions using the Lorentz collisional operator and add Landau damping to the parallel heat flux equations.

The advantages of such a setup include the absence of a heat flux closure, i.e. no heat flux limiter or similar as is often the case in drift-reduced Braginskii models. Parallel viscosity and heat conduction emerge for high collisionality from the Lorentz collision operator. In a numerical representation of the model the time stepper can thus be entirely explicit and there is no need to invert the costly parallel heat equation.

The model is implemented in the open-source code FELTOR [Wiesenberger2024, Feltor2023], which is fully parallelized on GPUs. Initial results of plasma edge turbulence on medium sized tokamaks (e.g. TCV) are presented.

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Poster Session MCF 1 - T

1 P 046 - Recent results of Doppler reflectometry systems operated at Wendelstein 7-X

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ABSTRACT TEXT

In the last operation phases of Wendelstein 7-X (OP2), multiple Doppler-reflectometry (DR) systems have been successfully operated at two different toroidal positions. While the individual systems are mainly used to measure the perpendicular plasma bulk rotation and the backscattered power, which depends nonlinearly on the rms density fluctuation level, the synced operation of different systems allows for a characterization of radial correlation lengths and zonal flow oscillations of the perpendicular velocity. The obtained profiles of the radial electric field are compared with neoclassical predictions in distinct plasma scenarios in mixed electron-ion root regimes with strong central electron heating and pure ion-root conditions, and benchmarked against measurements done with charge-exchange recombination spectroscopy (CXRS). Deviations between the measured and predicted radial electric field indicate a contribution of the turbulent phase velocity and allow to disentangle the underlying microinstabilities driven by temperature and density gradients. The latter findings are compared with results from linear gyrokinetic simulations. Two reflectometer systems at different toroidal positions have been equipped with steerable plasma-facing mirrors to measure variations on the flux surface and to detect fluctuations at different Bragg wavenumbers to measure full wavenumber spectra. This contribution gives an overview of the measurement results. Special attention is paid to characterize the nonlinear scaling of the backscattered microwave power. For this purpose, simulation results from recent three-dimensional gyrokinetic simulations (GENE3D) [2] with experimental W7-X plasma profiles that includes also the neoclassical radial electric field are used as input for a full-wave simulation code (CUWA) [1]. The results of the synthetic diagnostic are compared with the experimental measurements.

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Poster Session MCF 1 - T

1 P 047 - State transitions in turbulent eddies as captured by information entropy

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ABSTRACT TEXT

Conventionally, the Hasegawa-Wakatani equation, a fluid model describing drift wave turbulence and zonal flows in magnetized plasmas, is known to classify the states by focusing on the relative energy ratio between turbulent and zonal flows due to changes in physical parameters [Numata *et al.* Phys. Plasmas, vol. 14, 102312 (2007)]. A new classification of quasi-steady states has recently been discovered based on the von Neumann entropy (vNE) of turbulence inspired by quantum mechanics [Yatomi and Nakata, arXiv:2407.09098 (2024)]. The vNE is defined by a density matrix composed of orthonormal spatial bases obtained by singular value decomposition (SVD). It quantifies the spreading of singular value spectrum in mode space that characterizes the contribution to the original turbulence field. The vNE revealed a non-trivial transition boundary, which is essentially deviated from that for the energy ratio of turbulence and zonal flows.

The physical factors causing the newly discovered transition in turbulent structure are discussed. Examination of the SVD mode spatial structure for each state reveals that turbulent vortices are trapped in the zonal flow for the small vNE state. On the other hand, in the large vNE state, the trapping of turbulent vortices becomes less significant, and a near-uniform turbulent state is achieved despite the presence of a high-intensity zonal flow. Furthermore, the spatial correlation between turbulence intensity and zonal flow is investigated, noting that turbulence is driven by the shear rate (first-order derivative) and curvature (second-order derivative) of the zonal flow. We found that, for the small vNE state, turbulent vortices are trapped in the negative curvature region of the zonal flow, as suggested by previous theoretical studies [Sasaki *et al.*, Phys. Plasmas, vol. 25, 012316 (2018)]. However, for the large vNE state, the turbulence intensity has maxima in the positive curvature regions, and uniform turbulence associated with the shearing effect is observed.

Poster Session MCF 1 - T

1 P 048 - The ITER baseline scenario on JET in D-T with Neon seeding

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ABSTRACT TEXT

The *Joint European Torus* (JET) devoted the last years of its operations to investigating key physics aspects in support of future ITER operations [1,2]. During the last deuterium and deuterium-tritium campaigns, JET developed and optimized the Integrated Scenario [3], also known as the ITER baseline scenario, designed to operate at high plasma current, high triangularity, and in a divertor configuration to achieve partial detachment through Neon seeding [4, 5]. During the DTE3 campaign the Scientific Team dedicated a significant number of experiments in optimising the stationarity of the scenario by varying the nominal fuelling rate and the Neon seeding rate. Here we present the integrated modelling of 3.0 MA pulses performed with the JINTRAC suite of codes [6] equipped with the reduced first-principle transport model QuaLiKiz [7]. In this predictive-interpretative transport analysis, the plasma current diffusion profile, electron and ion temperature profiles, main ion density profiles, and impurity density profiles (i.e. Be, Ne, Ni and W) are predicted. The boundary conditions are imposed at the separatrix, with the pedestal region being modelled using ELM-averaged transport coefficients to match the experimental pedestal. This approach allows to obtain ELM-averaged transport coefficients and the corresponding ionization sources that are compatible with the core transport predicted by reduced first-principle transport models.

Using a systematic approach devised for D-T plasmas, from an unseeded pulse [8] we model two Ne seeded pulses, characterized by different Ne concentration. The focus is on assessing the interplay between particle sources and average pedestal transport, along with the effects of impurities, which impact both dilution, transport and radiative losses.

In an integrated fashion, the plasma kinetic profiles in the core are predicted, while the average pedestal transport is tuned to match experimental pedestal measurements, imposing realistic ionization sources. The sensitivity of the model to these assumed sources is explored in an effort to reproduce the experimental plasma performance and neutron yield, accounting for the effects of dilution and D-T ratio.

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Poster Session MCF 1 - T

1 P 049 - Initial Experiments Utilizing the Langmuir Probe on Tungsten Divertor of KSTAR

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ABSTRACT TEXT

The Langmuir Probe (LP) system was installed in the upgraded tungsten divertor of KSTAR to measure basic plasma parameters, such as Ion saturation current (I_{sat}), electron density (n_e) and electron temperature (T_e), and their poloidal profiles. Tungsten is an essential material for plasma-facing components of ITER and next-generation fusion devices; however, it poses significant challenges in plasma control due to its high Z material. Therefore, it is necessary to conduct research to reduce the sputtering of tungsten, thereby decreasing the amount that enters the core plasma.

As LPs are widely used diagnostics in tokamaks, the LP installed on the tungsten divertor was utilized in detachment research aimed at reducing tungsten sputtering. Optimization of an LP-based detachment control system provides a research tool for supporting examination of detached plasmas, including exploration of controllability. The LP detachment controller defines the attachment fraction (A_{frc}) as the measured I_{sat} normalized by an I_{sat} value representing attached conditions. The LP was directly connected to the Plasma Control System (PCS). Real-time control of detachment in the divertor region is now being attempted [1]. And RadFront (A metric representing the normalized position of the total radiation front relative to the X-point)-based detachment control by using RT-LP and AXUV was being tested.

By performing voltage sweeping on a single probe, the value of n_e and T_e at strike point are measured across various experiments. These values will be compared with the n_e and T_e measurements obtained through optical diagnostics. And these values are also used to ensure the reliability of the modeling by comparing the values from the SOLPS modeling.

For more precise real-time detachment experiments, additional probes will be connected to the PCS, and the LP systems will be upgraded to measure n_e and T_e through a greater number of probes.

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Poster Session MCF 1 - T

1 P 050 - Divertor-core integration in high-performance, negative triangularity plasmas on TCV

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ABSTRACT TEXT

Negative Triangularity (NT) plasmas on TCV and DIII-D have demonstrated reactor-relevant energy confinement in L-mode, avoiding key power exhaust challenges of H-mode, such as ELMs and the L-H power threshold. Ohmic experiments on TCV indicated that detachment was less accessible in NT than in comparable Positive Triangularity (PT) plasmas [1]. In DIII-D, detachment of high-power NT plasmas was achieved at high Greenwald fractions greater than one [2]. In this contribution, we present new insights into NT detachment dynamics and demonstrate stationary, deeply detached plasmas by combining a PT X-point (single-null or snowflake) with negative non-X-point triangularity. This configuration maintains L-mode at high power with improved confinement, demonstrating the core-edge integration potential of NT.

Ohmic core density ramp experiments showed that increased divertor closure enhanced outer target cooling in NT plasmas. However, divertor neutral pressures remained lower than in unbaffled PT cases, and no ion flux rollover was observed, suggesting that NT only reached an early detachment stage ($T_e \sim 6$ eV at the target, CIII front $\sim 80\%$ up the leg). In contrast, for similar core density ramps, PT plasmas achieved deeper detachment ($T_e < 5$ eV, CIII front up to the X-point). N_2 -seeded detachment was obtained in unbaffled NT discharges, impacting energy confinement (τ_E) by $\sim 20\%$, as in comparable PT plasmas. This core performance degradation could be mitigated with greater divertor closure, lowering the required seeding by $\sim 60\%$. Concurrently, Langmuir probe measurements from a reciprocating divertor probe array (RDPA) revealed SOL broadening along the outer leg in PT, a behavior absent in NT.

These studies were extended to high-performance scenarios. With negative non-X-point triangularity, a plasma current of 170 kA, and 750 kW of neutral beam heating (NBH), stationary NT plasmas reached β_N up to 1.8 with target temperatures ~ 5 eV. N_2 seeding led to an X-point radiator, deepening detachment but requiring increased NBH, real-time controlled, to sustain high β_N . A fully stationary, detached NT L-mode plasma with $\beta_N \sim 1.6$ was obtained, matching the core performance of an NBI-heated PT ELMy H-mode, which, if detached between ELMs, underwent reattachment during ELM burn-throughs.

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Poster Session MCF 1 - T

1 P 051 - Tungsten erosion and re-deposition studies utilizing ultraviolet spectroscopy in DIII-D and W7-X

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ABSTRACT TEXT

Ultraviolet spectroscopy of tungsten (W) emission for quantification of gross-erosion and re-deposition dynamics has been obtained in the DIII-D tokamak and W7-X stellarator. High-Z impurities circulating within future fusion devices could result in excessive radiation losses, fuel dilution, and reduced plasma performance. Erosion fluxes can be quantified in-situ by time-resolved line emission spectroscopy combined with S/XB coefficients from collisional-radiative atomic physics models. Ultraviolet wavelengths provide access to multiple neutral W emission lines for improved gross erosion measurements and higher W charge states enabling characterization of net erosion and re-deposition.

Empirical S/XB coefficients for W I emission lines in the ultraviolet range have been obtained during attached L-mode DIII-D plasmas. Tungsten-coated graphite samples were exposed using the Divertor Material Evaluation System (DiMES) manipulator. Observation of multiple W I emission lines combined with post-mortem Rutherford backscattering measurements of net erosion yield empirical S/XB values 2 to 5 times higher than predicted from recent atomic excitation calculations and is consistent with low predicted ionization rates. Material analysis yields gross-erosion rates of $\sim 5 \times 10^{19}$ atoms $\text{m}^{-2} \text{s}^{-1}$ which is the same order of magnitude as previous DIII-D measurements using visible spectroscopy. Simultaneous observation of neutral and singly ionized W emission lines provide a net erosion upper bound of 10 to 30% of the gross erosion for a 1.5 cm diameter sample demonstrating the importance of the prompt re-deposition mechanism.

In the W7-X stellarator, W I and W II spectral emission is observed when the heat flux on an array of W baffle tiles is purposely increased, namely by modifying the island divertor topology using control coils in the high-mirror magnetic configuration. Nevertheless, W emission intensities are frequently just above the noise floor, making inferences of erosion challenging. No increase in W radiation was observed when trace levels of impurities (N_2 , Ne, Ar) were injected. A correlation between W I and W II intensities with a quasi-continuum W band spanning 4 to 7 nm indicates that eroded W from the baffle tiles is transporting into the core.

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Poster Session MCF 1 - T

1 P 052 - A novel method for treating MAR in EMC3-EIRENE, and first applications to W7-X

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ABSTRACT TEXT

In this paper, we present a novel prediction-correction method for the treatment of molecule-assisted recombination (MAR) in the 3D EMC3-EIRENE boundary plasma transport code system. In this approach, certain MAR products are first isolated and removed from the particle trajectories in EIRENE and recorded as predictions, which are then implicitly corrected/reprocessed in EMC3 and subsequently fed back into EIRENE as an “external” source to compensate for the removed particles. In comparison to the conventional scheme used so far in boundary plasma modelling, this new method exhibits enhanced numerical stability and is believed to be broadly applicable also to other (e.g. also 2D fluid-kinetic) edge plasma transport calculations. Using a typical detached plasma from W7-X as an example, we apply the latest version of the EMC3-EIRENE code to perform, for the first time, a self-consistent analysis of the role of volume recombination processes, including MAR and electron-ion recombination (EIR), in a three-dimensional (3D) divertor, namely the island divertor. It is assumed that intrinsic carbon is the only impurity species and the radiation fraction f_{rad} is used as a control parameter. The simulation demonstrates that both EIR and MAR increase with f_{rad} , with the total volume recombination rate reaching approximately 30% of the total neutral source at $f_{\text{rad}} = 0.9$. The MAR contribution is typically around a factor of three larger than that of the EIR when the radiation is located in the edge magnetic islands outside the last closed flux surface (LCFS). No noteworthy effects of volume recombination on detachment performance are observed in terms of the power load on the target, the neutral pressure in the divertor chamber, or the distribution of impurity radiation. Nevertheless, volume recombination significantly changes the relative population of atoms and molecules in front of the targets, which may be generally important for edge plasma spectroscopy in fusion devices.

Poster Session MCF 1 - T

1 P 053 - Optimizing interpretative SOLPS-ITER simulation with an advanced Bayesian inference workflow

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ABSTRACT TEXT

Modelling the Scrape-off Layer (SOL) of tokamaks with SOLPS-ITER, a widely-used 2D fluid plasma simulation code [1, 2], typically requires the user to hand-tune complicated boundary conditions and model-specific parameters that stem from its limitations, e.g. anomalous diffusion corrections. Due to the nature of experimental data and its uncertainty, manual optimization of parameters in interpretive simulations is a complex process and it is heavily reliant on the researcher's empirical insight into each individual case. As a result, this approach tends to lead to a subjective bias.

To address these issues, we employ the Bayesian Optimization Likelihood-Free Inference (BOLFI) method [3, 4], combined with our general-purpose automatization workflow for SOLPS-ITER. The BOLFI method uses Bayesian inference with an approximated likelihood function on a selected set of input parameters. An efficient exploration of the parameter space minimizes the number of the computationally expensive runs of the SOLPS-ITER code needed to approximate the likelihood. The resulting posterior probability distribution provides robust and objective parameter estimates augmented by uncertainty estimates.

In this work, we present the application of BOLFI to a complex SOLPS-ITER scenario involving five inference parameters and real experimental data from a COMPASS tokamak discharge. Our analysis focuses on identifying the best-matching simulation parameters, quantifying their uncertainties and assessing the convergence properties of the BOLFI method itself. We then utilize the approximated likelihood function to explore the relations between the simulation parameters and the matches with different diagnostics. Finally, we discuss the effectiveness of various metrics used to compare simulation results with the experimental diagnostic data.

This advanced workflow allowed us to robustly match a SOLPS-ITER simulation to the tokamak discharge to assist in our SOL physics and heat flux management research. The method is readily applicable to other simulation cases with minimal setup and represents an effective use of automatization that minimizes time spent on repetitive tasks of parameter space exploration.

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Poster Session MCF 1 - T

1 P 054 - Development of divertor scenarios for quasi steady-state operation of Wendelstein 7-X

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ABSTRACT TEXT

The Wendelstein 7-X (W7-X) aims to demonstrate the HELIAS stellarator's potential for high-power, steady-state fusion, positioning stellarators as viable candidates for cost-effective continuous energy generation. To prepare for long-pulse operation, recent experiments have focused on optimizing divertor scenarios, particularly strike-line control on the island divertor. Using Electron Cyclotron Current Drive (ECCD), two key objectives were pursued: (1) rapidly establishing the full toroidal current with co-ECCD at low heating power to prevent overload in sensitive divertor regions near the pumping gap, and (2) using counter-ECCD to limit the toroidal current, ensuring the strike line remains in safe positions. The strike-line geometry in W7-X is determined primarily by the magnetic fields of the coil system [1], but evolves during plasma discharge due to changes in toroidal current, which affect the rotational transform and thus island divertor geometry [2]. Although the intrinsic bootstrap current in W7-X is small, even modest values can significantly impact open field line interactions with plasma-facing components, making precise strike-line control critical for overload mitigation and divertor neutral pressure maintenance in steady-state operation.

In a series of experiments, both ECCD methods enabled long-pulse discharges of up to 308 seconds plasma duration with an energy throughput of up to approximately 1 GJ, demonstrating effective strike-line control and preventing divertor risk during the rising bootstrap current phase. Results suggest that rapidly increasing toroidal current with co-ECCD is preferable for reactor-relevant scenarios, as ECCD is only required in the initial pulse phase.

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Poster Session MCF 1 - T

1 P 055 - Combining total flux expansion and strong baffling: initial observations on the X-point target divertor on MAST-U

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ABSTRACT TEXT

The Super-X divertor (SXD) configuration on MAST-U combines total flux expansion and strong baffling to improve the exhaust performance compared to more conventional divertor configurations. It has shown improved access to detachment, additional power and momentum losses through plasma-neutral interactions, and reduced sensitivity in the detachment front location to changes in the upstream parameters. The first results in high power (3.5 MW NBI) H-mode discharges in X-point target (XPT) configuration on MAST-U are presented. These are obtained by adding a secondary X-point in the divertor chamber to the reference Super-X configuration, and suggest further improvements in the exhaust performance.

While only one of the three strike points in each divertor chamber was covered by Langmuir probes, the behavior of the divertor can be monitored with magnetic and imaging diagnostics. In inter-ELM conditions only two of the strike points are activated, while the third strike point lights up during ELMs.

Both configurations are already strongly detached at the lowest level of fuelling achieved. The fulcher front position, used as proxy for the detachment front position, is initially inferred to be further upstream in the XPT than in the SXD, suggesting a deeper level of detachment. Once upstream of the region affected by the secondary null, the movement of front position for increasing fuelling is similar in both configurations, suggesting that the XPT retains the stability benefits of the SXD even if the detachment front escapes the secondary null.

In XPT, the connection length increases and the divertor cross-field profiles of electron density become wider, leading to an increase in plasma-neutral interactions in strongly detached conditions. These result in additional power losses, as evidenced by the lower measured peak heat fluxes and inferred target electron temperatures, and possibly additional momentum losses, which could explain the inferred divertor electron density profile being peaked in the secondary null instead of near the target.

Future studies will focus on extending the comparison to attached conditions, testing the predicted stabilizing effect of the secondary null on the detachment front location, and comparing discharges with more similar core conditions.

Poster Session MCF 1 - T

1 P 056 - A tightly baffled long-legged divertor for TCV

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ABSTRACT TEXT

The TCV tokamak contributes to the development of nuclear fusion energy with proof-of-principle experiments and by validating models that are used to predict reactor performance. As part of the Swiss Roadmap for Research Infrastructures, the SPC is upgrading TCV to test a tightly baffled, long-legged divertor (TBLLD), a novel concept designed to enhance power exhaust capabilities with minimal modification to the magnetic configuration [1].

Simulations using the SOLPS-ITER code indicate that a TBLLD can improve TCV's power exhaust capability by an order of magnitude compared to the unbaffled configuration [2]. Tight baffling sustains a high poloidal neutral density gradient, thereby, increasing the neutral density in front of the divertor target and enhancing volumetric power dissipation. The simulations informed the design of a proof-of-principle TBLLD for the outer TCV divertor, ensuring compatibility with high-power plasma scenarios. A straight, vertical design enables diagnostic access via TCV's reciprocating divertor probe array (RDPA), while maintaining engineering simplicity. The design incorporates 64 inner and 64 outer graphite baffle tiles that are mounted the vessel. Requirements on the gas tightness limits diagnostics access with poloidally distributed Langmuir probes, thermocouples, pressure gauges, and spectrometric lines of sight providing the measurements required to assess the TBLLD concept.

The procurement of essential components is underway, with a dedicated experimental campaign planned for 2026. Following a successful validation of the TBLLD concept, a second phase of upgrades would optimise the baffle geometry, extend the exhaust solution to the inner divertor, and integrate it with an attractive core plasma scenario.

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Poster Session MCF 1 - T

1 P 057 - Experimental observation of edge plasma transport characteristics after boronization on Wendelstein 7-X

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ABSTRACT TEXT

Since the OP1.2b experimental campaign, boronization has been frequently applied for the wall conditioning on W7-X, and significant enhancement of the plasma performance has been archived [1, 2]. The experimental observations reveal that the radiation of unwanted impurities (such as oxygen) was reduced significantly after a fresh boronization. Furthermore, the oxygen concentration can be controlled to a low level after several boronizations [3].

Recently, the impact of boronization on characteristics of edge plasma transport has been investigated experimentally by varying plasma heating power, density and size of edge island during the OP2.2 campaign. The results show that the effect of boronization on impurity radiation fraction can be up to 25% even after multiple boronizations within one campaign, but decreases with increasing plasma density. It was found that the impurity oxygen and carbon sources, as indicated by the OI and CII line emission intensities measured by visible overview spectroscopy looking at the divertor region in front of the vertical target plate, were not further reduced after multiple boronizations within one campaign, especially in high-density plasmas. However, the core impurity oxygen and carbon concentrations (CIV, OVI) measured by the High-Efficiency XUV Overview Spectrometer (HEXOS) [4] are significantly reduced by a factor of ~4 and are not strongly dependent on the plasma density. This result suggests that boronization may enhance impurity screening. It is noteworthy that the density of the plasma in the SOL region is higher after boronization. In addition, after the first boronization, some of boron will remain in the device despite a period of plasma operation, and a certain concentration of boron will always still be present in the plasma. However, each subsequent fresh boronization still increases the boron concentration by 40–60% at the boundary. In this paper, experimental observations of edge plasma transport characteristics after boronization will be presented.

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Poster Session MCF 1 - T

1 P 058 - Flexible grids for complex tokamak topologies

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ABSTRACT TEXT

The divertor problem is one of the biggest ongoing challenges in the fusion energy sector. The geometry of the divertor region in magnetic confinement devices significantly influences plasma edge dynamics as well as heat and particle exhaust.¹ Advanced divertor configurations, like the snowflake divertor, offer advantages in mitigating heat loads and enhancing plasma performance.² However, simulating these geometries can be extremely challenging due to intricate magnetic structures and the complex physics of the region.

BOUT++ is a widely used open-source framework for simulating plasmas at the edge regions.^{3,4} Its capability to handle complex divertor geometries and topologies has been limited by the current mesh, which is unsuitable for non-standard geometries. To address this, we are developing a new mesh that expands BOUT++'s ability to simulate complex divertor configurations, including the snowflake divertor. The new mesh will allow users to define arbitrary geometries with flexibility and precision. The new mesh will support non-orthogonal, flexible grids⁵ and handle coordinate singularities and discontinuities in the magnetic field, while still allowing for parallelization. In the following six months, we expect to get the mesh working with a consistent interpolator for overlapping grids and grids with different cell sizes, both working in a parallel paradigm, and expanding the mesh into 2 and 3D.

The expanded capability to simulate complex divertor geometries within BOUT++ opens new ways of investigating advanced divertor concepts and optimizing divertor design in future fusion reactors. Ongoing work includes working on the parallelization of the flexible grid as well as interpolation between overlapping and different sized grids, and implementing guard-cell communication between them to help with numerical stability⁶. This development provides a valuable resource for theoretical and computational exploration of plasma behaviour in complex divertor configurations. Understanding the behaviour and advantages of the advanced divertor geometries' will be crucial for any fusion powerplant in the future.

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Poster Session MCF 1 - T

1 P 059 - Assessing wall heat fluxes in the Quasi-Continuous Exhaust regime at ASDEX Upgrade

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ABSTRACT TEXT

The Quasi-Continuous Exhaust (QCE) regime is of significant interest as one of the most promising reactor plasma scenarios for future tokamaks, including ITER. It is distinguished by the absence of large, abrupt energy losses like ELMs and minimal confinement degradation. Its operational space lies at high separatrix density and high shaping.

The QCE regime is accompanied by a broadening of the Scrape-Off Layer (SOL) width, which can mitigate heat fluxes onto the divertor. However, the broad profiles could also increase the particle and heat load onto the machine's poloidal limiters [1,2]. Erosion of these components can reduce their lifetime and also serve as a significant source of tungsten in the main plasma.

This work addresses the important gap in estimating the limiter peak loads to better understand whether the QCE regime complies with reactor constraints. 3D simulations of three ASDEX Upgrade discharges have been performed using the EMC3-EIRENE code [4], from ELMy H-mode to a well-developed QCE discharge obtained by increasing the gas puff.

These simulations have been validated against experimental measurements, leading to bidimensional maps of the heat and particle fluxes onto the limiter. For the considered ASDEX Upgrade QCE discharge, the peak parallel heat flux onto one limiter has been estimated at approximately 3.5 MW/m², while taking into account the limiter geometry, the peak heat flux impinging perpendicularly onto the limiter is approximately 1 MW/m².

Finally, considerations are made to compare ITER's first wall limit of 4.7 MW/m² [3] with a possible scaling of the QCE limiter peak heat flux. The results indicate that since ITER wall clearance is much larger than the ones of the considered discharges, the peak heat flux onto ITER's first wall will probably be considerably less than the allowed maximum value.

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Poster Session MCF 1 - T

1 P 060 - The marginally stable state of runaway electrons controlled by self-excited waves

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ABSTRACT TEXT

When the driving electric field is strong enough, the number of runaway electrons (RE) tends to grow exponentially due to the avalanche effect caused by knock-on collisions. Above certain runaway currents, kinetic instabilities can arise, modifying the RE distribution and potentially halting the avalanche. Among self-excited waves in magnetized plasma, whistlers and magnetized plasma waves deserve the most attention. They upsurge on much shorter timescales than the runaway current lifetime, leading to a marginally stable state for the RE distribution. We have developed a code based on the discontinuous Galerkin method to solve the coupled wave-particle kinetic equations for runaway electrons and the excited waves. Our simulations involve collisional damping of waves, small-angle collisions, knock-on collisions, and synchrotron losses of the runaway electrons. We investigate the shape of a steady RE distribution in a given driving field and the corresponding RE current. We also determine the thresholds for the runaway avalanche and kinetic instability and plot the marginally stable runaway current versus the driving field.

Poster Session MCF 1 - T

1 P 061 - Evaluating energy fluxes during COMPASS disruptions

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ABSTRACT TEXT

A novel method to accurately estimate the integral plasma thermal losses during tokamak disruptions is applied to the analysis of COMPASS experiments. The method relies solely on magnetic diagnostics measurements and is based on the hypothesis of axisymmetry and evolution of the plasma through MHD equilibrium states, which is robust if the inertia to the plasma motion is rather due to eddy currents surrounding the plasma than due to the plasma mass itself. On the other hand, there is no specific hypothesis on the halo currents, whose effect on the energy balance is estimated by the means of generalized Shafranov identities. Our study confirms that the magnetic energy conversion depends on the current quench duration as compared to the typical resistive time of the vacuum vessel. The method is compared with a different estimation method based on the direct integration of heat fluxes and radiation obtained, respectively, by processed IR camera and AXUV pinhole signals, highlighting the difficulties of using these diagnostics during fast transients. The methodology presented can be used on other machines for a more accurate evaluation of the efficiency of disruption mitigation systems. Further, the method is suitable for a real-time implementation, in view of physics-based monitoring systems of tokamak experiments.

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Poster Session MCF 1 - T

1 P 064 - Kinetic modelling of runaway electron momentum distributions for the EU-DEMO tokamak

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ABSTRACT TEXT

In high-current devices, such as the planned EU-DEMO tokamak, a large fraction of the plasma current can be converted into runaway electron current, and the subsequent runaway beam can cause significant damage to the plasma-facing components. Both the simulations of runaway-electron-induced damage and the development of runaway electron handling strategies require the simulation of the runaway electron distribution. In this work, this is done in 3 dimensions: 1D in real space and 2D in momentum space. Self-consistent kinetic simulations with simplified handling of the magnetic geometry are relatively computationally inexpensive, and one tool capable of such is DREAM [1], which is used throughout this work.

In this work, disruption simulations have been performed for the 2021 baseline of EU-DEMO. Our goal was to qualitatively describe the evolution of the runaway electron distribution function, identify the parameters governing the runaway electron dynamics, and relate the numerical results to previously published analytical models [2,3]. Results show that the high electric field during the thermal quench results in a monotonic distribution function in energy [2]. On a longer timescale, a bump forms in the distribution tail, as predicted by [3,4]. The dependence of this time evolution is studied for different disruption parameters and is compared across various electron models available in DREAM.

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Poster Session MCF 1 - T

1 P 065 - Magnetic stochasticity and runaway electron dynamics in vertically unstable plasmas during tokamak disruptions*

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ABSTRACT TEXT

Magnetic stochasticity during tokamak disruptions can have a strong effect on the final runaway current and the resulting damage on the plasma facing components (PFCs) [1]. The dynamics and survival of runaway electrons following magnetic stochasticity and the reformation of the flux surfaces during the current-quench phase of the disruption in vertically unstable plasmas is analyzed. A 0-D model that self-consistently incorporates the vertical plasma motion and the runaway electron generation [2] is used, focusing on the conditions to avoid substantial runaway energy deposition on the PFCs which can occur because of the strong runaway avalanche during the scraping-off when the plasma hits the wall. Strong runaway electron losses (low characteristic runaway loss time, τ_d) and a sufficiently long stochastic period (τ) during the current quench are required to control the runaway damage. Under ITER-like conditions, for low temperatures ($\sim$ few eVs) of the residual ohmic plasma during the disruption, $\tau_d < 1$ ms and $\tau/\tau_d > 5$ would be needed to reduce the energy deposited by the runaways to a few MJ or below. Moreover, it is found that, independently of the model used for the magnetic stochasticity and the runaway losses, the relevant parameter determining the runaway energy deposition during scraping-off is the runaway current at the time the plasma touches the wall, I_{rc} , and this analysis suggests that I_{rc} should be quite low, in a range of a few kAs to tens of kAs. The role played by the primary runaway seeds after the stochastic phase is also discussed.

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Poster Session MCF 1 - T

1 P 066 - Kinetic modelling of hot tail runaway electron generation during plasma disruptions using the JOREK code

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ABSTRACT TEXT

Disruptions in ITER present the risk of generating large Runaway Electron (RE) beams that may cause intolerable damage when impacting the wall. Assuming short Thermal Quenches (TQs) lasting around 1 ms, the hot tail mechanism, driven by the rapid temperature drop and the resulting non-Maxwellian electron population, may produce dangerous amounts of RE seeds [1]. This motivates modelling with 3D non-linear MHD codes in order to accurately take into account electron losses due to magnetic field stochasticity and other 3D aspects of the dynamics. We leverage the JOREK 3D non-linear MHD code in order to post-process MHD simulations with test electrons. A dedicated computational framework has been developed to simulate the behavior of a hot test electron population evolving in the pre-calculated MHD fields and undergoing collisions with the bulk electrons and ions.

Before conducting comprehensive 2D and 3D hot tail seed estimations, we benchmark our results against the DREAM 1D-2P Fokker-Planck solver. Initial benchmarks involve a 2 dimensional (2P) velocity phase space within uniform fields, replicating a scenario from [2] where the temperature drops exponentially. Electron distribution functions from JOREK and DREAM show remarkable agreement. Using isotropic and pitch-dependent runaway criteria, we calculate the relative RE density and find that JOREK's RE seed results align with both DREAM and results from [2], with a relative error of 5%.

Further validation includes axisymmetric TQs in a DT H-mode ITER scenario. By varying the TQ duration from 0.36 ms to 7.2 ms, the generated RE population decreases from $4e18$ RE/m³ to $5e11$ RE/m³. Additionally, for a TQ duration of 0.36 ms, increasing the initial density (at constant thermal energy) from $8e19$ /m³ to $4e20$ /m³ reduces the RE seed from $4e18$ RE/m³ to 0.4 RE/m³. Across these cases, JOREK's RE estimates consistently match DREAM's predictions, even for low-generation scenarios.

Finally, experimental validation is performed. DIII-D pulse 178682, identified in [3] as producing a large hot tail RE seed, is currently being modeled with JOREK for this purpose.

The next step of our work will consist in predicting hot tail RE generation in ITER disruptions to optimize the ITER disruption mitigation strategy.

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Poster Session MCF 1 - T

1 P 067 - DECAF disruption avoidance and cross-device analysis of mode locking forecasting

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ABSTRACT TEXT

Tokamak experimental fusion reactors need to avoid major disruptions to be commercially viable. The Disruption Event Characterization and Forecasting (DECAF) code has been developed to address this key goal using a physics-first principle approach that tracks the set of precursor events to a disruption [1]. One phenomenon that can lead to plasma disruptions is called a neoclassical tearing mode (NTM). NTMs are rotating disturbances in the plasma, but they can slow down and lock to the lab frame due to fluid and electromagnetic forces that drag their rotation to that reference frame. When these modes lock, they can cause excessive device metal fatigue due to impulsive EM stresses and material damage to the first wall or other device components due to non-axisymmetric heat loads and/or runaway electrons, so predicting and avoiding locked modes is crucial for successful tokamak operation. A forecasting model has been developed that calculates the balance of torques that result in maintaining steady-state mode rotation. If the input torque is inadequate, the model forecasts a frequency threshold below which a rotating mode is expected to lock. Performance of this forecaster has been tested across devices of varying aspect ratio and error field conditions. Analysis has been carried out across the KSTAR, NSTX, and MAST-U databases to see how well the model predictions matches the observation of disruptions across the machines. In the KSTAR 2024 run a more fine-tuned version of the forecaster was used to now actuate with feedback the amplitude of the $n = 1$ rotating field managing to delay the plasma disruption up to half a second and avoiding a mode lock from causing the disruption altogether. This actuation was also accompanied with feedback actuation for vertical displacement events that led to even better plasma performance., tThis research was supported by the U.S. Department of Energy under grants DE-SC0020415, DE-SC0021311, and DE-SC0018623.

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Poster Session MCF 1 - T

1 P 068 - 3D MHD simulations of runaway electron avalanche in ITER mitigated disruptions

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ABSTRACT TEXT

The avalanche of runaway electrons (REs) during ITER disruptions could potentially generate several megaamperes of RE current during the current quench (CQ) which might damage the plasma-facing components. Previous studies have suggested that avoiding the formation of such a large RE current would be difficult [1;2]. However, before the number of REs increases to a large value, some REs might be lost due to the magnetic stochasticity from the growth of MHD instabilities such as tearing modes [3;4]. In our work, MHD-induced RE transport is modeled with the JOREK code, using a 3D reduced MHD model self-consistently coupled to a fluid description of REs.

The stability of the tearing modes is primarily determined by the current density profile and the properties of the conducting structures surrounding the plasma. Considering the uncertainty of the current distribution in the post-thermal quench (TQ) plasma, a scan of different current profiles is conducted to investigate their stability. The most stable case is chosen as the worst-case scenario for RE avoidance. The CQ phases with chosen initial current density profiles are being modeled using JOREK to investigate the maximum RE current generated in ITER disruptions.

In the stability scan, flatter core current profiles are more unstable. A flat current density profile in the plasma center leaves a steep edge where a high current density gradient drives the instabilities. Therefore, a peaked profile is used as the worst-case scenario where MHD activity is relatively mild and REs can be well confined over longer time scales. In this case, the growth of tearing modes near the plasma edge and the resulting local RE deconfinement are observed in the ongoing simulations, but the assessment of the final amplitude of the RE beam requires further analysis. However, in experiments on present tokamaks, the current profile usually flattens during TQ, leading to a typical spike in the plasma current waveform. Therefore, we performed another simulation with a flat current profile as a comparison with the worst-case scenario simulation mentioned above. Global magnetic stochasticity and massive RE deconfinement are observed in this case before a large RE current is generated.

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Poster Session BPIF 2

2 P 069 - Integrated Radiation-Magneto-Hydrodynamic simulations of magnetized burning plasmas

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ABSTRACT TEXT

Motivated by recent breakthroughs [1,2] in inertial confinement fusion (ICF), first achieving ignition conditions in National Ignition Facility (NIF) shot N210808 and then laser energy breakeven in N221204, modeling efforts have been begun to investigate the effect of imposed magnetic fields on integrated hohlraum simulations of igniting systems. Previous NIF experiments have shown fusion yield and hotspot temperature to increase in magnetized gas-filled capsules [3] in line with expected scalings [4]. In this work, we use the 2D radiation-magneto-hydrodynamics code LASNEX [5] with a Livermore ICF common model [6]. Simulations are tuned to closely approximate data from unmagnetized experiments. Investigated here is the effect of imposed axial fields up to 100 Tesla on the fusion output of historically high performing ICF shots, specifically N180128 N210808, and N221204. The main effect is increased hotspot temperature due to magnetic insulation. Namely, electron heat flow is constrained perpendicular to the magnetic field and alpha trajectories transition to gyro-orbits, enhancing energy deposition into the hotspot and cold fuel. However, magnetic fields must be fastidiously applied as secondary effects like magnetic pressure can resist or compromise the implosion. In addition, we investigate the impact of applied magnetic fields to future NIF designs, specifically an example Enhanced Yield Capability design with 3 MJ of laser energy as well as a high pR, low implosion velocity “Pushed Single Shell” design. In conclusion, it is found that magnetization can increase ion temperature by 50% and neutron yield by >2. Specifically, we see notable yield enhancement of at least 50% with only a 5–10 T applied magnetic field for N221204, while a 65 T field on N210808 with drive symmetrization gives an 8x increase in yield. This is all without further design optimization to best take advantage of an applied B field, which suggests even greater promise for future designs tailored specifically towards magnetization.

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Poster Session BPIF 2

2 P 071 - New developments in the laser-plasma interaction code HERA: broadband lasers and MHD

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ABSTRACT TEXT

The HERA platform is dedicated to modelling the physics of laser-plasma interactions in the context of inertial confinement fusion (ICF) research. In ICF, multi-kJ lasers propagate through a long and hot plasma. During their propagation, the lasers experience various instabilities that affect the beam quality (energy loss or beam breaking). However, these detrimental effects are partially mitigated by optical smoothing techniques that make the laser spatially and temporally incoherent. As an example, HERA models the widely used spectral dispersion, i.e. a combination of phase modulation and a grating [1, 2]. Spectral dispersion produces a small bandwidth, less than 0.1% at the laser megajoule facility (LMJ). Now that ignition has been demonstrated, there is a renewed interest in modelling a so-called broadband laser, where the bandwidth is greater than 1% of the laser frequency. Such lasers are expected to mitigate all the deleterious laser-plasma instabilities and thus to be the future game changer in the ICF community. Since there is a strong need to study this physics on a long time scale, where the lasers strongly modify the plasma dynamics itself, we also need to solve the plasma evolution coupled with the incoherent light propagation. For this purpose, the HERA code has been upgraded by introducing a broadband laser model and a 3D MHD module. In this poster we present the complete model and applications of these new physics modules.

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Poster Session BPIF 2

2 P 072 - First experiment using an hydrodynamic growth radiograph platform at LMJ

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ABSTRACT TEXT

Understanding and mitigating against the impact of hydrodynamic instabilities on indirect drive inertial confinement fusion implosions has been a key part of the success of ignition at NIF. It is then crucial to develop experimental capabilities to be able to measure and quantify the growth of any kind of perturbations. We present here the first experimental result of a new hydrodynamic growth X-ray radiography platform developed at LMJ. This platform, similar to the one developed at NIF [1], take advantage of a gold cone (keyhole geometry) to radiograph the growth through an imploded plastic capsule driven by the X-ray bath obtained in a rugby shaped hohlraum. These first experiments are devoted to measure the growth of engineering features such as fill tubes. Three different fill tube diameters are tested associated with three different glue plug. Adding two well-characterized divots perturbations on the side of the fill tube features gives a way to measure the capsule convergence as a function of time. We show that, if the fill tube diameter is an important parameter, the volume of glue is also a key parameter.

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Poster Session BPIF 2

2 P 074 - Ultra relativistic Weibel-like instabilities investigated with a Semi-Lagrangian adaptive mesh refinement method

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ABSTRACT TEXT

A dynamically adaptive mesh refinement (AMR) has been implemented in the 2D2V Semi- Lagrangian (SL) parallelized relativistic code VLEM (Vlasov ElectroMagnetic solver) [1], which consists of an embedded rectangular grid only in the velocity space [2]. This type of refinement is well suited to follow the perturbation of the distribution function in the momentum space such as filamentation, acceleration or heating processes. Indeed, following the filamentation process, which is a mathematical property of the Vlasov equation, requires a large sampling in the momentum space for SL method.

The application of SL methods to Weibel-like instabilities (current filamentation instabilities (CFI), two-stream instabilities (TSI) or oblique instabilities (OI)) can lead to the production of thin filaments in momentum space related to the energy transfer [3]. The AMR method helps to describe them with a lower numerical cost. This is more relevant when the temperature anisotropy between the beams is important as we need a wide momentum box to describe the hot beam but also a good precision to describe the cold beam. In this way, the AMR method helps to make numerical experiments that were much more difficult to do before, and to reveal the transition from OI to CFI in the regime where the OI growth rate is higher.

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Poster Session BPIF 2

2 P 076 - A simulation pipeline for short-pulse laser-driven hydrodynamics

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ABSTRACT TEXT

The interaction between a short, intense laser pulse and an initially-solid target can trigger a variety of physical responses over a wide range of time scales. A detailed understanding of these responses is vital to the design of experiments relevant to inertial fusion energy and high-energy-density physics. Different aspects of the target's response to the laser demand different modelling approaches, and a combination of simulation codes is required to capture the full range of key physical phenomena. We present a prototype of an integrated software pipeline linking a radiation-hydrodynamics simulation code, HYADES [1], to a particle-in-cell code, EPOCH [2], in order to facilitate the simulation of short-pulse laser-target interactions.

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Poster Session BPIF 2

2 P 077 - Scaling of Stimulated Raman Side-Scattering with focal spot size and density scale length in inhomogeneous plasmas

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ABSTRACT TEXT

Research into inertial confinement fusion (ICF) is thriving since the demonstration of ignition at the National Ignition Facility (NIF) via the indirect drive scheme. There is now a stronger push towards studying schemes such as direct drive and shock ignition, which are thought to be more appropriate for inertial fusion energy (IFE). A serious issue within these schemes is the growth of laser plasma instabilities (LPI) which act to scatter laser light and generate hot electrons, reducing the efficiency of the implosion and hindering the fusion process. Namely, we are concerned with the growth of the Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBS), and Two Plasmon Decay (TPD) instabilities. In laser-plasma experiments the standard approach is to measure scattered light from the SRS and SBS instabilities in the back-scattered direction i.e. down the laser cone. However, recent observations at the NIF and OMEGA facilities demonstrated that side-scattered Raman (SRSS), where the scattered light propagates nearly perpendicular to the density gradient, can also be a significant source of reflectivity that has previously not been captured well. Work remains to better understand the scaling parameters of SRSS and define the laser-plasma regimes where it can dominate, with a view of ultimately understanding how best to mitigate this LPI.

In this poster we present results from an experiment at PALS focused on studying the growth of SRSS using the “Octopus” fibre-based diagnostic to obtain angularly and spectrally resolved measurements of SRSS scattered light. Circular and elliptical phase plates were used to explore the influence of focal spot size in directions parallel and perpendicular to the laser E-field, and both thick targets and thin “exploding foil” targets were used to explore the effect of density scale length. We show that SRSS grows more strongly along the direction perpendicular to the laser E-field, and reflectivity significantly increases with longer focal spot size in this direction. Density scale length is seen to have a negligible effect on SRSS growth. Ray tracing simulations are also used to understand the effect of the density profile on the observed angular distribution of the SRSS scattered light.

Poster Session BPIF 2

2 P 078 - Laser-matter interaction in magnetized plasmas: x-ray diagnosis of enhanced hot electron energy deposition

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ABSTRACT TEXT

Recent progress in the development of strong laser-driven magnetic field generators at high energy laser facilities paves the way to new sort of experiments benefitting from application of well controlled external B-fields. In addition to basic research oriented investigation of fundamental phenomena in extreme parameter plasmas, these experiments also contribute to a design of alternate schemes of inertial confinement fusion where the plasma magnetization might increase the fusion yield [1]. Here we report on investigation of an increased deposition of hot electrons in laser irradiated targets affected by the magnetized plasma created near the target surface. The experiment was performed at the Prague iodine laser facility PALS. The random phase plate smoothed main laser beam (wavelength 1.315 μm , pulse duration 350 ps, intensity $2 \times 10^{16} \text{ W/cm}^2$) was focused onto the 50- μm -thick Cu disc connected with two grounded single-turn coils positioned near the target perpendicularly to its surface. The return current through the disc-coil holder circuit generated the magnetic field parallel to the target surface, its magnitude was assessed using two independent theoretical models. The effects of this field on properties of the laser-created plasma were studied by using the previously described diagnostic complex [2], here we concentrate on x-ray diagnosis of enhanced energy deposition of hot electrons inside the target. These electrons interact with copper atoms, the ionization of inner electronic shells results in $2p \rightarrow 1s$ fluorescence. The spectral distribution of the emitted Cu K α radiation was studied via high-resolution x-ray spectroscopy, the spatial and temporal characteristics of the hot electron deposition were investigated by time integrated and time resolved x-ray imaging. The increased conversion of the laser energy to hot electron flux inside the target qualitatively agrees with simulations.

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Poster Session BPIF 2

2 P 079 - Self-consistent laser dynamics in the ponderomotive acceleration of dense electronic beams

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ABSTRACT TEXT

The purpose of the present work is to extend previous results obtained on the subject of particle acceleration by electromagnetic ponderomotive potentials leading to a catapulting final phase, all derived from an Inverse Free-electron laser arrangement [1,2].

The very initial analysis of the problem neglected collective effects and therefore considered acceleration of single particles driven by given laser and wiggler fields [1]. We then recently added the collective effects due to a relatively dense electron beam and determined how space-charge effects affect the acceleration, with the external ponderomotive fields still held fixed [2]. Under these conditions we concluded that acceleration is still effective and can be even enhanced by space-charge.

Still considering the wiggler field as an externally given component of the problem, we are now developing the proper formalism to investigate the self-consistent dynamics of the laser field. Effects related with the expansion of the geometrical laser beam radius are discussed with help of average Lagrangian methods applied to the laser field. The laser beam radial expansion tends to deplete the laser intensity at the center of the co-aligned particle beam, which in turn limits the efficiency of the accelerating ponderomotive potential. We discuss relevant operational limits and how to preserve the efficiency of the process.

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Poster Session BPIF 2

2 P 080 - A canonical view on particle acceleration by electromagnetic pulses

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ABSTRACT TEXT

We explore how electrons are accelerated when exposed to high-frequency electromagnetic wave packets, particularly in situations where the wave's group velocity is less than the speed of light. This setup is key for effectively accelerating electrons, which is vital in laser-plasma interactions and cutting-edge particle acceleration techniques. Our research builds on earlier methods by presenting an enhanced ponderomotive canonical framework that accounts for adjustments needed for subluminal carriers. Using both theoretical analysis and numerical simulations, we test our model against traditional ponderomotive approximations. Our results show notable advancements in accurately predicting electron paths and energy increases. We establish a clear relationship between wave amplitude and group velocity that outlines the best conditions for acceleration. Furthermore, we examine the shift between passing and accelerating states, providing fresh perspectives on the boundary conditions necessary for optimal energy transfer. The canonical framework we propose offers a more precise depiction of wave-particle interactions, addressing inconsistencies identified in earlier models. These improvements are especially significant in high-intensity laser-plasma experiments, where meticulous control over acceleration dynamics is crucial. Our findings pave the way for enhancing electron acceleration in laboratory settings offering insights into laser-plasma interactions and radiation-driven acceleration mechanisms.

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Poster Session BPIF 2

2 P 081 - Impact of High-Power q-Gaussian laser Beam Propagation in Collisionless Magneto Plasma

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ABSTRACT TEXT

We have investigated the impact of high-power q-Gaussian laser beam propagation in collisionless Magneto plasma in this communication. The extraordinary mode and the ordinary mode are the two modes of propagation that occur when an incident moves along the direction of the magnetic field. Variations in the strength of the external magnetic field have a substantial impact on the redistribution of carriers. The redistribution of carriers occurs when the ponderomotive force drives the electrons away from regions of higher intensity. This raises the refractive index and further induces the input beam to focus itself. The ordinary differential equation of order two for the laser beam waist is derived using the well-known paraxial ray approximation. Furthermore, 2nd-order differential equations are numerically calculated using the Runge-Kutta 4th-order approach. Lastly, the effect of variations in the cyclotron frequency, q-values, beam radius, plasma density, and beam intensity on the beam width behavior as a function of normalized propagation distance is also investigated. The results investigated are very useful for better understanding laser-driven fusion.

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Poster Session BSAP 2

2 P 082 - Occurrence of Landau damping close to the Sun: Kinetic simulations and field-particle correlation

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ABSTRACT TEXT

Observations by the Parker Solar Probe (PSP) mission of electrostatic waves in the inner heliosphere open up questions on their role in the dissipation of turbulent energy (Píša et al. 2021; Mozer et al. 2021, 2023; Kellogg et al. 2024; Mozer et al. 2025). To characterize the generation and evolution of these waves, we perform kinetic simulations using a 1D1V Vlasov-Poisson code with drift Maxwellian distributions for electrons and core and beam protons, compatible with PSP observations. A comparison between kinetic theory and the amplitude of the electric field in the linear phase, besides the formation of ion holes in the beam phase velocity, confirms the observation of the ion-acoustic waves (Afify et al. 2024). Moreover, we investigate the conversion of energy between the electromagnetic field and charged particles by applying the field-particle correlation (FPC) technique to single-point time series simulated data (Klein & Howes 2016; Klein 2017; Klein et al. 2020). This method is particularly well-suited for diagnosing dynamics in systems where measuring integrated quantities, such as the electromagnetic work $\mathbf{j} \cdot \mathbf{E}$, does not distinguish between competing proposed mechanisms. The velocity-space structure of the energy transfer obtained by the field-particle correlation elucidates the dominance of Landau damping between 15 and 25 solar radii. These simulations reveal the processes likely operating in the inner heliosphere that are acting to reduce the free energy of drifting populations and lead to solar wind heating.

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Poster Session BSAP 2

2 P 083 - MHD wave modeling with Q-variables

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ABSTRACT TEXT

The Elsässer variables [1] have been widely used in magnetohydrodynamics (MHD) to describe Alfvén waves, providing a convenient representation of wave dynamics in the solar wind [2,3]. However, their applicability is limited when analyzing other MHD wave modes, as these often require a combination of both Elsässer components [4]. To address this limitation, we introduce Q-variables, a generalization of the Elsässer formalism, which allows tracking waves with phase speeds different from the Alfvén speed [5]. This extension provides a new framework for studying MHD wave dynamics. In this work, we further develop the analytical framework of Q-variables to describe linear and nonlinear MHD wave interactions. We aim to improve our understanding of wave coupling, energy transport, and mode decomposition in magnetized plasmas.

Additionally, we explore the application of Q-variables in numerical simulations as a tool for filtering wave modes in complex 3D MHD environments. This approach facilitates the separation of fast and slow magnetosonic waves, as well as surface Alfvén waves, offering new insights into plasma dynamics. The findings of this study could enhance theoretical models of plasma waves and contribute to improved simulations of space and astrophysical plasmas.

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Poster Session BSAP 2

2 P 084 - Advancements in GPU-accelerated particle-in-cell simulations with iPIC3D

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ABSTRACT TEXT

Particle-in-cell simulations are essential for studying kinetic-scale plasma behaviour in astrophysical and laboratory environments, where processes like magnetic reconnection and collisionless shocks can accelerate particles to extreme energies. We present the recent advancements in the semi-implicit iPIC3D code, which now supports GPU computation using CUDA (NVIDIA GPUs) and HIP (AMD GPUs). Comparisons with the CPU version of the code show a factor of 30 improvement in computational speed. We have integrated the exact energy-conserving semi-implicit method and the relativistic semi-implicit method that ensures energy conservation up to machine precision. This is essential to avoid artificial energy growth in the system over long time scales and obtain physically viable results. Furthermore, the code has undergone several methodological improvements that further boost its speedup by 10x. Owing to the implicit nature of the code and the recent algorithmic advancements, we are on course for exascale simulations of relativistic and nonrelativistic plasma, enabling unprecedented spatial resolution and temporal duration.

Poster Session BSAP 2

2 P 085 - Onset of driven magnetic reconnection and plasmoid formation in relativistic magnetized plasmas

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ABSTRACT TEXT

We investigate the onset of magnetic reconnection and plasmoid formation in highly magnetized, relativistic plasmas using particle-in-cell simulations of merging flux tubes. Two force-free, Lundquist-type flux tubes [1] are driven together by an externally imposed velocity, forming a thin current sheet (Phase I) that undergoes collapse, tearing instability, and rapid merging. The evolution of this process depends on the external drive, plasma magnetization, and system size relative to kinetic scales.

Our simulations reveal that the current sheet collapses when its aspect ratio exceeds a universal threshold, triggering the tearing instability and rapid plasmoid formation (Phase II). The reconnection rate can reach $\sim 0.1c$, remaining largely independent of magnetization and system size but strongly influenced by the external drive. We establish scaling relations linking the upstream magnetic field and magnetization to the driving velocity, showing that the upstream magnetization at collapse scales as the product of the in-plane magnetization and the push velocity. Once the flux tubes merge (Phase III), the energy conversion to kinetic and nonthermal particle energy follows a universal timescale, reinforcing a $0.1c$ reconnection rate. This suggests that the highly nonlinear evolution “forgets” the details of the external driving mechanism. These findings have significant implications for high-energy astrophysical environments—such as pulsar wind nebulae, magnetar magnetospheres, and active galactic nuclei—where reconnection is externally driven by shear flows, turbulence, or magnetic pressure imbalances.

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Poster Session LTDP 2

2 P 086 - Void closure in complex plasmas in microgravity with the future complex plasma facility COMPACT

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ABSTRACT TEXT

Complex, or dusty, plasmas consist of micrometer-sized grains injected into a low temperature noble gas discharge. The grains become charged and interact with each other via a screened Coulomb potential. On ground, gravity compresses the system and prevents the generation of larger, three-dimensional particle clouds.

COMPACT, the future facility for complex plasma research aboard the International Space Station (ISS) is designed as a versatile setup offering a large experimental parameter range. Currently, a first breadboard model of COMPACT is used to test its design features in the laboratory and on parabolic flights. The presented results impressively demonstrate the scientific capabilities that COMPACT will provide.

Here, the status of development of the facility is presented, alongside with a new experimental method for creating void-free complex plasmas under microgravity conditions. The method is based on a pulsed operation mode of a four-channel radio frequency generator for plasma sustainment. Utilizing this method, large three-dimensional, homogeneous complex plasma systems can be generated in microgravity, allowing fundamental studies of e.g. thermodynamical and statistical properties of the system.

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Poster Session LTDP 2

2 P 087 - Ion energy distribution and double layer formation in magnetized surface wave plasma (surfatron)

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ABSTRACT TEXT

This work investigates the **ion energy distribution functions (IEDFs) of ions extracted from an expanding surface-wave-sustained plasmas generated by a Surfatron source**, focusing on the impact of plasma parameters such as pressure, gas composition, applied power, magnetic field, and DC biasing of the extracting electrode. The study explores the underlying physical mechanisms responsible for the **observed multi-peaked IEDFs**, particularly in relation to **ion transit time effects and double layer (DL) formation in magnetically expanding plasmas**.

Plasma was produced using a surface-wave-sustained discharge (SWSD) system [1], wherein variations in operational parameters influenced both the plasma dynamics and ion acceleration processes. The IEDF was measured using a retarding field energy analyser (RFEA), while axial electron density and temperature profiles were obtained via Langmuir probe diagnostics. Experimental results indicate the presence of distinct ion energy peaks, suggesting a combination of transit-time effects and potential drops associated with double layers.

The ion transit-time-induced energy splitting has been extensively studied in capacitively coupled plasmas (CCPs), where the ratio of ion transit time to RF period plays a key role in shaping the IEDF [2]. Previous experimental works have validated this effect [3,4], demonstrating how variations in ion mass modifies the IEDF shape.

Additionally, double layers have been reported in magnetically expanding plasmas, where a sharp potential drop leads to the formation of an accelerated ion beam [5]. Plihon et al. [6] observed that these DLs appear spontaneously under certain discharge conditions, with their potential drop correlating with plasma parameters such as electron temperature and gas pressure. The review of Charles [5] further emphasizes the role of current-free DLs in plasma expansion, particularly in configurations involving diverging magnetic fields.

In this study, we analyse the interplay between these two effects—ion transit-time-induced energy structuring and DL-driven ion acceleration—by leveraging systematic variations in plasma conditions. The experimental results provide new insights into the mechanisms governing ion transport and energy distribution in surface-wave plasmas, with potential applications in surface processing and space propulsion systems.

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Poster Session LTDP 2

2 P 088 - Plasma Assisted Supersonic Jet Deposition for thin film growth

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ABSTRACT TEXT

Thin films, ranging from fractions of a nanometer to micrometers thick, are crucial in high-tech industries, especially when built from particles smaller than 100 nm, giving rise to nanostructured films with new properties. Controlled material synthesis via Chemical Vapor Deposition (CVD) or Physical Vapor Deposition (PVD) techniques is very important, shaping film properties for diverse applications.

We proposed a modified method, Plasma Assisted Supersonic Jet Deposition (PA-SJD), which divides gas precursor material synthesis into two steps for a better kinetic energy and cluster arrangement control of the flow on the substrate respect to conventional CVD/PVD methods. It offers chemistry control in a reactive cold plasma environment and assembly control with a supersonic inseeded jet over a substrate. The setup uses a vacuum system with separate plasma and deposition chambers connected by a nozzle. A pressure gradient forms between the chambers to induce supersonic jet formation. Plasma generation in the first chamber is followed by injecting a gaseous precursor into the system through an inductively coupled plasma source. Dissociated precursors move with the expanding supersonic jet in the deposition chamber. While particles accelerate, pressure and density drop, resulting in a low-collisional, energetic and directional flow.

Thanks to PA-SJD technique we can utilize dense plasma for fast deposition which is not possible yet with traditional techniques. Here we present some results that were obtained using plasma diagnostics, using electrostatic as well as optical emission techniques, in order to characterize the plasma state and the supersonic jet, together with its interaction with the substrate.

We discuss also some results obtained in the deposition of silicon oxide thin films, with different degree of organic retention. If controlled growth is achieved, such films are nanostructured materials suitable for applications like catalysis, photo catalysis, energy conversion, and storage, besides their traditional uses as a barrier or protective coatings. Besides composition and thickness, we will discuss also their structure and morphology and how this correlates with the film precursors flows and nanoparticle aggregation.

Poster Session LTDP 2

2 P 089 - Exploiting the synergy of a broad spectrum of light & surface dielectric barrier discharge (SDBD) plasma for ozone (O₃) production

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ABSTRACT TEXT

Non-thermal plasma (NTP) is extensively researched for its applications in air purification, pollutant abatement, and toxic gas treatment. Among the reactive species produced, ozone (O₃) is a persistent molecule capable of degrading volatile organic compounds (VOCs) and inactivating microorganisms. Nevertheless, maintaining regulated O₃ production within approved limits presents a significant challenge. This study investigates the integration of surface dielectric barrier discharge (SDBD) plasma with wide-spectrum light (UV-C and violet) to optimize O₃ generation from air at ambient conditions. The primary objective is to adhere to European Directive 2008/50/EC, which stipulates that O₃ concentrations must remain below 0.1 ppmv in enclosed environments. Critical parameters, including plasma duty cycle (1–30%) and energy density, are analyzed to regulate O₃ levels effectively. The results indicate that the production of O₃ is highly dependent on the duty cycle and energy input. Under optimized conditions—where the duty cycle is maintained at or below 3% and energy density is kept under 1.44 mWh/m³—O₃ concentrations remain within permissible exposure limits. The incorporation of UV-C ($\lambda \approx 275$ nm) and violet light ($\lambda \approx 405$ nm) enhances the reactivity of the plasma, thereby influencing the dynamics of both O₃ and nitrogen dioxide (NO₂). O₃ and NO₂ exhibit complex behaviour under varying energy densities as environmental parameters, such as humidity and temperature, further affect the formation of O₃ and NO₂. This dynamic necessitates precise control of operational parameters to achieve an effective balance between efficiency and safety. By employing duty cycle modulation and spectral light synergy; this study advances the controlled and safe production of O₃ for air purification purposes. The findings to the development of scalable and energy-efficient plasma-based systems for bacteria abatement, ensuring compliance with regulatory standards while maximizing performance. These insights facilitate improvements in environmental plasma applications, providing a practical solution for the management of indoor air quality and microbial disinfection.

Poster Session MCF 2 - L

2 P 090 - Gyrokinetic particle-in-cell turbulence simulations with an evolving background

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ABSTRACT TEXT

Physics based control variates are widely used to reduce the numerical noise and, consequently, the computational cost, of global particle-in-cell simulations. Nevertheless, when plasma profiles change significantly during the nonlinear evolution of the system, control variates based on fixed background distribution functions become less and less effective. Recently, a novel scheme has been proposed for the code ORB5 [1], based on an adaptive Maxwellian with time-evolving density and temperature profiles [2].

In this work, we propose an alternative time-varying control variate to study deviation from Maxwellian equilibria. This is based on the Phase-Space Zonal Structures transport theory, which plays a fundamental role in describing energetic particle dynamics and self-organization in burning plasmas [3, 4]. This work is based on the numerical infrastructure introduced in Ref. [5]. In particular, we show how the information provided by the finite element projection of the full distribution function can be used to adjust and update the control variate, i.e. the background distribution function, during the nonlinear evolution of the system for Maxwellian and non-Maxwellian plasma reference states.

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Poster Session MCF 2 - L

2 P 091 - An Improved Analytical Theory Model for Ion Temperature Gradient Instability in Tokamak Plasmas

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ABSTRACT TEXT

The Ion Temperature Gradient (ITG) instability, which is an important mechanism of heat transport, can cause significant energy loss and reduce fusion efficiency in tokamak plasmas. Since its discovery in 1961's [1], there has been theoretical attempt using various simplified approximations to derive analytical dispersion relations for ITG in a tokamak plasma. These previous theoretical dispersion relations are, however, found to yield results inconsistent with numerical results obtained from Particle-in-Cell (PIC) simulation codes and eigen solvers [2]. Upon clear examinations, the discrepancies are found to be due to either approximations of the small normalized ion magnetic drift frequency and/or normalized ion Larmor radius. In the present work, we have developed a new analytical theory without making above approximations but assume the wave frequency, the ion diamagnetic drift frequency and the ion magnetic drift frequency are of the same order of magnitude, which is much greater than the ion thermal velocity divided by the multiplication of the safety factor and the major radius. The resultant analytical dispersion relation is shown to be in good agreement with the numerical simulation and eigenvalue solutions [2] for both cases with and without the trapped electrons.

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2 P 092 - Numerical simulations of scrape-off layer plasma turbulence: evidence in support of stochastic modeling

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ABSTRACT TEXT

We present results from numerical simulations of a reduced two-field fluid model, describing turbulent motions and blob structures at the out-board mid-plane of magnetically confined plasmas. The model describes the nonlinear evolution of the electron density and the electric drift vorticity, and parametrizes losses along the field lines in the scrape-off layer through sheath dissipation terms [1, 2]. A detailed investigation of the fluctuation statistics is presented for variations in the sheath dissipation parameter in the vorticity equation, which describes the role of parallel electric currents through the target sheaths. The parallel particle loss rate is fixed, so the equilibrium state is the same for all cases investigated. This corresponds to a scan in the core plasma density in confinement experiments.

It is demonstrated that with increasing sheath dissipation parameter, both the linear growth rate of the interchange instability and the dominant length scale of the fluctuations become smaller. The turbulence simulations reveal radial motion of blob-like structures resulting in an exponential radial profile of the time-averaged particle density and large relative fluctuation levels. The statistical properties of the fluctuation time-series measured at a fixed point in the scrape-off layer are found to be in excellent agreement with a stochastic model describing these as a superposition of uncorrelated exponential pulses with an exponential amplitude distribution [3].

The stochastic model predicts a particle density profile e-folding length proportional to the radial blob velocity, in agreement with the results from numerical turbulence simulations. With increasing sheath dissipation parameter, the blob sizes and radial velocities both decrease, and the profile e-folding length becomes shorter. The radial particle transport is well described by an effective radial convective velocity, which is approximately constant as function of the radial coordinate in the scrape-off layer but decreases with increasing sheath dissipation parameter. Its scaling with the sheath dissipation parameter is well described by blob velocity scaling theories. Finally, the results from the simulations are shown to compare favorably with experimental measurements in tokamak plasmas.

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Poster Session MCF 2 - L

2 P 093 - Tungsten and high-Z impurity transport analysis using x-ray spectroscopy at Wendelstein 7-X

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ABSTRACT TEXT

Observations of high-Z impurities during the OP2.2 and OP2.3 experimental campaigns in Wendelstein 7-X (W7-X) plasmas were made using the High-Resolution X-ray Imaging Spectrometer (HR-XIS). The HR-XIS is one of three X-ray Imaging Crystal Spectrometer (XICS) systems installed on W7-X that exploit the Bragg diffraction of crystals and is specifically designed for investigating impurity transport. Utilizing a 3-axis translating and rotating stage and recently upgraded with a new InSb crystal, the HR-XIS can make non-perturbative measurements of a selection of impurities such as Al, Ti, Fe, and W existing in charge states from Z of 12–49 between 1–7 Å. In W7-X so-called “high-performance” plasma programs, where turbulent transport is reduced and neoclassical transport is expected to be more important, impurities were eroded in the plasma edge or injected into W7-X in a different manner by the Laser Blow-Off and TESPEL systems to investigate the characteristics of the impurity emission lines. The impurity transport diffusion coefficient profiles were inferred through an optimization loop using experimental data and the 1.5D AURORA transport code. Initial analysis has qualitatively shown strong impurity accumulation during the high-performance phases; quantitative comparisons between the turbulence-reduced plasmas with neoclassical theoretical transport predictions are presented.

Poster Session MCF 2 - L

2 P 094 - Enhancement of nonlinearly driven particle fluxes triggered by turbulence spreading in tokamak plasmas

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ABSTRACT TEXT

One of the most important issues for tokamak devices is sustainment of high-density plasma. Particles supplied at the periphery by pellet injection or gas puffing should be transported to the plasma core region, and an efficient method for the transport is needed. Control by utilizing turbulent transport is one of the ways, so we studied generation mechanism of the radial inward particle transport by global turbulence simulation.

Here, we consider relaxation of the background initial density profile peaked near the plasma edge. This initial profile is assuming the vicinity of a high-density region that is transiently created during pellet injection [1], which includes a strongly turbulent region with a strong density gradient and a weakly turbulent region with an inverted density gradient. Reduced MHD code R5F [2] is used to calculate resistive ballooning modes and variation of the mean profile by the turbulence for the whole region of the plasma. A radial outward particle flux near the density peak is dominant, but a radial inward particle flux is also generated and sustained nonlinearly in the inverted density gradient region [3]. This inward flux is nonlinearly increased as the density gradient is increased. To understand the generation mechanism of the inward flux, the energy balance and nonlinear mode coupling strength are quantitatively evaluated for dominant modes driving the particle flux. The results revealed a global mechanism whereby the propagation of turbulence from the strong turbulence region (turbulence spreading) triggers the inward particle flux in the weak turbulence region with nonlinear amplification of the fluctuation strength [4]. Energy transfer to the small wavenumber mode component is also important in the nonlinear process. The ratio of the inward particle flux can be increased by modifying the safety factor profile to select the spreading mode to enable direct flux generation.

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Poster Session MCF 2 - L

2 P 095 - Full-f gyrokinetic simulations of a linear plasma device based on the gyromoment approach

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ABSTRACT TEXT

We present first-of-a-kind state-of-the-art turbulent simulations of a linear plasma device, allowing for fluctuations on scales that range from the machine size to the ion Larmor radius. Relying on a spectral projection for the distribution function on a Hermite-Laguerre polynomial basis, we simulate plasmas at lower cost compared to standard approaches while including collisional effects.

The simulations integrate delta-f gyrokinetic[1],[2] and full-f drift-kinetic simulations[3],[4]. We split the gyromoments and electrostatic potential in one slowly varying large-scale component, relying on a drift-kinetic ordering, and one rapidly varying small-scale component, relying on a gyrokinetic ordering. The two components are coupled together through the dynamics perpendicular to the magnetic field. The simulations allow us to explore the link between large-scale and small-scale turbulent fluctuations.

Turbulent simulations of an LAPD plasma are presented. Despite the simple geometry of linear plasma devices, they still display complex turbulent dynamics. Comparisons of the kinetic effects and turbulent structures with respect to standard drift-kinetic full-f simulations are presented. This work is an important first step towards full-f global self-consistent simulations describing the plasma dynamics from the hot and dense core to the boundary characterized by large fluctuations and to the cold scrape-off layer.

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Poster Session MCF 2 - L

2 P 096 - A constant flux surface average electron model for BSL6D

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ABSTRACT TEXT

BSL6D is a six-dimensional, semi-Lagrange, electrostatic Vlasov code in slab geometry for the simulation of strongly magnetised plasmas with adiabatic electrons [1]. Previous work by Raeth et al. has demonstrated the framework’s ability to simulate high-frequency Bernstein wave instabilities [2]. As a preliminary step towards a more realistic drift-kinetic electron model and enhanced physics, we have implemented a constant flux surface average electron model in which the adiabatic electron motion is confined to slab flux surfaces. This model can be regarded as a one-dimensional reduction of a drift-kinetic electron model that ignores polarisation drifts, finite Larmor radius effects and any magnetic drift. The key aspect of the model is that the electron density is constant on average at each flux surface. In anticipation of future developments, our objective is to ensure quasi-neutrality and $j = 0$ orthogonal to the flux surfaces without resolving the fast plasma wave. The implemented algorithm achieves this through an explicit eigenvalue problem construction that dampens any current or quasi-neutrality deviation within one time step. Furthermore, a linear higher wavenumber correction has been implemented to ensure equal damping for all modes. This correction is necessary because the Lagrange interpolation employed in the BSL6D numerical scheme treats different wavenumbers differently.

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Poster Session MCF 2 - L

2 P 097 - Neoclassical Effects on Turbulent Transport in Tokamak Devices

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ABSTRACT TEXT

In magnetized fusion devices, plasma dynamics in the collisionless limit is governed by neoclassical drifts and turbulence. Based on the quasilinear approximation and the assumption of additive neoclassical and turbulent transport, it is common practice to consider that the neoclassical components of transport are null and one can evaluate the transport using only fluctuating fields. In this work, we challenge this assumption. Test-particle numerical simulations and semi-analytical estimations are used to prove that, depending on the physical regime, significant synergies can arise between neoclassical and turbulent components of motion.

Poster Session MCF 2 - L

2 P 098 - Reducing turbulent transport in tokamaks by combining intrinsic rotation and the low momentum diffusivity regime

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ABSTRACT TEXT

Based on the analysis of a large number of high-fidelity nonlinear gyrokinetic simulations, we propose a novel strategy to improve confinement in spherical tokamak plasmas by combining up-down asymmetric flux surface shaping with the Low Momentum Diffusivity (LMD) regime. We show that the intrinsic momentum flux driven by up-down asymmetry creates strong flow shear in the LMD regime that can significantly reduce energy transport, increasing the critical gradient by up to 25%. In contrast to traditional methods for generating flow shear, such as neutral beam injection, this approach requires no external momentum sources and is expected to scale well to large fusion devices. The experimental applicability of this strategy in spherical tokamaks, whose low aspect ratios are favorable to achieving LMD conditions, is addressed via simulations by considering actual equilibria from MAST and a preliminary equilibrium from SMART.

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Poster Session MCF 2 - L

2 P 099 - Investigation of the observed edge toroidal rotation acceleration due to Resonant Magnetic Perturbations on MAST-U

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ABSTRACT TEXT

Understanding and controlling plasma flow, particularly tailoring the rotation profile, is crucial for ensuring stability in fusion experiments. In future reactor-scale devices like DEMO, where large angular momentum injection is not currently foreseen, identifying alternative actuators for rotation control may become fundamentally important. This study presents a numerical and experimental characterization of the torque induced by the active non-axisymmetric coil system in MAST-U. In particular, the coils were configured in high-toroidal mode number ($n \geq 2$) setups, producing time-modulated Resonant Magnetic Perturbations (RMPs) to examine their effect on the plasma edge. Notably, experimental observations revealed significant acceleration of plasma flow, localized near the plasma boundary, synchronized with the RMP modulation. To interpret and quantify the mechanisms underlying this acceleration, modeling with the MagnetoHydroDynamic (MHD) MARS-F/K [1] code is being carried out. The code, in fact, allows to simulate RMP-induced effects on toroidal angular momentum after computing the plasma response to any external, non-axisymmetric field, within a linear framework. Moreover, the MARS-K formulation introduces drift-kinetic corrections [2] assuming different particle species. The final goal is to compare numerical results with the modulation amplitude and phase profiles directly obtained from the experiment, from which RMP coil-induced torque can be approximated. Among all the possible different torque sources, the Neoclassical Toroidal Viscous (NTV) torque [3], which arises due to the radial drift of trapped particles in the presence of non-axisymmetric fields, is the principal candidate for explaining the edge-flow acceleration [4]. Additionally, to increase the degree of realism and match the observations, a model to characterize the torque arising from edge stochasticity [5] has been recently incorporated into the MARS-F/K workflow. This implementation will be presented and discussed for the first time within this work. Finally, given the common presence of an intrinsic Error Fields (EF) during MAST-U discharges [6], the interaction between induced RMPs and unwanted EF has also been considered in order to address the possibility of observing the acceleration as a result of the competition between the two sources of symmetry breaking.

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Poster Session MCF 2 - L

2 P 100 - Gyrokinetic simulations of negative triangularity plasmas in ASDEX Upgrade using GX

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ABSTRACT TEXT

Recent developments in modelling tools have enabled high-fidelity simulations and predictions of core plasmas at significantly reduced costs. In particular, GX [1] is a new entrant to the constellation of gyrokinetic codes that has the advantage of accelerating computation by natively targeting graphic processors and can accommodate both axisymmetric and non-axisymmetric plasma geometries. The PORTALS framework [2], leveraging surrogate modelling and optimization techniques, can couple local gyrokinetic and neoclassical calculations with background profile evolution to iteratively solve for steady-state, flux-matched plasma profiles. In this study, we used GX to investigate the linear growth rates and nonlinear fluxes for negative triangularity plasmas in ASDEX Upgrade, and compared with previous studies [3] performed using CGYRO [4]. We will explore coupling GX with PORTALS for the first time to obtain flux-matched profile predictions in tokamaks. Future work will explore comparisons with other gyrokinetic codes and application of this framework for more complex plasma geometries that are up-down asymmetric or non-axisymmetric.

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Poster Session MCF 2 - L

2 P 101 - Study on the dispersion relation and the discrete spectrum of drift wave turbulence

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ABSTRACT TEXT

Drift wave turbulence is one of the most important transport mechanisms in magnetic confinement fusion devices [1]. It will become more important once self-consistent fusion reaction is achieved as it plays an important role in fueling and ash discharging. Drift wave pattern, which has been observed in linear devices is one of the most proper and economy carrier to realize efficient transport of Helium as and fuel because of strong spatial and temporal coherence as well as the modifiable relation between physical variables [2,3].

In this work drift wave pattern has been studied both experimentally and theoretically. The discrete spectrum and pattern structure are clearly observed and separated to temporal eigen vectors using fast camera, and the polarization and transport characters are studied by probe matrix. Interactions by non-linear phase evolution have also been observed in the experiments. The dispersion relation has been theoretically obtained using Schrödinger's-like equation to match the experimental results. The linear and non-linear phase-dynamic interaction between the eigen modes is one of the major mechanisms of pattern non-rigid deformation. The transport mechanism of the drift wave pattern is proved to be the electric potential well trapping and weak coherent scattering which is different from the non-coherent turbulence. The result shows a new view to study coherent turbulence and may promote transport regulation in the fusion reactor.

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Poster Session MCF 2 - T

2 P 033 - Multi-diagnostic plasma equilibrium reconstruction with Physics-Informed Neural Networks (PINNs) for tokamak applications

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ABSTRACT TEXT

Understanding the underlying physics and implementing effective diagnostic monitoring are crucial tasks for advancing thermonuclear plasma research. Many diagnostic data require inversion or rely on fundamental assumptions, and faulty or imprecise diagnostic measurements often lead to unreliable inference. To address the need for a deeper understanding of plasma physics and accurate data integration, Physics-Informed Neural Networks (PINNs) present a promising innovative solution.

PINNs are powerful tools capable of merging the governing physics of the observed phenomena with experimental measurements. They are robust to noisy data, outliers, and are capable of parameters modelling.

In this work, we present a numerical study for the reconstruction of thermonuclear plasma equilibria. We introduce the developed algorithm, alongside two possible neural network architectures: one based on the Grad-Shafranov equation and the other on the general Magnetohydrodynamic (MHD) equilibrium equation. Reconstructions are demonstrated using diverse synthetic noisy measurements, including different magnetic and optical diagnostics, such as coils, interferometry-polarimetry, Motional Stark Effect, and Thomson Scattering. The robustness against various forms of uncertainty, such as outliers or offsets, is also substantiated.

Overall, this study highlights the potential of PINNs for reconstructing MHD equilibria in thermonuclear plasmas by integrating multiple diagnostics with different resolution, accuracy and noise statistics. The results demonstrate that PINNs can serve as an effective tool for studying the physics of thermonuclear plasmas, bridging gaps between diagnostic data and physical models.

KEYWORDS

Physics-Informed Neural Networks (PINNs), MHD Equilibrium reconstruction, Data integration

ACKNOWLEDGEMENT

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Poster Session MCF 2 - T

2 P 062 - Scalable simulation-based inference framework for large-scale model validation in fusion

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ABSTRACT TEXT

Simulation-based inference (SBI) algorithms open a pathway for scalable large-scale validation of predictive models in magnetic confinement fusion research (MCF) [1]. Computationally costly models, with a selection of uncertain input parameters, are ubiquitous within MCF [2–5]. Due to the input uncertainties, multiple forward passes are typically required in model validation to quantify the distribution of the input parameters that best reproduces the experimental observations [6]. Solving this inverse problem is a key challenge in model validation and must be done algorithmically, such as using SBI, in large-scale validation workflows.

While data-efficient, inverse inference workflows have been demonstrated in model calibration applications within MCF [6–9], a large-scale adoption in model validation activities has not emerged yet. One of the entry barriers is the software infrastructure for large-scale applications, requiring custom solutions for distributed computing, database handling, and sorting out failed simulations within the workflow. However, these requirements align with those needed for data generation for general machine learning surrogate modelling of computationally expensive models [10–13]. Therefore, in this work, a scalable SBI framework is developed and presented, building on top of Enchanted-surrogates, originally designed for simulation data generation for surrogate models [13]. Application of this SBI framework for simulations of synchrotron emission pattern evolution in a JET plasma with argon induced disruption and runaway electron beam is presented.

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Poster Session MCF 2 - T

2 P 103 - Modelling type-I ELM detachment burn-through for SPARC

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ABSTRACT TEXT

SPARC [1], a compact tokamak under construction by Commonwealth Fusion Systems, is set for first operation in 2026. Operating at an on-axis magnetic field of 12T, SPARC is projected to sustain H-mode plasmas up to fusion powers ≈ 140 MW and gains up to ≈ 10 . H-mode enhances core performance by suppressing core-edge transport, but steep pedestal gradients can violate MHD stability, resulting in large ejections of pedestal energy/particles via type-I Edge Localised Modes (ELMs) into the Scrape-Off-Layer (SOL). Experiments in SPARC will seek to explore H-mode detached divertor operation for its Advanced Divertor Mission (ADM), but significant risk remains for the transient power loading from type-I ELMs to 'burn-through' the detachment front to the divertor targets, potentially melting plasma-facing components. Furthermore, low collisionality in the pedestal top complicates modelling of type-I ELMs, as kinetic 'non-local' parallel transport effects must be included.

This work presents a 1D ELM burn-through study for a prospective SPARC H-mode scenario using the Hermes-3 multi-fluid code. A simple model for ELM energy/particle fluence is constructed based on empirical multi-machine scaling [2], tokamak IR spectroscopy [3], and ASDEX upgrade ELM pedestal measurements [4–5], forming a type-I ELM-like energy/particle upstream source that is applied to a steady-state SOL plasma. Non-local transport effects are included via the reduced-kinetic Schurtz, Nicolai, and Busquet (SNB) model [6].

An ELM energy fluence scan ($7.5\text{--}45.5\text{ MJm}^{-2}$ injected upstream) for a SPARC super-X divertor scenario ($I_p = 5.0\text{ MA}$, $f_G = 0.43$) evaluates ELM impact on the detachment front. Results show rapid detachment burn-through ($\approx 0.6\text{--}0.2\text{ ms}$) that scales inversely with fluence, followed by slower recovery ($\approx 10\text{ ms}$) independent of fluence. Inclusion of pedestal density transport into the SOL has minimal impact compared to ELM energy fluence. Parallel detachment front location reduces to $< 0.5\text{ m}$ off the target plate consistently for ADM relevant ($15.5\text{--}45.5\text{ MJm}^{-2}$) fluences. However, complete burn-through is not observed as neutral density at the target remains high, identifying neutral over-compression as a crucial area of development for 1D transient simulations.

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Poster Session MCF 2 - T

2 P 104 - Effect of vibrationally-resolved D2 on detachment in SOLPS-ITER simulations of MAST-Upgrade

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ABSTRACT TEXT

Plasma-molecular interactions seen experimentally during deep detachment on the Super-X of MAST Upgrade are not replicated in SOLPS-ITER simulations [1,2]. Inaccuracies in the AMJUEL molecular charge exchange effective rate coefficient below 2 eV lead to an under-prediction of the D2+ in this regime [3,4,5,6]. A recent study outlays the construction of a new molecular rate dataset (X1EXT) using the vibrationally-resolved Yacora-H2(X1, v) model [7,8,9]. This dataset was applied to an isolated divertor leg geometry in SOLPS-ITER with MAST Upgrade L-mode Super-X conditions. Below $T_e = 1$ eV, X1EXT increases the levels of D+ 2, resulting in increased ion particle sinks (via MAR and EIR) and stronger power losses due to the formation of excited D (via MAR, MAD, and EIR). This provides better agreement with trends on MAST Upgrade [1,2]. Applying the X1EXT effective rate coefficients to L-mode Super-X MAST Upgrade simulations and comparing against the reference simulations and experimental analysis from Moulton (2024) we expect better agreement in MAR, MAD and EIR [1]. This should lead to an earlier onset of the rollover of ion-target flux, as well as radiative losses during detachment. Additionally, the Fulcher detachment front location should agree better with experiment due to more realistic populations of D2 in simulation. However, employing effective rate coefficients that act on the molecular ground state density results in an inherent assumption, that the lifetimes of all vibrational levels are assumed to be extremely slow [10]. This may not be valid in deep detachment as the mean free path of vibrationally excited molecules exceeds the divertor size [11]. Vibrationally-resolved SOLPS-ITER simulations will be constructed using data from X1EXT and compared to the prior study. Resolving the transport of D2(v) may result in an increase in vibrational excitation in detached regions via transport from hotter regions. This could enhance electron quenching so that the levels of MAR, MAD, EIR and molecular dissociation are elevated. This will further increase the power dissipation and enhance the ion target flux roll-over when compared to the effective rate simulations, providing greater agreement with experiment.

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Poster Session MCF 2 - T

2 P 105 - Stellarator divertor optimisation for a Stable Quasi-Isodynamic Design (SQuID): magnetic topology, divertor plates and baffle design

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ABSTRACT TEXT

This contribution studies divertor optimisation for the Stable Quasi-Isodynamic Design (SQuID) [Goodman et al., 2024]. SQuIDs are a promising class of stellarator design which simultaneously achieve low neoclassical transport, MHD stability, low electrostatic turbulent transport, buildable modular coils and an island divertor. Divertor optimisation, that is, managing the heat and particles expelled from the confined region without compromising machine lifetime or core performance, is an essential element of stellarator reactor design. Divertor performance depends upon both the magnetic topology in the stellarator edge and the location and shape of the plasma-facing components (PFCs); here we address both through the lens of optimisation. Firstly, topological methods (which have shown to be useful in diagnosing edge topology [Davies et al, 2025]) are applied to understand the edge magnetic structure in an example SQuID configuration. We show how the edge transport is crucially dependent on the number and location of the X- and O-points in the edge, and discuss ways in which these can be adjusted and optimised. Secondly, we present a scheme for designing (1) divertor plates to catch the exhausted heat and (2) baffle structures to impede the movement of neutral particles back into the main plasma. This applies and extends existing semi-automated design schemes [Davies et al, 2024a, Davies et al, 2024b] in a reactor context, using reduced physical models to evaluate our designs. Our PFC design approach is under-constrained, and we comment on how this freedom may be used to target additional properties in a SQuID reactor.

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Poster Session MCF 2 - T

2 P 106 - Spectroscopic investigation of main impurity flows under magnetic field reversal in the TCV divertor

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ABSTRACT TEXT

Plasma ion and electron temperature and flow velocity were measured simultaneously in the divertor of TCV discharges in opposing magnetic field directions to reveal any effects of magnetic drifts on Scrape-off Layer (SOL) profiles. In divertor modelling, $T_i = T_e$ is often assumed due to a lack of direct measurements. However, deviations between ion and electron temperatures influence the energy distribution across species. TCV's new Tangential Divertor Spectrometer System (TDSS) infers ion temperature and flow velocities from Doppler broadening and Doppler shift from spectral observations. Ohmic L-mode discharges in an attached divertor configuration were conducted on TCV, where the divertor leg was aligned with Thomson Scattering measurement chords and the TDSS lines of sight to simultaneously measure ion- and electron-radial and poloidal profiles. With a toroidal field direction corresponding to a ∇B drift away from the X-point (unfavourable configuration), the C2+ ion temperature (T_i) was equal to the electron temperature (T_e) near the separatrix, whereas T_i exceeds T_e in the far-SOL. The flow velocity, directed towards the outer target, strongly increased radially from the separatrix to the far-SOL. To examine the effect of magnetic drifts, the experiment was repeated with the toroidal field reversed (favourable configuration). Reversing the toroidal field direction shifted the electron density peak in the radial direction without strong changes in the temperature profiles. The strong radial velocity shear in the SOL was absent for the favourable scenario, resulting in a flatter velocity profile. This flattening is consistent with SOLPS-ITER simulations that include magnetic drifts, reinforcing the role of drifts in shaping the SOL flow. The simultaneous availability of electron and ion temperature profiles, along with their flows and impurity emissions, provides an unprecedented opportunity to validate and challenge SOLPS-ITER models to improve predictive capabilities. Since parallel flow shear at the plasma edge influences cross-field turbulent transport [1][2], further analysis is needed to assess the impact of toroidal field reversal on turbulence and transport mechanisms.

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Poster Session MCF 2 - T

2 P 107 - Transient-divertor interaction studies in the MAST-U super-X divertor

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ABSTRACT TEXT

Transient events such as ELMs, sawteeth and H-L back-transitions are ubiquitous on current devices and inevitable in some form in future reactor scale tokamaks. In steady state burning plasmas detachment will be a key part of maintaining manageable heat fluxes to divertor target tiles [1]. The impacts of transient power fluxes on detachment and divertor tile heat loads are of interest to understand survivability of divertor targets for future devices.

In this work a combination of novel and established diagnostics has been used to study the impacts of transients on the super-X divertor of MAST-U. The super-X is an advanced divertor configuration which influences the intended STEP design [2]. When a transient event occurs the increased flux of energetic particles into the divertor ionises the neutral cloud built up by detachment. This burn-through of the detachment front can eventually reattach the plasma to the target which can lead to potential damage.

Results are presented from a recently installed ultrafast divertor spectroscopy diagnostic. This diagnostic tracks burn-through by measurement of Fulcher emission along a typical super-X strike leg and can resolve events within $\sim 10 \mu\text{s}$. Infrared camera data has been used to measure the power incident on divertor tiles due to transients, enabling quantification of transient energy buffering by the divertor neutral cloud. These analytical techniques are also applied to recent experiments to investigate the effects of impurity seeding on transient-divertor interactions.

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Poster Session MCF 2 - T

2 P 108 - Study on poloidal field configuration effect to electron cyclotron wall cleaning in KSTAR

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ABSTRACT TEXT

This study investigates the performance of an electron cyclotron wall cleaning (ECWC) technique between shots under different background poloidal magnetic field structures. In superconducting tokamaks, the toroidal field cannot be turned off between shots, making glow discharge-based wall cleaning infeasible. Instead, wall cleaning is performed using plasmas generated by electron cyclotron heating (ECH).

In KSTAR, previous research has shown that applying the background poloidal magnetic field predominantly in the vertical direction, rather than the radial direction, is more effective [1]. Additionally, recent wall-cleaning studies have adopted the magnetic field structure used in pre-ionization experiments [2], modifying the vertical magnetic field by introducing a slight curvature to the high field side (HFS) [3].

In this study, we experimentally investigated the ECH plasma characteristics and the effectiveness of wall cleaning under different curvatures and magnitudes of the background poloidal magnetic field. The operational conditions for ECWC, apart from the poloidal magnetic field and the helium pressure, were set based on previous studies [3]. By improved density generation of the ECRH plasma, we identified optimized poloidal magnetic field curvature and magnitude conditions that maximize outgassing from the plasma facing components (PFC). Langmuir probe measurements in the divertor region confirmed that most ions were incident in the high-field region. Since KSTAR has a much larger PFC area in the high-field region compared to the HFS, properly managing the high-field PFC is crucial for controlling plasma-wall interactions. Building upon this study, we plan to further investigate not only the effects of the poloidal magnetic field condition but also the influence of pressure and ECH conditions to wall cleaning. Additionally, we aim to study plasma transport physics induced by different magnetic field structures.

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Poster Session MCF 2 - T

2 P 109 - Neural network surrogate model trained on EMC3-EIRENE database for rapid prediction of edge plasma parameters from experimental measurements

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ABSTRACT TEXT

This work aims to explore the feasibility of directly predicting EMC3-EIRENE [1,2] outputs from diagnostic measurement data using neural network models, based on the EMC3-EIRENE simulation database. The machine learning approach focuses on training a neural network model to learn the relationship between synthetic diagnostics, generated by EMC3-EIRENE simulations, and the corresponding EMC3-EIRENE outputs. Once trained, the model directly predicts EMC3-EIRENE results using diagnostic data collected during W7-X operations. Preliminary results demonstrate that the optimized neural network model achieves good agreement between the predicted edge plasma parameters and the EMC3-EIRENE simulation results, while also showing satisfactory consistency with diagnostic measurement data. This suggests that the method, trained on the EMC3-EIRENE database, ensures physical self-consistency, while significantly reducing computational costs and eliminating the labor-intensive processes typically involved in simulations and experimental validation. The diagnostics currently employed include Thomson scattering, divertor spectroscopy, alkali metal beams, and divertor Langmuir probes. The EMC3-EIRENE database only contains parameter scans for heating power, radiation fraction, separatrix electron density, and cross-field transport coefficients on standard configuration. To further enhance the model's applicability, the next step is to expand the EMC3-EIRENE database to encompass a wider range of W7-X operational scenarios and incorporate a broader variety of experimental diagnostics.

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Poster Session MCF 2 - T

2 P 110 - Upgrade glow discharge cleaning system on the Uragan-2M stellarator

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ABSTRACT TEXT

Various methods are used to wall conditioning fusion facilities such as tokamaks and stellarators. One of the most common of these is the method of wall conditioning using glow discharge plasma [1–2], as this method is both effective and technically simple. A glow discharge cleaning system (GDC) was developed and implemented on the Uragan-2M (U-2M) stellarator [3–5]. This system was upgraded, and a new anode system was developed and manufactured, which includes two identical anode units. The shape of the anodes is mimicking to that of the anodes of the GDC at the Wendelstein 7-X stellarator.

This paper compares the results of investigation glow discharge plasma in helium and hydrogen atmospheres at the same conditions. The experiments were carried out in the pressure range ~ 0.3 – 13 Pa, in the range of discharge currents from 0.1 to 1 A. The breakdown voltage in both gases is measured. As expected, a higher breakdown voltage is observed in helium than in hydrogen. Volt-ampere characteristics of the discharges were obtained, showing that the discharge voltage in the helium atmosphere lower than in the hydrogen atmosphere. The triple probe was used to measure the plasma parameters. The electron temperature and plasma density are observed to be higher in helium atmosphere compared to plasma in hydrogen. Thus, for example, the temperature in helium plasma was up to ~ 15 eV and in hydrogen plasma up to ~ 6 eV. The plasma density was up to $\sim 6 \cdot 10^{14} \text{ m}^{-3}$ in a helium atmosphere and up to $\sim 1.5 \cdot 10^{14} \text{ m}^{-3}$ in a hydrogen atmosphere. The maximum density and temperature is observed at the center of the plasma column. The plasma composition was determined with a optical emission spectroscopy. The results obtained are discussed.

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Poster Session MCF 2 - T

2 P 111 - The construction and experiment of divertor target biasing system (DTB) on J-TEXT tokamak

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ABSTRACT TEXT

Recently, a quasi-toroidally distributed divertor target biasing (DTB) system has been installed on the high-field side of the J-TEXT tokamak, aiming to utilize biased targets to modulate the $E \times B$ flows in the scrape-off layer (SOL). During the high field side mid-plane single-null (MSN) divertor configuration [1], the $E \times B$ flows are believed to be able to correct the asymmetric distribution of divertor parameters, and increase the particle and heat flux characteristic lengths. The DTB system consists of the upper target array and the lower target array, which are misaligned in the magnetic flux surface coordination. The upper target array entirely located within the SOL, and the lower target array covering the lower strike point and extending partially into the private flux region (PFR).

In experiments of unipolar DTB, the asymmetric particle flux near the strike points was modulated using unipolar DTB. When a biased voltage of +100 V was applied between the upper target array and the vacuum vessel wall, the SOL potential was effectively raised and a radially inward electric field E_r near the last closed flux surface (LCFS) generated. This induced an $E_r \times B$ poloidal flow directed toward the lower divertor, which subsequently increased the electron density and pressure in the vicinity of the lower divertor. Conversely, negative bias produced the opposite effect. When the DTB system operated in the differential bias mode, i.e., a +100 V bias was applied between the upper and lower target arrays, the poloidal and radial electric fields (E_θ and E_r) were simultaneously driven due to the misalignment of the two target array in magnetic surface coordinates. They resulted in an outward radial $E_\theta \times B$ flow and a poloidal $E_r \times B$ flow directed toward the lower divertor, broadening the SOL particle and heat flux distributions while modulating the divertor asymmetric distribution.

The experiment results preliminarily verify the DTB system efficiency for mitigating extreme heat flux and asymmetric distribution issues near the divertor target, which provides a possible solution for the future fusion reactors operating at high power and long pulses. More experimental data are being accumulated to support further development on J-TEXT.

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Poster Session MCF 2 - T

2 P 112 - 3D nonlinear MHD modeling of detachment, burn-through and the X-point radiator regime with kinetic neutrals and impurities

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ABSTRACT TEXT

In reactor-scale tokamaks like ITER, both transient and stationary heat and particle fluxes pose significant threats to the lifetime of plasma-facing components and the safe operation of the machine. Stationary fluxes can be mitigated by “detaching” the divertor plasma by seeding neutral or impurity atoms in the divertor region, which effectively act as a neutral cushion. The plasma can quickly re-attach to the divertor targets by transient heat fluxes originating from magnetohydrodynamic (MHD) edge instabilities, such as type-I or even small Edge Localized Modes (ELMs)—a phenomenon known as burn-through. Therefore, predicting such transients under realistic scrape-off layer (SOL) conditions is crucial. The JOREK nonlinear hybrid fluid-kinetic code [1] is routinely used to predict large and small ELM regimes, among other phenomena. The base fluid model has been coupled with kinetic neutral and impurity extensions [2, 3], allowing for the simultaneous simulation of transient MHD and SOL processes. In this contribution, the first 3D simulations of small ELM burn-through and the X-point Radiator Regime (XPR) in the ASDEX Upgrade tokamak are presented. Initial results are analyzed from simulations where an EDA H-mode plasma is detached by puffing deuterium and nitrogen, with the full time evolution modeled in 2D. Starting from a fully detached state, the simulation is switched to 3D and the burn-through caused by arising small ELM activity is assessed. Furthermore, initial 3D simulations of the XPR regime interacting with MHD modes are also presented. Ongoing work aims at direct experiment comparisons in ASDEX Upgrade and JET, leading to predictive simulations for ITER.

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Poster Session MCF 2 - T

2 P 113 - Optimizing fuelling pellet injection geometry for COMPASS Upgrade using HPI2

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ABSTRACT TEXT

COMPASS Upgrade [1] is a high-magnetic field (5 T) tokamak, currently being built at the Institute of Plasma Physics in Prague. The HUN-REN Centre for Energy Research plans to develop a pellet injector for COMPASS-U. This work aims to optimize the pellet injector parameters — pellet velocity, size, injection direction, and investigates the pellet-plasma interaction, using various plasma scenarios of the Compass Upgrade tokamak with the HPI2 code [2]. HPI2 is a widely used 2D+ pellet injection simulation code that can handle 3D geometries and related secondary phenomena, like inhomogeneous pellet ablation.

The dependence of material deposition and penetration depth on pellet size and velocity were examined, and results show that for the desired material deposition, pellets with a diameter of 1.5 mm should be injected into the plasma. Higher injection velocity is advantageous, but based on technical considerations, the simulations were run using an injection velocity of 500 m/s.

In most cases, pellet injection into the high-performance H-mode scenario (#5400) was considered, since it has the highest temperature, density and magnetic field, resulting in the shallowest penetration. Analysing other H and L-mode scenarios, much larger penetration depths and larger deposition ratios were observed, so finding the best injection geometry in the high-performance H-mode yields adequate geometries for other lower-performance scenarios.

The properties of different injection directions were also explored, based on which the optimal injection geometry of the pellet injector was defined. While LFS injection is the easiest to realize technically, it results in the least efficient fuelling, as expected, as drift phenomena quickly accelerates the pellet cloud out from the plasma. The internal, HFS injection is the most efficient, where the drift direction points inward the plasma; due to accessibility constraints, pellets cannot be delivered here. A good compromise is the vertical (VHFS) injection, the optimal location and direction of which was delimited with further simulation series. In vertical LFS injection in high-performance H-mode, strong drifts eject most material from the plasma.

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Poster Session MCF 2 - T

2 P 114 - Characterization of gas flow in the JET sub-divertor

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ABSTRACT TEXT

EIRENE simulations for the Joint European Torus (JET) vacuum system predict that the gas flow from the main chamber to the cryogenic pumps in the sub-divertor remains inversely proportional to the square root of the mass of the hydrogenic molecules H₂, D₂ and T₂ even in the transition-regime and the viscous flow regime. Quantifying the gas flow of these hydrogenic gases in vacuum conditions (no plasma) is a critical model calibration step in computational plasma edge physics, for providing accurate pumping speed in model configurations, and for plasma density control in existing and future nuclear fusion devices. The findings confirm higher sub-divertor pressures for heavier hydrogenic gas species, which in turn imply higher throughput and thus improved density control in future magnetically confined fusion devices. The neutral gas transport code EIRENE is used to study the gas flow and its dependence on the molecular mass of the hydrogenic isotopes, as well as the effects of the sub-divertor structures and the cryogenic pump located in the sub-divertor of the fusion device. The code solves stationary linear and non-linear kinetic transport equations to simulate the transport of gas self-consistently in vacuum systems and plasma domains. In low pressure conditions in JET, i.e., for sub-divertor pressures below 0.2 Pa, linear transport equations assuming free-molecular flow of the molecules are solved with EIRENE. For sub-divertor pressures higher than 0.2 Pa, the non-linear BGK approximation is applied to account for inter-molecular interaction observed in viscous flow conditions. The time evolution of the main chamber and sub-divertor gas pressure is calibrated against measurements in gas-into-empty-vessel experiments. The gas flow in both: detailed and simplified geometries of the JET sub-divertor allows the determination of vacuum conductances in the JET vacuum vessel and the effective pumping speeds of the divertor and neutral-beam cryogenic pumps, and the vessel turbomolecular pumps, in such various model configurations. Multiple gas injection locations are implemented, and multiple hydrogenic gas species are studied. The impact of including the entire main chamber, and the neutral beam ducts and pumping system in the computational domain are explored.

Poster Session MCF 2 - T

2 P 116 - Theory and simulation of phase space transport in burning plasmas

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ABSTRACT TEXT

Burning plasmas in fusion reactors are complex systems where energetic particles (EP) play a fundamental role in cross-scale interactions [1]. This study reviews phase space zonal structures (PSZS) [2–5] and their significance in transport analyses. Using synthetic diagnostics from the HMGC and ORB5 codes [6,7], we illustrate the role of PSZS in capturing transport dynamics in burning plasmas Gyrokinetic simulations accurately. While transport studies assume Maxwellian equilibria, for EPs and burning plasmas in general, a more comprehensive description is needed to capture self-organization processes. By deriving governing equations for PSZS using multi-scale perturbation theory, we can model modifications of the equilibrium caused by resonant interactions. This approach allows us to recover standard transport equations in the proper limit.

A new phase space transport workflow called ATEP [8] is proposed to accurately describe PSZS dynamics. This workflow enables us to restart Global Gyrokinetic codes from PSZS distributions, extending simulations over long time scales without assuming a model distribution function. By comparing global gyrokinetic simulation results, e.g. from ORB5, and ATEP we effectively construct a hierarchical approach for PSZS evolution. Additionally, we introduce the Dyson-Schrödinger model (DSM) [9] in the hierarchy of transport models, filling the gap between ORB5 and ATEP. A numerical workflow [10] based on the PEANUTS suite of codes is presented to solve DSM.

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Poster Session MCF 2 - T

2 P 117 - The effect of strong plasma rotation on nonlinear ideal MHD instabilities and associated sustainment of sawtooth-avoiding magnetic configurations

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ABSTRACT TEXT

A generalised set of equations are derived for the linear and non-linear evolution and saturation of non-resonant ideal MHD instabilities [1]. Investigated are $n = m = 1$ and $n = m > 1$ modes [2] with the effect of toroidal plasma rotation and associated centrifugal corrections to the magnetic equilibrium. By explicitly evaluating the nonlinear effect of these modes on the magnetic flux, it is possible to analytically calculate the effect of the 3D magnetic structures on the q-profile, which itself corrects the mode amplitude. The modified q-profile then has a cascade effect in modes with smaller wavenumber. Over the initial phase of the resistively diffusing plasma scenario, the associated 3D magnetic perturbations, of quantified amplitude, are assumed to cause strong cross-field transport, thus flattening pressure gradients in the core. Saturated modes continue to exist despite vanishing pressure-gradient drive, and despite the stabilising effect of plasma rotation, due to the internal inductance effect on the Shafranov shift. Under these conditions the plasma will cease to resistively diffuse, so that the hybrid regime can in principle be sustained, providing a sawtooth-avoiding ideal-MHD alternative mechanism to that of the flux pump [3]. The picture remains robust to potential kinetic corrections of core instabilities in the weakly collisional regimes of future tokamak reactors. The nonlinear equations presented here are also shown to agree with the nonlinear saturated amplitude of current driven external kink modes [4], thus proving to encompass the salient physical properties of the most important long wavelength instabilities in near-axisymmetric machines.

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Poster Session MCF 2 - T

2 P 118 - Magnetic equilibria during enhanced plasma performance phases in Wendelstein 7-X stellarator

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ABSTRACT TEXT

In experiments at the Wendelstein 7-X stellarator, additional plasma fueling with frozen hydrogen pellets has been shown to lead to a phase of significantly improved plasma parameters. This phase lasts only for a few confinement times and is characterized by enhanced plasma pressure, ion temperature, and global energy confinement [1]. The enhanced performance might be related to a strong density gradient that stabilizes ion temperature gradient modes [2]. In some of the experimental programs, magnetohydrodynamic (MHD) events are observed within the high performance phase. These events are potentially caused by changes in the iota profile and might accelerate the confinement degradation. In this contribution we investigate the MHD equilibria for pellet-fueled experiments in order to gain a more profound understanding of the plasma properties. For this purpose, we study the equilibrium characteristics before, during, and after the high energy phase and with respect to potentially occurring MHD events. Additionally, we compare the results to alternative enhanced performance scenarios, which combine electron cyclotron resonance heating and neutral beam injection. In order to determine the equilibrium as accurately as possible, we perform reconstructions with the STELLOPT code [3], taking into account multiple measurements, including magnetic diagnostic coil signals, the temperature and density of ions and electrons, as well as the soft x-ray emissivity of the plasma.

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Poster Session MCF 2 - T

2 P 119 - Observation of Helically-Trapped Energetic Particle Transport Induced by Energetic-Ion-Driven Resistive Interchange Mode using Imaging Neutral Particle Analyzer in LHD

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ABSTRACT TEXT

Energetic-ion-driven resistive interchange mode (EIC) is one of magnetohydrodynamic (MHD) instabilities often observed in the Large Helical Device (LHD). EIC has been excited by helically-trapped energetic particles (EPs) injected by positive-source neutral beam (P-NB) in high ion-temperature discharges in Large Helical Device (LHD) [1], significantly enhancing radial transport and causing the loss of EPs [2,3]. Understanding these instabilities is critical for improving EP confinement. In this work, we investigate the transport of helically trapped EPs induced by EIC in LHD using a newly developed Imaging Neutral Particle Analyzer (INPA) [4]. The INPA employs a magnetic spectrometer utilizing a ZnS:Ag scintillator to detect charge-exchanged energetic neutral particles escaping from the plasma. The system uses a 90 nm thick carbon foil to ionize these energetic neutrals, which are subsequently deflected by the local magnetic field toward the scintillator for detection. This setup provides spatially and energy-resolved measurements of energetic neutral flux with time resolution, offering detailed insights into EPs behavior during MHD instabilities. In this experiment, negative-source-based NBs (N-NBs) and P-NBs were injected with energies of 160–180 keV and ~ 40 keV, respectively. The total INPA intensity decreases following EIC bursts, indicating substantial energetic-particle transport. The detailed analysis of the energy and radial transport will be presented.

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Poster Session MCF 2 - T

2 P 120 - Magnetic topology of phase-locking driven Plasma-Wall Interaction in RFX-mod RFP discharges

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ABSTRACT TEXT

This work focuses on the analysis of tearing modes responsible for Plasma-Wall Interaction (PWI) observed during a magnetic reconnection event in a high current plasma discharge of the RFX-mod ($R = 2$ m, $a = 0.5$ m) device. During a typical Reversed Field Pinch (RFP) discharge, phase-locking of resonant tearing modes with poloidal mode number $m = 0$ or $m = 1$ and toroidal mode number $n \geq 7$ may lead to significant PWI [1,2]. The interaction is captured via a fast camera monitoring the graphite-covered inner wall [3], which reveals two distinct stripes of neutral carbon radiation. The analysis aims at characterizing the PWI pattern in relation to the underlying magnetic topology.

Initial results indicate that $m = 1$ tearing mode phase-locking is the primary mechanism that drives the observed PWI. The role of the higher- n modes is linked to secondary hidden structures [4], which are investigated through a 3D map of Connection Length [5] calculated with the Hamiltonian guiding center code ORBIT [6]. This analysis confirms the importance of $m = 1$ phase locking as well as uncovering a novel contribution of the $m = 0$, $n = 7$ mode to the PWI [7]. The upgrade of magnetic pickup arrays in the next RFX-mod2 device [8] will allow for improved feedback control on tearing mode phase-locking, highlighting the eventual $m = 0$ mode contribution to PWI. Meanwhile, a new system of 7 fast cameras will be installed to increase the observations of such PWI events.

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Poster Session MCF 2 - T

2 P 121 - The recent development of the ASCOT code

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ABSTRACT TEXT

Thermonuclear fusion is moving from academic research to solving the remaining technological challenges towards energy production. This process includes multiple numerical simulations to be carried out for design studies. These activities are carried out not only by public sector but also by various private industries aiming to design working fusion power plant. The modeling tools need to undergo similar “industrialization” as the private fusion sector have done. Properly documented and validated tools are critical components of any design activity, even more so for the nuclear field given the licensing and safety procedures. However, the current standard is rather a typical academic code with documentation in the source code than a commercial software.

The ASCOT code is widely used for modeling fast-ion physics for magnetically confined fusion plasmas. In this contribution, we overview the recent development of the code towards a high quality software engineering practices, and new physics modeling capabilities. The former include tutorials (using Jupyter notebooks) and extensive user support. The latter includes the new official releases including the models for interaction of fast-ions with the Ion Cyclotron heating using the RFOF operator, a coupling to IMAS data structures using python interface, and the ability to effectively employ GPUs for the computations. These features allow even wider use cases for the user community of the ASCOT code.

This contribution provides examples of software engineering features, together with simulation results obtained using the new numerical models. A performance analysis is presented to show the parallel optimization of the GPU and CPU runs for a selected hardware.

Poster Session MCF 2 - T

2 P 122 - Hysteresis of amplitude-frequency relationship of MHD instabilities and its modeling in toroidal magnetically confined plasmas

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ABSTRACT TEXT

The relationship between the amplitude and frequency of magnetic fluctuations caused by MHD instabilities in toroidal magnetically confined plasmas has been investigated. Modeling this relationship would enable the prediction of frequency and amplitude in future devices, contributing to the development of operational scenarios and control strategies based on these predictions.

Previous studies in tokamaks and helical devices have shown that the trajectory of amplitude and frequency remains unique during both frequency increase and decrease. This relationship is well explained by the torque balance model of decelerating electromagnetic force and accelerating viscous force proposed by Fitzpatrick [R. Fitzpatrick, NF 1993]. The main decelerating force depends on the device and the source of the instability. In neoclassical tearing mode (NTM) discharges of the JT-60U tokamak, it is the electromagnetic force from the interaction between the perturbed magnetic field driven by eddy currents due to the instability and the perturbed current (F_{rw}) [A. Isayama+, PFR 2010]. In JT-60U discharges where NTMs occur following the onset of the resistive wall mode, the different amplitude and frequency trajectories during frequency increase and decrease have been newly observed. Specifically, while the frequency increases gradually, during the decrease, a rapid decrease in frequency occurs at a specific frequency. The behavior during frequency decrease is explained by the F_{rw} model. The frequency at which the jump occurs is approximately consistent with observations, and the lack of a jump when the frequency decreases below this threshold is also reproduced. The behavior during frequency increase cannot be explained by this model because it predicts frequency jumps in both the increasing and decreasing phases in the low-frequency band. The F_{rw} model describes the case where the difference frequency between the perturbed magnetic field and the instability is small. By introducing a model for cases where the difference frequency with a perturbed magnetic field driven by another factor is large, the behavior during frequency decrease could be explained. A candidate for the driving source of the perturbed magnetic field is external coils.

Poster Session MCF 2 - T

2 P 123 - B-field dependency of high-beta plasmas at Wendelstein 7-X stellarator

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ABSTRACT TEXT

In previous experimental campaigns of the Wendelstein 7-X stellarator, different routes to achieve high plasma beta ($\beta \sim \langle p \rangle / B^2$, the ratio between plasma pressure $\langle p \rangle$ and magnetic confinement field B) have been investigated. In the recent 2024 campaign, the low B-field plasma start-up with a reduced magnetic field of $B = 1.8$ T (with respect to the standard $B = 2.5$ T) has been successfully demonstrated and is foreseen for further exploration in the upcoming campaign [1]. One advantage of the operation in low B-field is the access to higher beta with the same or lower heating power ($\beta \sim 1/B^2$). There are predictions [2], that kinetic ballooning modes (KBMs) become relevant for transport in W7-X high-beta plasmas, with one important parameter being the magnetic configuration. In experimental data from the soft X-ray tomography system [3], mode activity in the frequency range of 30 kHz becomes visible, which is analyzed by advanced tomographic inversion methods [4] to estimate radial location, poloidal mode number and the ballooning character.

We discuss related aspects of the different heating scenarios and compare the achievable global plasma parameters for the two magnetic field strengths. The latter analysis could also shed some light on whether there are experimental indications that the observed mode activity is leading to performance limitations in certain magnetic configurations of Wendelstein 7-X stellarator.

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Poster Session MCF 2 - T

2 P 124 - A multi-machine study of the interaction between locked modes and plasma rotation

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ABSTRACT TEXT

In magnetic fusion devices, locked modes— a class of resistive magneto-hydrodynamic (MHD) instabilities— can result from the slowing down of spontaneous neoclassical tearing modes. They can also be triggered when exploring low-density regimes or induced by externally applied magnetic field perturbations. In all these cases, locked modes can lead to particle and energy losses, causing confinement degradation and often resulting in a disruption [1]. Such events need to be avoided in disruption-adverse devices, such as ITER and DEMO.

Furthermore, locked mode dynamics is related to plasma rotation braking [2], which starts at the mode resonant surface and expands to a wider radial region due to viscous and neoclassical toroidal viscosity torques. This is a matter of concern for tokamak operations, as plasma rotation is known to play a beneficial role in reducing or even suppressing both macroscopic MHD [3,4] and turbulence instabilities [5].

In this context, the interplay between intrinsic plasma rotation and locked mode dynamics has been studied in this work, through an analysis of a series of experiments performed at JET, MAST-U and AUG, in which locked modes were induced by applying external 3-D fields in Ohmic heated plasmas characterized by low rotation, which is an ITER-relevant regime.

The study of rotation data from Charge Exchange Recombination Spectroscopy, in combination with magnetic signals to reconstruct locked mode activity, allowed us to identify common features. In particular, we have investigated the magnetic field penetration in plasmas with peaked and hollow rotation profiles, depending on the density regime.

ACKNOWLEDGMENT

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Poster Session MCF 2 - T

2 P 125 - Progress on [N]TM modelling and control in the ITER Plasma Control System design

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ABSTRACT TEXT

[Neo-classical] Tearing Modes ([N]TMs) represent one of the most significant MHD instabilities in tokamaks. They primarily degrade plasma performance and can act as precursors to plasma disruptions, which may have potentially damaging impact, especially on large tokamaks with high stored energies. Consequently, the detection and control of [N]TMs are critical functions of the ITER Plasma Control System (PCS), which manages all aspects of the ITER plant to achieve the desired pulse scenario. The primary objective is to develop a **real-time robust [N] TM real-time control for the PCS**, which can identify this instability as early as possible, assess its characteristics (e.g., size, growth rate, and frequency), and decide on an appropriate strategy to either suppress or stabilize the modes.

Recently, the **extended co-MRE** (comprehensive Modified Rutherford Equation) solver [1,2], which incorporates coupled width and frequency equations, has shown promising results both theoretically and experimentally on the TCV tokamak. These results were achieved using electron cyclotron heating (ECH) to stabilize and suppress [N]TMs. An adapted version of this solver thus emerges as a strong candidate for an **ITER [N] TM model** to support the commissioning and operation of [N]TM control functions within the PCS.

This work presents a demonstration of an **ITER use case for an [N]TM control scenario** executed on the ITER plasma control simulation platform, PCSSP. The example involves a closed-loop system comprising the [N]TM model, a PCS event handling and control system, which is robust against disturbances and failures on actuators or diagnostics, and the ECH plant model. With the enhanced ECH capabilities in the ITER new baseline—doubling from 20 MW to 40 MW in the early operation phase and increasing further up to as much as 67 MW for the DT campaigns—the feasibility of the control task is significantly improved. However, within this closed-loop system, certain components, such as the [N]TM controller, remain in their early development stages. While simplified versions of these components can already offer an initial insight into their expected behavior, further improvements and completions of these blocks are part of ongoing and future work.

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Poster Session MCF 2 - T

2 P 126 - First evaluation of gamma-ray emission from alpha-boron reactions in the ITER tokamak with a tungsten wall

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ABSTRACT TEXT

Obtaining experimental information on the properties of alpha particles, such as their energies and spatial profile, is quite challenging. One of the methods currently planned for the ITER tokamak is gamma-ray spectroscopy.

Until 2023, alpha particle measurements via gamma-ray spectroscopy relied on nuclear reactions between alpha particles and ⁹Be impurities. However, since ITER will feature a fully tungsten first wall conditioned with natural boron instead of a ⁹Be wall, new approaches are needed. Boron will be injected to condition the wall and support plasma operations, but no experiment has yet studied boron-based reactions to derive alpha particles information in tokamaks.

This work makes a first contribution to this problem by computing the alpha-boron gamma-ray emission expected at ITER involving an estimate of the background. The calculation focuses on the RGRS (Radial Gamma Ray Spectrometer) diagnostic, which consists of three gamma-ray spectrometers observing the plasma through three co-planar, collimated and radial lines of sight. The numerical evaluations performed in this work are based on simulations of ITER plasma scenarios stored in the IMAS database. Starting from the density, emission and temperature profiles of the particles in a DT plasma discharge, quantities of interest were derived to predict the signal expected from the ¹⁰B(α , p)¹³C reaction. From these data, it was possible to implement scenarios with different fuel composition (D3He) and different thermal equilibrium (supra-thermal scenarios) to study the alpha particle measurement capability of RGRS under a range of conditions.

In order to assess the RGRS performance in a DT/D3He plasma scenario, specific Monte Carlo simulations were conducted. These took into account the geometrical and structural aspects of the tokamak and the diagnostics under consideration, together with the expected amount of neutron and photon fluxes.

Two methodologies for estimating the background were used: one relying on JET DTE2 experience and one based on MCNP simulation of the ITER environment. Depending on the adopted methodology, different conclusions can be drawn about the alpha particle measurement capability of RGRS.

DISCLAIMER

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

Poster Session MCF 2 - T

2 P 127 - Simulations of trapped electron clouds in gyrotron electron guns and comparison with experimental data

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ABSTRACT TEXT

Gyrotrons are critical devices for the development of magnetic confinement fusion, but their design and reliable operation face significant challenges. A key issue is the trapping of electrons in the electron gun region, leading to the formation of dense electron clouds that can cause undesired currents and operational failures [1]. In gyrotrons, these electron clouds consist of high-density non-neutral plasmas subjected to strong, externally imposed flows and trapped in coaxial cylindrical cavities. This unique environment introduces complexities that are not yet fully understood, such as the effects of space charge on cloud dynamics, and the impact of electron-neutral collisions. Furthermore, these electron clouds are prone to diocotron instabilities, driven by the collective azimuthal drift of the plasma. Gaining insight into these phenomena is essential for enhancing gyrotron performance and advancing the broader study of non-neutral plasmas. We present a comparative analysis between simulations performed with the 2D particle-in-cell code FENNECS [2] and experimental data from the TRapped Electron eXperiment (T-REX) [3], an experimental setup designed to reproduce the characteristic conditions of gyrotron electron guns leading to electron trapping. A comprehensive set of simulations exploring the influence of various parameters on the electron cloud formation and evolution is directly compared with experimental measurements from T-REX. The study demonstrates agreement between simulations and experiments on many aspects. However, discrepancies arise due to the development of the diocotron instability within the electron cloud, a phenomenon not accounted for by FENNECS due to its 2D axisymmetric geometry. These discrepancies have motivated the development of a 3D simulation tool, FENNECS Lite, based on a fluid model that retains the advantageous features of FENNECS while extending its capabilities. Fluid simulations with this new code have revealed the impact of the diocotron instability on the dynamics of the electron cloud, further supported by additional experimental evidence from T-REX.

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Poster Session MCF 2 - T

2 P 128 - Improved calibration of the high-resolution tunable ECE system for power deposition and transport studies in Wendelstein 7-X

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ABSTRACT TEXT

Electron Cyclotron Resonance Heating (ECRH) modulation and switching experiments offer a unique method of exploring energy and physics conditions and their impact on particle transport in magnetically confined plasmas^[1]. When the plasma is heated using ECRH at the second harmonic of electrons' gyration in extraordinary mode (X2), the microwave beams are absorbed in a thin layer where they are in resonance with the gyration frequency of the electrons. Electron Cyclotron Emission (ECE) resulting from such optically thick plasmas behaves like blackbody radiation from a localized layer in the plasma, allowing us to study any local effects.^{[2], [3]}

ECRH beam power modulation initiates perturbations in electron distribution that are observed as an immediate response in the ECE signals^[4]. The goal of this work is to explore the zone of power deposition, and the resulting transport using ECE at Wendelstein 7-X. The study is done by performing a conditional averaging of the ECE signals over the ECRH modulation periods to derive the localized temporal evolution of radiation. The change in slope (dT/dt) along the effective radius gives us the location of power deposition.

We have upgraded a high frequency-resolution radiometer backend, called the ZOOM^[5] system, to gain high spatial resolution in this zone of interest. The absolute calibration required for quantitative analysis is achieved by Hot-Cold switching^[6]. For this, a continuously rotating mirror alternatively directs the emissions from a cold source (liquid nitrogen) and a room temperature source. This produces a calibration signal consisting of alternating voltages that correspond to each temperature source. We analyze the data using conditional averaging to account for transmission line losses and identify the periods of hot and cold temperatures. To improve the accuracy of this calibration with respect to the high plasma electron temperature, a third ceramic hot source is included.

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Poster Session MCF 2 - T

2 P 129 - Tomographic Reconstructions in RFX-mod via neural networks

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ABSTRACT TEXT

This study investigates the performance of different neural network architectures in reconstructing the emissivity of soft x-ray radiation from the plasma of the RFX-Mod [1] reversed field pinch experiment. These models have been developed to establish a dependable mechanism for tomographic inversion, achieving the same accuracy at a fraction of the computational cost of existing techniques.

A carefully curated database of approximately 300 discharges, comprising nearly 70,000 pairs of line-integrated brightness and poloidal cross sections of the emissivity maps, serves as the foundation for this analysis. The brightness are obtained from the soft X-ray diagnostic of RFX-mod, while tomographic emissivity maps are computed using the Cormack algorithm [2].

We compare two neural network architectures: a Multi-Layer Perceptron (MLP) and a transposed Convolutional Neural Network (tCNN). The primary difference between these approaches lies in their target outputs. The tCNN directly reconstructs the emissivity map from brightness data, while the MLP predicts the Fourier series coefficients of the emissivity decomposition in Bessel functions, with the final map computed analytically.

Both methods have distinct advantages: the MLP is simpler to train and deploy but requires an additional computation step, whereas the tCNN, though slightly more complex to train, offers greater flexibility. Both models achieve highly accurate emissivity reconstructions. The MLP yields a mean absolute error of approximately 0.46 W/m³, while the tCNN produces a mean absolute error of 1.30 W/m³. Given that the mean emissivity value in our dataset is ~90 W/m³, these results are highly promising. However, both models have potential for further improvement. Additional findings will be discussed in this work and explored in future research.

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2 P 130 - AI Tools for Plasma Diagnostics by X-ray Imaging and Spectroscopy in the PANDORA Project Frame

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ABSTRACT TEXT

Magnetized plasmas in compact trap may become experimental environments for fundamental investigation. PANDORA is a multidisciplinary project aimed at investigating β decays in plasmas. It is based on a new facility capable of creating stellar-like plasma properties, representing a breakthrough for fundamental studies on weak interactions in astrophysical contexts. Additionally, it will enable a wide range of applications, including materials science, accelerator physics, ion source technology, and more.

In this context, an innovative algorithm for X-ray imaging in Single-Photon Counting mode was developed, enabling powerful space-resolved plasma spectroscopy in the soft X-ray domain and magneto plasma properties investigations in terms of local thermodynamic parameters, confinement dynamics and structure. The diagnostics setup consists in a X-ray pin-hole camera. In this work I'll present the results of further development and optimization of the algorithm by implementing an AI-based machine learning model encoded in MATLAB.

Starting with different datasets acquired under varying plasma conditions in two magnetic plasma traps — the ECR ion source at ATOMKI Laboratories (Debrecen) and the Flexible Plasma Trap at INFN-LNS — each event (i.e., photon impinging on the CCD) was characterized in terms of its geometrical and intensity-related parameters. Through the AI tool based on the K-means clustering algorithm, clusters of events exhibiting similar features were identified, highlighting parameters that allow discrimination between real and spurious events. Then, a labelled dataset for training a neural network, capable of discriminating and minimizing spurious pile-up events, was created. This approach aims to retrieve in a much shorter time plasma emission spectra with higher energy and spatial resolutions, maximize the signal-to-noise ratio, and provide unprecedented accuracy in characterizing soft X-ray fluorescence and bremsstrahlung emissions from such plasmas.

The AI tools, including the ongoing stage of neural-network implementation, and the first results, obtained through systematic measurements on the new advanced X-ray diagnostic testbench, named PYN-HO will be presented in this contribution

Poster Session MCF 2 - T

2 P 131 - Calibration of Thomson scattering density measurements at ASDEX Upgrade

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ABSTRACT TEXT

Accurately measuring plasma parameters is a crucial task in modern fusion research reactors. The electron density is one main parameter to be determined. At ASDEX Upgrade the Thomson scattering diagnostics is one of the systems used for this purpose [1]. It was observed that after the initial calibration, errors due to misalignment emerge in the measurements. Until now, these errors have been corrected by determining and applying correction factors to each individual measurement channel by hand. In this work, two new and reproducible ways of determining correction factors for the Thomson scattering diagnostic have been implemented and tested.

The first approach uses a neural network to determine the specific error pattern due to misalignment in the diagnostic for a measured electron density profile. This method has been developed and implemented recently at W7-X and was adapted to AUG during this work [2]. Once the error pattern is found, the correction factors are calculated to correct for the errors due to the misalignment. Since it has been found that these errors do not change quickly but stay constant over extended periods of time, as a second approach a reference discharge method has been developed. The correction factors are determined during a standard H-mode discharges by applying a smooth fit function to a density profile during the L-mode phase at the beginning of the discharge and are used for subsequent shots until the next standard discharge, which is run approximately once per week.

In order to compare the different calibration methods, electron density calculations using integrated data analysis (IDA) have been used [3]. IDA combines different diagnostics to determine the density profile of the plasma. In addition, the residuals for the individual diagnostics are calculated. These residuals have been examined to quantify if the agreement between the Thomson scattering and the interferometry (DCN) density measurement is improved with the new calibration methods. It was found that both methods give better results than the previously used one, with the reference discharge method yielding the best agreement with DCN measurements.

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Poster Session MCF 2 - T

2 P 132 - Machine learning surrogate model for peeling-ballooning pedestal MHD stability

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ABSTRACT TEXT

High-confinement mode tokamak scenarios rely on the formation of an edge transport barrier and an associated pedestal [1]. Fast and accurate pedestal predictions are needed for agile reactor and scenario design as well as for real-time prediction activities. The standard paradigm for pedestal performance predictions combines magnetohydrodynamic (MHD) stability simulations with assumptions on pedestal transport and is encompassed by workflows, such as EPED, Europed, IPED and IMEP [2–5]. While previous efforts have investigated developing surrogate models for EPED-like models [6,7], focusing on surrogating only the key computationally demanding part – the MHD stability, could enhance the performance without embedding the transport assumptions. Such a surrogate model could accelerate any integrated modelling workflows exhibiting repeated pedestal MHD stability evaluations.

In this work, a fast machine learning (ML) surrogate is developed for the pedestal ideal MHD stability, MISHKA, simulations [8]. A framework called *Enchanted-surrogates* [9] has been developed and used to generate a database of HELENA equilibria and MISHKA stability simulations for a subset of JET plasmas based on the EUROfusion pedestal database [1,8,10]. Through supervised ML methods, a fast regression model is developed based on the generated database. The MISHKA surrogate model has been integrated into Europed for demonstrations within a pedestal prediction workflow. Demonstration application of the surrogate model for physics analysis will also be shown in detail for a number of JET pulses as well as compared statistically to the experimental JET pedestal database and the Europed database. [11] Potentially extending the capability of the surrogate model with resistive MHD features using CASTOR will be explored [12].

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* See the author list of 'Overview of T and D-T results in JET with ITER-like wall' by CF Maggi et al. to be published in Nuclear Fusion Special Issue: Overview and Summary Papers from the 29th Fusion Energy Conference (London, UK, 16–21 October 2023).

Poster Session MCF 2 - T

2 P 133 - Reproducing edge localized modes mitigation by RMPs using neural networks on JET

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ABSTRACT TEXT

Edge Localized Modes (ELMs) are instabilities that occur at the edge of confined plasma in tokamaks, leading to periodic collapses of the H-mode pedestal. Resonant Magnetic Perturbation (RMP) systems have been demonstrated to effectively mitigate or suppress ELMs in various tokamaks; however, their effectiveness is limited to specific operational windows [1–4]. With the rapid advancement of artificial intelligence, neural networks are transforming numerous scientific disciplines. Inspired by large language models, which predict the likelihood of subsequent words based on contextual relationships, neural networks can similarly be employed to predict ELM bursts by learning the correlations between operational parameters and ELM events. Although predicting the exact timing of individual ELMs is challenging, their overall pattern and frequency remain predictable. In this study, hundreds of H-mode discharges from the JET tokamak were analyzed, with half employing RMPs and the other half operating without them. A total of 18 input signals, including plasma current, heating power, diamagnetic energy, edge safety factor, and RMP current, were utilized as input features. A three-layer Long Short-Term Memory (LSTM) network was trained to predict the probability of ELM bursts based on these parameters. The results demonstrate that the effect of RMPs on ELM mitigation can be reproduced by the LSTM network, providing a predictive framework for ELM control in future experiments.

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Poster Session MCF 2 - T

2 P 134 - Electron-temperature-gradient mode evolution in the presence of a corrugated electron temperature gradient in the tokamak pedestal

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ABSTRACT TEXT

Microinstabilities can produce radial corrugations on the density and temperature gradients in tokamaks [1–5]. Studying the evolution of a microinstability in the presence of such a corrugation helps understand how such profile modulations affect turbulent transport. We focus on the pedestal, studying electron-temperature-gradient (ETG) mode destabilisation and saturation in the presence of significant radial corrugations on the electron temperature gradient that result from microtearing turbulence [4,5]. A linear dispersion relation is derived for a shearless slab case, which indicates that in the presence of a sinusoidal background corrugation, each ETG mode splits into three distinct eigenvalues, with one being the original, one being more unstable and one being less unstable. However, despite the presence of more unstable linear modes, nonlinear gyrokinetic simulations of ETG with corrugated background electron temperature show a reduction of fluxes. This could be crucial to understand the reduced turbulent transport in the pedestal that enables a high-performance H-mode. Preliminary analysis indicates that an unstable mode is active at those radial positions corresponding to higher gradients of the corrugation, whereas a stable mode is active at the radial locations corresponding to lower gradient. We investigate how such a radial inhomogeneity in stability properties affect the saturation mechanism.

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Poster Session MCF 2 - T

2 P 135 - Investigating Fueling Location and Transient Fueling Effects on Scrape-Off Layer Transport in MAST-U

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ABSTRACT TEXT

Understanding the role of fueling location and transient fueling in shaping the scrape-off layer (SOL) is crucial for optimizing plasma confinement and power exhaust in tokamak devices. Previous studies have highlighted the impact of fueling and transport on pedestal structure and pedestal density formation [1]. In this study, we analyze data from the first MAST-U experimental campaign (MU01), which investigated the impact of different fueling sources, high-field-side (HFS), low-field-side (LFS), and private flux region (PFR), on SOL profile formation and transport dynamics which feed in pedestal formation in H-mode plasmas. Preliminary results indicate evidence of SOL broadening following transient gas puffs, with fueling location appearing to have a limited effect on shoulder formation. Similar observations have been reported in other tokamak experiments where gas puff modulation has been employed to probe edge transport [2]. Additionally, early observations suggest a potential hysteresis effect, where SOL profiles remain altered beyond the density relaxation timescale, a phenomenon that has also been linked to pedestal transport regulation [3]. To enhance these findings, a detailed analysis is planned, incorporating time-resolved Thomson Scattering (TS) density profiles and Langmuir probe (LP) divertor conditions to quantify transport timescales and identify dominant mechanisms driving profile evolution. Similar investigations on MAST have previously provided insights into H-mode pedestal characteristics and edge transport dynamics [4]. This contribution will present an extended analysis of fueling location effects on SOL structure, transport response, and possible memory effects. These results will inform ongoing efforts to improve fueling strategies in spherical tokamaks and aid in the development of advanced transport models.

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Poster Session MCF 2 - T

2 P 136 - Impact of the divertor conditions on L-H transition in KSTAR

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ABSTRACT TEXT

A contrasting effect on the L-H transition was confirmed when Resonant Magnetic Perturbations are applied resonantly or non-resonantly using a high-precision asymmetric in-vessel control coil (IVCC) in KSTAR with carbon divertor. Specifically, the threshold power according to the transition from L-mode to H-mode observed a rather 'non-flat' dependence of low-n resonant magnetic field, while observing literally no impact of non-resonant magnetic field on H-mode threshold power. A sensitive change in the low-n resonant magnetic field was well observed because KSTAR has a single-digit smaller magnitude of the intrinsic non-resonant magnetic field [1] and toroidal magnetic field ripple [2]. We found no sensitivity of the non-resonant magnetic field at the L-H transition even at the maximum current in the non-resonant magnetic field in KSTAR with carbon divertor.

KSTAR upgraded to tungsten divertor last year. Therefore, we experimented with the effect of tungsten divertor on the L-H transition and confirmed that the L-H transition power threshold is increased in tungsten divertor than in carbon divertor. If this is the effect of tungsten impurities, the L-H transition power is expected to be higher when KSTAR upgrades to the entire tungsten inner wall in the future. We have also performed experiments on the effect of the $n = 2$ resonance field on the L-H transition in tungsten divertor, and will further investigate the effect of the $n = 1$ resonance field and so on.

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Poster Session MCF 2 - T

2 P 137 - Experimental discovery of micro-tearing modes in the pedestal of MAST-U

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ABSTRACT TEXT

Edge turbulence is a primary contributor to anomalous heat and particle transport in fusion plasmas with micro-tearing modes (MTMs) playing a potentially significant role in electron heat transport within the pedestal. As electromagnetic instabilities characterized by high-amplitude magnetic fluctuations, MTMs impose a fundamental limit on the achievable electron temperature gradient, thereby constraining pedestal confinement and overall plasma performance. While MTMs have already been observed in conventional aspect ratio tokamaks such as JET [1] and DIII-D [2], their presence in spherical tokamaks remains an open question.

This study reports the first experimental observation of MTMs in MAST-U pedestals. This instability was observed in plasmas with increased line-integrated electron density and enhanced squareness compared to the similar experiments in the previous experimental campaign. These conditions facilitated the alignment of rational surfaces with the peak of the electron drift frequency profile (ω^*), thereby promoting MTM destabilization. To isolate MTM signatures, rapid vertical displacements were applied to the plasma while minimizing collisionality via maximum neutral beam injection power. Magnetic fluctuations were analyzed using spectrograms of fast Mirnov coil data. Density fluctuations were characterized via the beam emission spectroscopy diagnostic. The experimental findings were compared against gyrokinetic simulations, which predicted MTM growth rates and mode frequencies consistent with observations.

These results provide strong evidence that MTMs can be excited in the pedestal of spherical tokamaks under specific plasma shaping and density conditions, offering new insights into their role in pedestal transport physics.

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Poster Session MCF 2 - T

2 P 139 - Ideal and Non-Ideal Pedestal Stability of Seeded Plasmas, Cross-Device Analysis

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ABSTRACT TEXT

This study examines the impact of neon, nitrogen, or argon impurity seeding on pedestal stability in H-mode plasmas across tokamak devices (JET and TCV), using both ideal and resistive MHD approaches. We assess how impurity seeding influences pedestal behavior and evaluate the predictive accuracy of various modeling techniques. Our analysis employs a recently developed workflow that integrates CHEASE and MARS-F for equilibrium and stability assessment, benchmarked against established ideal pedestal models. Impurities like nitrogen radiate at the edge and increase, which scales with resistivity. Consequently, the validity of the ideal MHD description is questioned for pedestal stability in such plasmas, as noted in [1]. Previous modeling on JET for impurity-free pulses [2] has shown that in experiments with high gas rate, higher resistivity is destabilizing to the modes and associated with more frequent ELMs. Experimental studies on JET [3]–[6] found that nitrogen seeding induced an increase in pedestal pressure. Additionally, nitrogen can modify ELM frequency and amplitude, also contributing to improved pedestal stability [7]. Similar effects were observed on TCV, where nitrogen seeding also led to an increase in pedestal top, however, this effect depends on the main gas fuelling level [8], [9]. We will exploit the newly developed framework in two distinct datasets of seeded discharges, collected respectively on JET and TCV. The capability offered by the new framework to incorporate resistive effects will allow to verify the possible modification of stability boundary in j-a plane caused by impurity seeding. These findings will guide the optimization of operational regimes for improved fusion performance.

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Poster Session MCF 2 - T

2 P 140 - Machine learning methods for modelling local, linear gyrokinetic simulations of MAST-U pedestal turbulence

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ABSTRACT TEXT

Gyrokinetic (GK) stability has a key role in the performance of high confinement mode pedestals in spherical tokamak devices and is an active topic of research [1–3]. While the features of GK are encompassed by high-fidelity models, such as GENE [4], the required computational resources and time consumption prevent the routine applicability of these models in integrated pedestal models, such as EPED or Europed [5, 6]. Instead, these pedestal simulation workflows rely on model reductions, such as assuming ballooning critical pedestal.

The aim of this work is to investigate methods to develop machine learning surrogate models for the GK features of spherical tokamak pedestals. Such models could potentially represent higher fidelity alternatives to the reduced pedestal transport models that are presently used in the pedestal simulation workflows. This contribution will present a proof-of-principle surrogate model for local, linear GK stability simulations, conducted with GENE, in the vicinity of the operational space of a dedicated MAST-U plasma (#49108). A GK simulation sampler is developed that is able to generate 2D Grad-Shafranov equilibria, using the equilibrium code HELENA [7], with a pedestal parameterized through modified hyperbolic tangent (mtanh) and with normalized confined plasma pressure as a boundary condition, similar to EPED [5]. This sampler allows physically self-consistent variations of the pedestal plasma conditions near the chosen reference point, such as MAST-U #49108, while restricting the parameter space through the mtanh-parameterization. Focusing on the local, linear GK, limits the overall computational requirement, making the generation of training data feasible.

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Poster Session MCF 2 - T

2 P 141 - Effect of diamagnetic flow stabilization on pedestal stability in JET and its importance for isotope mass effects

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ABSTRACT TEXT

Changing the isotope mass from deuterium to tritium in JET-ILW leads to an increase in the electron pedestal pressure (p_e^{ped}) due to an increase in the electron pedestal density (n_e^{ped}) [1]. The increase of the pressure with increasing effective mass (A_{eff}) has been explained via resistive MHD and by a change in the diamagnetic stabilization [1]. The results discussed in [1] were however obtained with a simple model for the diamagnetic stabilization. The present work aims to more properly model these effects using the code JOREK [2], which self-consistently treats the diamagnetic flows.

The analysis has started with the JET deuterium shot 96208 at 2MA/2.3T. The pedestal height has then been increased, by adding heat and particle sources at the pedestal top, until an unstable mode starts growing. When the T_e^{ped} is increased at fixed n_e^{ped} , no unstable modes are found. However, when n_e^{ped} is increased at fixed T_e^{ped} a ballooning mode is driven unstable by just a small increase in the density. This can be explained by the fact that the diamagnetic frequency, which scales as $\omega^* \propto \nabla p/n$, also increases with the pressure gradient drive when T_e^{ped} is increased but when n_e^{ped} is increased there is a negligible change in the diamagnetic frequency. This shows that the balance between the diamagnetic stabilization and the instability drive is the key to understanding the ELM-triggering mechanism in this plasma (and not just the instability drive itself). This has also been noted in previous studies of type-I ELMy pedestals [3]. To assess the effect of the isotope mass, A_{eff} has been changed from 2 to 3. The increase in A_{eff} led to a higher critical n_e^{ped} . This increase in n_e^{ped} is comparable to the increase in n_e^{ped} that is achieved by only rescaling the diamagnetic flow terms consistent with a change from $A_{\text{eff}} = 2$ to 3. We can therefore conclude that it is the change in the diamagnetic flows that increases n_e^{ped} when we go from deuterium to tritium. Quantitatively, the predicted increase in n_e^{ped} is smaller than the one seen in experiment, but qualitatively a good agreement is obtained.

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Poster Session MCF 2 - T

2 P 142 - Comparisons between edge turbulence in EDA and QCE plasmas using the CECE diagnostic at ASDEX Upgrade

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ABSTRACT TEXT

High performance plasmas that are free of large Type I ELMs are imperative for sustainable operation of fusion power plants. Many promising Type I ELM-free regimes have been developed over the past years [Viezzer et al Nucl. Mater. Energy 2023] and studied on AUG, such as the enhanced D_α (EDA) H-Mode and the quasi-continuous exhaust (QCE) regime. Both regimes display a ubiquitous edge fluctuation dubbed the quasi-coherent mode (QCM) and have similar access conditions. It is not clear if these regimes are fully distinct or some operational limit of the same regime. To answer this question, a database containing QCE and EDA discharges in D and He is constructed, and the correlation ECE (CECE) system [Creely et al RSI 2018] is used to measure the QCM's spectral features (amplitude, width, frequency), electron temperature fluctuations, and radial correlation lengths. Additionally, discharges showing transitions between EDA and QCE and non-deuterium plasmas are investigated to understand the underlying physics of the QCM in these different scenarios.

Analysis of the database shows no differences in QCM properties between QCE and EDA plasmas. Their associated temperature fluctuations (4–6%), spectral widths (10–40 kHz), frequencies (20–50 kHz), or correlation lengths (1–2 cm) are very similar.

However, when comparing the coherence vs. cross-power spectral density, of the same QCM case, the cross-power is observed to be much narrower compared to the width of the coherence spectra, suggesting the presence of a broadband turbulence in conjunction with the QCM. This observation is indifferent to plasma type as it is seen in both EDA and QCE plasmas. The possible interaction between the QCM and broadband turbulence measured in the coherence spectra is explored in greater detail.

Poster Session MCF 2 - T

2 P 143 - Development of high plasma performance scenarios with small/no ELMs on HL-3

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ABSTRACT TEXT

HL-3 is exploring the scenarios with high operation parameter such as super H-mode, where the large edge localized modes (ELMs) should be avoided. Results of EPED reveals that the pedestal density can be less than the Greenwald density limit for the HL-3 super H-mode operation. With the equilibria generated by the integrated framework in OMFIT[1], stability analysis shows that two methods may be used to sustain the super H-mode operation[2]. The first is mitigating the ELMs at the peeling boundary, so that the one single small ELM will not lead to the transition to the high collisionality H-mode. The second is suppressing the ballooning instabilities at the upper ballooning boundary of the bifurcation, which may enlarge the parameter space of super H-mode. Auxiliary techniques such as impurity injection[3] or Resonant Magnetic Perturbation can also be used to control ELMs on HL-3.

According to the simulation results, 2 key issues are studied in experiments on HL-3. The ELM-free H-mode with low density is achieved for more than 600 ms by increasing the triangularity. And the density is further increased during the H-mode by replacing the gas puffing by supersonic molecular beam injection. Some other small/no ELM operation scenarios such as Enhanced D α mode and “Staircase” H-mode are also observed on HL-3.

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Poster Session BPIF 3

3 P 144 - Study on Polarized Emission and its effect on Laser Induced Breakdown Spectroscopy

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ABSTRACT TEXT

High-intensity lasers, when interacting with matter, can generate highly dynamic plasma known as laser-produced plasma (LPP). LPP has garnered significant attention from the scientific community due to its fundamental importance and diverse applications. This plasma is highly transient, exhibiting steep gradients in both temperature and density, making it an ideal subject for various studies. Notably, LPP facilitates the investigation of the spectroscopic behavior of atoms and molecules, thereby accessing spectroscopic energy levels that are typically unpopulated under normal conditions. This technique is widely known as Laser-Induced Breakdown Spectroscopy (LIBS). LIBS has broad applications, ranging from the analysis of plasma-facing components in tokamaks to interplanetary missions. Due to its wide range of applications, several techniques have been employed to enhance the signal-to-noise ratio in Laser-Induced Breakdown Spectroscopy (LIBS). One such technique is Polarization-Resolved LIBS (PRLIBS), which utilizes a specific polarization to suppress the background.

Polarized emission from LPP has been extensively studied as it can be used to understand electron distributions [1] and extract valuable information about self-generated electric [2] and magnetic fields [3] within the plasma. Additionally, it is of particular importance in atomic physics and spectroscopy [4]. In our recent work [4], we have investigated the spatio-temporal evolution of polarized emission using high-resolution imaging techniques. Specifically, we examined the effect of polarized emission on the parametric calculations of plasma characteristics during PRLIBS experiments [5]. Our findings show that to extract reliable information, the extent of polarization need to be determined at a particular instance. In this presentation the significance of quantifying the extend of polarization and its implications on PRLIBS and parametric estimation of LPP will be thoroughly discussed.

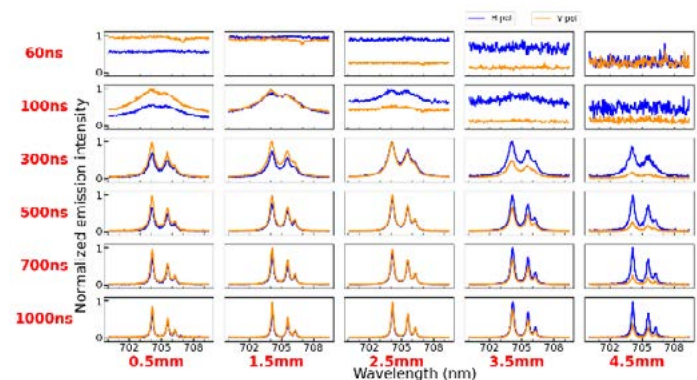


Image title: Spatio-temporal evolution of the emission spectrum of Al II. Row-wise it shows the spectra with increasing time after the laser ablation and column-wise the spectra with increase in the distance from the sample/target. Blue curve shows the horizontal polarization and the orange shows the vertical polarization. All plots are normalized to the maximum intensity of emission among the two polarizations.

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10/07/2025, 14:30–16:15, Room: Poster area - Lobby

Poster Session BPIF 3

3 P 145 - A Stark broadening line profile library for spectroscopic modeling of warm dense plasma

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ABSTRACT TEXT

Absorption and emission lines from warm dense matter have complicated line profiles due to Stark broadening. The detailed knowledge of the line shape is an important ingredient of opacity models and often provide valuable diagnostic utilities for plasma density and temperature in both emission and absorption spectroscopy. Complex spectroscopic modeling tools often use simplified fitting formula to describe these broadening processes. However, such simplifications often lead to inaccurate line profiles. In this work, we present a numerical line profile library obtained with detailed calculations using the Multi-Electron Radiator Line-shape (MERL) code. MERL is based on standard theory of Stark broadening, and includes effects of both plasma dynamic electrons and static ions. The numerical library tabulates line widths of individual spectral lines on a grid of plasma density and temperature. Important K-shell and L-shell transitions, including satellite transitions of low to mid Z elements up to Krypton are covered. The suite of spectral modeling tools (PrismSPECT, Spect3D, Helios-CR) developed at the Prism Computational Sciences have been updated to use this library to model the line broadening for both absorption and emission spectroscopy.

Poster Session BPIF 3

3 P 146 - Investigation of strongly coupled and weakly degenerate plasmas in supercritical fluid mixtures

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ABSTRACT TEXT

Strongly coupled plasmas (SCPs) are found in various astrophysical environments, including white dwarfs, neutron stars, the interiors of Jovian planets, and the solar photosphere. Despite their significance, generating SCPs in the laboratory remains challenging due to their high energy density and transient nature, which hinder precise measurements of fundamental plasma parameters such as electron density and transport properties.

In this study, we generate SCPs using high-power laser pulse in supercritical fluid (SCF) mixture environments composed of noble atomic species (He, Ar, Kr) and molecular species (H₂, O₂). Our results show that H₂ molecules enhance plasma radiation intensity and prolong its duration, indicating increased electron density and improved charge confinement. Moreover, when both H₂ and O₂ are introduced, we observe that chemical reactions release additional energy, contributing to the formation of high-density plasmas.

We determine electron temperature and density using optical emission spectroscopy based on the blackbody radiation analysis and ionization potential depression theory for SCPs. The measured electron temperature and density are 1 eV and 10²⁷ m⁻³, corresponding to the Coulomb coupling parameter above unity. The high electron density is confirmed by a pump-probe interferometry with a 266 nm UV laser. It is worth noting that the laser produced SCPs in SCF media are weakly degenerate. This study provides a new approach for generating and controlling SCPs in the laboratory, paving the way for further investigations into high-density, weakly degenerate SCP systems.

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Poster Session BPIF 3

3 P 147 - XUV imaging of electron heating and density changes femtosecond laser heating of solid titanium

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ABSTRACT TEXT

The short timescale solid-to-plasma transition encompasses a plethora of physics relevant to fundamental light-matter coupling and extreme conditions found in inertial fusion experiments and compact objects in space. Femtosecond laser heating of solids provides a natural separation of timescales, starting with electron heating during the pulse, electron-ion coupling during the first picoseconds, and then hydrodynamic expansion on the picosecond to nanosecond timescale. Measuring these effects are challenging, as an ultrafast probe sensitive to any one of these effects is a challenge. Here, we use ultrashort extreme ultraviolet (XUV) pulses to probe laser heated titanium foils in transmission. The wavelength of the XUV light is chosen to correspond to a bound-free electron transition in titanium, that is sensitive to the vacancies produced by electron heating. Simultaneously, the density is tracked by the shifting absorption edge as the plasma expands and the ion potential increases. The transmitted XUV pulse is imaged to allow the measurement of several conditions, in a single shot. We compare the results with predictions of a coupled DFT and Hydro code.

The time-dependant relative transmission of an XUV probe pulse through a femtosecond laser heated titanium:

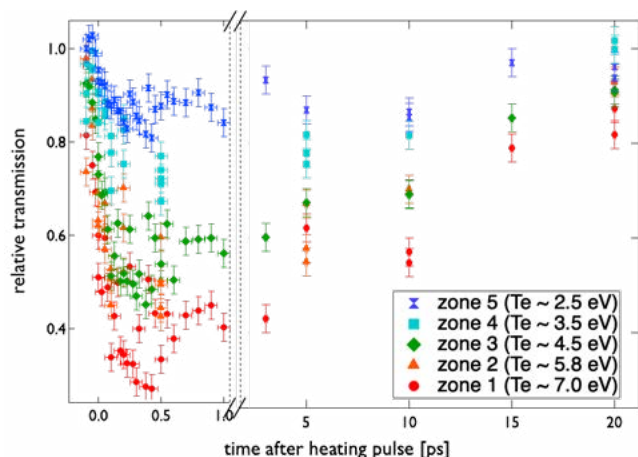


Fig. 1. The time dependant absorption of the XUV pulse as a function of time relative to the heating pulse. Zones 1 to 5, refer to concentric rings within the heating pulse that has a Gaussian intensity distribution, with zone 5 being the central region and therefore the highest temperature.

Poster Session BPIF 3

3 P 148 - Transport and focusing of ultrashort electron bunches

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ABSTRACT TEXT

Since its proposal in 1979, laser wakefield acceleration (LWFA) has advanced significantly. Techniques such as laser pulse shaping, plasma waveguides, and various injection mechanisms have been developed to produce high-quality, high-energy electron bunches in a compact setup. Modern facilities can now generate near-monoenergetic, low-emittance, or very high-energy (up to 10 GeV) bunches. However, achieving all these parameters simultaneously remains a challenge.

Multi-stage acceleration offers a path to even higher energies. But due to their small size and the strong wakefield forces, LWFA-accelerated bunches are highly divergent, rapidly spreading after leaving the accelerator. This makes efficient refocusing essential for injection into the next stage. Transport can be achieved using conventional electron optics (multipole magnets) or plasma lenses (active or passive). Since LWFA's main advantage is its high acceleration gradient, keeping the transport line compact is essential to avoid effectively reducing this gradient. Plasma lenses, with their much shorter focal lengths, could be a better option, but so far, only a few percent of the bunch charge have been successfully transported to the next stage using this method.

While tight transverse focusing is achievable even with a few percent energy spread, preserving the ultrashort bunch length is more challenging. Large or highly divergent beams experience geometric dispersion during focusing—outer particles take longer paths to the focal point than central ones, extending even monoenergetic bunches. To reduce this effect, the transport line should be positioned as close as possible to the end of the acceleration stage. Additionally, focusing bunches off-axis using multiple lenses may provide a correction for geometric dispersion.

This work investigates methods to mitigate geometric dispersion and improve transport efficiency by optimizing the positioning of the transport line and employing multi-lens focusing schemes, potentially enhancing the performance of staged LWFA.

Poster Session BPIF 3

3 P 149 - Simulating the focusing of laser-plasma accelerated proton beams

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ABSTRACT TEXT

The interest in laser-plasma accelerated ion beams with potential applications in the biomedical field is rapidly growing along with the major advances in laser technologies [1,2]. Laser-driven particle beams present distinct characteristics over RF-accelerated beams, imposing the need to develop specially designed focusing and beam transport systems that can control the delivery of the beam with a predefined set of parameters to meet rigorous therapeutic requirements [3]. The particularities of laser-plasma accelerated ion beams that could benefit the biomedical field refer to the ultra-short pulse duration of the particle bunch (on the order of picoseconds) and high fluxes (ranging from 10^{11} – 10^{13} particles per shot), enabling the delivery of ultra-high dose rates (> 40 Gy/s) and thus providing access to the FLASH therapy regime, which manifests by effectively targeting the tumoral cells whilst reducing the damage to the normal tissue. To benefit from these features, the scientific community needs to address the more challenging aspects of employing ultra-short accelerated hadrons in clinical applications, which refer to the broad energy spectrum and to the large divergence of the beam.

Here we present simulation-based studies that aim to understand the focusing effects of various solenoid configurations on laser-plasma accelerated proton beams. To determine the optimal focusing solution, we compared the performance of multiple solenoids by varying the dimension and shape of both single solenoid configurations and two-solenoid focusing systems. The proposed beamline configurations are being analyzed in terms of collection efficiency, focusing position, and profile of the beam. The simulation also includes a dose monitoring study upon a predefined target volume, resembling a superficial tumor, for which we calculated the absorbed dose, and the dose delivery rates, confirming the accessibility to the FLASH therapy regime.

ACKNOWLEDGEMENT

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Poster Session BPIF 3

3 P 150 - High Energetic Proton Acceleration and Alpha Particle Generation from Laser-driven Proton-Boron nuclear reaction

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ABSTRACT TEXT

The Proton-Boron fusion reactions ($p^{11}\text{B}$) are the holy grail in the pursuit of advanced fusion fuels, wherein the primary reactions produce the three energetic alpha (α) particles with a total energy of 8.7 MeV. The advancement of highly relativistic laser systems has increased interests in proton-boron fusion reactions owing to their aneutronic reactions. The generated alpha particles have promising multi-disciplinary applications in fusion energy, astrophysics and medicine, in particular for the production of radioisotopes for the cancer therapy. Proton acceleration by interaction with highly intense laser with hydrogenated targets is one of the preferred ways to initiate the $p^{11}\text{B}$ reactions. Recent experiments with high-intensity lasers have shown significant yield in α particles using pitcher-catcher target geometry. High- Intense laser irradiating on the pitcher (over-dense) target produces the high energetic protons of around 30 MeV through Target Normal Sheath Acceleration (TNSA) and Hole Boring (HB) Acceleration mechanisms. The generated protons impinge on the catcher (Boron or Boron Nitride) target to produce the alpha particles of the energy around 10 MeV. Numerical Simulations EPOCH PIC is performed to generate the highly energetic protons of around 30 MeV and to study the angular divergence of the proton beams. Monte-Carlo code Geant4 is used to measure the alpha particle's flux of around $5 \times 10^{10}/\text{sr}$, energy of around 10 MeV and also angular distribution. Different types of targets and the acceleration mechanisms have been studied numerically to accelerate the protons through various acceleration mechanisms and also to generate a high yield of alpha particles.

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Poster Session BPIF 3

3 P 151 - Effect of Parabolic Plasma Channel Shaping on Electron Acceleration and Betatron X-ray Emission

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ABSTRACT TEXT

Betatron X-ray generation in Laser Wakefield Acceleration (LWFA) is a promising approach for producing high-brightness, ultrashort X-ray pulses with applications in ultrafast imaging, medical diagnostics, and high-energy-density physics. This study investigates the enhancement of electron acceleration and Betatron X-ray production using preformed parabolic plasma density channels. Parabolic profiles improve laser guiding and electron injection, leading to stronger transverse oscillations and enhanced X-ray emission. Through Particle-In-Cell (PIC) simulations, we analyze the impact of varying the channel radius on key parameters, including electron injection efficiency, oscillation amplitude, and X-ray yield. Our findings indicate that a properly tuned parabolic density profile significantly enhances both the Betatron X-ray flux and the critical energy of the emitted radiation. This optimization presents an improved pathway for developing high-brightness, compact X-ray sources, with potential applications in scientific, industrial, and medical imaging.

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Poster Session BPIF 4

3 P 228 - X-Ray Sources for Non-Destructive Testing (NDT) Using Laser-Plasma Acceleration

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ABSTRACT TEXT

The acceleration of relativistic electron beams by lasers fascinates by its ability to produce electron beams with energy of hundreds of MeVs or even GeV energies on mm to cm distances [1]. In that case, an ultrahigh peak power laser is focused to reach an intensity of a few 10^{19} W.cm⁻² in a gas that is instantaneously ionized. In addition to its exceptional compactness, this source offers several advantages over conventional accelerators, making it highly appealing for various applications: a small source size, an ultra-short duration of just a few fs, and remarkable versatility; for instance, it can generate ultrafast X-rays in the keV or even MeV range. It was thus noticed that thanks to their micrometric source size, the beams produced by laser plasmas accelerators could be used to improve the resolution of industrial radiography for non destructive testing [2].

For that application, the electron beam is sent through a piece of high-Z metal (the converter) to produce an X-ray beam through the Bremsstrahlung process [3]. Obtaining a quality image with high resolution requires an X-ray source that has both a small source size and a high photon flux. The flux is directly related to the charge of the electron beam. As the electron source size is almost punctual, the X-ray source size is partly the product of the electron beam divergence $\Delta\theta$ by the distance from the accelerator exit to the converter L. When very small defects (<1 mm) need to be detected, the optimal electron source would, therefore, have a large charge and a low divergence. The problem is that these two parameters tend to increase together.

In this work, we present the results on source performance obtained with a 10 TW (0.300 J, 30 fs) laser. The limitations of this source will be discussed, and examples of x-ray imaging will be provided.

KEYWORDS

X-Ray Sources, Laser-Plasma Acceleration, Bremsstrahlung process, Control Non Destructive.

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Poster Session BSAP 3

3 P 152 - Measurement in Koopman Von Neumann approach

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ABSTRACT TEXT

Simulating non-linear dynamics with a quantum computer is a longstanding goal, with significant efforts from both the plasma computational physics community and the quantum computing community. Identifying which non-linearities can be simulated efficiently by a quantum computer is crucial for developing new computational tools for plasma physics simulations and for understanding the capabilities of quantum computers. The Koopman-von Neumann (KvN) mapping proposes a straightforward method to address some nonlinear systems through phase-space simulation. The advantage of this scheme lies in the fact that, in many cases, the quantum numerical scheme requires only the Quantum Fourier Transform and diagonal operators that are efficiently implementable on quantum computers.

In this work, we discuss how to extract information about the evolution of a system simulated with the KvN approach. Of particular interest are measurement based on diagonal unitary sampling which make it possible to extract moments from a particle density function e.g fluid moments in kinetic plasma simulations. We will present how the KvN approach can be applied to a Lotka-Volterra system simulation and how information can be extracted from the quantum simulation.

Poster Session BSAP 3

3 P 153 - Thin-target bremsstrahlung of plasmas with high-Z impurities

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ABSTRACT TEXT

The bremsstrahlung is one of the key quantities to accurately characterise the electron population in momentum and configuration spaces of hot magnetised plasmas. Recent developments have led to use high-Z elements for plasma facing components like tungsten in tokamaks, but also for the mitigation of a beam of runaway electrons generated during a major disruption. The presence of these elements may change the core thin-target electron-ion bremsstrahlung, because of the screening effect of partially ionised atoms. Consequently, a general method for calculating the electron-ion bremsstrahlung using an accurate multi-Yukawa representation of the atomic potential has been carried out. The original work concerning neutral atoms is here generalized to any element and arbitrary ionisation states, a primary requirement for plasma physics. The approach herein described, allows to calculate mostly analytically the electron-ion bremsstrahlung either for slow or very fast electrons, whatever the screened charge of the atoms present in the plasma. Consequences of the presence of partially ionised impurities on the electron-electron bremsstrahlung are also discussed. Numerical results are obtained by the R5-X2 bremsstrahlung code [Y. Peysson and J. Decker, Phys. Plasmas, 15, 9 (2008) 092509] in which all new cross-section formulae have been implemented.

Poster Session BSAP 3

3 P 154 - Light dragging in moving magnetized plasmas*

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ABSTRACT TEXT

Wave propagation in media is affected by the medium's motion. This effect of motion on waves, commonly referred to as light dragging, is now regarded as a key concept for the development of Special Relativity. From Fizeau's 1851 pioneering experiment [1] to the observation of augmented drag in slow light conditions [2], these effects have received considerable attention in isotropic dielectrics.

Comparatively, the effect of motion on waves in magnetized plasmas has been much less studied. Yet, addressing this problem is important in that plasma waves are extensively used for plasma control and diagnostics, and also often known to feature flows. One may for instance want to know how motion can affect plasma accessibility, especially in configurations relying on flows for plasma confinement, such as rotating configurations [3]. These effects may also prove important beyond the laboratory, and notably in astrophysics, where the motion of plasma screens could affect the signal received on Earth [4,5].

A challenge in determining light dragging on a moving plasma is that it is anisotropic in the presence of a background magnetic field. In this work we present a general theory for refraction at the interface of a moving anisotropic medium, including formulas for the drag experienced by waves propagating in the plasma. We then use this tool to discuss the effect on the low frequency Alfvén waves, as well as on the ordinary and extraordinary modes, considering where drag effects could be important.

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Poster Session BSAP 3

3 P 155 - Characterization of pure electron plasmas in APEX-LD using an electron beam diagnostic

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ABSTRACT TEXT

Laboratory non-neutral plasmas (NNPs) typically consist of only one species of charge. In a device with open magnetic field lines, such as a Penning trap, the trapped plasma can be ejected along the field lines and analyzed. In a toroidal device with closed field lines, such as the compact levitating dipole APEX-LD [1], NNPs must be analyzed in a different manner. Wall probes allow for non-invasive measurements of time-varying density perturbations present in a plasma [2]. However density perturbations do not always exist, therefore additional diagnostics are required to establish the presence of a plasma and determine the confinement time.

In this contribution, the results of a new, non-destructive electron beam diagnostic are presented. Electrons are emitted onto the open field line passing through the center of the floating coil and collected on the opposite side. When a NNP is trapped in the dipole, its space-charge potential can reflect the electron beam. The collected current therefore provides a way to determine the potential of the trapped plasma as a function of the beam energy.

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Poster Session BSAP 3

3 P 156 - Evidence of energy transfer from Helium metastables to Hydrogen in CCRF plasma: An Optical Emission Study

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ABSTRACT TEXT

Capacitively Coupled Radio Frequency (CCRF) plasma has been the subject of intensive research interest due to its potential applications and fundamental insights. Optical Emission Spectroscopy (OES) is a non-invasive diagnostic technique that effectively characterizes plasma parameters and enables the comprehension of underlying atomic and molecular interactions. The present study integrates CCRF plasma and OES to investigate the energy transfer between helium metastables and hydrogen atoms. A 13.56 MHz RF source is employed to generate the plasma from various gas species, such as helium, argon, and air, at pressures ranging from 0.1 to 5 mbar. OES is conducted using a low-resolution spectrograph with an EMCCD detector. In addition to the characteristic line emission of the gas species under investigation, the Balmer series of hydrogen and the molecular emissions of nitrogen are also recorded. The emission from hydrogen and nitrogen is primarily attributed to the presence of water contamination and residual air within the chamber, respectively. Interestingly, OES reveals a pronounced enhancement in Balmer series of hydrogen lines in the helium plasma, which is not observed in other gases or in air. A comprehensive study regarding this enhancement in hydrogen line intensity in helium plasma has been conducted, which points to the hypothesis that the energy exchange between helium metastables and hydrogen atoms should be the underlying mechanism. As the energy of the helium metastables exceeds the ionization energy of hydrogen, Penning ionization is expected to happen during the interaction of helium metastable with hydrogen atoms[1,2]. Subsequently, recombination process occurs in hydrogen atoms, leading to the observed Balmer series. Furthermore, the emission intensity of Balmer series of hydrogen shows a dependency with plasma density in helium plasma whereas no such dependency is observed for other gas species, indicating the role of energy exchange between helium metastables and hydrogen atoms. We believe that these results will have significance besides the fundamental understanding of energy transfer. The observed enhancement can be effectively used to quantify hydrogen contamination in various materials[3]. A comprehensive presentation of the observed OES results, in correlation with plasma parameters will be made during the presentation.

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Poster Session BSAP 3

3 P 157 - Generation of Multiple Double Layers and Ion Beam in RF expanding plasma

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ABSTRACT TEXT

Multiple Double Layers (MDLs) are detected across a grounded ring kept between the source and expansion chambers when Argon plasma is allowed to expand at working pressure of 7×10^{-4} mBar and magnetic field of 500 G. Sharp potential drops of 18 V and 11 V exist in the axial potential profile, resembling a potential well like structure. A XOOPIC code based on this experimental condition agrees well with the experimental data and the MDL structure is found to be formed due to the grounded ring. A four grided Retarding Field Energy Analyzer (RFEA) is placed in the downstream of the multiple Double Layers (MDLs) for analyzing ion energy. Supersonic ion beams of energies 28 eV and 44 eV are found in the region just after the second layer. Potential drops due to the MDLs and geometrical expansion due to pressure gradient are responsible for ion acceleration. Ion beams of 28 eV is generated due to MDLs and 44 eV due to geometrical expansion. Axial ion density profile of energy 44 eV confirms the geometrical expansion of plasma governed by the plasma jet equation.

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Poster Session BSAP 3

3 P 158 - A non-destructive method for plasma blob trajectory estimation using capacitive probe arrays for non-neutral plasma diagnostics

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ABSTRACT TEXT

Nonneutral plasmas have been stably confined in traps with cylindrical and toroidal geometries. In the presence of an external magnetic field, the plasma's self-electric field organizes it into a blob. The dynamics of the plasma blob facilitates the characterization of diocotron instability and associated phenomena, such as resistive wall instability [1], ionization instability [2], etc. The conventional method for determining the plasma blob trajectory relies on M-phosphor-screen-based imaging [3], [4], which provides a two-dimensional density profile of the plasma at a given instant. However, this technique is inherently destructive, requiring multiple shots of reproducible plasma to estimate the complete trajectory of the blob. This approach is particularly challenging to implement for certain trap geometries, such as partial or full tori and stellarators.

In this work, an alternative, non-destructive method for plasma blob trajectory estimation is presented, utilizing signals from multiple wall-mounted capacitive probes positioned around the trap. The blob's location is determined at each time step using a triangulation method applied to the signals detected by these probes. Ideally, three probes are sufficient, provided that each registers a sufficiently high signal at every instant. However, this constraint is alleviated by incorporating additional probes at different locations around the trap, allowing the selection of any three probes with adequate signal strength at each moment, depending on the blob's instantaneous position and motion relative to the probes. Using this approach, a predefined plasma blob trajectory was successfully reconstructed, showing good agreement with the expected path. Furthermore, implementing this technique in toroidal traps and stellarators is readily feasible.

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Poster Session BSAP 3

3 P 159 - Fluid V-state dynamics through magnetized electron plasmas

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ABSTRACT TEXT

Experiments and techniques using nonneutral plasmas (NNPs), as well as simulation and analysis tools developed to aid predictions and interpretations, have proved to be relevant to the study of nonlinear dynamics in other collective systems. A primary example is the physics of two-dimensional (2D) fluids. A highly-magnetized, single-species plasma confined in a magneto-electrostatic Penning-Malmberg device is isomorphic in its transverse dynamics to a 2D inviscid and incompressible fluid. And while the direct experimental investigation of 2D fluids is limited, the ability to produce tailored particle density (corresponding to fluid vorticity) patterns and the ease of manipulation and diagnosis typical of trapped plasmas offers opportunities for verification of theoretical predictions as well as extensions beyond analytical models [1, 2]. An example of 2D fluid dynamics explored through a trapped, magnetized NNP is the evolution of Kelvin-Helmholtz (KH) perturbations in an electron column of initially circular cross-section (axisymmetric fluid vortex). Such perturbations may be induced by the application of suitable multipolar rotating electric fields (fluid strain fields) [3], which lead to deformed vortex structures called V-states in the nonlinear regime, for which stability was predicted first by Kirchhoff (in the case of a quadrupolar deformation) and then by Deem and Zabusky (for arbitrary deformation order) [4].

By means of a combination of experiments and simulations, we systematically analyze the insurgence of KH perturbations, the full development of V-states and their collapse, with a focus on the parameters expected to have a significant influence on the nonlinear dynamics of the vortex, i.e. the initial vorticity profile and the structure of the strain field. In particular, different multipolar fields are compared and autoresonant (frequency-locked) control of the perturbation is implemented. The forced and free relaxation of the V-state after its saturation by continued excitation is discussed, where we observe that the ‘natural’ axisymmetric equilibrium may not be reached, in favour of permanently or intermittently deformed structures.

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Poster Session MCF 3 - L

3 P 160 - Mode conversion and parametric decay instabilities in electron cyclotron resonance heated helium and hydrogen plasmas in TOMAS

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ABSTRACT TEXT

The TOMAS device is a TORoidally MAGnetized System (TOMAS), which is operated by LPP-ERM/KMS at the FZ-Jülich. It is a facility designed to study plasma production, wall conditioning and plasma – surface interactions. A magnetron with a frequency $f_{\text{EC}} = 2.45$ GHz is used as microwave source for Electron Cyclotron Resonance Heating (ECRH) of the plasma and can inject 0.7–6.0 kW of power. The device is equipped with various plasma diagnostics. The Langmuir probe system consists of two quadruple movable probes. The optical diagnostics include video diagnostics, a photo-detector, optical emission spectroscopy and a microwave interferometer. Particle diagnostics include a time-of-flight neutral particle analyzer, a retarding field energy analyzer, a residual gas analyzer (quadrupole mass spectrometer) and vacuum gauges. A sample holder allows us to study plasma-material interactions, e.g boronized tungsten.

The waves injected by the magnetron interact with the electrons at the Electron Resonance layer and heat up the plasma. The resulting density profiles were measured by a triple Langmuir probe. These measurements suggest that a considerable amount of the injected wave is converted to the Electron Bernstein Wave, which is verified by measurements of the forwarded and reflected power. This mode conversion process is characterized by nonlinear phenomena of parametric instability, which can introduce for example Lower Hybrid Waves in the plasma. Additional power deposition locations appear when the injected power reaches a certain threshold, suggesting convective parametric decay instabilities. The observed non-monotonic density profile can also cause additional parametric decay, called Two Plasmon Decay (TPD). The daughter waves are trapped in a density bump, which reduces the convective losses. This can drastically reduce the power threshold for parametric decay down to 1 kW.

A spectrum analyzer is subsequently connected to a movable pin probe and to a single strap ICRF antenna, to verify the different waves present in the machine. Various plasma parameters are scanned (power, gas pressure, species,...) and the observed wave spectra are characterized and compared to theoretical predictions and experimental results from other diagnostics.

3 P 161 - Modelling current and pressure evolution in Gauss Fusion stellarator power plant

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ABSTRACT TEXT

In a fusion power plant, the preferred choice for heating the plasma is electron cyclotron resonance heating (ECRH). However, in existing experiments, purely ECRH-heated plasmas show poor coupling between electrons and ions, and therefore it is important to develop a self-consistent and predictive tool that simulates, in a stellarator, the plasma equilibrium and profiles evolution between start-up and fusion self-heating phases. In this work, simulations of the current and pressure evolution during ECRH ramp-up are presented. The considered magnetic equilibrium is that of GIGA, a stellarator power plant currently being developed by Gauss Fusion GmbH. The current-diffusion simulations are performed with the THRIFT code, which evolves the toroidal current in time and has been recently integrated with the neoclassical codes DKES+PENTA which make fast and accurate calculations of the bootstrap current. While DKES solves the 3-D drift-kinetic equation to obtain mono-energetic diffusion coefficients, PENTA corrects these coefficients to account for the effects of collisional momentum conservation and parallel flows. The results of DKES+PENTA are compared against SFINCS, a more expensive code that solves the 4-D drift-kinetic equation, and a good agreement is observed at different collisionality regimes.

The coupling of THRIFT with a 1-D transport solver that evolves the pressure equations of all species in the plasma is further presented. Preliminary results of the power ramp-up phase in GIGA show that, during the start-up phase that leads to ignition, the time-variations of the iota on the edge are small and should produce little displacement of the fieldlines divertor strikepoints—an essential requirement for island-divertor operation. The viability of achieving different steady-state scenarios, as well as the minimum heating power required to reach them, is discussed.

Poster Session MCF 3 - L

3 P 162 - ASCOT-RFOF modelling of JET and ITER distribution functions of energetic particles accelerated by ion cyclotron heating within the IMAS framework

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ABSTRACT TEXT

The confinement and dynamics of Energetic Particles (EP) in fusion plasmas play a crucial role for their performance, making ad-hoc predictive numerical simulations an essential tool for EP characterization. Among the mechanisms to generate EPs in a tokamak, Ion Cyclotron Resonance Heating (ICRH) enables thermal or even neutral beam injected particles to reach MeV-range energies exploiting wave-particle resonances. ICRH is present as an auxiliary heating system in devices such as JET and ITER, alongside Neutral Beam Injection (NBI) or Electron Cyclotron Resonance Heating (ECRH). Accurate ICRH modeling requires the coupling of a full-wave code with a Fokker-Planck solver to determine both the power absorbed by plasma species and its redistribution via Coulomb collisions.

In this contribution, we model ICRH with the ASCOT [1] orbit following Monte Carlo code integrated with the RFOF library [2], which is a quasilinear diffusion operator simulating wave-particle interaction. The study has been carried out within the IMAS framework [3] where ASCOT-RFOF has been coupled to the CYRANO [4] full-wave code. This study aims to validate the ASCOT-RFOF IMAS implementation and then apply it for ICRH-accelerated energetic particles in ITER scenarios. To achieve this goal, as a first step, we validate the code integrated in IMAS on JET ICRH DT plasma experiments. This allows testing the IMAS implementation's consistency with previous results from other Fokker-Planck codes and experimental data. Subsequently, we explore an ITER-relevant scenario, simulating a half field ITER deuterium plasma with hydrogen minority heating at the fundamental frequency. We analyze the power partitioning between electrons and ions after the slowing down, as well as the distribution functions of the ICRH-accelerated particles, considering various minority concentrations and wave frequencies. Finally, the potential impact of NBI synergy is discussed as part of the future research directions.

This work contributes to the development of the Heating and Current Drive workflow [5], enabling the possibility of using ASCOT-RFOF as an additional advanced tool to model ICRH, as well as the synergy with NBI and alpha particles. Furthermore, the application of this code will contribute to the optimization of ICRH scenarios in the ITER research plan.

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Poster Session MCF 3 - L

3 P 163 - Turbulence-inclusive modelling of electron-cyclotron wave-plasma dynamics in Tokamaks

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ABSTRACT TEXT

Electron-cyclotron waves are widely used for plasma heating and current drive in tokamaks. The possibility of very localised deposition renders them appealing for instability mitigation as well as tailored control of current and pressure profiles. They are also envisioned as the main heating source for the ITER project [1]. However, previous work [2] indicates that simulations overlooking turbulence effects tend to overestimate the method's efficacy significantly. The discrepancy with experimental results is believed to stem from two effects [3]: microwave beam broadening due to turbulent plasma density fluctuations and wave-enhanced turbulent transport of suprathermal electrons.

This project concerns the coupling of two codes, WKBeam [4] and LUKE [5], to consistently simulate both effects simultaneously for the first time, yielding a comprehensive model of the combined dynamics. WKBeam solves the wave-kinetic equation for the propagation of EC waves under the influence of time-averaged density fluctuations, while LUKE solves the linearised electron Fokker-Planck equation, considering the quasilinear wave-plasma interaction and allowing for ad-hoc radial transport of suprathermal electrons. A theoretical framework to describe the one-way coupling has been devised and implemented. The resulting combined scheme was benchmarked against previous research, and new results from a dedicated upcoming experimental campaign with strong turbulence diagnostic coverage on the TCV tokamak will be compared to simulations through multiple dedicated synthetic diagnostics.

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Poster Session MCF 3 - L

3 P 164 - Towards Steady-State Fusion: Demonstration of a Stable, Integrated High-Performance Scenario in the W7-X Stellarator

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ABSTRACT TEXT

We demonstrate, for the first time, an integrated, quasi-stationary operation scenario in a stellarator that sustains high plasma performance and effective peak-heat-load-mitigation over reactor-relevant timescales in quasi-steady-state operation.

In Wendelstein 7-X (W7-X), steady-state pellet fueling and electron cyclotron resonance heating (ECRH) in O2-mode enabled plasmas with line-averaged densities beyond the X2 cut-off, equilibrated core temperatures of $T_{e0} \approx T_{i0} > 2$ keV, and energy confinement close to established stellarator scaling. These conditions were maintained for up to 40 seconds—well beyond the confinement times, the characteristic L/R-time and achieving thermal equilibrium on highly loaded divertor targets—while the plasma current remained low and stationary. Regular pellet injection cycles enhanced the central density and sustained favorable density gradients. Feedback-controlled neon seeding maintained a high radiative fraction, keeping divertor heat loads within technical limits. Despite operating in a strongly radiative regime, no evidence of impurity accumulation was observed.

These results establish the viability of pellet-fueled, radiation-cooled long-pulse operation in optimized stellarators, and mark a significant step towards steady-state fusion scenarios.

Poster Session MCF 3 - L

3 P 165 - Towards high performance long pulse operation with combined LHCD and ECCD in WEST

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ABSTRACT TEXT

The WEST tokamak provides key insights into long pulse operation in a tungsten (W) environment, anticipating challenges for future reactors like ITER. The Lower-Hybrid Current Drive (LHCD) system enables fully non-inductive regimes to be achieved by efficiently driving a current. Recently, 100 to 800 s long plasmas were routinely sustained. However, the off-axis current and power deposition constrains the operational domain in terms of plasma parameters (I_p , P_{IN} , n_{el}). In particular, insufficient central plasma heating complicates burn-through W and increases the risk of core radiative collapses when radiation losses exceed heating power [1]. Additionally, reduced current drive in plasma core may reverse the safety factor profile, compromising MHD stability [2].

To expand the operational domain, a new 3 MW/1000 s Electron Cyclotron Resonance Heating (ECRH) system will be operational in 2025. Its antenna, equipped with steering mirrors, allows variations of injection angles in both toroidal and poloidal directions, enabling current to be deposited and location to be scanned respectively. This contribution assesses its impact on plasma operation through stand-alone Radio-Frequency (RF) heating modeling and integrated simulations. First, the thermal effect of ECRH on LHCD deposition properties is examined using first-principles modeling with ALOHA/C3PO/LUKE framework [3] and a reduced model from METIS [4,5]. Central EC Current Drive (ECCD) is expected to shift LHCD profiles on-axis, while off-axis ECCD drives them further outward. Next, recent full-radius L-mode plasma simulations with the IMAS-compatible HFPS framework demonstrated accurate long-pulse predictions [6], by combining synergies between LHCD efficiency and turbulent transport. In particular, the determination of the operational domain, based on loop voltage, guided new record-long pulses to be obtained at a reduced cost in terms of experimental scenario development. Expanding on this integrated modelling approach, this study incorporates self-consistent ECRH predictions using TORBEAM [7] to prepare combined LHCD and ECCD experiments. The role of ECRH in preventing core W radiative collapses through enhanced core heating, as well as its potential to access higher density regimes, are analyzed. Additionally, ECCD flexibility in shaping current profiles is evaluated to mitigate MHD instabilities. Finally, the prospects of achieving high-performance, high-beta plasmas with dominant electron heating are discussed.

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Poster Session MCF 3 - L

3 P 166 - Impact of turbulent tokamak edge plasma on ion cyclotron wave propagation: A stochastic 1D model in a DTT plasma scenario

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ABSTRACT TEXT

Ion Cyclotron Resonance Heating (ICRH) is recognized as a powerful approach for plasma heating and current drive in tokamak experiments. In our earlier studies [1,2], we developed a 1D semi-analytical and numerical model to describe the propagation and absorption of an Ion Cyclotron wave in a DTT (Divertor Tokamak Test) plasma scenario, benchmarking it against more comprehensive full-wave codes such as TORIC [3]. Building upon this foundation, the present work introduces stochastic density fluctuations in the tokamak edge region. Such fluctuations, commonly observed in experiments [4], can significantly influence the antenna-plasma coupling by modifying the wave reflection and altering power absorption profiles.

In this study, the 1D wave equation employed in earlier analyses is modified to include random perturbations of the local plasma density, characterized by specific correlation lengths and amplitudes. A Monte Carlo procedure generates multiple realizations of these fluctuations, and for each realization the wave equation is solved numerically to obtain reflection coefficients and power deposition profiles. These findings can pave the way for more accurate predictions of ICRH performance in forthcoming devices, where steep density gradients and turbulent fluctuations are expected. Future works will refine the fluctuation model based on experimentally measured correlation functions and compare the present 1D stochastic results with selected full-wave simulations in realistic tokamak geometries.

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Poster Session MCF 3 - L

3 P 167 - First experiments on ICRF plasma start-up at Wendelstein 7-X

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ABSTRACT TEXT

The Ion Cyclotron Resonance Heating (ICRH) method is one of the main methods for heating plasma to high-temperatures in tokamaks and stellarators. In addition to this, the ICRH system can be used for fast ion generation, selective ion heating, wall conditioning, and providing plasma start-up [1, 2]. The Wendelstein 7-X (W7-X) ICRH system has recently been installed on this machine. The first tests and experiments had been performed during the OP2.1 campaign [3] in year 2023. In support for the W7-X experimental program, the scenario of ion cyclotron frequency range (ICRF) plasma production had been developed on Uragan-2M (U-2M) and Large Helical Device (LHD) stellarators [4, 5]. The ICRF discharges can offer the possibility of plasma production and sustain in conditions where plasma generation by the available electron cyclotron resonance heating (ECRH) systems at toroidal devices is not possible.

This paper presents the first results of ICRF plasma start-up at Wendelstein 7-X obtained in the latest experimental campaign OP 2.2. The two straps of the ICRH antenna were operated in zero-phasing to produce the plasma. The ICRF start-up scenario at W-7X was similar to the scenarios of U-2M and LHD. The used frequency of 25 MHz corresponded to the fundamental hydrogen cyclotron harmonic of hydrogen, and the ion cyclotron resonance zone resided in the plasma column. The magnitude of the magnetic field in the centre was 1.815 T. The working gas was helium. Under these experimental conditions, stable gas breakdowns and plasma generations were observed even at low values of injected RF power of ≈ 25 kW. Higher plasma densities up to $\approx 10^{18} \text{ m}^{-3}$ were achieved with more RF power of ≈ 545 kW. In the optical emission spectrum of the plasma, lines of helium, hydrogen, and carbon are observed. The plasma produced by the ICRF discharge can be used as a target plasma for further NBI and / or third harmonic ECRH and for the wall conditioning procedures.

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Poster Session MCF 3 - L

3 P 168 - DTT Hybrid scenario development with ASTRA-TGLF predictive modelling

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ABSTRACT TEXT

Hybrid scenarios in tokamak experiments represent a significant step forward in achieving optimized plasma performance. These scenarios highlight the advantages of operating at high normalized beta (β_N) with a tailored current profile and a central safety factor (q_0) above one, reducing the risk of MHD instabilities and enhancing plasma stability.

This study employs the ASTRA-TGLF(SAT2) [1,2] transport code, as done for the baseline case [3], to design and simulate, for the first time, the complete time evolution of the hybrid scenario in the Divertor Tokamak Test facility (DTT). We investigate the most performing scenario, the so-called Scenario E which will operate in Single Null (SN) divertor configuration with a magnetic field $B_T = 5.85$ T, plasma current $I_p = 3.8$ MA at flat-top and total auxiliary heating power of ~ 45 MW. Preliminary, the METIS [4] code is used to perform an initial fast screening of the possible discharge definitions, helping to identify the most promising solutions. The results are then passed to ASTRA for a more detailed description, and various strategies to optimize the hybrid scenario are explored, leveraging the flexibility of the ASTRA code. The current ramp-up (RU) with overshoot, previously applied in hybrid plasmas at JET [5], is tested. However, due to the limitations in the achievable current ramp rate in DTT, the effect on the q -profile is mild: the current evolution replicates the case without the overshoot, featuring similar $q = 1$ arrival time and a limited effect on the q profile shape. To overcome this limitation, an Electron Cyclotron-assisted RU is investigated. The impact of the different on-axis and off-axis power distributions is evaluated. Moreover, to better understand the impact of this actuator, the distinct effects of the pure EC heating and the additional effect of the EC Current Drive on the q profile shaping are carefully analyzed. The assessment of the optimized current RU enables the study of the flattop phase, evaluating the performance achieved when the total input power from ICRH and NBI is also delivered to the plasma.

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Poster Session MCF 3 - L

3 P 169 - Alya4fusion: Advancing plasma equilibrium and electromagnetic wave propagation modelling for fusion reactor simulations

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ABSTRACT TEXT

In the global effort to mitigate climate change, nuclear fusion emerges as a promising energy source. The complexity of fusion reactor design and operation demands advanced numerical simulation tools capable of accurately modeling diverse multi-physics phenomena. The Barcelona Supercomputing Center (BSC) hosts the Fusion Group within the Computer Applications in Science and Engineering (CASE) department. To address the rising need for computational capabilities in fusion, the group is developing a Digital Twin for fusion reactors using **Alya** [1], a Finite Element Method (FEM) framework under development in CASE since 2004. This project, **Alya4fusion**, aims to simulate a number of relevant multi-physics processes in a fusion reactor by leveraging high-performance computing (HPC) and artificial intelligence (AI) through MareNostrum 5, a pre-exascale European-funded supercomputer at BSC.

Alya4fusion comprises several independent yet coupled code modules. The Fusion Group has already developed NEUTRO [2] and MAGNET [3], while two more are underway: EQUILI, which computes plasma equilibrium, and EMWAVE, which simulates electromagnetic wave propagation and absorption in plasma environments.

EQUILI is a free-boundary solver of the 2D Grad-Shafranov equation, designed for tokamak geometries. Based on a CutFEM numerical scheme, it handles deformable and evolving domains, converging toward equilibrium by iteratively balancing magnetic confinement and plasma pressure. This solver has been validated through several analytical cases [4] and tested on the ITER tokamak geometry [5,6] with promising results. EMWAVE simulates plane or finite-source waves propagating in 2D through arbitrary gyrotropic media, including cold plasma and dielectrics. The code has been benchmarked against ERMES [7] and tested using the 2nd harmonic tritium scenario, which is one of the main ICRF heating scenarios in ITER [8]. The wave demonstrated excellent accessibility to the plasma region. Future developments will extend EMWAVE to 3D domains and incorporate a hot-plasma model for radiation absorption analysis.

This contribution presents recent advancements in EQUILI and EMWAVE, demonstrating their validation and preliminary application to reactor-relevant scenarios. These developments are essential steps toward Alya4fusion's objective: an integrated, exascale-ready simulation tool for fusion reactor design and optimization. By leveraging the MareNostrum 5 supercomputer, Alya4fusion aims to provide a computational framework capable of addressing the challenges of next-generation fusion reactors.

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Poster Session MCF 3 - L

3 P 170 - A workflow integrating simplified physics and engineering models for an initial design of the new DEMO Low Aspect Ratio baseline

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ABSTRACT TEXT

The development of the DEMO low aspect ratio baseline addresses key challenges identified in the 2020 design review [1]. The new proposed design space ($A = 2.8$, $R_0 = 8.6$ m) is calculated to deliver a net electric power of 350MW, meeting stakeholder requirements of 300–500MW with a 2 h pulse duration. This is achieved while nearly halving reattached divertor heat loads to levels manageable with emergency manoeuvres and improving access to detachment. Additionally, the toroidal field strength is reduced by $\approx 10\%$, and stored energy by $\approx 40\%$, addressing critical concerns regarding the TF system feasibility, and reducing weight and cost. By design, the safety factor margin is increased by raising q_{95} from 3 to 3.6, increasing plasma stability operational space and providing flexibility to recover performance due to inherent confinement uncertainties. This approach allows to “insulate” the engineering machine design, which can then be fixed (in term of A , R_0), from the physics uncertainties, enhancing robustness and flexibility for future DEMO developments.

This work presents a workflow for defining the preliminary low aspect ratio baseline, starting from system code studies [2], and integrating, since the beginning, physics and engineering aspects. Simplified physics models are employed to provide time-evolving plasma profiles that are used to produce electromagnetic plasma scenarios at critical snapshots, such as: Pre-Magnetization, Start of Flat-Top, Start of Burn, and End of Flat-Top. Engineering feedback from all systems is integrated early to ensure feasibility. Preliminary assumptions on the breeding blanket, magnet system optimization, and vacuum vessel are assessed, leading to a more self-consistent model of in-vessel components and the magnetic cage. For the divertor, and the first wall, initial poloidal profiles are derived from simplified models, incorporating also constraints such as grazing angles, vertical stability assumptions, and strike-point sweeping and wobbling requirements.

This workflow establishes a more streamlined and robust framework for detailed analysis and design, enabling faster iterations and improving an early alignment between physics and engineering to finalize the DEMO baseline while supporting multidisciplinary collaboration.

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Poster Session MCF 3 - L

3 P 172 - NSFsim code for machine design and scenario development

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ABSTRACT TEXT

NSFsim is a free-boundary Grad-Shafranov and 1D transport solver, inheriting numerical approaches developed for the DINA code [1]. Recent upgrades have expanded its application capabilities while improving performance and flexibility. Currently, NSFsim serves as a powerful tool for tokamak performance prediction, scenario development, machine learning applications, and device optimization. It is extensively used for scenario development on existing tokamaks and future projects, enabling the estimation of plasma parameter evolution, coil current dynamics, and induced currents in passive structures. From breakdown to shutdown, full scenario development provides deeper insights into the magnetic system and control requirements for scenario optimization. Additionally, its integrated transport solver ensures a self-consistent core transport solution alongside magnetic equilibrium. Inverse solvers are available to fit coil currents for given plasma shape and kinetic profiles. It is applied for static plasma state generation that is useful as an initial guess for preliminary scenario development. NSFsim simulates magnetic system actuators and a wide range of sensors (magnetic probes, flux loops, coil current, and voltages). Linear response models for vertical stability and density are included in NSFsim. The vertical stability model is designed to apply the artificial magnetic field required to keep the plasma vertical position at a given coordinate. The value and distribution of this artificial field may be used as a figure of merit for optimization of the poloidal magnetic system and passive stabilization. NSFsim mathematical core is implemented in Fortran and offers Python and C++ APIs for external use. It is accessible through the Fusion Twin Platform [2], which leverages the C++ API and enables parallel execution of multiple simulation runs. Users can configure simulations via a graphical user interface and analyze results using predefined plotting tools. The Python API allows for more flexible configurations and supports user-defined simulation setups, such as training reinforcement learning (RL) based controllers [3]. Module structure allows easy integration of external modules for auxiliary heating and current drive, transport codes, or magnetic and kinetic controllers. Python API also enables Gymnasium-compatible interface, a widely used standard for RL training applications.

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Poster Session MCF 3 - L

3 P 173 - Cascaded parametric amplification of lower hybrid waves using microwave beams

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ABSTRACT TEXT

We present a novel method for exciting lower hybrid waves in magnetically confined fusion plasmas using two microwave beams: a high-power pump beam (e.g., from a gyrotron) and a low-power signal beam. The method, termed cascaded parametric amplification (CPA), is inspired by recent advances in nonlinear optics, where a similar technique is proposed to tackle the terahertz gap [1].

The two microwave beams are designed to reach the upper hybrid layer with X-mode polarisation, where they are linearly converted to electron Bernstein waves. We demonstrate that by spectrally separating the beams by approximately the lower hybrid frequency, a long cascade of parametric three-wave mixing processes can be initiated, giving rise to a significant transfer of energy to a lower hybrid wave.

We analyse the mechanism in one spatial dimension by solving a steady-state coupled mode system. All involved plasma waves as well as the coupling coefficients are treated with kinetic theory. For verification, we benchmark our model against a fully kinetic particle-in-cell simulation, which shows good qualitative agreement and reasonable quantitative accuracy. We perform a parameter scan, where different configurations are found to yield conversion efficiencies to lower hybrid waves of several percent, thereby overcoming the Manley Rowe limit. This suggests that the CPA method could find relevance in magnetic confinement fusion experiments, e.g., during tokamak start-up.

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Poster Session MCF 3 - L

3 P 174 - Establishing a new operation point for Wendelstein 7-X at 1.8T with third harmonic electron cyclotron heating

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ABSTRACT TEXT

At the Wendelstein 7-X (W7X) stellarator the nominal magnetic field strength is 2.5T in combination with second harmonic (X2) electron cyclotron resonance heating (ECRH) at 140 GHz as the standard heating scenario. A desirable average plasma beta (ratio of kinetic and magnetic pressure) of at least 4% is potentially not achievable at this field, even with the foreseen power upgrades of the ECRH [1] and neutral beam injection (NBI) systems. A reduction of the magnetic field strength will lead to a plasma beta increase, compared to 2.5T, for the same heating power. At 1.67T the third harmonic (X3) can be used in a multipass heating scenario, but the diamagnetic effect of the envisaged high beta plasmas leads to a reduction of the magnetic field in the core, so a vacuum magnetic field around 1.75T is necessary. The reduced forces at 1.75T also allow to operate the superconducting coils in magnetic configurations which are not accessible at 2.5T.

One of the challenges for W7-X at a reduced field is the plasma start-up, which cannot be performed by the 140 GHz gyrotrons (high power microwave sources) at the third harmonic. A temperature of at least 0.7 keV is needed for effective coupling between electrons and 140 GHz microwaves [2]. However, the plasma start-up can be performed with X2 at a magnetic field strength of 1.8T with a gyrotron that is detuned to 101 GHz. The detuning reduces the power output to 250 kW and restricts the pulse lengths to 50–70 ms. This is insufficient for plasma start-up with the standard single pass scenario, so a multipass scenario with six beam passes through the plasma core was developed.

Plasma start-up at a reduced field of 1.8T was successfully demonstrated for the first time in the operation campaign OP 2.2 at the end of 2024. Direct X3 take-over is not possible, but an intermediate NBI phase, between the X2 and X3 heating, increases the plasma beta, so the resonance region of the X3 shifts inwards, towards the plasma core. Stable plasma operation of several seconds was demonstrated, enabling W7-X to operate with high power ECRH at two different magnetic field strengths.

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Poster Session MCF 3 - L

3 P 175 - Effect of stray magnetic fields on particles in the Wendelstein 7-X neutral beam box

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ABSTRACT TEXT

Neutral Beam Injection (NBI) is an essential tool for achieving high performance plasmas in the Wendelstein 7-X (W7-X) stellarator. NBI beams are observed to deflect in experiment when the main magnetic field of W7-X is active, suggesting that stray magnetic fields penetrate the NBI system. This phenomenon potentially restricts NBI operation as it could lead to overheating of NBI components. The effect of these stray fields on particle trajectories inside the neutral beam box must be investigated to identify any potential issues for NBI operation and to make the NBI system more reliable.

In this contribution, we present a comprehensive model for calculating ion trajectories inside the NBI system of W7-X. The model consists of two parts: First, the magnetic materials code MUMAT calculates the magnetic response of ferritic materials to external magnetic fields. This code has been verified through application to a textbook magnetic field problem and can be applied to the W7-X NBI system. Second, the Monte Carlo particle following code BEAMS3D simulates the motion of charged particles through magnetic fields and can be used to estimate heat loads on the NBI components.

MUMAT was used to determine the magnetic field inside the NBI system for the high-iota magnetic field configuration. The code predicts significant fields (>1 mT) inside the NBI neutralizer region. Subsequent BEAMS3D simulations with these fields show a shift of heat loads on the NBI components when compared to the case without stray fields. This shift agrees qualitatively with experimental observations and confirms the role of stray fields within this phenomenon. A quantitative comparison with infrared imaging and calorimetry is planned to further validate the model.

Poster Session MCF 3 - L

3 P 176 - Development of high-performance scenarios and H-mode operation on the ST40 tokamak

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ABSTRACT TEXT

ST40 is a high-field, low-aspect-ratio spherical tokamak with a major radius of 0.4–0.5 m, aspect ratio of 1.6–1.8 and toroidal magnetic field up to 2.1 T. It is equipped with two deuterium neutral beam injectors with 1.0 MW at 55 keV and 0.7 MW at 24 keV. One of the goals of the device is to extend the physics basis of high field spherical tokamaks, and as part of this, demonstrate high plasma performance towards reactor-relevant scenarios with plasma current > 700 kA and density approaching 10^{20} 1/m³ in double null diverted (DND) high confinement H-mode operation.

In this contribution, we present the results from recent experimental campaigns aiming at developing scenarios for high performance operation and optimising the scenarios for access into H-mode, and discuss the plasma performance and confinement achieved in these scenarios. DND scenarios have been developed ranging from medium-density hot ion modes with $T_i \gg T_e$, to high density H-modes with $n_e > 1 \times 10^{20}$ 1/m³ and $T_i \sim T_e$. H-mode access has been developed with rapid transition into DND configuration after startup and tailoring the gas puff and neutral beam injection timing to maximise flat top duration. The H-modes on ST40 typically exhibit high density pedestals with sustained ELM-free phase and modest 30–50% increase in stored energy. Regular boronisation and intershot helium glow discharge cleaning are applied to maintain vessel conditions for repeatable high-performance operation.

Poster Session MCF 3 - L

3 P 177 - Crayon: a flexible, fully relativistic ray tracer for electron Bernstein wave heating and current drive

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ABSTRACT TEXT

Electron Bernstein waves (EBWs) are an attractive option for microwave heating and current drive in spherical tokamak (ST) power plants. Higher plasma beta in STs means electron cyclotron (EC) heating has limited applicability as plasma surrounding the fundamental cyclotron harmonic is opaque to microwaves. EBWs are quasi-electrostatic waves which can be excited using O-X-B mode conversion. EBWs have no density cutoff and damp energy on super-thermal electrons resulting in enhanced current drive efficiency.

Modelling EBWs in power plant relevant temperatures requires solving fully relativistic dispersion relations for accurate wave propagation. In existing ray tracing codes such solvers can become intolerably slow. O-X coupling is commonly described using ad-hoc methods which lack physics basis and numerical robustness. Other important effects like X mode tunnelling, electromagnetic collisional damping models and higher order optical effects (i.e. diffraction) are not addressed for EBWs in any existing code.

Crayon is a new ray tracing code designed to calculate microwave propagation, damping and current drive in fusion plasmas with focus on electron Bernstein waves (EBWs). It is relevant to both existing experiments and modelling of fusion power plant concepts. Crayon features a fast fully relativistic dispersion relation solver for propagation and damping that is up to 100x faster than existing implementations [1]. A linear current drive model accounting for momentum conserving collisions and finite Larmor radius effects allows rapid evaluation of current drive [2].

Other novel features include a bespoke scheme for mode conversion / tunnelling based on asymptotically matching WKB rays to local wave equation solutions and a fully electromagnetic collisional damping model. Generalised geometry model allows application to a range of scenarios from tokamak start-up to flat top to stellarators. Analytic derivatives of the dispersion relations are calculated using a new simplified method.

Novel aspects of the code will be discussed alongside plans for experimental validation on the MAST-U tokamak.

ACKNOWLEDGEMENT

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Poster Session MCF 3 - L

3 P 179 - Fast scoping of fusion power plant parameter space using the new 0D system code D0FUS

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ABSTRACT TEXT

New non-conservative approaches, driven by the increasing number of startups and recent technological innovations, particularly high-temperature superconductors (HTS), have motivated the development of a new fast and tractable system code. Building on the approaches of [1] and [2], this 0D system code, named D0FUS, predicts key quantities of interest for a power plant by using fusion power (P_{fus}), maximum magnetic field (B_{max}), and geometrical parameters (a , R_0) as main inputs. The main equations of the plasma model include the definition of fusion power, the power balance, and a scaling law for the confinement time. In addition, the code also includes a radial build model to ensure that Toroidal Field and Central Solenoid coils can generate the required B field and plasma current and withstand the $j \times B$ forces.

Thanks to its high computing speed, D0FUS efficiently generates typical outputs by performing scans over minor a and major R_0 plasma radius for a given B_{max} and P_{fus} . This capability enables rich and flexible visualization, facilitating the identification of potential operating regions and the evaluation of innovative solutions.

First application suggests the existence of high-aspect-ratio solutions ($A > 3$) with higher Q and lower I_p , potentially reducing the size and costs of a Fusion Power Plant (FPP) by allowing for a reduction of the plasma minor radius at a given R_0 design point. However, these solutions may pose challenges in terms of neutron flux and vertical control. Secondly, the code highlights the impact of HTS on FPP design. Specifically, increasing B_{max} primarily enhances plasma stability (Troyon, Kink, and Greenwald limits), revealing interesting parameter space regions at low a . However, radial build constrains R_0 solutions due to strong $j \times B$ forces, while still allowing viable solutions with larger Q values compared to those at lower B . Thus, the respective benefits of alternative mechanical configurations (most notably wedging vs. bucking and C-clamp) are reviewed. Finally, the code is also useful for assessing the uncertainties associated with various parameters and particularly highlights the significant impact of confinement time scaling laws.

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Poster Session MCF 3 - L

3 P 181 - Tokamak GOLEM for fusion education — chapter 16: plasma edge, transport barrier, fast ion temperature, spectroscopy, magnetic islands, MHD stability

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ABSTRACT TEXT

This contribution is devoted to current student's projects at the GOLEM tokamak at the Czech Technical University in Prague with support of the Institute of Plasma Physics (IPP CAS). This device is the oldest operational tokamak in the world and is focused on the education of future fusion specialists. Uniquely, GOLEM tokamak features a full remote-control system which extends its reach worldwide. This is the first part of two contributions on this subject.

A new **combined Langmuir-Ball-pen electric probe** equipped with two Langmuir and two ball-pen probes has been installed, calibrated, and used for **advanced studies of the plasma edge**. **Spectral calibration of three compact spectrometers for visible light and near spectral ranges** was performed by students of the SUMTRAIC & EMTRAIC 2024 events. Surprisingly, several chlorine emission lines were identified in the measured spectra on GOLEM, **revealing erosion of the in-vessel diagnostics wiring**. Building on previous work [Macha-2023], the formation of a **spontaneous transport barrier was studied in helium plasma**. Scaling laws were derived to explain the dependence of the electron temperature gradient on plasma input power and density. **Ion temperature was measured** with an **ultra-fast temporal resolution of 5 μ s using a swept ball-pen probe** in hydrogen and helium plasmas. The study of MHD activity on GOLEM includes the **detection of magnetic islands using Mirnov coil signals**. A user interface was developed to enhance manual signal processing and visualization, with future plans for automation using AI. The **MHD stability of plasma** was also **investigated** by varying the plasma current intensity, pressure, and toroidal magnetic field. The **CAD geometry of the Golem tokamak** was converted to a suitable format to be **displayed via Google AR**. The attendees of the poster session will have a chance to look at the oldest working tokamak in the surrounding environment through their mobile device.

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Poster Session MCF 3 - L

3 P 182 - Fusion Twin Platform: an innovative tool for fusion research and education

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ABSTRACT TEXT

The Fusion Twin Platform (FTP), recently launched at <https://fusiontwin.io/>, is a free web-based tool designed to democratize access to advanced tokamak simulations, enable collaborative research in fusion science, and enhance plasma physics and fusion engineering education. FTP allows researchers, educators, and students to use pre-built digital replicas of tokamaks, enabling precise simulations, exploration of machine learning (ML) models, visualization of plasma dynamics, and flexible data management. By leveraging NSFsim [1], a free boundary equilibrium and transport solver, FTP supports customizable simulations and discharge scenario development. The platform supports diverse tokamak configurations, providing access to essential datasets and machine geometry while ensuring user privacy and data security. Fully web-based, FTP requires no additional software or hardware to run, making it accessible to users worldwide.

FTP offers fast and precise simulations, enabling users to customize magnetic equilibrium models, optimize discharge scenarios, and assess plasma stability for tokamaks like DIII-D, ISTTOK, SMART, and others. Its customizable visualization and analysis tools integrate AI-driven data interpretation, streamlining research workflows. Comprehensive data management ensures seamless access, upload, and download of fusion datasets. Collaborative workspace tools support data sharing, public links, and open science initiatives. The integrated JupyterHub environment provides Python notebooks and advanced extensions for interactive analysis. FTP also demonstrates and integrates ML tools, including a plasma boundary reconstruction model and reinforcement learning agents for plasma control.

Besides being a powerful tool for fusion research, FTP also has the potential to become an exceptional educational tool. It provides educators, students, and professionals transitioning from other fields to fusion with access to realistic tokamak simulations and interactive tools that bring fusion concepts to life. FTP enables hands-on learning experiences by allowing users to explore plasma dynamics, test ML models, and simulate real-world discharge scenarios within a secure, user-friendly environment. Furthermore, its collaborative features, such as shared workspaces and public links, foster teamwork among students and professionals while encouraging interaction between institutions. By integrating cutting-edge technology with practical educational applications, FTP bridges the gap between theoretical knowledge and practical understanding, inspiring both the next generation of fusion scientists and engineers and those seeking to expand their expertise into this field.

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Poster Session MCF 3 - T

3 P 183 - Compact shunts for the upper divertor of ASDEX Upgrade

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ABSTRACT TEXT

Thermocurrent shunt measurements of tiles in the upper divertor are required to support studies of advanced X-divertor and snowflake divertor configurations, which will be produced by the newly installed upper divertor coils of ASDEX Upgrade [1]. A thermoelectric voltage is generated by the plasma electron temperature difference in front of the two target plates of the divertor cassette. This voltage drives the halo current flowing in the tokamak scrape-off layer [2]. To locate the entry and exit points of halo currents from plasma-facing components, the voltage drop across the shunt resistor of the divertor tile is measured. This voltage is then used to determine whether the current is flowing into or out of the tile. In a tokamak, the heat flux to the target plates of the divertor must be controlled to avoid damage. Heat flux control is achieved by using nitrogen gas puffing to feedback control the tile current to achieve plasma detachment and reduce the heat flux to the plasma facing components in the divertor [3].

The compact shunts installed in the upper divertor of ASDEX Upgrade are based on the NSTX design [4]. The key component is the resistive shunt element, which is fabricated from a stainless-steel foil 5 cm long, 2.5 cm wide, and 0.3 mm thick. The toroidal symmetry of the shunt measurements can be studied because 4 toroidal arrays of 5 tile elements are available. In a discharge with a locked MHD mode, an $n = 1$ pattern was observed on the upper divertor shunts. In an X-point radiator discharge [5], edge-localised mode suppression was confirmed by the shunt measurements.

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Poster Session MCF 3 - T

3 P 184 - Tokamak GOLEM for fusion education – chapter 16: Bayesian discharge optimization, Artificial Neural Network tomography, runaway electrons, lithium evaporator, impurities

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ABSTRACT TEXT

This contribution is devoted to current student's projects at the GOLEM tokamak at the Czech Technical University in Prague in support of the Institute of Plasma Physics (IPP CAS). This device is the oldest operational tokamak in the world and is focused on the education of future fusion specialists. Uniquely, GOLEM tokamak features a full remote-control system which extends its reach worldwide. This is the second part of two contributions on this subject.

The **first test of the Golem tokamak discharge optimization using direct algorithmic control** of the device was conducted. With 4 discharge control parameters, the **Bayesian optimizer found optimal conditions for the longest discharge** with the given configuration and wall conditions within 30 iterations. The algorithm successfully controlled the machine for a full experimental session in the quest to reach the longest possible discharge. Training dataset optimization is being studied to enhance the performance of an **Artificial Neural Network (ANN)-based tomographic reconstruction of visible plasma radiation distribution** at the GOLEM tokamak. The **Timepix3 pixel detector** is being evaluated for its ability to **characterize X-ray emissions from runaway electrons (REs)**. Multiple scintillation probes, combined with Geant4 modeling, help infer RE properties from indirect HXR observations. Additionally, **in-vessel scintillation probe is being developed to enable direct RE detection**, offering more precise measurements. A **Lithium evaporator is currently being developed** to be used as an **impurity source for transport studies**. In the future, it could also be used as a lithium source for wall conditioning purposes. A remote experimental campaign was conducted from PUC-Chile, employing **2 ms spectrometry to evaluate wall conditioning and impurity effects** on hydrogen and helium plasma performance in GOLEM, through the time-resolved monitoring of emission lines. An **upgraded diamagnetic ring** was also installed into the tokamak.

Poster Session MCF 3 - T

3 P 185 - Efficient pinpointing of mode-particle resonances and transport barriers in realistic tokamak equilibria

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ABSTRACT TEXT

The equilibrium magnetic field in fusion plasmas is modified by symmetry-breaking magnetic field perturbations, which can arise either from intrinsically excited magnetohydrodynamic (MHD) modes, such as Alfvénic Eigenmodes (AEs) and GeoAcoustic Modes (GAMs), or from externally applied fields, such as Resonant Magnetic Perturbations (RMPs) and Toroidal Field (TF) ripples. The perturbative modes interact strongly with particles through resonances, facilitating the transport of particles, energy, and momentum. In our previous works [1–5], we considered a Large Aspect Ratio (LAR) equilibrium and derived compact analytical formulas [2,5] for the Orbital Frequencies (OF) of the Guiding Center (GC) motion and the kinetic q -factor (q_{kin}) as a function of the particle's Constants Of Motion (COM) using a Hamiltonian Action-Angle (A-A) formulation. The kinetic q -factor determines the selective conditions for resonant mode-particle interactions and allows for pinpointing the exact resonance locations in the COM space, as well as in the GC phase space [1,5]. Moreover, the local extrema of q_{kin} correspond to the locations of Transport Barriers (TB) formed in the GC phase space [4,5].

In this work, we extend the applicability of our Orbital Spectrum Analysis (OSA) methodology from LAR to numerically reconstructed equilibria. We employ a computationally efficient semi-analytical geometrical method applied on any given unperturbed equilibrium. The calculated resonance diagrams contain all the essential information for the response of all particle species — including energetic particles — in the specific equilibrium under the presence of any type of multi-scale symmetry-breaking perturbations. Systematic comparisons with numerical particle tracing show an excellent agreement with the predicted locations of the resonances and the Transport Barriers.

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Poster Session MCF 3 - T

3 P 186 - Robust solver for MRxMHD equilibria

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ABSTRACT TEXT

We present the development of a new robust equilibrium solver based on the stepped pressure equilibrium code (SPEC) [1]. Thanks to the MRxMHD model [2], the existing code SPEC allows for equilibria with arbitrary topology, including nested flux surfaces, magnetic islands, and chaos. As such, it has been used for fixed [3] and free boundary [4] equilibrium studies in cylindrical, tokamak, and stellarator geometries. In addition to the equilibrium calculation, SPEC also provides information on linear stability [5] and nonlinear stability, leading to applications such as the prediction of the saturated state of neoclassical tearing modes [6]. Despite its flexibility, the use of SPEC has been limited to simplified cases, e.g. poorly-resolved profiles or simple boundaries, due to severe issues with its numerical robustness. These stem from the numerical approach SPEC uses for finding force balance in the plasma, which is based on the Powell root-finding scheme [1] that exhibits fragility and is sensitive to initial conditions. In addition, the problems are caused by the representation of the force, which is expressed in a truncated Fourier spectrum [1] that hides significant non-zero force components, sometimes leading to an erroneous sense of convergence. Our approach overcomes these issues by employing trust-region-based least squares minimization scheme [7] that operate directly on the force in real space. We demonstrate the benefits of our approach by simulating equilibria in a cylinder with non-axisymmetric boundary, shaped tokamak, and an optimized stellarator. Furthermore, we show that the equilibria are robust to perturbations of the starting configuration. Finally, we also demonstrate that the approach works for configurations with multiple bifurcated equilibria, such as a cylindrical plasma subject to the tearing instability, where both the axisymmetric and magnetic-island equilibria are equilibrium solutions. By modifying the minimization objective, it is possible to select the non-axisymmetric equilibria and directly predict the saturated mode.

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Poster Session MCF 3 - T

3 P 188 - Initial simulations of core instabilities in MAST-U with the non-linear code JOREK

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ABSTRACT TEXT

Fast Ions (FIs) are ions which are more energetic than the thermal ion population and are present either as a result of fusion reactions (such as alpha particles) or deposited by auxiliary heating sources such as Neutral Beam Injectors (NBI). Certain MHD instabilities can cause a loss or redistribution of FIs, for instance fishbone (FB) modes, which are driven by resonant interaction between FIs and the MHD internal kink mode. FBs are undesirable as the confinement of FIs is imperative for heating and current drive; moreover loss of FIs can cause significant damage to plasma facing components. Detailed simulation of the interplay between FBs and MHD instabilities are therefore essential to understand the underlying physics and to develop mitigation strategies in order to maximise plasma performance and avoid unnecessary damage to the device.

Experimental studies of the interplay between FIs and MHD instabilities have been carried out on MAST-U already [1]. The source of FIs consists of two NBIs, one on-axis and one raised 65 cm above the midplane which drive a broad spectrum of instabilities among which FBs have the strongest impact on FI confinement.

This contribution reports about initial simulations of the interaction of FIs with the background plasma using the JOREK code [2,4] with the ultimate goal of comparing the results with experimental observations. First results of the simulation of internal kink modes in MAST-U using reduced and full-MHD models are presented here. This work builds up on a hybrid kinetic-MHD model that was previously implemented, benchmarked against other hybrid codes in simplified geometry, and applied to TAE modes in ASDEX Upgrade geometry [3].

For a full list of JOREK team members, refer to the author list of [4].

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Poster Session MCF 3 - T

3 P 189 - Convolutional Neural Network driven analysis of Strike Point Splitting in MAST-U

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ABSTRACT TEXT

In magnetic fusion devices, undesired non-axisymmetric magnetic field perturbations, typically called error fields (EF) [1], have been observed to have a detrimental effect on plasma stability and confinement and can lead to a brutal plasma termination. In particular, EFs with toroidal mode number $n = 1$ can cause mode locking of otherwise rotating magnetic island, such as the $m = 2$, $n = 1$ mode (being m the poloidal mode number), which is known to have a disruptive behavior [2].

Locked modes can also cause severe power exhaust problems since they tend to focus the boundary and scrape-off layer heat flux into small, intense, hot spots through strike point splitting. These events can impact plasma operations and cause substantial damage to plasma facing (PF) components [3, 4].

In this context, a wide database of MAST-U discharges has been analyzed considering heat flux data calculated from the InfraRed (IR) cameras viewing the lower divertor at nominal toroidal angles [5]. These data have been used to train a Convolutional Neural Network (CNN) [6] deployed for image recognition identifying the time of strike point splitting. The machine learning model performs a binary classification task on subsequent time slices of the heatflux map returning the likelihood of divertor strike point splitting in that time slice.

The reliability of such model has been assessed using different metrics based on the level of the prediction accuracy. The relevance of this work lies also on the possibility to detect, through the CNN, the LM formation and infer, from the IR data having high probability of strike point spitting, the topology of the EF itself [7, 8]. The knowledge of the EF is of fundamental importance to implement an effective correction strategy by means of 3D externally applied fields.

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Poster Session MCF 3 - T

3 P 191 - Neutral Beam Injection in a high-field reactor-like stellarator

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ABSTRACT TEXT

Stellarator power plants will require larger and denser plasmas than current experiments, thus necessitating higher-energy Neutral Beam Injection (NBI) systems. They will also operate at higher magnetic fields, with important consequences for confinement, including of energetic particles. This study aims to optimize NBI parameters for achieving efficient core power deposition while minimizing energetic particle losses in high-density, high-magnetic-field stellarators. It examines fast ion losses and their dependence on beam energy and injection direction. Different loss mechanisms exhibit distinct behaviors: prompt and non-collisional losses occur on short timescales, with non-collisional losses primarily affecting trapped particles over intermediate timescales. Collisional losses dominate later, driven by stochastic trapping-detraping processes responsible for transport toward the plasma edge. This research highlights the critical role of injection locations and directions in influencing loss fractions, plasma heating, and fueling, enabling a refined parameter space for optimization. Results indicate that beam energies around 300 keV may be necessary for high-field stellarators. While these require negative-ion NBI systems[2,3], they remain below the 500–1000 keV range[1] where engineering challenges become substantial.

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Poster Session MCF 3 - T

3 P 192 - Study of kinetic effects on the 1/1 internal kink mode using the hybrid kinetic MHD spectral code VENUS-KMHD

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ABSTRACT TEXT

Large scale instabilities, which present a major risk for the integrity of fusion devices, must be prevented. Ideal magnetohydrodynamics (MHD) is often successfully used to study these modes. However, kinetic effects due to bulk particles or minority energetic ions can alter significantly their ideal stability property. In order to describe such effects that go beyond the MHD description, we consider the kinetic MHD model of [1] that add to the MHD momentum equation kinetic pressure corrections obtained using a drift-kinetic equation. Many existing works handle such kinetic MHD equations by solving at least partially analytically the kinetic equation before inserting the result in the MHD momentum equation. Some approximations, mainly on the particle orbits, are often required in this process. Another option is to do a time integration of the particles orbits. This does not require the previously mentioned assumptions but results in a higher numerical cost. Using the Case-Van Kampen approach [2], we express the linearised kinetic MHD system of integro-differential equations as a standard linear generalised eigenvalue problem where the mode frequency is the eigenvalue and the eigenvector consists of the MHD displacement along with the non-adiabatic contribution to the perturbed distribution function of the kinetic species. The resulting eigenvalue problem is solved using an iterative sparse eigenvalue solver. In this work, we limit ourselves to a single kinetic species. The 1/1 internal kink mode is studied here as it is a good test case to observe significant kinetic effects. We consider at first a simplified case in cylindrical screw pinch geometry. This allows us to test most of the code components at a lower numerical cost since there is no coupling between poloidal Fourier modes. It also enables the benchmarking of certain relations against exact analytical derivations. One can for example solve exactly the drift-kinetic equation and obtain the corresponding kinetic perturbed pressures for a given MHD configuration. Benchmarks against analytical and semi-analytical results are presented in this geometry. First results as well as relevant benchmarks are then presented in realistic toroidal geometry.

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10/07/2025, 14:30–16:15, Room: Poster area - Terrace

Poster Session MCF 3 - T

3 P 193 - Auburn University CTH and W7-X Research Progress and Plans*

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ABSTRACT TEXT

The Compact Toroidal Hybrid (CTH) is a torsatron/tokamak hybrid. The main goals of the CTH experiment are to study disruptive behavior as a function of the applied 3D magnetic shaping, and to test and advance computational tools able to describe 3D MHD physics such as the V3FIT reconstruction code and NIMROD modeling of CTH. Recent non-resonant divertor experiments, vertical stability, and runaway electron studies will be overviewed and their relevance to tokamaks and quasi-symmetric stellarators will be discussed. Ongoing diagnostic development for the experiment includes development of new Hall probe array measurements, new spectroscopic studies of W and other high Z materials. Auburn research on W7-X will be summarized including the development of a new coherence imaging ion temperature measurement, study of drift effects on divertor operation, plans for plasma edge Tungsten optical measurements and core Tungsten transport experiments using x-ray spectroscopy.

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Poster Session MCF 3 - T

3 P 194 - Testing the modes coupling effect on flux pumping in plasmas

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ABSTRACT TEXT

Recent obtained results [1] show a possible connection between the sawtooth oscillations suppression via the magnetic flux pumping mechanism and the poloidal coupling between the $n = 1$ modes leading to the anomalous transport and broadening of the plasma current profile. It has been found a clear association between the amplitude of the edge plasma modes and the occurrence of the sawtooth activity. A multi-mode perturbations model [2] that comprises a full poloidal modes coupling technique description is used to assess these results. Due to the considered axisymmetric approach, there is no toroidal modes coupling taken into account other than the one driven by the plasma external structures toroidally inhomogeneous resistivity, obviously not relevant from an inner plasma point of view. Therefore theories stating the broadening of the current profile explained by the coupling between ELMs of various toroidal mode numbers and the $3/2$ mode whose lower sideband is resonant with $q = 1$ [3] cannot be covered here due to our model limitations. However the plasma robust poloidal coupling is fully considered in order to test and check the possible flux pumping boost due to the $1/1$ and its upper sideband $n = 1$ modes poloidal coupling. It will be determined how the $n = 1$ modes coupling affects the calculated central safety factor via the derivation of the mode location, while theoretically retrieving the measured $q = 1$ mode amplitude, compared to the uncoupled case.

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Poster Session MCF 3 - T

3 P 196 - Benchmarking pressure stabilisation of neoclassical tearing modes in a spherical tokamak using the reduced MHD implementation of the JOREK code

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ABSTRACT TEXT

Plasmas in the Mega Ampere Spherical Tokamak-Upgrade (MAST-U) are performance limited by MHD instabilities. The $q = m/n = 2/1$ tearing mode has been identified as one of the most deleterious modes, occurring in the majority of MAST-U shots and reducing plasma beta by $\sim 25\%$ [1]. Without an active stabilisation scheme, such as Electron Cyclotron Current Drive (ECCD), it is imperative that alternative stabilisation schemes are found if record performance is to be achieved. Such proposed schemes include current profile modification through heating to reduce classical drive[2], H-L-H mode transitions with vertical kicks to temporarily stabilise the mode[3], flux pumping to mitigate sawteeth which seed tearing modes[4], Electron Bernstein Wave Current Drive (EBWCD)[5] and plasma shaping[6]. Experiments for these approaches have been proposed for the MU04 and upcoming MU05 MAST-U campaigns. However, the limited number of experiments in each of these scenarios may limit exploration of the full parameter space. Hence, modelling these scenarios using an MHD code, such as JOREK[7], aims to provide further insight into the effectiveness of each stabilisation scheme listed above.

JOREK is an MHD solver capable of simulating tokamak plasmas with arbitrary shape. Present in JOREK are models for both reduced and full MHD. The reduced MHD implementation in JOREK removes fast magnetosonic waves which are assumed to be decoupled from the slower, resistive behaviour in many of the MHD phenomena observed in tokamaks[7]. A consequence of this is that parallel magnetic field fluctuations and the contribution of FF' to the equilibrium toroidal field are neglected. Thus, core pressure-driven instabilities may be overstabilised[8], resulting in inaccurate growth rates. In this work, we perform benchmarks between JOREK, linear, and non-linear analytic theory using experimental MAST-U equilibria. These benchmarks determine the significance of the reduced-MHD approximation on the tearing mode-stabilising Glasser-Greene-Johnson term in the Modified Rutherford Equation, which primarily forms due to the interaction of pressure fluctuations with magnetic field curvature[9]. Such stabilisation is important in spherical tokamaks such as MAST-U where curvature is significant. The outcome of this work will provide a basis for exploring the tearing mode stabilisation schemes outlined above using JOREK's reduced MHD implementation.

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Poster Session MCF 3 - T

3 P 197 - Simulation study of magnetohydrodynamic instabilities in Variable Symmetry Torus

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ABSTRACT TEXT

The Variable Symmetry Torus (VAST) is one of the next device candidates at the National Institute for Fusion Science (NIFS), and has the feature that different quasi-symmetric magnetic configurations such as quasi-axisymmetric (QA) and quasi-isodynamic (QI) magnetic configurations can be realized by adjusting the coil current[1]. In this study, the magnetohydrodynamic (MHD) stability of the QA and QI configurations in VAST was evaluated using simulations. In the analysis, MHD equilibria were constructed using the HINT code, and linear and nonlinear evolution of MHD instabilities were analyzed using the MIPS code and the MEGA code, where the MIPS code is based on an MHD model, and the MEGA code is based on a kinetic MHD model that takes into account the kinetic effects of thermal ions. The analysis has been carried out for the MHD equilibrium with a central beta of 2% for both the QA and the QI configurations. In the VAST, the equilibrium magnetic field has a two-period symmetry in the toroidal direction, so that the linear modes generate coupling between the toroidal modes in addition to coupling between the poloidal modes. From the simulation results, it was found that ballooning modes with strong toroidal mode coupling can be destabilized in both the QA and QI configurations. It was also confirmed that these modes can be further destabilized by the diamagnetic drift effects. Using the MHD model that neglects the kinetic effects of thermal ions, there is no significant difference in the perturbed pressure profile of the MHD instabilities in the QA and QI configurations. However, when considering the kinetic effects of thermal ions, the perturbed pressure profile in the nonlinear saturated state showed distinct characteristics: in the QA configuration, the perturbed pressure profile was isotropic, whereas in the QI configuration, the perturbed pressure component perpendicular to the magnetic field increased in the weak magnetic field region, resulting in a pronounced anisotropy in the perturbed pressure profile.

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Poster Session MCF 3 - T

3 P 198 - Analytic and numerical investigation of global ideal magnetohydrodynamic instabilities driven by strong toroidal rotation in tokamaks

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ABSTRACT TEXT

Toroidal rotation in tokamak plasmas has been shown to stabilize several performance-limiting instabilities. However, for toroidal flows of the order of the ion sound speed (Mach number $M \sim 1$), a rotation-driven magnetohydrodynamic (MHD) instability can grow [1]. Two main driving mechanisms for the mode have been identified; the first is a dynamic pressure gradient across the mode width, which can be regarded as a rotational analogue to the thermal pressure drive of infernal modes. The second involves the rotation-induced variation of density along magnetic field lines which occurs for isothermal equilibria. This mechanism is purely stabilizing for poloidal mode number $m = 1$, but can drive the instability for $m > 1$ given sufficiently large (negative) density and rotation gradients. In this work, an $M \gg 1$ asymptotic expansion of the rotation-driven mode dispersion relation is used to analyze the mode's driving and damping mechanisms in the presence of strong density, temperature and thermal pressure gradients. This analytic model is compared favorably against the full MHD code VENUS-MHD [2]. The rotation-driven mode is shown to be damped by the $M \gg 1$ limit of the geodesic acoustic mode frequency [3]. For large rotation amplitudes, strong mode drive is observed when the density is peaked in the core and the temperature and rotation profiles are flat. If, on the other hand, density is held constant and the (negative) temperature gradient is increased, a stabilizing effect is observed. In cases where this stabilizes the mode completely, a sufficiently large density gradient can re-excite the mode. A competition between rotation and thermal pressure drive for the instability is additionally found. The relationship between the rotation-driven instability and the pressure-driven internal kink is explored analytically and numerically by 'scanning' from the sub-sonic ($M \ll 1$) to the sonic ($M \sim 1$) regimes. In the sub-sonic regime, rotational stabilization of MHD modes is expected. The 'window of stability' existing between both regimes is explored.

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Poster Session MCF 3 - T

3 P 199 - Spectroscopic diagnostics for the plasma edge of RFX-mod2 device

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ABSTRACT TEXT

RFX-mod2 experiment is the upgraded version of RFX-mod Reversed Field Pinch device, designed to obtain improvements in the magnetic boundary. The magnetic structure will be characterised by the presence of modes, that will give a 3D shape to the plasma edge and to the plasma-wall interaction. In order to characterize this complex structure, starting with the knowledge obtained with the previous RFX-mod experiment, different spectroscopic diagnostics in the visible range have been designed, that view a large part of the internal wall. The 3D plasma-wall interaction will be monitored by 7 visible cameras equipped with CII filters; a MANTIS device integrates this information by measuring different emission lines; the Light Impurity Tomography will provide the poloidal structure of the plasma edge by measuring 3 different neutral species; a Thermal Helium Beam will measure n_e and T_e profiles in the edge, and the GPI the high frequency turbulence. All together, they would allow a complete characterization of the 3D plasma edge, and of the interaction between magnetic topology, plasma shape, and turbulent transport. These diagnostics are described, and their performances are discussed.

Poster Session MCF 3 - T

3 P 200 - Investigation of mode structure from BES signals in MAST Upgrade

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ABSTRACT TEXT

The 2D beam emission spectroscopy (BES) system of the MAST Upgrade spherical tokamak is a diagnostic tool for the measurement of various turbulent and MHD phenomena. With the help of recently developed tools to assess the effective resolution of the system, the localization of its different channels can be even better understood. Vertical resolution is in the range of 2–5 cm, radial resolution is between 1 and 1.5 cm, while the sampling frequency of the system is 4 MHz. The MAST-U BES system is, therefore, a great candidate for testing novel BES-signal-analysis methods.

In this work, we present the first results of using the continuous time-frequency transform-based tools of the NTI Wavelet Tools [1,2] data analysis package to characterize plasma waves observed in the BES signals of MAST-U. These signal analysis tools are especially well-suited for the study of transient phenomena, like chirping Alfvén eigenmodes or fast particle modes. NTI Wavelet Tools can be used to identify coherent plasma fluctuations across multiple signals, determine the phase relation between signals, and determine the mode number or wave number, and the radial structure of the modes, depending on the spatial localization of the available measurement channels. A high temporal resolution and time-shift invariance are ensured using continuous linear time-frequency transforms to acquire time-frequency spectra without major distortions.

The BES system of MAST-U provides a set of channels arranged in a matrix in the radial-vertical direction, thus, radial localization and poloidal structure of the modes can be studied, which can contribute to the identification and characterization of plasma waves. Neoclassical tearing modes and fast-particle-driven MHD instabilities are still widely studied at MAST-U, and they pose as prime candidates for such an analysis.

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Poster Session MCF 3 - T

3 P 201 - Enhancement of the TCV radio frequency antenna for detection of plasma instabilities by runaway electrons and electron cyclotron waves

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ABSTRACT TEXT

In 2021, an in-vessel radio frequency antenna was installed in one of the exterior ports of the Tokamak à Configuration Variable (TCV). Since then, a series of experiments has been conducted to detect electromagnetic waves originating from runaway electron (RE)-driven plasma instabilities. These instabilities have attracted particular interest in recent years, as they may contribute to RE mitigation strategies in tokamaks by enhancing RE transport and limiting their energy. TCV is particularly attractive for its ability to safely generate RE under a variety of conditions and is well equipped to diagnose their dynamics, thus becoming a noteworthy facility for investigating these instabilities across a variety of RE scenarios. The antenna system is currently undergoing a comprehensive enhancement aimed at advancing its diagnostic capabilities. The refurbishment focuses on improving the detection efficiency of plasma instabilities driven by RE and, additionally, on exploring the potential to measure hundreds-of-MHz-range daughter waves that may be produced by the parametric decay instability of second-harmonic gyrotron beams polarized in extraordinary propagation mode. The upgraded antenna system will incorporate innovative design solutions to address the limitations of the current setup. Different possibilities for a new antenna configurations are being explored. Electromagnetic simulations using Ansys HFSS and CST Studio Suite are guiding the design process, ensuring the compactness required for the system to fit within the spatial constraints of the relatively narrow TCV port. Furthermore, a state-of-the-art data acquisition system will replace the existing digitizer, enabling longer acquisition times and improved flexibility for detecting signals. The current status of the enhancement activity is presented.

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Poster Session MCF 3 - T

3 P 203 - Spatiotemporal investigation of visible radiation distribution around attachment-detachment transition on Wendelstein 7-X

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ABSTRACT TEXT

Detachment is an active and important research topic of magnetically confined fusion experiments. During detachment, a significant fraction of thermal power is dissipated as radiation, which reduces the loads on the divertor target plates. This makes it a promising candidate for an exhaust solution in future fusion power plants. On Wendelstein 7-X (W7-X) detachment is routinely achieved, a stable detachment lasting 110 s was already demonstrated for input power of 4 MW, during which the heat flux to the divertor target plates was negligible[1]. Understanding the changes in the transport processes around the attachment-detachment transition is of utmost importance not just in terms of getting a deeper insight into the process itself, but also to further optimize the operational scenarios. The EDICAM overview camera system can observe the majority of the vacuum chamber of W7-X. The EDICAMs have a view at the inner wall, where—after a spatial calibration and in the presence of plasma—the observed visible radiation patterns can be put in relation to the edge magnetic topology. Using this view and visualizing the magnetic field lines following the X- and O-points, the dynamics of the radiation distribution around these points can be observed in time. During detachment the divertor radiation is getting less intense than in the attached phase. Usually, filamentary structures brighten up around some of the X-points and inside some islands, especially at the inboard side of the device. The purpose of this contribution is to compare detachment dynamics in different magnetic configurations by using all available EDICAMs.

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3 P 204 - Electron density and temperature profiles from spectroscopy in the upper divertor plasma of ASDEX Upgrade

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ABSTRACT TEXT

The analysis of advanced divertor configurations in the new upper divertor of ASDEX Upgrade requires measurements of electron density and temperature profiles not only at the target but also in the volume of the divertor plasma. In addition to a new Thomson scattering diagnostic in the upper divertor, a new spectroscopic diagnostic now also delivers this information. Four optical heads observe the divertor plasma with purely toroidal viewing geometry guiding the lines-of-sight (LOS) to boron tiles, which have a black surface. Each head has LOS at a constant height and probes the plasma with 10 to 15 tangency radii. Fits similar to an Abel-transformation, deliver local data, i.e. radial profiles at the four heights, for all spectroscopic accessible quantities.

The spectra of a high- n Balmer line, i.e. $D\epsilon$ ($n = 7-2$), has been measured on all LOS and the radial electron density profiles are obtained from the spectra via the Stark broadening. Furthermore, also the emissivity profiles of $D\epsilon$ is a result of the fits of the absolutely calibrated spectra. From emissivity and electron density, the radial profiles of the electron temperature are obtained. This is possible since the three body recombination, i.e. the inverse process of the electron impact ionisation, is much more frequent than the radiative recombination and the ionisation time scale is much shorter than transport time scales, such that the Saha equilibrium between the bound electrons in the high- n state and the free electrons is established at the local electron temperature. Collisional-radiative models yield that at $n_e = 1E20 \text{ m}^{-3}$, the emissivity deviates from the Saha equilibrium by less than 1% for $T_e = 0.5-50 \text{ eV}$ while the equilibration is established on time scales shorter than 5 ns.

For divertor plasmas in the parameter range of interest, i.e. cold plasmas near detachment, the measured radiances are very strong, as they scale with $n_e^2 T_e^{-3/2}$. Thus, the temporal resolution of $\approx 3 \text{ ms}$ is only limited by the capabilities of the CCD cameras used in conjunction with the four spectrometers dedicated to these measurements. The analysis method will be discussed and the profile evolution for interesting cases will be presented.

Poster Session MCF 3 - T

3 P 205 - TWINTOK: a digital twin approach for refined comparison between experimental data and plasma simulations

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ABSTRACT TEXT

Studying fusion plasmas in tokamaks is challenging due to the difficulty of obtaining complete measurements in extreme environments. To overcome this, we are developing TWINTOK [1], a digital twin that integrates synthetic diagnostics to enhance the interpretation of plasma behavior beyond what direct measurements can provide.

This work expands TWINTOK's scope by incorporating synthetic diagnostics for visible cameras, spectroscopy, bolometry, interferometry, reflectometry and infrared imaging to analyze WEST discharges during ramp-up and different magnetic configurations as a testbed. The SOLEDGE-HDG fluid transport code [2], based on a high-order Hybridized Discontinuous Galerkin (HDG) scheme, offers a detailed yet computationally efficient model of heat exhaust and plasma evolution throughout an entire discharge, making it an ideal input for TWINTOK. TWINTOK uses synthetic diagnostics to compare simulations with experimental data while following the IMAS [3] data standard foreseen for ITER. The TIP interferometer synthetic diagnostic, adapted for WEST, shows strong agreement with experimental results. Spectroscopic diagnostics, simulated with Raysect [4] and Cherab [5], help track impurity sources and plasma radiation. Bolometry synthetic diagnostic reveals how plasma composition and reflections affect signal levels. FeDoT synthetic reflectometry, using 1D and 2D full-wave simulations, provides insight into edge fluctuations and turbulent transport. Our project on a transport model in the SOL includes predictive AI tools detecting filaments in simulations and both experimental and synthetic reflectometry data, producing an effective transport coefficient for simulations. We are currently focusing both on improving the reliability of plasma simulations, in particular by refining the models for neutrals, impurities and heating sources in SOLEDGE-HDG, and on developing AI-based tools for detecting patterns such as separatrix position and filaments in TWINTOK outputs. In parallel, we are investigating how variations in plasma conditions, such as density, impurity content or magnetic topology, affect diagnostic signals. By quantifying these effects, we aim to improve the reliability of comparisons between simulations and experiments, reducing uncertainties in the validation process. Together, SOLEDGE-HDG and TWINTOK provide a powerful framework for improving our understanding of plasma behavior and edge physics.

ACKNOWLEDGEMENTS

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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10/07/2025, 14:30–16:15, Room: Poster area - Terrace

Poster Session MCF 3 - T

3 P 206 - Real-time Bayesian inference from TCV bolometry data

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ABSTRACT TEXT

Bolometer data acquired by the RADCAM diagnostic at TCV will soon become available in real-time. This upgrade opens the possibility of integrating new key information into the TCV plasma control system. This work demonstrates how Bayesian tomographic techniques can be leveraged to perform real-time tomography-based estimates of the core, edge, and divertor radiated power at TCV. The Bayesian nature of the considered techniques allows them to provide uncertainty quantification metrics associated with the predicted quantities. We illustrate the potential of the proposed approach by analyzing both model phantoms and TCV discharge data, showing that insightful results can be obtained. We benchmark the results by comparing the real-time predictions both to simpler non-Bayesian approaches and to post-shot offline traditional tomographic pipelines, which are not real-time compatible due to computational requirements. Finally, we discuss a possible way to integrate magnetic equilibrium information in the procedure and address the overall limitations of the approach.

Poster Session MCF 3 - T

3 P 207 - First results from LIBS characterization of plasma facing components in ADITYA-U Tokamak

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ABSTRACT TEXT

The performance and longevity of tokamak discharges are significantly influenced by Plasma-Wall Interactions (PWIs), including impurity deposition, re-deposition, and fuel retention in plasma-facing components (PFCs). In ADITYA-U, wall-conditioning techniques such as Lithiumization, Boronization, and Glow Discharge Cleaning (GDC) are routinely employed, with a residual gas analyzer (RGA) used for volume gas analysis. However, RGA does not provide direct quantitative measurements of surface impurity levels.

To address this limitation, we have developed an in-situ Laser-Induced Breakdown Spectroscopy (LIBS)-based diagnostic system for real-time characterization of PFCs. LIBS offers remote, rapid and precise impurity analysis without the need for sample preparation or vacuum vessel exposure. The system operates by focussing a pulsed laser onto PFC surfaces, generating a plasma plume whose emitted spectra are analyzed using a spectrometer. The sample assembly is isolated from the tokamak vacuum by a gate valve, enabling operation between plasma discharges and under varying ambient gas conditions.

This paper presents the design and calibration of the LIBS setup for PFC characterization. Plasma-facing component (PFC) samples, exposed to different regions of the plasma for varying durations, were extracted from ADITYA-U during the maintenance phase following an experimental campaign. The impurity deposition and fuel retention in these samples were analyzed using LIBS and compared to unexposed reference materials. The results demonstrate LIBS as a promising tool for in-situ monitoring of PFC conditions, contributing to improved plasma performance and wall-conditioning strategies.

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Poster Session MCF 3 - T

3 P 208 - Leveraging neural networks for real-time beam emission inference

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ABSTRACT TEXT

Beam emission spectroscopy [1] (BES) is an active plasma diagnostic employed for plasma density measurements. In multiple BES applications such as synthetic diagnostics and density inference models computationally expensive emission inference calculations are utilised to determine the expected emission for a given density profile. The resource intensiveness of such calculations limits the applicability of BES for real-time measurements, while also restricting the speed of synthetic diagnostics.

In this work, we present a possible solution to this problem in the form of a neural network that can predict the expected emission profile on a sub-millisecond timescale.

Building on our previous work [2] we trained an extreme learning machine [3] network and show that not only it works well on various synthetic datasets generated to simulate different BES beam flavours, but also it maintains its high performance on experimental data obtained from the Li-BES system on ASDEX Upgrade [4].

We also show that even in the most extreme edge localized mode burst like cases, the emission predictions provided by the network remain smooth with no additional roughness other than the one coming from the numerical resolution of the profiles.

A separate model was developed to provide prediction uncertainty estimates for the emission profiles predicted by the neural network.

Finally, we examined the possibility of integrating the neural network into the IDA framework [5].

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Poster Session MCF 3 - T

3 P 209 - Modeling electron cyclotron emission for investigation of ECE – Thomson Scattering discrepancy in Alcator C-Mod

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ABSTRACT TEXT

Electron cyclotron emission (ECE) radiometry is a well-established diagnostic technique capable of providing high spectral and temporal resolution measurements of electron temperature profiles in toroidally confined plasmas. However, for many years, there have been reports of discrepancy between ECE and Thomson scattering (TS) measurements. This poster will present two formulations for ECE and identify a possible candidate for the discrepancy between two diagnostics. The initial model is based on the ECESIM code [1], which assumes plasma in a thermodynamic equilibrium and treats the emission-absorption phenomena using power transfer [2]. This established framework is compared with a further enhanced model which utilizes generalized expressions for optical constants [3]. A heuristic bipolar model of perturbed Maxwellian [4] is applied to the novel modelling tool. Performance of the code is evaluated by deployment of both models across three different machines. Calculations are compared with experimental ECE measurements from Alcator C-Mod and DIII-D. Prediction of ECE behavior is projected for SPARC. A variety of perturbations to the distribution function and the effect on ECE are investigated computationally. The ECE model has been applied to a database of Alcator C-Mod data to study the implications of a perturbed distribution function for the Thomson-ECE discrepancy.

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Poster Session MCF 3 - T

3 P 210 - Overview of the optical emission analysis of the hydrogen gas puff experiments in the linear plasma device PSI-2

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ABSTRACT TEXT

The linear plasma device PSI-2 [1] is actively used for both material-plasma interaction research and for studies of atomic and molecular kinetics in strongly ionized magnetized plasmas. In particular, this experiment can be utilized for validation of the models of molecular processes relevant for boundary plasma of magnetic fusion devices. Dissociation of hydrogen molecules as well as other molecular reactions, such as formation and destruction of molecular ions, are sources of electronically excited atoms. Thus, they affect the intensity of the Balmer line radiation [2] which can be examined by means of Optical Emission Spectroscopy (OES) and compared with model predictions. The PSI-2 experiment is equipped with several OES diagnostics: imaging spectrometer, high resolution spectrometer, hyperspectral camera. The main plasma parameters are measured with a movable Langmuir probe. Extra H₂ gas puff in the target chamber allows to increase the gas pressure and scan over different regimes ranging from ionizing to recombining plasma [3, 4]. The typical discharge parameters are electron temperature 0.1..10 eV, electron density of the order of 10¹⁸ m⁻³, molecule density 10¹⁸..10¹⁹ m⁻³. Spatially resolved intensities of H α ...H δ lines measured by the imaging spectrometer are analyzed. In addition, Fulcher- α bands recorded by the same spectrometer provide the information about the rotational and vibrational temperatures [5, 6]. Current status of the experimental work and theoretical analysis of the results will be discussed.

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Poster Session MCF 3 - T

3 P 211 - Real-time pellet ablation radiation monitoring for a refined plasma core density control in ASDEX Upgrade

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ABSTRACT TEXT

The capability for reliable core density control is a key requirement in a future fusion reactor. In e.g. EU-DEMO, the designated solution relies entirely on pellets; mm-sized bodies formed from solid hydrogen fuel. Fuelling pellets have to be injected from the torus inboard side and hence transferred through a curved guiding system. Thus, pellets undergo high mechanical stresses during acceleration and transfer. This will result in considerable size distribution of pellets and in some cases their complete loss. In EU-DEMO, unrecognized missed-out pellets are predicted a potential cause of disruptions and regarded even as safety importance class events.

At ASDEX Upgrade (AUG) efforts are under way to develop methods that recognize and counteract the effects of missed-out pellets and pellet mass variations. They rely on pellet arrival recognition and monitoring of the arriving pellet mass in real-time. Our approach analyses the intense radiation emitted during pellet ablation, for any pellet launch request either its arrival is confirmed or a missed-out case is stated. As a first test for corrective action in case of a missed-out detection, an immediate substitution request will be implemented. Subsequently, rather than characterising the pellet size just as 0 (missed-out) or 1 (confirmed), we envisage to commission an estimator for the arriving pellet mass, mapping the total amount of emitted ablation radiation to the pellet size range 0–1, with 1 being the maximum size. This mapping requires not only the numerical integration of the ablation radiation signal in real-time, but also to consider the potential impact of several pellet and plasma parameters. Data from past investigations indicates an empirical power function comprised of the relevant pellet and plasma parameters is capable of a tentative control approach. Modelling with the HPI2 pellet ablation/deposition code is planned to explore the underlying physics of such a correlation. It showed a sufficiently precise determination of the number of particles deposited by the pellet is achieved in experiments where pellets induce a temporal density perturbation under steady plasma conditions. Development efforts on the new features during the ongoing AUG campaign, ongoing analysis and the achieved results will be reported.

Poster Session MCF 3 - T

3 P 212 - Upgrade of the TJ-II passive-spectroscopy system to improve estimations of carbon ion temperatures

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ABSTRACT TEXT

Understanding the dynamics of impurity ions in MCF plasmas is essential to optimise the performance of future reactors. To determine impurity parameters, spectroscopic techniques are typically employed. The Doppler Effect is used to analyse spectral broadening of spectral lines, which is related directly to ion temperature, T_i . This technique, combined with CXRS [1], enables localized measurements of spectral lines emitted by plasma impurity ions, which provides valuable information about their temperature. These methods complement each other by offering a deeper insight about the T_i . In this work, Doppler spectroscopic measurements are performed to determine the C^{+4} ion temperatures. For this, a CCD, with a 400×1340 -pixel matrix, is coupled to a 1 m focal length spectrometer. The 400 pixels are oriented along the wavelength dispersion direction, the 1340 pixels are oriented to collect light from across the plasma diameter, and a mechanical shutter is used during readout. Then, the 1340 pixels are binned into 72 channels. This represents a significant improvement over the previous system in TJ-II, which was based on 9 lenses with 9 optical fibres [2]. The T_i 's are derived from the FWHM of the spectra using a Gaussian fit. Moreover, the new setup allows us to estimate the T_i with 43 points per profile instead of the previous 9 ones. Eliminating the 9 lenses with their corresponding 9 fibres simplifies system alignment, and avoids dead zones where information was lost due to the multiple mount assemblies. With this, a more accurate extraction of spectroscopic parameters is ensured, increasing the reliability of the measurements.

Experiments are performed with 150 discharges of NBI-heated TJ-II plasmas with different plasma conditions, including different hydrogen isotopes. The results show a dependence of the T_i not only on plasma density but also on the NBI. These preliminary results will be compared with neoclassical transport simulations. Experimental measurements of radial electric fields will also be used to analyse T_i profiles. These findings contribute to a better understanding of impurity transport in stellarator plasmas and provide a basis for future studies of the interaction between fast NBI-driven ions and the impurities in MCF plasmas.

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Poster Session MCF 3 - T

3 P 213 - A neural network approach to real-time electron density reconstruction from alkali beam emission spectroscopy data at W7-X

Balázs Molnár¹, Gergő Pokol^{1,2}, Azarakhsh Jalalvand³, Örs Asztalos^{1,2}, Máté Karácsonyi^{1,2}, Leon Armbruster⁴, Miklós Vécsei⁵, Anders Henry Nielsen⁶

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ABSTRACT TEXT

Understanding edge plasma behavior in stellarators is essential for optimizing confinement and stability. Electron density profiles provide key information for studying turbulent transport, detachment and impurity dynamics. The alkali beam emission spectroscopy (ABES) is a powerful diagnostic for measuring density fluctuations in the edge plasma, offering a temporal resolution below 10 μ s and a spatial resolution under 0.5 cm. Reconstructing absolute electron density from ABES signals requires solving the inverse of the rate equations governing the excitation, de-excitation, and ionization of injected neutral beams. If rate matrices are available by means of e.g. other diagnostics, the electron density can be inferred from measured atomic transition light yields. Traditionally, this reconstruction is performed using a Bayesian approach, maximizing the a posteriori probability of a given density profile producing the observed light profile [1]. While accurate, this method is computationally expensive and unsuitable for real-time plasma control. To accelerate the reconstruction, a direct linearized reconstruction technique has been developed [2], relying on a database lookup to first find an approximate density profile close to the real solution such that the linear assumptions hold. However, this approach is limited by database completeness and is prone to noisy input. Recent advances in machine learning have enabled fast surrogate models for density reconstruction. In particular, multilayer perceptrons have demonstrated promising results in predicting electron density profiles from ABES data, as shown in JET tokamak experiments [3].

Our previous studies [4], focusing on the forward problem i.e. predicting light profiles from density data, confirmed that extreme learning machines can capture the underlying physics of the forward problem but exhibit high sensitivity to noise. Here, we propose solving the inverse problem using a similar model architecture with modifications to improve robustness against noise. Specifically, we investigate reservoir computing, allowing the model to retain memory of previous time steps, and physics-informed neural networks (PINNs), which incorporate physical constraints into the loss function to exclude non-physical solutions typically arising from noisy input. These methods aim to improve the accuracy and reliability of real-time density reconstructions, paving the way for data-driven plasma control strategies.

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Poster Session MCF 3 - T

3 P 214 - Conditional averaging of overlapping pulses — a method to characterize large-amplitude fluctuations in the SOL

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ABSTRACT TEXT

Conditional averaging is a signal processing method often used in analysis of measurement data from Langmuir probes and imaging diagnostics in the edge and scrape-off layer of magnetically confined plasmas to extract information about large-amplitude events [1–7]. The method is commonly used to obtain the amplitudes, waiting times, durations and average pulse shape of the signal for the events.

The main objective of this work is to use synthetic data to examine if the outputs from conditional averaging are representative of the underlying statistical properties of the signal. We focus primarily on the effects of overlapping pulses, while earlier studies have focused on the effects of noise and non-overlapping pulses [8–10]. The synthetic data consists of a superposition of pulses where amplitudes, arrival times, durations and pulse shapes are predetermined. We also examine different additional conditions to the basic amplitude threshold condition and see how they affect the results.

We find that input amplitude distributions, mean durations and pulses are reproducible when the ratio of the average pulse duration to the average waiting time is less than one. Symmetric input pulses are generally more reproducible than asymmetric ones, with conditionally averaged pulse shapes becoming more symmetric as pulse overlap within the signal increases. Pulse overlap is shown to efficiently destroy information about the underlying waiting time distribution for all but the lowest degrees of pulse overlap. This leads to conditionally averaged waiting time distributions which resemble exponential distributions for a wide variety of input waiting time distributions. We also find that the mean of the waiting time estimates is not representative of the underlying mean.

In conclusion, conditional averaging is best used for signals with low to moderate degrees of pulse overlap. Input amplitude distributions, mean durations and pulse shapes are reproducible, but information about underlying waiting times is lost with use of the method.

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Poster Session MCF 3 - T

3 P 215 - Projecting stellarator reactors based on empirical scaling: uncertainties, risks and implications for the international stellarator research

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ABSTRACT TEXT

In recent years, the stellarator research community has made substantial progress in developing and verifying models and codes that will eventually allow predictive simulations of non-existing devices, such as future stellarator reactors. However, empirical scaling (e.g. of energy confinement time and density limit [1,2]) is still used today to discuss and project future machines. This will possibly continue to be the case in the near or medium term, before full-device (core, edge and SOL) first-principles simulation capabilities materialise.

In view of the ever more likely prospect of starting the design and construction of a first stellarator fusion reactor in the coming decades, an analysis of the uncertainties and risks when basing design decisions on an empirical scaling is in order. Moreover, such analysis can help identify research areas of high priority to increase the confidence on those projections and retire risks, which is an on-going activity within the EUROfusion plasma science department.

In this contribution we will review the physics behind the International Stellarator Scaling for the energy confinement time (ISS04) and the Sudo density limit and the largest leaps in extrapolating them to reactor conditions. The latter was derived in present day devices with carbon-dominated radiation [3], whereas the former is based on a low beta, low radiation-fraction multi-device dataset. Furthermore, a prescription of the global energy confinement time leaves ample room for interpretation in as much as profile shapes, relative electron/ion energy confinement times, plasma composition, radiation fraction, etc. are not controlled for in the derivation of the scaling.

Using a prescribed profile-shape one dimensional model, we will show how different assumptions result in slight or profound changes in forecasting a stellarator reactor physics scenario. In particular, we will argue that the largest effect lies in the global confinement quality and that the Sudo limit is quantitatively inadequate for assessing the density operation point in a reactor scenario. The consequences for some the most pressing stellarator physics gaps will be drawn.

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Poster Session MCF 3 - T

3 P 216 - Comparison of iota scan experiments in different experimental campaigns of the Wendelstein 7-X stellarator

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ABSTRACT TEXT

Wendelstein 7-X (W7-X) is a modular advanced stellarator, realizing magnetic configurations optimized for fusion-relevant plasma properties [1]. The machine went into operation in December 2015 at the Max-Planck-Institut für Plasmaphysik in Greifswald, Germany. The latest experimental campaign lasts from February until end of May 2025.

Configuration or iota scans were performed in several W7-X experimental campaigns, varying the rotational transform (iota) between some reference magnetic configurations. The investigated configuration space included magnetic configurations between Standard and High iota magnetic configurations (variation of the boundary iota value from 5/5 to 5/4) as well as between Standard and Low iota configurations (variation of the boundary iota value from 5/5 to 5/6). The change in the rotational transform was produced by a systematical variation of the ratio of the planar- to nonplanar-coil currents of the main magnet system of the machine, reflected in the change of the magnetic field topology. Several intermediate limiter configurations, where the plasma volume is restricted by divertor plates intersecting nested flux surfaces, demonstrated an increase of the plasma confinement time [2]. These configurations were characterized by a location of a chain of five magnetic islands inside plasma column, but close to the last closed magnetic surface. The highest values of the diamagnetic energy in W7X were reached explicitly in these configurations. The confinement improvement was accompanied by a bursty MHD-activity, observed by several diagnostics [3]. Power and density scans as well as a modification of the island size complemented iota scans in several configurations to analyze confinement and mode activity variation. This contribution summarizes observations in iota scan experiments of different campaigns and presents their comparison to experiments in reversed field.

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Poster Session MCF 3 - T

3 P 217 - Piecewise omnigenous stellarator magnetic fields with zero bootstrap current

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ABSTRACT TEXT

The optimization of the magnetic field of Wendelstein 7-X, the largest and most advanced stellarator ever built, is based on the concept of quasi-isodynamicity [1]. Quasi-isodynamic fields are a subset of omnigenous fields. The property of omnigenity [2] guarantees that radial neoclassical transport at low collisionality is as small as in tokamaks; in particular, the deleterious $1/\nu$ regime, that gives intolerably large radial transport in a generic stellarator, is absent. Omnigenity also imposes severe constraints (that can lead to complex coils) on the topology of contours of constant magnetic field strength B , which must close poloidally, toroidally or helically. Specifically, quasi-isodynamic fields are omnigenous fields with poloidally closed B contours, and one can show that they give zero bootstrap current [3]. This is a crucial feature in stellarator designs that, like Wendelstein 7-X, incorporate an island divertor (the most mature stellarator divertor concept) and, consequently, cannot afford a large bootstrap current that modifies the magnetic configuration and the island structure.

Recently, the notion of *piecewise omnigenous fields* has been introduced [4]. They are magnetic fields with exactly zero $1/\nu$ transport that, however, are not omnigenous and are not subject to the aforementioned topological constraints on B contours. The discovery of piecewise omnigenous fields broadens enormously the space of stellarator configurations optimized with respect to radial neoclassical transport.

In this conference contribution, we analytically prove that there exists a subset of piecewise omnigenous fields that are also optimized with respect to neoclassical transport parallel to the magnetic field, giving exactly zero bootstrap current. This subset is defined by a simple mathematical condition on the B contours that also has a clear physical interpretation. Finally, we verify the analytical calculation by means of neoclassical simulations. The results of this contribution open the door to optimized stellarator configurations compatible with an island divertor that are qualitatively different from quasi-isodynamic fields.

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Poster Session MCF 3 - T

3 P 218 - Study of the density limit physics for stellarator devices by means of an energy balance model

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ABSTRACT TEXT

In magnetic fusion devices, there is an observed upper limit for achievable plasma density. Although the physics mechanisms causing this limit are not yet fully understood, they are thought to be related to radiative collapse [1]. In the present work, a physics model is developed to delve into the mechanisms governing the density limit in stellarator devices. The model, based on the work presented in [2], assumes that both radiation and transport losses influence the density limit. The model relies on the global energy balance equation in stationary state, $P_h = P_{rad} + P_{trans}$, where P_h , P_{rad} and P_{trans} denote the heating, radiation, and transport power, respectively. An estimation for the density limit can be attained by solving the former equation for the minimum heating power needed to maintain the plasma in a stationary state. It is shown that the model is well represented by a scaling law of the form $n_{lim} \propto (P_h/V)^\alpha B^\beta c_{imp}^\gamma$, where V is plasma volume, B is the on-axis magnetic field, and c_{imp} is impurity concentration. The model has been tested against TJ-II experimental data. By mining the TJ-II database, a dataset of approximately 500 different plasma states at the density limit has been obtained. It is observed that the solutions yielded by the model are similar to the measurements, suggesting the density limit in TJ-II is indeed strongly related to the global power balance. In particular, the dependencies of n_{lim} on P_h/V and c_{imp} in the experimental data align well with model predictions. However, the dependence on B could not be verified, since the variation in B was minimal for the TJ-II discharges investigated ($B \sim 1$ T). Future work is expected to extend this validation to the W7-X device.

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10/07/2025, 14:30–16:15, Room: Poster area - Terrace

Poster Session MCF 3 - T

3 P 219 - Analyzing flows in high-performance pellet discharges at W7-X

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ABSTRACT TEXT

The radial electric field and plasma flows of high-performance pellet discharges at W7-X are investigated using measurements from the x-ray imaging crystal spectrometer (XICS). In high-performance pellet discharges at W7-X, substantial evolution of flows has been observed, with indications that parallel flows might exceed neoclassical predictions. To explore this further, the evolution of plasma flows—with a focus on the parallel component—will be analyzed using charge exchange recombination spectroscopy (CXRS) as well as an updated XICS analysis that includes consideration of parallel Pfirsch-Schlüter flows during the tomographic inversion. We will compare the measurements of plasma flows with those predicted by neoclassical theory using SFINCS simulations. Of interest is also how these flows are connected to the changes in turbulent transport regimes that have been observed after pellet injection. Further understanding of the flow evolution and its effects will improve understanding of the high-performance discharges and how they are achieved with pellet injection.

Poster Session MCF 3 - T

3 P 220 - Characterisation of the pellet cloud drift in stellarators

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ABSTRACT TEXT

The cryogenic pellet fuelling efficiency in hot magnetically confined plasmas is largely influenced by the drift properties of the high-pressure pellet cloud. In tokamaks, due to the axially symmetric magnetic field, a radially outward drift is the dominant process, so inboard side injected pellets can fuel with better efficiency. In the much more complex (non-axially symmetric) magnetic field of stellarators, the advantage of the inboard side pellet injection does not necessarily apply [1], therefore detailed investigations are needed to characterize the drift processes and therefore the fueling properties. In addition to the fueling pellets impurity pellets—even millimeter in size—are also injected into the plasma mostly for diagnostic purposes. These pellets behave in a similar way to cryogenic pellets and therefore also well suited for drift studies: they are also shielded by a dense cloud, which also drifts from time to time. Furthermore, the different cloud ions can be spectroscopically observed more easily.

Experiments were performed in the W7-X and TJ-II stellarators injecting both cryogenic and impurity (tracer-encapsulated solid pellet, TESPEL) pellets into the plasma. To study the drift of the pellet cloud, the radiation distribution of both the attached and drifting clouds were recorded using fast framing cameras with a framerate high enough (up to 700kHz) to resolve the dynamics. Wavelength selection by interference filters was used to separate certain ionic species of the cryogenic H pellet (H α , Bremsstrahlung) and polystyrene polymer shell of the TESPEL (C I and C III spectral lines). The recorded movies were image processed to determine the main parameters (frequency, speed, etc.) of the drift. This contribution presents the results of this characterisation and discusses the dependency on the plasma and injection parameters.

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Poster Session MCF 3 - T

3 P 221 - A physics basis for the Gauss Fusion 1 GWe stellarator fusion power plant

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ABSTRACT TEXT

The physics basis is presented for a gigawatt class stellarator fusion power plant (GIGA) being developed by Gauss Fusion GmbH to begin operation in the early 2040s. Stellarator power plant scoping is well established [1], with the physics basis bolstered by results from Wendelstein 7-X [2] and the Large Helical Device [3]. Scoping studies exploring costs, timelines, and supply chains indicate that the stellarator concept solved many of the outstanding issues of the tokamak (recycling power, transients, steady-state). A device size of 1500 m³, magnetic field strength of 6 T, and aspect ratio ~10 has been chosen in line with engineering, physics, and power plant considerations. The stellarator equilibrium is optimized for magnetic symmetry, stability, bootstrap current, and transport. Scaling laws predict that this equilibrium will be capable of producing ~3 GW of fusion power at core temperatures of ~22 keV and densities of ~2x10²⁰ m⁻³. Electron cyclotron resonance heating at 170 GHz provides startup with less than 40 MW required to reach ignition. Such a device is capable of producing a tritium breeding ratio >1.00 with a 50 cm thick breeding zone. Non-uniform neutron wall loading allows optimization of in-vessel component placement to minimize the degradation of lifetime components. Inclusion of neutron shielding allows for vacuum vessel lifetimes of 40 full power years while adequately protecting the superconducting coils. Design of the coils has focused on achieving a minimum coil-plasma distance of approximately one plasma minor radius.

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Poster Session MCF 3 - T

3 P 222 - Can turbulent transport in optimized stellarators be as low as in tokamaks?

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ABSTRACT TEXT

To be a competitive fusion reactor candidate, optimized stellarators need to demonstrate a turbulent transport level similar to or lower than that in a tokamak. In this work, global gyrokinetic simulations show that turbulent transport driven by electrostatic ion temperature gradient (ITG) instability in model equilibria of quasi-isodynamic (QI) and quasi-helical (QH) stellarators is at a level similar to that in an ITER tokamak with the same size and temperature gradient, despite much larger linear growth rates in the stellarators.

The underlying physics is found to be the turbulence suppression by zonal flows. The reduction of the ITG transport by the zonal flows in the QH and QI stellarators are much larger than the tokamak or a quasi-axisymmetric (QA) stellarator, thanks to higher linear residue levels[1] and more coherent nonlinear structures of the zonal flows in the QH and QI. The QH and QI energy confinement times are comparable to the tokamak, all are much longer than the QA.

The finding of the more pronounced turbulence suppression by zonal flows in the QH and QI stellarators highlights the opportunity for further improving plasma confinement by maximizing zonal flow residue in the design of optimized stellarator reactors. Effects of kinetic electrons and electromagnetic turbulence on the confinement properties will also be reported using the global gyrokinetic code GTC [2], which has been extensively utilized for stellarator simulations [3–8].

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Poster Session MCF 3 - T

3 P 223 - Modeling transport in stellarator island divertors in the presence of magnetic chaos

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ABSTRACT TEXT

The island divertor is a promising exhaust solution for future stellarator-based fusion reactors. Its concept relies on the formation of large magnetic islands around low-order rational surfaces due to resonant magnetic perturbations. However, real coil spectra and MHD-driven currents can excite neighboring higher-order resonances, leading to magnetic field chaos (MFC). Chaotic magnetic fields induce additional field line diffusion [1] and can create localized transport channels such as turnstiles [2], which may redirect heat loads to unexpected remote locations [3]. This study investigates the impact of MFC on additional diffusive transport and divertor operation to determine under what conditions magnetic chaos must be explicitly accounted for.

MFC is predicted in Wendelstein 7-X (W7-X) for specific configurations: (i) for GYM, JYM, and TYM [4], (ii) for high-beta scenarios, and (iii) for large island structures controlled by external coils. To avoid the complexities of real W7-X geometry and coil spectra, we employ a synthetic model with circular flux surfaces and island structures based on a Hamiltonian formulation. This approach allows for precise control over the perturbation spectrum, enabling a systematic study of the excited resonances and their transport effects.

Using EMC3-Eirene, a 3D steady-state transport code that combines Braginskii-like fluid equations with a kinetic neutral model, we analyze MFC-induced heat transport and develop a metric to define transition thresholds: (i) strike line broadening for weak MFC, (ii) strike line splitting for moderate MFC, and (iii) remote heat loads for strong MFC. The quadratic magnetic flux (QF) through quadratic-flux-minimizing (QFM) surfaces is introduced as a proxy for chaotic transport. This method is applied to both the Hamiltonian synthetic model and W7-X configurations. At extreme MFC levels, turnstile-induced double strike-line footprints appear on the divertor target, akin to resonant magnetic perturbations (RMP) in tokamaks, leading to a 20% reduction in peak heat flux. However, even for unrealistically large MFC, remote heat loads were not observed, as turnstiles predominantly follow the island structure, consistent with predictions in [5]. The QF metric provides a valuable tool for optimizing island divertor performance in future stellarator reactors.

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Poster Session MCF 3 - T

3 P 224 - Fast-ion density measurements with FIDA spectroscopy in Wendelstein 7-X

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ABSTRACT TEXT

Energetic particles play a key role in heating and current drive in fusion plasmas therefore understanding their confinement is essential for optimizing plasma performance in future fusion devices. Diagnosing their distribution and transport remains challenging, especially in stellarators where complex three-dimensional magnetic fields affect fast-ion confinement. Fast-ion D α (FIDA) spectroscopy provides a powerful tool for studying fast-ion populations by measuring the Doppler-shifted Balmer-alpha emission from charge-exchange reactions.

In this work, we present the first reconstructions of fast-ion density profiles at the Wendelstein 7-X stellarator using active FIDA measurements. By applying modulated Neutral Beam Injection, we have successfully isolated the active FIDA signal [1], allowing for direct measurements of the local fast ion density. These measurements provide valuable insights into fast ion transport and confinement in the optimized magnetic geometry.

To validate our results, the reconstructed fast-ion density profiles were compared with simulations from the BEAMS3D code [2], a guiding-center Monte Carlo code that models fast-ion slowing down in three-dimensional magnetic fields.

The results demonstrate the viability of FIDA spectroscopy as a diagnostic for fast-ion studies in advanced stellarator configurations. Further refinement of measurement techniques and modeling efforts will improve our understanding of fast-ion transport processes and contribute to the optimization of plasma scenarios for future fusion reactors.

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Poster Session MCF 3 - T

3 P 225 - Designing ALPES: an Adaptable Lab for Plasma Experiments in Stellarators at university scale

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ABSTRACT TEXT

We present the design of a university-scale stellarator based on a compact, optimized configuration from the QUASR database [1]. The paper is the result of the joint course “Fusion Reactor Design” [2] for undergraduate and graduate students from TU Graz and TU Munich, supported by the Max-Planck-Institute for Plasma Physics and Proxima Fusion. The device fits inside a vacuum vessel of dimensions 190 cm × 90 cm and confines a plasma of major radius 0.5 m and minor radius 0.125 m at a magnetic field strength of up to 87.5 mT. The project combines innovation in compact stellarator design with a focus on experimental flexibility. The outer vessel design allows replacement of coil configurations for rapid prototyping and design studies. We aim to demonstrate the potential of compact fusion devices at the interface between advanced engineering and plasma physics, as well as education and research. The design integrates simplicity, adaptability and functionality, with a 12-coil configuration and a robust chamber capable of reaching a vacuum below 1×10^{-8} mbar and withstanding temperatures up to 200 °C. The copper coils are realized via a double pancake winding and a dedicated mounting system to ensure precise magnetic geometry, adjustable in-situ during operation. Plasma is generated by electron cyclotron resonance heating from a 2.45 GHz microwave system [3]. Diagnostics include Langmuir probes for plasma parameter characterization, magnetic sensors for current measurement and interferometry for electron density evaluation based on previous findings in the university-scale stellarator TJ-K [4]. The adaptability of the design is further enhanced by universal flange standards, allowing seamless integration of future upgrades.

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Poster Session BPIF 4

4 P 226 - Simultaneous Transverse Radiography of a Dynamic Event Using Short-Pulse Laser-Generated Beams

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ABSTRACT TEXT

We hypothesize that more information can be gained from a dynamic object if radiographs are taken using more than one kind of probe beam. For example, X-rays attenuation is greater for high atomic number elements, while protons are attenuated by both high-Z and low-Z elements. Using both types of particle beams can then give information about an object with greater fidelity across a wider range of materials. Short-pulse laser beams have proven to be versatile and efficient sources of such beams. Our project at Los Alamos has generated, characterized, and applied these beams to create radiographs using the Omega EP laser. Both X-rays and protons were used to create radiographs of static and dynamic objects. Difficulties arose when simultaneous radiography was attempted. The high electron background produced in the targets saturated some of the detectors. A simple metal filter was employed to shield the detectors so that high-quality simultaneous radiographs of a static object could be obtained. Creating a dynamic object, in which a shock is driven through the object, required development of a hohlraum to drive a shock due to the geometry of the Omega EP facility. The hohlraum, heated by a 6 kJ, 4ns long-pulse laser, drove a shock through a physics package. The shock speed was measured using VISAR (Velocity Interferometer System for Any Reflector). Experiments using this platform to drive a shock through a physics package with simultaneous radiography using X-rays and protons are planned for Spring 2025.

Poster Session BPIF 4

4 P 227 - Complex characterization of hot electron emission from laser produced plasma on thin foil targets

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ABSTRACT TEXT

The investigation of laser interaction with thin foil metal targets was carried out at Prague Asterix Laser System (PALS). The iodine laser system PALS is capable of delivering energy up to 600 J at wavelength 1.315 μm to generate the plasma by focusing the energy at the target reaching the intensity up to 10^{16} W/cm². The hot electron distribution was measured using angular array of electron spectrometers to obtain angularly resolved distribution of hot electron temperature. The spontaneous magnetic fields generated in laser plasma were measured with complex interferometry using the synchronized femtosecond titanium-sapphire laser system. The characterization of the bremsstrahlung radiation along the laser beam axis was done using the scintillator stack diagnostic and evaluated using Monte Carlo simulation of particle transport.

The target parametric study was carried out to characterize the hot electron emission from the laser produced plasma for the tin targets with respect to target thickness and the energy of the main laser beam. Several other target materials were also investigated. The magnetic field distribution is shown for the target parameters in this study. Comparison with previous investigations is done to indicate further insight in the interaction of laser with plasma as well as the comparison with known scaling laws for hot electron temperature. The results of this experiment have further application for radiation sources and generation of accelerated particles.

Poster Session BPIF 4

4 P 230 - Real-Time Detection and Characterization of Ion Beams in Laser-Plasma Interactions

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ABSTRACT TEXT

With the development of high-intensity, high-repetition-rate laser systems, it has become critical to be able to detect and characterize in real time the laser-generated plasma parameters such as gamma rays, electrons, high-energy protons, and heavier ions. The accurate detection and characterization of ion beams provide insights into energy distribution, charge state composition, and beam divergence, which are essential for applications in particle acceleration, medical therapies, and nuclear science.

In this work, we present a comprehensive study on the detection of ion beams using advanced ion diagnostics techniques, including scintillator detectors, time-of-flight (TOF) spectrometry, Thomson Parabola Spectrometry (TPS), together with the detectors sensitive to each individual particle like CR-39 nuclear tracker detectors and TimePix detectors. These diagnostic tools enable precise measurements of ion energy spectra, charge state distributions, and temporal evolution of the ion flux. By employing a calibrated experimental setup, we obtained high-resolution data that allowed us to do the ion beams dosimetry with exceptional accuracy.

The collected data were analyzed using computational algorithms to reconstruct the ion beam parameters and assess the underlying plasma dynamics. The use of absorbers placed in front of the time-of-flight detectors might help in the discrimination of proton and alpha particles energy spectra and ensures no heavier ions (carbon, boron etc) contributes to the total signal, while the TPS can be used to check the maximum energies for different ion species.

Our results indicate a strong dependence of ion energy and beam divergence on target material, laser intensity, and pre-plasma conditions. A detailed comparative analysis of ion energy spectra for different laser and target configurations was performed, revealing optimization strategies for achieving high ion beam efficiency. Additionally, we discuss the implications of these findings in the context of next-generation laser-driven ion acceleration schemes.

Poster Session BSAP 4

4 P 232 - Quasilinear theory from first principles: reinstating the ponderomotive forces

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ABSTRACT TEXT

The classic quasilinear theory (QLT) of resonant wave-particle interactions [1] fails to conserve the action of nonresonant waves and mostly misses (oversimplifies) the adiabatic ponderomotive effects caused by the slow evolution of the wave parameters in time and space. Postulating action conservation instead of the usual amplitude equation for the waves' electric-field amplitudes undermines QLT's exact energy-momentum conservation, which is a significant part of the classic QLT's appeal. The 'oscillation-center' QLT [2] reinstates both action and energy-momentum conservation ad hoc, but a general first-principle QLT has been lacking. Here, we report a rigorous formulation of QLT based on the Weyl symbol calculus [3, 4]. This formulation captures both adiabatic and nonadiabatic dynamics and leads to an exactly conservative model for any Hamiltonian wave-plasma interactions. Effects of plasma inhomogeneity and Balescu-Lenard collisions are also accommodated. The known results for electrostatic, relativistic electromagnetic, and gravitational interactions are reproduced as special cases.

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Poster Session BSAP 4

4 P 233 - A Quantum Algorithm for Simulating Dissipative Processes in Hot Plasma

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ABSTRACT TEXT

Although quantum algorithms have been theoretically proven to offer a quantum advantage over classical methods for simulating dynamics, including linear wave propagation in plasmas [1], their effectiveness in dissipative and potentially nonlinear physical systems is an increasingly active area of research. To this direction, we extend the results of [2], where we introduced an efficient quantum framework for collisional dissipation in the cold plasma approximation, by developing a quantum algorithm that incorporates the characteristics of the hot-plasma non-Hermitian kernel. We then present the algorithm's circuit implementation, analyze its computational complexity, and compare its theoretical performance with the Finite-Difference Time-Domain (FDTD) method.

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Poster Session BSAP 4

4 P 234 - Impact of phase shift and magnetic field configurations on BiGyM design

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ABSTRACT TEXT

A major challenge in magnetically confined fusion research is the development of plasma-facing materials capable of withstanding the harsh conditions of prolonged plasma exposure. This issue is widely studied in linear plasma devices like GyM [1], which generates steady state plasmas with electron temperatures up to 15 eV, densities of 10^{15} – 10^{17} m⁻³, and ion fluxes up to 10^{21} m⁻²s⁻¹, making it suitable for investigating plasma-facing materials in the tokamak main chamber wall. GyM is currently being upgraded to BiGyM, which will replace the current plasma sources with a pair of helicon wave-generating birdcage antennas[2], operating at 13.56 MHz with a maximum power of 10 kW each. This enhancement will expand the parameter space toward divertor-relevant plasmas with densities up to 10^{19} m⁻³ and ion fluxes up to 10^{23} m⁻²s⁻¹. This contribution focuses on BiGyM design, supported by a full 3D finite element model developed using COMSOL software[3]. The key objective is to optimize plasma performance by maximizing the power deposited by the helicon waves in the plasma region where the samples will be exposed. The model is exploited to evaluate the effects of varying the phase between the two antennas and applying different magnetic fields on helicon wave propagation, in different vessel configurations. The first tuning alters the field resulting from the superposition of the waves from the two antennas, the other affects the wavelength. Both these refinements impact the power density distributions in the vessel. Preliminary results show that the power density is maximized at the sample position when a uniform magnetic field is applied and constructive interference between the two antenna fields locally occur.

ACKNOWLEDGMENTS

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11/07/2025, 14:30–16:15, Room: Poster area - Lobby

Poster Session BSAP 4

4 P 235 - APEX-LD and EPOS: companion HTS devices for e+e- pair plasmas

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ABSTRACT TEXT

Electron-positron “pair plasmas” are a fascinating frontier in basic plasma science, due to the effects of the unity mass ratio (in stark contrast to the large mass asymmetry of electron-ion plasmas) on the number and nature of collective modes that can arise. The APEX (A Positron Electron eXperiment) Collaboration aims to study strongly magnetized e+e- pair plasmas in the laboratory by confining them in two different, complementary devices, both tabletop-sized (plasma volume of order 10 liters) and based on small (10-cm-scale) high-temperature superconducting (HTS) coils. The first device, APEX-LD, is a levitated dipole trap; it is already in operation for pure-electron plasma studies, and next year it is expected be installed on a beam line of the world’s strongest cold e+ source (NEPOMUC). The second device, EPOS, is a stellarator; following optimization studies and engineering tests, and incorporating feedback from design reviews (Q1 2025), design finalization and construction are planned for this year. This poster will present an overview of recent results, current progress, and upcoming plans for these two novel devices.

Poster Session MCF 4 - L

4 P 236 - Development of the Persistent Actor Framework (PAF) version of the European Transport Simulator (ETS)

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ABSTRACT TEXT

The first version of the ETS was developed within the European Fusion Development Agreement Work Package on Integrated Tokamak Modelling [ETS-2008, ETS-2010a, ETS2010b]. That version was essentially a Fortran workflow using Consistent Physical Objects (CPOs) to couple a number of codes providing the standard building blocks of a core plasma simulation (equilibrium codes, the calculation of sources and transport coefficients and the transport solver). To allow for the inclusion of components in other languages, KEPLER was used as a coupling environment [ETS-2012, ETS-2013a, ETS-2013b, ETS-2014, ETS-2018, ETS-2019, ETS-2021a], and after some years of using CPOs, these were replaced by Interface Data Structures (IDSs) [ETS-2020, ETS-2021b, ETS-2022, ETS-2024]. This has been in use for a number of years, but the decision has been made to look at other coupling frameworks. This contribution describes the development of the ETS-PAF, where the functionality of the ETS uses the MUSCLE3 framework to couple the various physics modules (mostly in fortran, C or C++), together with python modules to implement some of the workflow logic. The workflow takes the form of a number of separate programs (currently about 60) that communicate IDSs to other programs via one-way communication channels (currently about 150) sending/receiving IDSs. Minimal changes are needed to the physics codes, and scalar, OpenMP, MPI and hybrid codes are seamlessly supported for the components, and the MUSCLE3 framework will ensure that separate models will be run in parallel if the dataflow allows it. Test workflows have been implemented for AUG, JET and ITER.

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Poster Session MCF 4 - L

4 P 237 - Efficient uncertainty quantification in plasma micro-instability simulations with mode transitions

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ABSTRACT TEXT

Uncertainties are inherent in numerical simulations of real-world phenomena [1]. In the context of gyrokinetic micro-stability of magnetic confinement fusion scenarios, large computational cost per simulation and mode transitions make efficient uncertainty quantification (UQ) very challenging [2]. Previous research on sensitivity-driven, adaptive sparse grid approximations show that by employing the lower intrinsic dimensionality of the problem as well as the anisotropic coupling of the inputs, both of which are typical features of physics simulators, a significant efficiency gain is obtained [2]. However, a characteristic feature of plasma micro-instability simulation is that mode transitions appear as discontinuities, either in the quantity itself or its first derivative, e.g., mode growth-rate and frequency. This property renders approaches assuming global smoothness locally ill-conditioned. This work is focused on extending this sensitivity-driven, adaptive sparse grid methodology with means to operate efficiently within a domain with mode transitions. Spatially adaptive sparse grid interpolation can be used to approximate quantities of interest violating the assumption of global smoothness, as shown in other applications [3–5]. Adaptations of these methods will be tested for data efficiency to approximate growth-rate across local linear GENE mode transitions [6].

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Poster Session MCF 4 - L

4 P 238 - Effects of Neon seeding on density profiles and particle sources in the Integrated Scenario at the Joint European Torus

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ABSTRACT TEXT

Recent experiments at the Joint European Torus (JET) [1,2] have addressed the compatibility of a sufficiently hot pedestal, essential for good energy confinement, with a partially detached divertor through Neon seeding. The JET Integrated Scenario, also called ITER baseline scenario, has been developed in the closest conditions and divertor configuration to the one optimal for achieving partial detachment on ITER [5]. However, the JET higher collisionality and the differences in the radiation pattern within the divertor region, do not allow direct extrapolation to ITER. ITER baseline and JET baseline studies have demonstrated that Ne seeding enhances core energy confinement by reducing turbulence, while also decreasing pedestal density and increasing pedestal temperature. The synergy between reduced pedestal density and elevated pedestal temperature is identified as the primary driver of improved confinement [6,7]. Additionally, [3] suggests that variations in pedestal profiles may arise from higher Ne concentrations, which increase ELM frequency and decrease ELM amplitude, and/or from enhanced radiation below the X-point, reducing particle sources in the edge. This paper investigates the underlying causes of pedestal density reduction using core integrated modeling, exploring the range of ELM-averaged transport coefficients and sources that align with experimental pedestal data. We have selected two ITER baseline pulses at 2.5 MA and 2.7 T being the only difference between them the injection of Ne. We present the results obtained using the JINTRAC suite of codes [9] equipped with the first-principle based transport model QuaLiKiz [10]. In the simulations the evolution of the plasma current density, electron density, electron and ion temperatures are computed self-consistently, as well as the equilibrium. The transport of impurities is evolved by SANCO [11], considering an impurity mix of Be, Ne, Ni and W, where initial concentrations are prescribed according to spectroscopy estimates. Boundary conditions are imposed at the separatrix, the pedestal transport is prescribed to match the experimental pedestal with the ionization sources being computed by FRANTIC [12]. We obtain the ELM-averaged transport coefficients, and the sources required to achieve agreement between modelling predictions and experimental data. We present the comparison of pedestal transport and particle sources between the unseeded pulse and the seeded one.

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Poster Session MCF 4 - L

4 P 239 - Investigating the pedestal intrinsic torque at the ASDEX Upgrade tokamak

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ABSTRACT TEXT

Accurate methods for predicting toroidal plasma rotation in magnetically confined tokamak plasmas are of great interest due to the effect rotation has on MHD stability, impurity transport, and turbulence suppression. Predictive capabilities for the toroidal rotation have been challenging to develop due to the complexities of momentum transport; in addition to the convective and diffusive components present in heat or particle transport, momentum transport includes a residual stress component, which is neither proportional to the rotational velocity nor its gradient, and causes an intrinsic, turbulence-induced torque that can spin up the plasma from rest. In order to develop predictive models for the plasma rotation, this phenomenon needs to be better understood.

A momentum transport analysis methodology was recently developed at ASDEX Upgrade to analyze the contributions of the different transport components [1], including intrinsic torque. This is done by using the ASTRA code [2,3] to solve the momentum transport equation [4] and infer a set of momentum transport coefficients to best match experimental rotation profiles. While this analysis framework was mainly applied to study the plasma core, in this work it is adapted for application in the pedestal region of the plasma. To simplify the fitting problem, convective and diffusive components were determined from existing scaling laws, isolating the intrinsic torque and its parametric dependencies. Furthermore, a neoclassical correction was added to experimental profiles to account for the relatively greater impact of the neoclassical effects in the pedestal. For the first time, this workflow was applied to a database of ASDEX Upgrade discharges to determine scaling laws for the intrinsic rotation in the pedestal region, with new pedestal results compared to the previously obtained core results. Ultimately, this should lead to a more complete picture of the formation of plasma rotation profiles.

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Poster Session MCF 4 - L

4 P 240 - Investigation of cross-scale interaction between high-k and low-k turbulence in Large Helical Device (LHD)

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ABSTRACT TEXT

Some simulation studies suggest that the cross-scale interaction between electron-scale and ion-scale turbulence affects the turbulent transport in certain T_e/T_i region[1], where “electron-scale” and “ion-scale” mean scales around the electron Larmor radius and the ion Larmor radius, respectively. To study such a cross-scale phenomenon, we observed electron-scale and ion-scale turbulence in combination with millimeter-wave backscattering system [2] and Doppler backscattering system. To obtain a significant change in T_e/T_i , we performed several ECH power scan experiments. As a result, we successfully observed electron-scale ($\rho_i k_{\perp} \sim 5$) and ion-scale ($\rho_i k_{\perp} \sim 0.5$) turbulence simultaneously at the same position with significant change in T_e and constant T_i . We performed a special bi-spectral analysis and found a non-linear correlation between them in a part of the discharge. We will discuss the results of further analysis.

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11/07/2025, 14:30–16:15, Room: Poster area - Lobby

Poster Session MCF 4 - L

4 P 241 - T3ST code: Turbulent Transport in Tokamaks via Stochastic Trajectories

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ABSTRACT TEXT

We present the Turbulent Transport in Tokamaks via Stochastic Trajectories (T3ST) code, which tackles the turbulent transport in tokamak devices via a statistical approach. The code tracks the dynamics of charged particles in axisymmetric magnetic equilibria in the presence of collisions and turbulent fields. The latter are formally separated from plasma dynamics, thus, represented through a statistical ensemble of synthetic random fields with apriori known spectral properties. This approach enables T3ST to compute transport coefficients as Lagrangian correlations—orders of magnitude faster than gyrokinetic codes.

Poster Session MCF 4 - L

4 P 243 - Particle Transport and Turbulent Cascade Rate in the Scrape-Off Layer

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ABSTRACT TEXT

The comprehension of turbulent transport at the edge of fusion plasma devices is of crucial importance for the optimization of magnetic confinement. In this work, we studied the dynamics of blob-like structures in the region of the scrape-off layer using a two-dimensional Braginskii model and, following the Yaglom-Monin approach, we derived a new third-order exact law that describes the turbulent cascade in fusion plasmas. The dynamics have been investigated by using both classical Eulerian analysis and the Lagrangian approach, by varying the ambient conditions of the plasma. It has been found that both the magnetic shear and the plasma mean profiles of density and temperature are crucial for setting the properties of the transport. By following fluid tracers, diffusive transients for the radial transport are observed, at length scales larger than the typical blob size. Finally, we obtained a third-order von Kàrmàn-Howarth equation in increment form, in the case of electrostatic Braginskii turbulence. We verify the Yaglom-Braginskii law by means of direct numerical simulations. The analysis revealed that the plasma dynamics obey the new cross-scale balance, showing a clear inertial range of turbulence. The new third-order law can accurately measure the cascade rate of density fluctuations in the scrape-off layer of laboratory settings

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Poster Session MCF 4 - L

4 P 244 - Utilizing dynamic heat transport simulations to extract information out of measured ELM frequencies

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ABSTRACT TEXT

Heat transport is one of the key processes determining the quality of the energy confinement in high temperature plasmas. In a tokamak at the plasma edge a self sustaining heat transport barrier forms. This transport barrier is dominated by an interplay of diffusive heat transport and filamentary heat loss due to edge instabilities. The most common example is found in type-I ELMy H-modes which was described by the peeling-ballooning instability. It is driven by the plasma current and the pressure gradient. The filamentary transport during an ELM relaxes the pressure gradients, then the gradients will start to recover and ultimately result in another ELM.

When analysing the heat transport in the edge barrier it is common practice to extract the profiles from a short phase before the ELM crash occurs. In this phase a quasi-stationary balance between temperature gradients and heat fluxes is assumed. Based on this assumption transport coefficients can be deduced. When comparing phases with significantly different ELM frequencies such a quasi-stationary treatment can result in misleading conclusions.

While different ELM frequencies should be a cause for caution in edge transport analyses, it is also a source of information. Under the assumption of a fully dynamical interplay of diffusive and filamentary heat transport, quasi-stationary conditions might never be met. To access the information provided by the ELM frequency we built a 1D transport model with basic assumptions for the non-linear nature of the dynamics in the edge transport barrier. Simulations of these dynamics with the transport solver ASTRA yield trends in the ELM frequency. From experimentally observed trends in the frequency information on heat transport and ELM stability can be deduced.

We show how the isotope mass dependence of transport coefficients is inferred from the ELM frequency. Even without ELMs—e.g. at an LH-transition—the model allows us to estimate the heating power required to match profiles when the heat transport coefficients change. This might explain how small changes in transport coefficients—as predicted by high fidelity transport simulations under stationary conditions—can lead to large heat fluxes when the dynamics is taken into account self consistently.

Poster Session MCF 4 - L

4 P 245 - Predictions of gyrokinetic turbulent transport in proton-boron plasmas on EHL-2 spherical torus

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ABSTRACT TEXT

The EHL-2 spherical torus at ENN is the next-generation experimental platform under conceptual design, aiming at realizing proton-boron (p-11B) thermonuclear fusion which is an attractive pathway towards neutron-free fusion. In order to achieve high performance steady-state plasma, it is extremely necessary to study the turbulence transport characteristics with high boron content in the plasma core. This work investigates the transport properties in the core internal transport barrier (ITB) region of p-11B plasma utilizing the gyrokinetic code GENE in view of the high ion temperature scenario of EHL-2, specifically focusing on the impact of boron fractions and plasma β on the microinstabilities and corresponding transport features. Numerical findings indicate that the inclusion of boron species effectively suppresses the trapped electron modes (TEMs) as well as promoting a transition from electromagnetic to electrostatic turbulence with increased boron fraction, which is a result of the suppression of microinstabilities by effective charge and mass. Moreover, it has been identified that the external $E \times B$ rotational shear has a notable inhibitory influence on transport which can reduce the transport level by 2–3 orders of magnitude especially at medium boron contents. The suppressive effect of $E \times B$ on turbulence is weakened once the kinetic ballooning mode (KBM) is excited and the transport shows a rapid increase with β together with a reduction in zonal flow amplitude which is consistent with previous findings. Therefore, it is strongly suggested that exploring advanced strategies for mitigating turbulent transport at high β regimes is necessary for the active control of plasma behavior regarding H-B11 plasma based fusion devices such as EHL-2.

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Poster Session MCF 4 - L

4 P 246 - Density fluctuation measurements during confinement transitions in Wendelstein 7-X by phase contrast imaging

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ABSTRACT TEXT

In high performance stellarator plasmas at Wendelstein 7-X (W7-X), phase contrast imaging (PCI) observations reveal diverse phenomena, including significant variations of turbulent broadband fluctuations and changes in their spectra, intermittent bursts of broadband activity, narrow frequency band Alfvénic modes as well as indications of kinetic ballooning mode activity. Due to its neoclassical optimization, turbulence plays a large and often dominant role in determining W7-X's plasma confinement. It limits achievable kinetic plasma profile gradients for a given heating and fueling scenario and magnetic configuration. To maximize plasma performance, these scenarios are varied and combined to reach record values of ion temperature, plasma beta or confined energy. In most cases, improved confinement is achieved by increasing the density gradient, with the most successful actuators being cryogenic pellet injection and neutral beam injection. After successful steepening of the density gradient by either means, electron cyclotron resonance heating, W7-X's primary heating method, is much more effective at simultaneously raising the ion temperature for a limited period of time before a fast transition back to the pre-injection state. This is reflected in substantial variation in heat and particle diffusivity, which seem to bifurcate.

This presentation attempts to relate these confinement states and their transitions to the particular type of density fluctuations in the kHz to MHz range using the PCI diagnostic. PCI provides (absolutely calibrated) continuous density fluctuation data throughout the core with high time resolution, including the poloidal wavenumber spectrum, and is sensitive to broadband fluctuations across a large frequency range as well as to coherent frequency modes. In this work, these aspects are connected to changes in kinetic profiles, providing evidence that turbulent processes may be responsible for these transitions.

Poster Session MCF 4 - L

4 P 248 - Investigating Density Pump-out and Wall Conditioning in RFX-mod Reversed Field Pinch Plasmas

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ABSTRACT TEXT

The Reversed Field Pinch (RFP) is a magnetic configuration where the edge toroidal magnetic field is reversed relative to the central field. RFX-mod, the world's largest RFP experiment, with a plasma current up to 2 MA and an aspect ratio $R/a = 2 \text{ m}/0.459 \text{ m}$, is currently undergoing an upgrade to become RFX-mod2.

RFX-mod experiments frequently observe a phenomenon, occurring during the startup phase, known as density 'pump-out': after an exponential density rise, a rapid decay occurs within 1–2 milliseconds, sometimes leading to discharge termination. This study investigates the mechanisms driving density pump-out, using a database of hydrogen discharges. Our analysis identifies a strong correlation between the rapid density collapse and the edge safety factor (q_a). Pump-out is observed prior to the reversal of the edge toroidal field, when the plasma traverses the Ultra-low- q configuration ($0 < q_a < 1$), particularly when $q_a \approx 0.3$. We observe that MHD instabilities, triggered as q_a approaches zero, contribute to the pump-out, likely enhancing particle transport to the wall and exacerbating the density loss [1]. Interestingly, MHD perturbation amplitude decreases as the more stable RFP configuration is established.

While the initial peak density is largely determined by gas puffing, the minimum density after pump-out depends on gas release from the first wall, underscoring the role of wall fueling (gas release from the wall). Also, plasma density during the current flat-top phase is also influenced by wall conditions rather than initial gas input.

These findings highlight the critical importance of wall conditioning via Glow Discharge Cleaning (GDC), which can precisely control the amount of gas adsorbed by the plasma surrounding materials (wall "loading"). Optimal wall loading is essential: insufficient charge compromises density sustainment and the transition to the RFP state, whereas excessive loading risks disruptions. Achieving an optimal wall loading is therefore crucial to control pump-out and sustain high-density discharges.

This study has direct implications for the GDC system being developed for the RFX-mod2 upgrade within the PNRR NEFERTARI project. By understanding and controlling wall fueling, we aim to mitigate density pump-out, optimize plasma performance, and support stable, high-density operation in future RFP devices.

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Poster Session MCF 4 - L

4 P 249 - Exposure of ultra-high temperature ceramics to scrape-off layer plasma in the WEST tokamak

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ABSTRACT TEXT

Ultra-high temperature ceramics (UHTC) like nitrides, borides, and carbide-based composites present a very high phase change temperature, typically above 3000 K [1, 2]. Their excellent thermal and mechanical properties make them promising candidates for use as heat shield ablators for the thermal protection system (TPS) of space vehicles during atmospheric re-entry [3]. To assess their resistance to extreme heat fluxes, typically of the order of 10–100 MW/m² [4], and particle fluxes, several samples of four pre characterized UHTC of different types are exposed to Scrape-Off Layer (SOL) plasma and strike point fluxes in the WEST tokamak. These environments offer relevant heat fluxes for testing the resistance of these materials to space re-entry conditions. This contribution presents the methodology for exposing UHTC samples to strike point fluxes and SOL plasma, and preliminary results obtained in 2024 from the exposure of four samples -BN, Si₃N₄, Al₂O₃, and SiC- to SOL plasma. The samples were mounted on a reciprocating probe, equipped with thermocouples for in-situ temperature measurements, and Langmuir probes for monitoring plasma parameters [5]. Pre- and post-mortem observations and analyses, including confocal microscopy and scanning electron microscopy coupled to energy-dispersive X-ray spectroscopy, enable the assessment of erosion rates, detection of possible trapped impurities or changes in the chemical composition of the materials, and quantification of surface damage. The data from the Langmuir probes measurements and pre- and post-mortem analyses are used to support future modelling efforts aiming at understanding and predicting material behaviour under harsh conditions.

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Poster Session MCF 4 - L

4 P 250 - Characteristics and Control of Tungsten Impurity Transport in KSTAR

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ABSTRACT TEXT

Since high-Z impurity like tungsten causes significant radiative loss and plasma performance degradation, understanding their behavior is a critical issue for steady tokamak operation. To investigate physics issues for tokamak operation with tungsten PFC, the KSTAR divertor has been upgraded with tungsten monoblock cassette in 2023. It has been observed that the core plasma radiation is dominated by the tungsten impurity transported from the tungsten divertor target. After divertor upgrade, typical radiative loss fraction and averaged Z_{eff} were elevated significantly. In 2024 KSTAR campaign, to investigate tungsten impurity behavior in KSTAR plasmas further, changes in tungsten source and its transport inside plasma were studied with various plasma shapes. To estimate how quickly tungsten impurity from source flow into plasma, or tungsten impurity inside plasma flow out, the transitions between lower single null and upper single null configurations were compared. Since ELMs can result in the generation of the impurity source by sputtering of the PFCs, tungsten source reduction with ELM mitigation with RMP were also analyzed. For above studies, the effects of tungsten source reduction in Z_{eff} profiles and plasma performances were also analyzed.

ACKNOWLEDGEMENTS

This work was supported by the R&D Program of the “KSTAR Experimental Collaboration and Fusion Plasma Research (EN2501)” through the Korea Institute of Fusion Energy (KFE) funded by the Korean Ministry of Science and ICT.

Poster Session MCF 4 - L

4 P 251 - Development towards integrated modeling of the X-point radiator in ASDEX Upgrade with JINTRAC

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ABSTRACT TEXT

It has been shown that controlling an X-point radiator (XPR) in a fully detached H-mode plasma can lead to a naturally more ELM-stable regime[3]. This might become an important strategy in heat load-, and ELM-control as it has been shown to be a robust phenomenon across tokamak devices [4–8]. Not only must the ELM amplitude be kept minimal to prevent unacceptable degradation of the plasma-facing components in larger tokamaks, ELMs likely need to be suppressed for W density control [9]. So far, modeling work regarding the XPR regime has been solely focused on divertor and scrape-off layer characteristics. However, broader aspects regarding plasma operations have not been well studied, e.g. core-edge interaction in the case of the XPR. To address this issue, in this contribution, we further develop the integrated modeling code JINTRAC to model the XPR regime. As a first step, we compare the divertor/SOL model EDGE2D-Eirene—which is used in JINTRAC—with the well-established SOLPS-ITER code in the XPR regime in the ASDEX Upgrade tokamak[10]. By utilizing identical grids, a benchmark is carried out in this regime. In this set-up, the models do not use drifts, and Dirichlet conditions are applied on the core boundary on temperatures and ion density. We show that EDGE2D-Eirene is able to obtain qualitative and quantitative similar solutions for the XPR. Herein, the strongly radiative region just inside the separatrix radiates away almost all the power coming from the core boundary, while the divertor receives virtually no power. We further present ongoing work to obtain the first integrated model solution for the XPR regime, where the edge and core are coupled.

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Poster Session MCF 4 - L

4 P 252 - Influence of magnetic configuration on scrape-off layer drift effects in the Wendelstein 7-X stellarator

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ABSTRACT TEXT

Experiments in the Wendelstein 7-X (W7-X) stellarator show evidence that the effect of the poloidal ExB drift, v_E , on scrape-off layer (SOL) transport weakens with increasing edge rotational transform. The effects of ExB drifts in the W7-X island divertor SOL are assessed by reversing the magnetic field in magnetic configurations with different edge rotational transforms of $\iota \equiv n/m = 5/6, 5/5$, and $5/4$. SOL parallel flows measured by coherence imaging spectroscopy and divertor density profiles measured by Langmuir probes are compared between plasmas with matched control parameters (line-averaged density and heating power) but opposite field directions, and therefore opposite drift directions. In the low-iota configuration ($\iota = 5/6$), v_E strongly affects SOL transport at low density ($n_e < 2 \times 10^{19} \text{ m}^{-3}$), creating an up/down density asymmetry within the edge islands. Concomitantly, the SOL flow pattern transitions from the usual counter-streaming flows to near-unidirectional flow. The flow direction reverses with magnetic field, indicating that drifts are responsible for the flow pattern transition. Simplified 1D isothermal modelling explains that the transition is caused by the v_E -driven density asymmetry shifting the flow stagnation point toward the X-point in the drift direction. As density increases, v_E decreases, resulting in a smaller density asymmetry and the re-establishment of the counter-streaming flow pattern. In the standard configuration ($\iota = 5/5$), near-unidirectional flow is only observed for forward magnetic field and $n_e < 1.5 \times 10^{19} \text{ m}^{-3}$. In the high-iota configuration ($\iota = 5/4$), the counter-streaming flow pattern is observed for the entire accessible density range down to $n_e = 1 \times 10^{19} \text{ m}^{-3}$. The density range where v_E induces near-unidirectional parallel flow thus reduces with increasing ι , indicating a weakening of this drift's impact on the overall SOL transport. Raising ι results in complex changes to the edge island geometry, increasing the field line pitch that governs the ratio between parallel and poloidal transport, altering the island-divertor intersection geometry, and increasing the radial/poloidal island width. The weakening impact of v_E on SOL parallel flow with increasing ι is consistent with the expectation that poloidal transport plays a weaker role with increasing island field line pitch.

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Poster Session MCF 4 - L

4 P 253 - Investigation of limiter ramp-up phase of WEST discharge with integrated core-edge fluid transport code SolEdge-HDG

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ABSTRACT TEXT

The updated ITER baseline introduces a change in the First Wall (FW) material from beryllium (Be) to tungsten (W) [1]. While this transition offers several advantages, a key challenge remains: the risk of plasma contamination during the ramp-up phase, when plasma directly interacts with the FW. Due to limited experimental data and diagnostic constraints, numerical modeling plays a crucial role in understanding this phase. This led to the first-ever ITER limiter plasma simulations using SOLPS-ITER and JINTRAC [1].

Despite the high accuracy of employed physical models, some difficulties remain. The reliance on the prescribed anomalous transport limits predictive capabilities of the codes, while the poor description of the FW complicates detailed investigation of wall loads and far Scrape-off Layer (SOL) physics. The steady-state approach, which assumes a single magnetic equilibrium, seems to be in contradiction with the nature of ramp-up phase, with the evolution of magnetic equilibrium and the change of plasma shape from limiter to diverted configuration.

To tackle the above issues, there is continuous development effort of fluid transport code SolEdge-HDG, based on high-order Hybridized Discontinuous Galerkin (HDG) method [2]. The magnetic equilibrium free high-order meshes allow to cover the whole poloidal cross-section from the magnetic axis to precisely described Plasma Facing components (PFC). Complemented by the efficient time marching scheme, the code has already shown the capability of modelling limiter-divertor transitions in WEST [3] and ITER [4]. With recently implemented adaptive mesh-refinement, the numerical efficiency is improved. The self-consistent turbulent transport model, based on [5], increases the predictive capabilities of SolEdge-HDG. The recently improved neutral model [6], additional heating and radiative losses models improve the description of particle and heat loads onto the PFC.

In this study we investigate the WEST ramp-up phase of the discharge, focusing on FW plasma exhaust under various heating profiles. The modeling effort directly supports WEST's ramp-up experimental campaign, which explores discharges with extended limiter phases. This work is conducted within the TWINTOK [7] framework and is supplemented by synthetic diagnostics, enabling a direct comparison between simulation and experiment.

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Poster Session MCF 4 - L

4 P 254 - Ultrashort pulse series of electron cyclotron resonance heating for wall conditioning at Wendelstein 7-X

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ABSTRACT TEXT

One of the effective methods of wall conditioning of fusion devices is hydrogen wall conditioning [1], the principle of which is to produce atomic hydrogen which, in turn, chemically interacts with impurities at the wall surfaces. The reaction is aimed to produce light volatile substances that can be removed by a pumping system.

A scenario for wall conditioning Wendelstein 7-X (W7-X) stellarator using a pulsed ECRH discharge was proposed, the feasibility of which was demonstrated during the OP1.2b experimental campaign [2], where a chain of ultrashort pulses with heating using electron cyclotron resonance was investigated, and also confirmed by numerical calculations [3]. Within OP2.1 experimental campaign, a series of such sequential ultrashort ECRH pulses [4] was analyzed at W7-X.

In further experiments in OP2.2 described here, a longer series of such pulses had been launched to study the influence of it on the residual gas content after the series. The series of experiments were conducted with a variable number of pulses and series duration. The first experiments with ten pulses showed that all pulses are similar. The starting preionization pulse is wider and has a higher power. This pulse produces a plasma with a density of $2.3 \cdot 10^{19} \text{ m}^{-3}$. After this pulse, plasma decay is not observed. The next few pulses also support the plasma. At the same time, the energy of these pulses is not enough to maintain the plasma energy. And eventually, the energy drops completely. As soon as the energy drops, plasma decay begins until the next pulse, after which the plasma decays more slowly. Further, plasma decay is not observed and on the last pulses we see an increase in plasma density, and only after some time decay begins. This typical pattern is observed in the following series of experiments lasting 10 s and 100 s.

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Poster Session MCF 4 - L

4 P 255 - Integrated modelling of coupled free-boundary equilibrium and core-edge-SOL transport with improved conservation of plasma quantities during 2D edge-SOL grid evolution

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ABSTRACT TEXT

The ITER High Fidelity Plasma Simulator (HFPS) is being developed by integrating a core-edge-SOL transport modelling code (JINTRAC) and a free-boundary equilibrium evolution code (DINA). It has demonstrated the possibility of modelling time-evolving 2D edge/SOL plasmas using a new scheme for conserving plasma scalar quantities (density and energy) across a sequence of pre-prepared grids generated for a prescribed plasma equilibrium evolution. This scheme calculates the residual of each grid cell using the Leibniz-Reynolds transport theorem and a second-order Runge-Kutta method to compensate the plasma quantities for the deviation of the static grid solution from the time-evolving one. Recently, the HFPS has been further enhanced to allow dynamic 2D edge/SOL grid generation at run-time, matching the evolution of the free-boundary plasma equilibrium calculations. In this work, the conservation of plasma fluid quantities (density, energy, and momentum) is demonstrated for a time-dependent integrated plasma transport simulation of an ITER diverted plasma in which the 2D edge/SOL grids are dynamically generated. The results are compared with simulations using a static grid and the pre-prepared sequential grids. This capability of performing self-consistent free-boundary/core-edge-SOL transport simulations with improved conservation properties will, in the future, be further refined to allow longer-time scale simulation in which plasma transients such as current ramp-up/down and L-H/H-L confinement transitions are modelled.

Poster Session MCF 4 - L

4 P 256 - Blob motion and flattened far-SOL profiles in Alcator C-Mod: evidence in support of stochastic modeling

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ABSTRACT TEXT

The cross-field transport of particles and heat in the scrape-off layer (SOL) of magnetically confined plasmas is strongly influenced by filamentary structures known as blobs. These coherent, field-aligned structures propagate radially outward, broadening and flattening the radial density profile and significantly affecting plasma-wall interactions. Understanding their statistical properties and transport mechanisms is crucial for predicting and mitigating plasma-material interactions in fusion devices.

In this study, fluctuations in the boundary region of the Alcator C-Mod device [1] are investigated with mirror Langmuir probe and gas puff imaging measurements in a series of experiments scanning core plasma density. This reveals broadening and flattening of the radial electron density profile in the scrape-off layer. A time delay estimation method [2] is applied to deduce blob velocities at various radial positions. In low-density discharges, blob dynamics manifest in the far scrape-off layer, exhibiting radial velocities up to 500 m/s. As the core plasma density approaches the empirical discharge density limit, blob dynamics dominate the entire scrape-off layer, extending inside the last closed magnetic flux surface with velocities exceeding 1 km/s.

The fluctuations measured at any given diode view position display pronounced intermittency in the region governed by blob structures. These fluctuations have probability density functions well described by a Gamma distribution and power spectral densities characterized by a Lorentzian shape. This agrees with a stochastic model describing blobs as a superposition of uncorrelated pulses moving radially outward, predicting a profile e-folding length given by the product of radial blob velocity and parallel loss time [3, 4]. With increasing core plasma density, blobs move faster, the average particle density in the far scrape-off layer increases, and fluctuations become more intermittent, resulting in enhanced plasma interactions with material surfaces.

These observations have significant implications for future fusion devices, as increased blob transport at high densities results in stronger heat loads and more intense plasma-material interactions. The findings further validate stochastic modeling approaches for describing edge plasma fluctuations, providing a quantitative framework for predicting SOL transport under different operational conditions.

ACKNOWLEDGEMENTS

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Poster Session MCF 4 - L

4 P 257 - Inner wall limiter startup experiments in WEST on bulk tungsten tiles

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ABSTRACT TEXT

The 2024 ITER re-baseline and, in particular, the change from a beryllium to a tungsten (W) wall could impact not only the access to H-mode and performance if W sources and edge transport result in significant core concentration [1], but also the ramp-up phase where plasmas will spend several seconds in a limiter configuration on the inner wall [2]. Predicting W sources and core contamination is instrumental in optimising this phase in terms of MHD, radiative collapse and flux consumption.

In this context, part of the WEST restart in 2024 was dedicated to this startup phase, leveraging the newly installed bulk W inner limiters. The goal is to provide experimental data on which further core-edge modelling can be validated. The first phase of this restart focused on achieving plasmas in limiter configuration without prior boronisation and following a relatively long maintenance period. Under these conditions, cold and radiative plasmas were obtained. After several attempts, only plasmas of duration up to 1.5 s were achieved, with plasma current up to $I_p = 600$ kA. Plasma radiation originated mostly from light impurity contamination with no W emission seen in visible spectroscopy lines of sight looking at the inner limiter. Following a first, non-uniform boronisation (3/6 injection points, also performed in support of the ITER re-baseline activity), 10 s flattops in limiter configuration on bulk W were easily achieved without external heating. This allowed pulses to be obtained with several density and plasma current combinations in stationary ohmic phases and, in particular, a variation of the Greenwald fraction from 0.15 to 0.9 at 300 kA. Stable conditions for higher currents (500 and 700 kA) could only be attained at high Greenwald (>0.8) fractions due to strong outgassing in this early phase of the campaign. Tungsten visible line intensities were found to evolve rapidly from pulse to pulse, with a concomitant decrease in the central electron temperature. Nitrogen seeding was used in a similar way as in previous WEST campaigns [3] and its impact was found to be similarly favourable in these new experiments, reducing W inner limiter sources, core radiation and flux consumption.

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Poster Session MCF 4 - L

4 P 258 - Numerical modelling of underexplored edge plasma scenarios in tokamaks using the SOLPS-ITER code

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ABSTRACT TEXT

In the pursuit of magnetic confinement nuclear fusion energy within tokamak design, a key challenge is balancing the core's high temperatures and densities with the control of edge plasma properties. This would ensure safe power exhaust, preserve plasma purity, and maintain plasma facing component (PFC) integrity. In the context of boundary plasma physics, the present contribution numerically investigates two underexplored edge plasma scenarios that are of potential interest for future fusion reactors.

Firstly, the edge transport properties of negative triangularity (NT) plasmas are investigated due to their potential for H-mode grade confinement in an inherently ELM-free L-mode [1], though detachment remains more challenging than in positive triangularity (PT) [2]. Secondly, the properties of a pure H-mode helium edge plasma heated with hydrogen neutral-beam injection (NBI), produced at ASDEX Upgrade (AUG), are studied in support of the non-nuclear phases of ITER [3]. All scenarios are analyzed using the SOLPS-ITER edge plasma solver [4], coupling the multi-fluid B2.5 code for charged species with the kinetic Monte Carlo Eirene code for neutrals, supporting experimental interpretation.

Regarding NT, two deuterium discharges in TCV are considered, sharing the same divertor geometry but opposite upper triangularity. Experimentally, under equal upstream conditions, NT exhibits lower target cooling. SOLPS modelling, including drifts and carbon impurities, indicates that magnetic geometry alone cannot account for the observed differences. To reproduce experimental observations of electron density, temperature, gas puff, and neutral pressure, a suppression of cross-field particle transport in the core and scrape-off layer for NT plasmas must be assumed.

Regarding helium plasmas, SOLPS simulations of increasing complexity are compared with experimental data from a pure helium H-mode discharge heated with hydrogen NBI at AUG. The modeling choices, the optimal selection of transport coefficients, and the inclusion of drifts are discussed, starting from an initial simplified assumption of a pure helium plasma. The effects of hydrogen introduced by NBI heating and the presence of potential radiating impurities are also analyzed.

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Poster Session MCF 4 - L

4 P 259 - Improvement of helium exhaust on STEP by divertor design

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ABSTRACT TEXT

When managing particle and power exhaust on the Spherical Tokamak for Energy Production (STEP)[1], one significant challenge will be to exhaust helium to prevent core degradation, without compromising the divertor detachment. In this study, we assume a fixed helium (He) pumping speed and explore ways of improving He exhaust by changing the divertor design, such as altering the pumping/fueling locations. Due to engineering constraints, STEP is likely to have a pump only in the outer divertor (horizontal target) on the Scrape-Off-Layer (SOL) side unlike ITER/DEMO[2][3], relying on a dome to direct particles from the inner to outer target.

SOLPS-ITER simulations have shown that locating the pump duct at the target (i.e. near the strike point) may reduce He density at the outer-midplane (OMP) up to ~30% compared to a location further up in the outer divertor on the SOL side. This can be explained by an increase of He atom compression, $c_{\text{cmp,He0}} = n_{\text{He0,div}}/n_{\text{He0,main chamber}}$ with the duct at the target. However, the duct at the target requires a higher DT puff to obtain the same upstream electron density, and thus level of detachment, which ultimately results in a higher tritium flow which is unfavourable for the fuel cycle[4].

As for the fuelling location, unlike the clear impact on the argon (Ar) distribution in the earlier design[5], midplane fuelling did not reduce the upstream Ar/He density. This can be understood by the facts that 1) the larger machine size ($R = 3.6$ m) would require higher fuelling to see the effect reported in [5] ($R = 2.6$ m) or/and 2) lower Z He is subject to a weaker thermal/friction force.

Optimising the pumping location for both He pumping and detachment will require a careful balancing between the multiple constraints. Work is ongoing to improve the He pumping efficiency (without changing the He pumping speed) also by enhancing transmission of particles between the inner and outer legs.

This work has been funded by STEP, a major technology and infrastructure programme led by UK Industrial Fusion Solutions Ltd (UKIFS), which aims to deliver the UK's prototype fusion powerplant and a path to the commercial viability of fusion.

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Poster Session MCF 4 - L

4 P 260 - Deuterium Fulcher Band measurements in WEST tokamak

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ABSTRACT TEXT

Molecular triplet bands of hydrogen and its isotopes, of which the most prominent and well-known are the $d\ ^3\Pi_u$ to $a\ ^3\Sigma_g^+$ transition called Fulcher Band, are widely used for the study of the divertor regions in different fusion devices [1,2,3]. The intensity of those bands, due to their high excitation energy, is highest in the regions where strong fluxes of electrons and ions encounter molecular gas, so they are frequently used as an indication of so-called ionization front [3]. Both the intensity and the internal energy of the molecules depend on plasma parameters in the studied region—electron temperature, density, ion flux etc. In [1] the multimachine dependence of the rotational temperature on the plasma density is proposed, but the investigations are still ongoing.

In this contribution we present first Fulcher Band measurement data from WEST tokamak, with full tungsten plasma-facing components. Most of the investigations reported previously concentrate on the divertor region; in WEST a significant signal is observed also in the other parts of the plasma close to the tungsten surface of the plasma vessel (e.g. in the top part of the machine). The estimated molecular parameters (rotational temperature, intensity of the different vibrational states of D_2 triplet d level) is presented for different lines of sight, and the results are compared with data from other tokamaks.

* See <http://west.cea.fr/WESTteam>.

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Poster Session MCF 4 - L

4 P 261 - Study of the divertor pumping capability in V-Shaped JT-60SA divertor

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ABSTRACT TEXT

In this work, we present a systematic modelling to investigate the pumping capability of the divertor pumping system in JT-60SA tokamak[1]. This work aims to identify the main parameters affecting the pumping system performances and proposing possible improvements.

The numerical study has been performed with two edge/SOL transport code suites, SOLPS-ITER[2] and SOLEDGE3X-EIRENE[3], addressing the high-performance full-current Single Null scenario (scenario #2[1]) of JT-60SA equipped with a metallic wall. The computational domain is extended up to the pump location in the subdivertor region. The outer divertor is characterized by a V-shaped geometry, with the outer strike point very close to the corner designed to enhance the divertor detachment at low mid-plane density. In attached and partially detached outer divertor plasma conditions, a quite low D pumping rate is observed. A scan of the injected input power at the simulation inner boundary and of the pump albedo shows the negligible effect of the latter. The low D pumping rate is mainly related to the outer divertor corner geometry leading to a trapping of recycled neutrals. By increasing the level of detachment, the subdivertor pressure and the corresponding pumping rate increase while the ionization front moves upwards so that a path opens for the neutral molecules toward the subdivertor.

Two possible alternatives are proposed to improve the pumping performances. The first would require to modify the shape of the first wall so to widen the outer corner and decrease the trapping of neutral molecules. The simulations show an increase by a factor of 1.5 in D pumping rate. The comparison between closed V-shaped corner and open V-shaped corner shows an higher neutral compression in the former. The second option would be an upward shift of the strike point position, e.g. by 8 cm, so to place it above the outer divertor corner. Simulations show that the D pumping rate rises by a factor of 4. A higher neutral compression is observed in the lower strike point case. These two comparisons indicate the lower strike point configuration with the closed V-shaped corner results in high neutral compression, leading to lower detachment onset density.

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Poster Session MCF 4 - L

4 P 262 - Fast-ion model validation for He plasmas in W7-X

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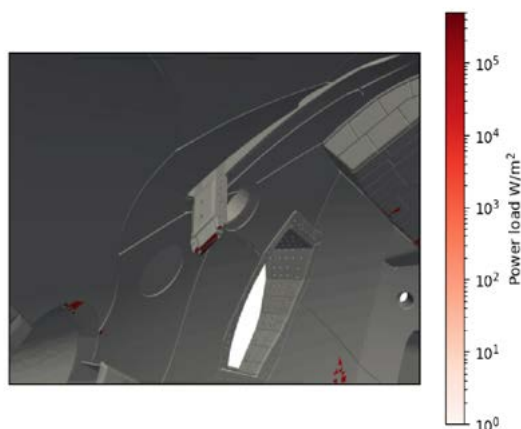
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ABSTRACT TEXT

The current Wendelstein 7-X (W7-X) campaign now includes He plasmas to investigate their impact on fast-ion confinement. Predictive ASCOT5 simulations indicate more efficient beam ionisation in He plasmas compared to H, but accompanied by increased fast-ion losses. Comprehensive modelling is required to assess the combined effects of ion losses and shinethrough to prevent hot spots on unshielded vessel components. The new experimental data will facilitate the model validation to support He and D-beam simulations for upcoming and future experiments. One of the vulnerable components is the sFILD detector[1], now in the manufacturing phase, which requires power-load estimates to ensure its integrity.

Figure 1: 3D view of sFILD probe head in ASCOT wall geometry.



BBNBI5 and ASCOT5 will be used to generate the ionisation profiles and calculate the slowing-down distributions, respectively. The recently upgraded BBNBI5 derives the ionisation coefficients from the ADAS database utilising ASCOT5's atomic reactions module[2]. This enables generating birth distributions for beams and target plasmas of non-hydrogenic species. Selected He-plasma discharges will be modelled to compare the estimated shinethrough with the heat shield thermography (HST) data[3]. Aside from the validation, sFILD power loads will be assessed and synthetic signals using FILDSIM will support optimising the balance between loads and detection coverage. The detailed geometry of sFILD has been implemented in ASCOT5 (fig 1).

In this contribution, a comparison of the shinethrough and the HST data for He-plasma cases will be shown for model validation. Also, the estimations of total losses as well as the power loads on the sFILD for the standard, high and low-mirror configurations will be presented. For this, H and He will be included as both injection species and target plasmas.

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Poster Session MCF 4 - L

4 P 263 - Nonlinear Control Strategies for Divertor-Safe Burning Operation in ITER

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ABSTRACT TEXT

Controlling the core-plasma kinetic state, defined by the temperatures and densities of all the species, arises as one of the most fundamental problems in nuclear fusion. This control problem, usually referred to as burn control, represents a formidable challenge for future reactor-grade tokamaks like ITER due to the multi-dimensional, coupled, and nonlinear characteristics of the burning-plasma dynamics. A well-designed burn controller must keep the operating point far from stability, controllability and safety boundaries to avoid disruptions and protect the device while regulating the fusion power. This requires the controller to not only achieve tight regulation around a desired operating point, rejecting perturbations driven by changes in plasma confinement, impurity content, or operation conditions, but also to drive the plasma from one operating point to another during the burning phase, manage transitions into and out of the burning phase, incorporate operational constraints arising from temperature and flux limits imposed by the plasma facing components, and handle the nonlinear coupling with other competing controllers using shared actuators.

These control objectives necessitate incorporating the nonlinear plasma dynamics into the control design process. Control designs that account for these nonlinearities have demonstrated superior performance, stability, and robustness against model uncertainties [1]. These nonlinear burn controllers utilize multiple actuators simultaneously to either heat up the plasma to prevent quenching (e.g., ion/electron cyclotron heating and neutral beam injection) or cool down the plasma to avoid thermal excursions (decrease of fusion power density by isotopic fuel tailoring, reduction of plasma energy by confinement degradation, and increase of radiation losses by impurity injection), while regulating the density via fueling (e.g., pellet injection and gas puffing). Both model-based (Lyapunov techniques) and data-based (deep-learning techniques) approaches that are capable of handling the nonlinear and coupled dynamics of the burning plasma are presented in this work, highlighting the advantages and limitations of each approach. The role of zero-dimensional (e.g., COBALT) and one-dimensional (e.g., COTSIM) control-oriented codes in each one of these approaches is discussed from three perspectives of the control design process: (i) control-synthesis model, (ii) training environment, (iii)- simulation test before implementation.

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Poster Session MCF 4 - L

4 P 264 - Direct reconstruction of density fluctuations observed by Alkali Beam Emission Spectroscopy

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ABSTRACT TEXT

The Alkali Beam Emission Spectroscopy (ABES) of W7-X allows the determination of the radial electron density profiles in the SOL and edge plasma at the outboard side of the bean-shaped cross section of the plasma [1]. The injection axis of the sodium atoms lies on the mid-plane of the stellarator and as such it crosses the centre (O point) of one of the divertor islands for the standard configuration.

Based on a recent density reconstruction method [2], an iterative approach has been implemented, aiming at resolving density fluctuations directly [3]. The study presents the limitations of the fluctuation analysis using direct reconstruction detail. For this purpose simulated experimental data is presented and the magnitude of the fluctuations, the measurement uncertainties and the shape of the exact density profiles are changed in order to characterize the method.

Using experimental results obtained during the recent campaigns of W7-X in autumn 2024 and spring 2025, the fluctuation reconstruction is applied to analyse the correlation between the peaking of the density profiles often observed near the O point of the island divertor and fluctuations in the ABES signals.

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Poster Session MCF 4 - L

4 P 265 - Simulations of tungsten dust transport and survivability in DEMO

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ABSTRACT TEXT

Dust is routinely produced in fusion devices as a consequence of plasma-wall interactions. These nanometric-to-micrometric particles result from the delamination of loosely attached wall deposits grown during steady-state discharges [1], and may also be formed by splashing from transient metallic melt pools generated by high-energy off-normal events [2–4]. The presence of such particles in a fusion device is linked to various operational issues: dust residing on the vessel wall can absorb fuel elements [5], whereas grains and droplets that are mobilized with large enough velocities to cross the last closed magnetic surface vaporize into impurities, potentially causing disruptions or preventing plasma start-up [6]. In either case, large particles whose size may range from tens to hundreds of micrometers are especially important since they both contribute most strongly to the total in-vessel dust mass—on which regulatory limits are typically imposed [5]—and are the most likely to survive plasma heating long enough to penetrate into the confined region [7].

In parallel with dust surveys carried out between experimental campaigns in contemporary devices [4], modelling activities for ITER and DEMO focus on estimating the intensity of various dust and droplet sources, along with the properties of the resulting particles [1,5]. Here, we report on a predictive study of tungsten dust inventory evolution over the course of multiple steady-state DEMO discharges. Following the methodology detailed in [7], the MIGRAINE code is used to simulate the transport of individual dust particles sampled from a prescribed population, whose size distribution and mobilization characteristics are varied within typical ranges expected from experimental data [2–4] as well as previous modelling studies [8,9]. Statistical analysis of millions of MIGRAINE trajectories is then conducted to determine the characteristic inventory decay times and their sensitivity to initial dust size and velocity, but also to map out the atomic impurity source due to vaporization. The impact of the drag force due to bulk ion flows is also quantified.

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Poster Session MCF 4 - L

4 P 266 - Numerical study of the X-point radiator regime in WEST

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ABSTRACT TEXT

The X-point radiator (XPR) regime, observed in the WEST tokamak, is characterized by the appearance of a stable radiative ring above the X-point with sufficient nitrogen seeding. The transitions from high-recycling regime to the XPR regime usually happen within milliseconds. XPR regime can significantly mitigating the heat load at the divertor target while maintaining core plasma performance, which offers a promising approach for advanced tokamak operation and control.

This study employs the SOLEDGE3X-EIRENE code in transport mode to numerically reproduce the XPR radiation regime under WEST boundary conditions. Simulations were conducted with a constant input power up to 2 MW, deuterium gas puffing combined with nitrogen seeding, and included full drift effects. The simulation results show that nitrogen seeding, introduced either from the midplane or the private flux region, can lead to the formation of an XPR inside the separatrix. When XPR occurs, there is a significant reduction in the target temperature, dropping from above 10 eV to 2 eV, while the upstream conditions remain nearly unchanged. The density profile, initially asymmetric with higher values at the inner target and lower values at the outer target, becomes symmetric. As the seeding rate increases, the XPR shifts toward the low-field side along the magnetic field line, consistent with experimental observations. Further analysis indicates that drifts may play a critical role in the formation and dynamics of the XPR. During the onset of the XPR, an electrostatic potential well develops at the X-point. Changes in the potential map and the leading reversed ExB flux are strongly correlated with the abrupt system transitions observed during the cliff-like behavior associated with XPR onset, with a characteristic timescale of 10 ms observed in the simulation. The dynamics of the cliff-like transition from an attached plasma to the XPR state are also under investigation.

Poster Session MCF 4 - L

4 P 267 - The NSTX-U Research Program: closing the gaps towards a Fusion Pilot Plant

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ABSTRACT TEXT

The overarching goal of the U.S. fusion program is to produce net electricity in a Fusion Pilot Plant (FPP) in the 2035–2040 time frame. There is significant interest both within and outside the U.S. in achieving this goal through the Spherical Tokamak concept. With 12 MW of neutral beam heating, 6 MW of High Harmonic Fast Wave heating, and the capability of 2 MA, 1 T, 5 sec discharges, the National Spherical Tokamak Experiment-Upgrade (NSTX-U) is uniquely positioned to target several science and technology gaps in physics regimes close to those expected in a compact, steady-state FPP. In particular, the two most significant gaps are core confinement improvement and heat flux mitigation, neither of which have been closed in an integrated fashion for any planned fusion power production device. High core confinement and stability are essential for producing majority self-driven plasmas in FPPs, with confinement being the major driver for cost reduction in FPP through its direct effect on device size and required heating power. NSTX-U capabilities will allow for assessing confinement improvements seen in NSTX and other STs in physics regimes much closer, than ever before, to those anticipated in ST-based FPPs. Both conventional and transformative heat flux mitigation methods, such as liquid lithium plasma facing components, will be developed and tested in-situ in NSTX-U at incident heat fluxes of $\sim 100 \text{ MW/m}^2$, and these results will inform plans and reduce risk for a subsequent upgrade to fully heated, high-Z wall and full liquid lithium divertor capability, a technology that could be implemented on any magnetic confinement device at any aspect ratio. These gaps will be assessed by a full complement of diagnostics and analysis tools, which will also aid in the development of the underlying theory and predictive models needed for further optimization. NSTX-U research has direct connection to the private sector by informing design choices for future power production facilities being developed by these companies. This presentation will give a more detailed overview of the elements and deliverables of the NSTX-U research program.

Poster Session MCF 4 - T

4 P 268 - On the analysis and calculation of loop voltage involving tokamak inductance variations

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ABSTRACT TEXT

In this work, we focus on the problem of how to correctly calculate and deal with the loop voltage component produced by internal inductance variations in a tokamak configuration. Some confusion exists in the literature, as some authors use Faraday's law applied to flux variation, while others adhere to the Poynting theorem applied to energy variations. While the two laws coincide in the textbook case of constant inductance with current variations (i.e., $V = L \, dI/dt$), in the case of inductance variation one formulation yields $V = I \, dL/dt$, while the other gives $V = \frac{1}{2} I \, dL/dt$. These contradictory formulations, including their full matrix and/or integral versions, appear in several papers and are used for experimental data analysis and plasma current control. Even though the difference between the two is not quantitatively significant for most practical purposes, it can become relevant during strong transient phases, such as internal reconnection events and disruptions.

In our view, Faraday's law gives the correct approach, while the inappropriate application of the Poynting theorem leads to an erroneous formulation that is, unfortunately, often used. As practical proof, in this paper we compare the loop voltage calculated using the two formulations, using experimental data from an RFX-mod tokamak discharge and comparing it with its numerically simulated counterpart, produced by a reliable transport code.

Poster Session MCF 4 - T

4 P 269 - Two-dimensional kinetic full wave analysis in plasmas using integral form of dielectric tensor

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ABSTRACT TEXT

For the modeling of wave heating and current drive in magnetic fusion plasmas, stationary full wave analysis based on the finite element method (FEM) is a powerful and flexible scheme in various configurations. An issue remaining in the FEM analysis, however, is to describe kinetic effects due to thermal motion of particles without wave number. Usually, kinetic effects in dielectric tensor are expressed with wave number vector in a uniform plasma. Several approaches based on cold-plasma wave number, differential operator, or Fourier analysis, have been developed for inhomogeneous plasmas, but their applicability is limited. We have developed systematic scheme using integral form of dielectric tensor for kinetic full wave analysis in inhomogeneous plasmas. The integral form is derived by following the particle orbit in inhomogeneous plasmas. In Maxwellian plasmas, two kinds of kernel functions have been derived: the plasma dispersion kernel function (PDKF) for parallel motion and the plasma gyro kernel function (PGKF). Recently PDKF has been extended to magnetic configuration with parabolic inhomogeneity of magnetic field strength. In order to solve the integro-differential form of Maxwell's equation, an extended finite element method which includes the coupling between different elements within the extent of particle orbits was developed. One-dimension analyses were applied to various phenomena in inhomogeneous plasmas; laser-plasma resonant interaction, magnetic beach heating in the presence of linear magnetic inhomogeneity, localized cyclotron heating near the extremum of magnetic field, and mode conversion to the Bernstein waves. In tokamak plasmas, two-dimensional inhomogeneity has to be taken into account. For simplicity, the coupling between the parallel and perpendicular motions is ignored. The two-dimensional FEM full wave code TASK/WF2D was extended to use the applied to the analysis of ion cyclotron heating in the presence of energetic ions and coupling with Bernstein waves. It was also applied to the lower hybrid current drive and the O-X-B mode conversion of the electron cyclotron waves.

Poster Session MCF 4 - T

4 P 270 - 3D full-wave simulations of the O-SX mode conversion process in MAST Upgrade

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ABSTRACT TEXT

Electromagnetic waves in the microwave frequency range are essential in fusion plasmas for both heating and diagnostics. Conventional *electron cyclotron resonance heating* (ECRH) relies on the electron gyrofrequency resonating with the microwave frequency. Heating at harmonics of the gyrofrequency, and thus at higher frequencies, is in principle possible, allowing access to plasmas with higher plasma density, but requires high electron temperatures to be efficient. An alternative approach is coupling to *electron Bernstein waves* (EBWs), which are strongly absorbed even at high harmonic numbers and low electron temperatures. Additionally, EBWs can drive significant toroidal net currents, a crucial advantage for spherical tokamaks like MAST Upgrade, which have limited inductive current drive due to a small or completely absent central solenoid.

The O-SX-B mode conversion scheme excites EBWs through a two-step process. The first step, the O-SX coupling, is a cold plasma process that largely determines the overall efficiency, while the second step is often assumed to be ideal, neglecting nonlinear effects and collisional damping. Here, we present 3D full-wave simulations of the O-SX coupling process for the MAST Upgrade spherical tokamak, using the novel 3D finite-difference time-domain code FOCAL. Our results demonstrate that the envisaged 28 GHz heating system can achieve high coupling efficiencies. Notably, MAST Upgrade exhibits ideal parameters for efficient coupling to EBWs.

Poster Session MCF 4 - T

4 P 271 - Integrated plasma scenario analysis of the EHL-2 spherical torus

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ABSTRACT TEXT

The EHL-2 spherical torus, a next-generation experimental device being designed by ENN, is intended to verify p-11B fusion thermal reaction rates, establish scaling laws for spherical torus/tokamak configurations at ion temperatures in the tens of keV range, and provide a foundation for future p-11B burning plasma experiments. The key design parameters include a central ion temperature (T_{i0}) of approximately 30 keV, an ion-to-electron temperature ratio (T_i/T_e) greater than 2, a central electron density (n_{e0}) of approximately $1 \times 10^{20} \text{ m}^{-3}$, a plasma current (I_p) of around 3 MA, a toroidal magnetic field (B_t) of approximately 3 T, and an energy confinement time (τ_E) of approximately 0.5 s. The physics design of EHL-2 is focused on three primary operating scenarios: (1) high ion temperature scenario, (2) high-performance steady-state scenario, and (3) high triple product scenario. In this study, the potential discharge regimes of the EHL-2 are explored and analyzed using the integrated modeling codes. Initial results suggest that a central ion temperature exceeding 30 keV, with T_i/T_e greater than 2, can be achieved by injecting 10 MW of 60 keV and 4 MW of 100 keV neutral beam injection (NBI) systems (with tangency radius $R = 0.8 \text{ m}$) under conditions of $I_p = 3 \text{ MA}$, $n_{e0} \sim 1 \times 10^{20} \text{ m}^{-3}$, and $B_t = 3 \text{ T}$. Additionally, with 10 MW of 80 keV NBI (tangency radius $R = 0.8 \text{ m}$) and 5 MW of electron cyclotron resonance heating (ECRH) current drive (deposition at $p = 0.4 \text{ m}$), a high-performance plasma with a significant bootstrap current fraction ($f_{bs} > 50\%$) can be sustained within a plasma current range of 1.0–1.5 MA, $n_{e0} \sim 7 \times 10^{19} \text{ m}^{-3}$ and $B_t = 2 \text{ T}$. The design of the high triple product scenario presents complex physics challenges and will require further exploration and verification.

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Poster Session MCF 4 - T

4 P 272 - Flight simulator development for the COMPASS-Upgrade Tokamak

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ABSTRACT TEXT

Flight simulators will play an increasingly crucial role in tokamak controller development, discharge preparation and simulation. They integrate a reduced-model plasma simulator with machine-specific components such as feedback controllers, diagnostic measurements, and technical limits to simulate discharge evolution and assess performance within the operational constraints of the tokamak. To be effective for machine optimization and discharge design—including testing between discharges in the tokamak control room—a flight simulator must maintain high computational efficiency.

A flight simulator is being developed for the COMPASS Upgrade tokamak[1, 2], which is currently under construction in Prague. Its long-term objectives include providing a testing environment for the development and validation of the machine's magnetic control system, reconstructing magnetic equilibrium using magnetic diagnostics, and assessing discharge feasibility. Implementing the flight simulator for the COMPASS Upgrade is particularly complex due to the lack of experimental data, as the tokamak is still under construction.

This work details recent progress in the implementation of the COMPASS Upgrade flight simulator. The simulator currently uses the MEQ suite of codes—FBT[3], LIUQE[4], and FGS/FGE[5]—developed at EPFL-SPC to model plasma discharges within the COMPASS Upgrade geometry. The flight simulator's workflow is presented along with the first attempt to model a tokamak discharge with a closed-loop feedback system.

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Poster Session MCF 4 - T

4 P 273 - Overview of progress in establishing the plasma basis of STEP

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ABSTRACT TEXT

The STEP programme has achieved its first major milestone of providing a conceptual design for a prototype fusion power plant targeting 2040. The design includes a fully non-inductive plasma solution [1] and a robust control system [2]. External heating and current drive (CD) are microwave-based, with both pure electron cyclotron CD (ECCD) and a mix of on-axis ECCD and off-axis electron Bernstein wave CD (EBCD) in the design. EB CD is projected to have a normalised current drive efficiency three times higher than that of ECCD, providing possible access to a $Q_{\text{fus}} = P_{\text{fus}}/P_{\text{aux}} \sim 30$ flat-top operating point (FTOP) compared to $Q_{\text{fus}} \sim 11$ needed for net electricity output $P_{\text{net}} \sim 100\text{MW}$ [1]. The published design [1], with geometric major radius $R_{\text{geo}} = 3.6\text{ m}$, aspect ratio $A = 1.8$, and toroidal field $B_t(R_{\text{geo}}) = 3.2\text{T}$ generating fusion power $P_{\text{fus}} \sim 1.5\text{--}1.8\text{GW}$, has proved technically challenging due to constraints on the inner build, leading to a pivot to a larger design with $R_{\text{geo}} = 4.3\text{ m}$ but the same A and P_{fus} . We report on recent work that reduces uncertainties in the design, explores control strategies, and develops whole-pulse operating scenarios. Integrated modelling is used as an assumption integrator, with Bohm/gyro-Bohm transport scaled to achieve the desired P_{fus} . Scenarios are constrained by seven other conditions, for example $Q_{\text{fus}} > 10$. Nonlinear gyrokinetic simulations show that the transport is dominated by hybrid kinetic ballooning modes (hKBMs) [3] which can cause unsustainable heat fluxes. However the first flux-driven transport calculations using a new quasilinear model for hKBM transport provide confidence in the existence of an FTOP with only a small ($\sim 10\%$) decrement in P_{fus} relative to the target [4]. The model does not yet include the effects of fusion α -particles, but analysis so far indicates that these particles do not drive toroidal Alfvén eigenmodes, which threaten the achievement of burning plasmas in other reactor concepts.

This work has been funded by STEP, a major technology and infrastructure programme led by UK Industrial Fusion Solutions Ltd (UKIFS), which aims to deliver the UK's prototype fusion powerplant and a path to the commercial viability of fusion.

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Poster Session MCF 4 - T

4 P 274 - Simulation study of ECH multiple resonance heating and energetic electron generation in the QUEST spherical tokamak

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ABSTRACT TEXT

Recently, energetic electrons with energies up to 200 keV have been observed in the electron cyclotron heating (ECH) plasma of the QUEST[1], a spherical tokamak at Kyushu University. These observations cannot be explained by simple second harmonic resonance heating. Notably, a toroidal current of approximately 80 kA was achieved under oblique ECH injection at a parallel wave number ($N_{\parallel}$) of 0.7. The acceleration of supra-thermal electrons (SEs) is theorized to be facilitated by third harmonic resonance, with additional acceleration from the fourth harmonic. This multi-harmonic heating process is believed to significantly contribute to the population of energetic electrons, although theoretical validation using kinetic theory is still not done.

This study investigates the generation of supra-thermal electrons through higher harmonic resonance heating and their impact on plasma behavior, particularly the toroidal current. We employ the GNET code[2–4], which solves a linearized drift kinetic equation for the deviation of the electron distribution function from the Maxwellian distribution ($\delta f = f - f_{\text{Maxwell}}$) by simulating ECH in 5-dimensional phase space using the Monte Carlo method. The quasi-linear ECH driving term serves as a source term in velocity space, and we also include additional non-linear heating terms for the third and fourth harmonic resonances in this analysis.

In our GNET simulation, we assume plasma parameters of $T_e \sim 2$ keV, $T_i \sim 2$ keV, and $n_e \sim 1.0 \times 10^{18} \text{m}^{-3}$. We obtain the steady-state distribution (δf) with contributions from 2^{nd} , $2^{\text{nd}}+3^{\text{rd}}$, and $2^{\text{nd}}+3^{\text{rd}}+4^{\text{th}}$ harmonic resonance accelerations. Our results indicate a substantial formation of an energetic tail due to heating from the third and fourth harmonics, with the relative electron populations in the 100–200 keV and over 200 keV ranges showing good agreement. As $N_{\parallel}$ increases, the formation of the energetic tail is enhanced, and a significant tail is observed at $N_{\parallel} = 0.8$. We find that the induced current increases monotonically with increasing $N_{\parallel}$, and the obtained electron current closely matches the experimental value, reaching up to 70 kA.

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Poster Session MCF 4 - T

4 P 275 - Developing plasma scenarios for the updated STEP design point

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ABSTRACT TEXT

The Spherical Tokamak for Energy Production (STEP) programme aims to design a prototype reactor with the goal of demonstrating net electricity production [1]. Following a series of technical reviews of the design for the STEP prototype power plant SPP-001, it was decided that an increase to the plasma inner radius from 1.6 m (R_{geo} = 3.6 m, SPP-001) to 1.9 m (R_{geo} = 4.3 m, SPP-002) was necessary to provide more space for shielding and toroidal field passive quench protection. These changes require development of new plasma scenarios for the updated STEP design point, SPP-002.

Scans of potential operational spaces have been explored for the flat-top operating points, following a similar methodology used for the previous STEP design [2]. Initial scans have kept key plasma parameters fixed from SPP-001, such as $P_{fus} \sim 1.7\text{GW}$, $Q > 11$, $f_{rad} = 70\%$, $f_{GW} = 100\%$, $A = 1.8$. Alternative scenarios are also being investigated, e.g. scenarios at lower f_{rad} , higher f_{GW} or lower elongation κ , to assess whether there could be other promising operating points that STEP has access to. A significant impact of the larger device size is the change in efficiencies of the Electron Cyclotron (EC) and Electron Bernstein Wave (EBW) current drive. One aspect driving this change is the lower density and higher temperature due to keeping $f_{GW} = 100\%$ in these scenarios. Another aspect is the change in profile shape due to the adjusted transport coefficients based on flux driven GK simulations [3]. The larger size also reduces pedestal confinement because of lower β_p . These changes result in ECCD benefiting since the on-axis efficiency increases, whereas the EBWCD is reduced due to lower off-axis efficiency. This causes the EC and EBW scenarios optimal operating space to move further apart.

Based on the knowledge from SPP-001, ramp-up and ramp-down scenarios have been developed for SPP-002. These transient phases of plasma operation require careful optimisation of plasma parameters to ensure that they remain within operational constraints. This work aims to capture the changes to the flat-top operating points due to the larger STEP design, as well as showcasing the progress made on developing plasma scenarios for the new SPP-002 design point.

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This work has been funded by STEP, a major technology and infrastructure programme led by UK Industrial Fusion Solutions Ltd (UKIFS), which aims to deliver the UK's prototype fusion powerplant and a path to the commercial viability of fusion.

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Poster Session MCF 4 - T

4 P 276 - Next-Generation TRANSP: Enabling High-fidelity Fusion Simulations with IMAS and GPU Optimization

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ABSTRACT TEXT

TRANSP [1] is widely used in the fusion community for both interpretive and predictive tokamak plasma analysis. This paper presents major advancements that significantly enhance TRANSP's capabilities, enabling higher-fidelity simulations, improved interoperability, and faster computational performance.

A key development is the *integration of the Integrated Modeling & Analysis Suite (IMAS) interface*, allowing TRANSP to interact directly with the IMAS database. This integration provides a unified framework for accessing experimental data and simulation results, facilitating standardized workflows across fusion experiments. By improving data interoperability, IMAS integration enhances reproducibility and enables cross-experiment comparisons, supporting large-scale transport studies for existing and next-generation tokamaks.

Another major improvement is the *GPU optimization of the NUBEAM module*, which accelerates neutral beam injection (NBI) simulations to near real-time performance. This breakthrough enables high-fidelity between-shot analysis, a crucial capability for advanced scenario development. GPU acceleration was tested on Perlmutter at NERSC, demonstrating significant speedups while maintaining accuracy. This work highlights how GPU-powered computational techniques can make high-resolution simulations more accessible for time-sensitive transport studies.

Additionally, the *integration of the T3D (TRINITY) transport solver with the gyrokinetic GX model* [2] introduces embedded turbulence modeling within TRANSP. This advancement enables self-consistent transport simulations, incorporating fast ion effects, RF heating, and turbulent transport in a unified framework. By addressing a longstanding gap in predictive transport modeling, this development improves the accuracy of transport studies for both current and future tokamaks.

Finally, we *present validation studies of the TRANSP/T3D/GX system*, focusing on NSTX discharges. These studies assess the predictive capability of the gyrokinetic model, comparing results with experimental data and reduced transport models. The findings demonstrate the feasibility of turbulence-aware transport modeling within TRANSP, supporting both near-term experiments and long-term reactor design efforts.

These improvements make TRANSP as a comprehensive multi-physics modeling tool, providing essential capabilities for transport studies in present-day devices and upcoming fusion experiments.

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Poster Session MCF 4 - T

4 P 277 - Nonlinear microwave physics at the upper hybrid layer in MAST-U

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ABSTRACT TEXT

The spherical tokamak MAST-U is preparing to test the viability of electron Bernstein wave (EBW) based current drive using two newly acquired gyrotrons. The EBWs are electrostatic waves in magnetized plasmas which are strongly damped on harmonics of the electron cyclotron resonance. Quasilinear theory indicates that EBWs are able to drive current efficiently in parameter regions where conventional electron cyclotron resonance heating is less efficient. This is supported by older lower power experiments at MAST. If proven effective, EBW based current drive may play an important role in the future UK demonstration fusion device STEP.

In order to excite the EBWs, MAST-U will be using the O-X-B mode coupling scheme, coupling an injected O-mode gyrotron beam to an EBW through an intermediate X-mode wave. The coupling into the EBW occurs at the upper hybrid (UH) layer which is a caustic where the waves slow down and amplify. Because of this, several nonlinear wave-wave and wave-particle effects are associated with the excitation of EBWs, such as the parametric decay instability, stochastic electron heating and nonlinear Landau damping. Particle-in-cell simulations indicate that these nonlinear effects can substantially impact the linear excitation of EBWs.

In this contribution, we discuss the key nonlinear effects in connection with EBW current drive in MAST-U near the UH layer. The nonlinearities occur near several caustics which are points where the common WKB approximation breaks down. To tackle this, we apply phase space methods and the Wigner-Weyl formalism. Because MAST-U is an overdense plasma and the microwave parameter region differs somewhat from that of other European fusion devices such as ASDEX Upgrade and Wendelstein 7-X, other wave-wave interactions may be possible in MAST-U. We discuss how this could impact the power deposition profile in MAST-U.

Poster Session MCF 4 - T

4 P 278 - Reinforcement learning-based magnetic control on the DIII-D tokamak

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ABSTRACT TEXT

Magnetic plasma control in tokamaks relies on a combination of toroidal and poloidal field (PF) coils, which are essential for stabilizing and shaping the plasma. Traditional shape control algorithms depend on equilibrium reconstruction techniques, such as rEFIT, LIUQE, and Equinox, which solve the Grad-Shafranov equation in real time. However, these methods introduce computational delays and require extensive tuning of PID-based controllers.

This work introduces a novel reinforcement learning (RL)-based approach to magnetic control of high-performance DIII-D discharges. The control problem is formulated as a partially observable Markov decision process (POMDP), with an RL agent trained using the Soft Actor-Critic (SAC) algorithm. The training leverages an asymmetric Actor-Critic architecture, where the Critic has access to privileged information, accelerating learning and improving robustness. NSFsim, a free-boundary equilibrium and transport solver, provides a high-fidelity simulation environment that allows the agent to learn plasma response dynamics under varying heating conditions. By avoiding reliance on equilibrium reconstruction, the RL controller directly maps raw magnetic sensor signals to actuator commands, enabling faster and more adaptive control.

Experimental validation on DIII-D demonstrates the efficacy of the RL controllers across different plasma conditions, including high-performance H-mode and transient H-L transitions. The controllers maintain robust performance despite varying auxiliary heating power, achieving precise plasma shape control without explicit equilibrium reconstruction. Tests show that RL-based controllers successfully regulate plasma position and shape, even under conditions significantly different from the training domain. The developed controllers integrate seamlessly with the DIII-D Plasma Control System (PCS) and operate at real-time speeds.

Results highlight the potential of RL for advancing tokamak control strategies, offering improved adaptability and computational efficiency. Future work will focus on incorporating heating and current drive models to enhance transport accuracy and extending RL-based control methods to address reactor-scale fusion challenges. The success of this study underscores the viability of RL in real-time plasma control, paving the way for more sophisticated control solutions in future fusion power plants.

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Poster Session MCF 4 - T

4 P 279 - Theoretical and experimental comments on rf current drive phenomenon

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ABSTRACT TEXT

Radio-frequency current drive in tokamak is often explained by the quasi-linear theory¹⁾, however, many discrepancies are pointed out in experiments. First, the phase velocity of the injected rf travelling wave for the current flowing is much larger than the plateau regime on the electron distribution function, which indicates the current flowing is less smaller. This is called the spectrum gap problem. Second, much current must be flowing when the rf wave spectrum is much broader because of causing the more wide plateau resume in the distribution function, however, experimentally much current is flowing only for the sharp rf spectrum²⁾. Third, the current drive using the cyclotron wave can also flow due to the perpendicular heating, whose current must be saying 3/4 of the case of the lower-hybrid(LH) current drive³⁾. However, experimentally the current drive using cyclotron wave is much smaller than that by LH wave, which is not three quarter of the LH wave, but is below one tenth of it⁴⁾. The basic understanding of the current flowing is the equation of motion applying the electric field E : $mdv/dt = eE - mnv$, where n is the collision frequency. In the stationary state($d/dt = 0$), $v = eE/mn$, the flowing current is $J = env = e^2n/mn = sE$, where $s(= e^2n/mn)$ is the conductivity. In the quasi-linear understanding of the current flowing is formed by the asymmetry of distribution function between the positive and negative direction of travelling wave. Denoting positive quasi-linear distribution function as f_{quasi} the flowing current expressed as $J = -e \int (vf_{quasi})$. Following above derivation the precise current is expressed as $J = \int (sE_{eff})$. Hence E_{eff} is the effective electric field receiving from rf travelling wave⁵⁾. In the cyclotron current drive, it is denoted rf wave field E is perpendicular to the magnetic field. The equation of motion is $mdv/dt = eE - mv/t'$ and $mdv/dt = -mv/t'$, where $t' = 1/n$. Assuming $v = v_0$ when $t = 0$, the parallel current by E is $J = env \exp(-eEt/mv)$, which shows the formed current decays only.

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4 P 280 - Numerical investigation of the O-X mode conversion in the TCV device

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ABSTRACT TEXT

In view of future feasible fusion reactors, spherical tokamaks provide a promising design as they are compact while achieving good performance. However, the plasma density in a spherical tokamak exceeds the cut-off density of the microwave intended for ECR heating. In order to overcome this limitation, coupling an electromagnetic wave to electron Bernstein waves (EBWs) is a possible alternative. The major advantages of EBWs are that they do not have a high-density cut-off, they are well absorbed at the electron-cyclotron resonance layer, and can drive significant toroidal net currents.

Typically, a two-step process is followed for the EBWs. The first step is to convert an O-mode to an X-mode (O-X conversion) at the O-mode cut-off layer, while the second one is the conversion from X-mode to EBW (X-B conversion) at the upper hybrid (UH) resonance. Neglecting non-linear effects, the X-B conversion is usually perfect, making it more important to focus on the O-X process.

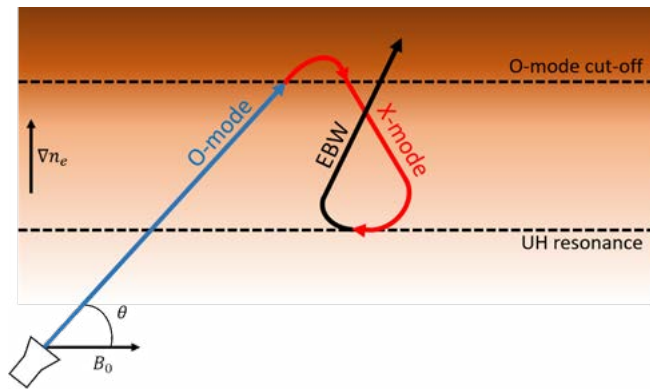


Figure 1: Scheme of the O-X mode conversion.

Experimental investigations, as well as numerical calculations with ray-tracing have been performed in the past for O-X-B mode conversion at the TCV device, but never with a full-wave approach, which allows to study the effects of finite size of the beam. In this work, the O-X conversion efficiency is numerically investigated with a 2D Finite-Difference Time-Domain (FDTD) simulation code. A frequency of 82.7 GHz is selected as it is the operation frequency of two gyrotrons installed at TCV, providing each up to 0.75 MW of heating power.

The angle of incidence with respect to the background magnetic field is varied as the conversion efficiency is heavily depended on the angle. Moreover, the effect of the steepness of the electron density profile is explored as well. It is shown that shallow profiles are more sensitive to angular mismatch, as the window for higher conversion efficiency is smaller.

The numerical setup allows for a direct comparison with experimental results from TCV. In the course of complementary studies, the exploration of edge localized modes (ELMs) effect on the conversion efficiency is of major interest.

Poster Session MCF 4 - T

4 P 281 - Family of phase space rays tracing model for RF heating

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ABSTRACT TEXT

In laboratory toroidal plasmas, experimental measurements of wave beam propagation and absorption show broader spatial profiles than predicted by numerical simulations. To address this, we have been improving the geometrical optics model used in simulations. In early methods, rays are traced from multiple initial positions in real space, with each ray having a specific initial wavenumber, a technique known as “family of rays” tracing. Recently, the quasi-optical method has been developed to better represent the diffusive behavior of wave beams. This method restricts tracing to a single ray corresponding to the optical axis, introducing complex wave fields near the axis via series expansion to account for higher-order effects like diffraction and scattering. However, it struggles when wave fields become too broad for an “optical axis” to be defined, leading to a dilemma: as the beam spreads, accuracy deteriorates.

In this study, I aim to create a wave beam model that maintains accuracy even as the wave field diffuses. I achieve this by revisiting the family of rays tracing, expanding it to the “ray phase space,” which combines real space with wave vector space. By applying the Wigner-Weyl transform and the Moyal product, concepts from quantum theory, a general linear wave equation is mapped to a von Neumann-type equation in ray phase space. This results in the Liouville-type equation, which describes the evolution of the ray phase space profile of wave energy. I found that the understanding of this Liouville-type system based on the Lagrangian method can be interpreted as an extension of a family of rays tracing, which has been limited to real space, into the ray phase space. I will report on the model equations of this Liouville-type system and the specific concept of a family of phase-space rays tracing approach.

Poster Session MCF 4 - T

4 P 282 - A multi-synthetic diagnostic framework for SOL/edge plasma density studies on the W7-X stellarator

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ABSTRACT TEXT

A novel synthetic diagnostic framework was developed focusing on diagnostic systems able to resolve fast density fluctuations. The framework incorporates the RENATE beam emission spectroscopy (BES) synthetic diagnostic [1] and the FW2D reflectometry code [2]. The framework allows for the same modelled plasma density fluctuations to be observed and processed by both synthetic diagnostics simultaneously, enabling comparative studies with both methods, resulting in a more holistic interpretation and understating of the observed phenomenon.

The framework was adapted to the W7-X stellarator, the Alkali BES system [3] and the phase correlation reflectometry (PCR) system [4], both capable of resolving fast density fluctuations and observing the same region, the scrape-off layer and edge regions at the outboard side of the bean-shaped cross-section of the plasma. Modelled and artificially introduced density fluctuations allowed for the generation of a blueprint on the potential synergy of the two diagnostic systems observing plasma density fluctuations and the enhancement of their capabilities. The framework was used to enhance the provide modelling aided measurement interpretation for observed plasma density fluctuations in the scrape-off layer, island divertor and close to the plasma edge regions.

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Poster Session MCF 4 - T

4 P 283 - Latest results from a multi-energy soft x-ray diagnostic for Te measurements and W transport studies on the WEST tokamak

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ABSTRACT TEXT

The WEST tokamak is a full-metal (W) PFC device focused on long-pulse experiments. Long-pulse operation up to 1000 s is available at a nominal magnetic field of 3.7 T with dominant electron heating and no external momentum source using RF waves. To access new physics and operational expertise, a versatile multi-energy soft x-ray camera has been developed, calibrated, and deployed at WEST, providing measurements of the local x-ray emissivity in multiple energy ranges simultaneously. This innovative diagnostic leverages a pixelated detector capable of independently adjusting the lower energy threshold for photon detection on each pixel providing unprecedented flexibility in the configuration of an imaging x-ray detection system. Through meticulous trimming and calibration of the lower energy thresholds it is possible to separate signal from W line emission from the continuum, in order to simultaneously investigate multiple plasma properties.

From these measurements it is possible to infer profiles of electron temperature, impurity density and the effective plasma charge with no a-priori assumptions of plasma profiles, high-density limitations, or need of shot-to-shot reproducibility.

Central electron temperature values are derived by modeling the slope of continuum radiation ($\propto \exp(-E/T_e)$), extracted from ratios of inverted radial emissivity profiles across multiple energy ranges. Recent results at WEST include the temporal evolution measurement of $T_{e0} \sim 3.5$ keV during plasma experiments lasting more than 1000 s, encompassing truly non-inductive ($V_{loop} \rightarrow 0$) long-pulse discharges with no external input torque, with injected energy exceeding 2 GJ.

Impurity transport analysis in steady-state without perturbing the plasma is carried out by measuring the SXR emission at few keV photon energy where the radiation is dominated by tungsten line emission. Tungsten density is estimated by modeling the inverted radial emissivity profiles with an analytic SXR tomography code based on plasma emissivity calculated with the FLYCHK spectral tool [1]. Tungsten concentration is found to be of the order of $\sim 10^{-5}$ – 10^{-4} with a rather flat core profile.

The diagnostic is also used to identify transient event such as tungsten UFOs, through enhancement of the reconstructed emissivity profile.

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Poster Session MCF 4 - T

4 P 284 - Energy-resolved soft x-ray camera in the TCV tokamak: First data

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ABSTRACT TEXT

A compact multi-energy soft X-ray diagnostic [1] has been deployed on the Tokamak à Configuration Variable (TCV) to study high-Z impurity transport and measure electron temperature profiles with temporal and spatial resolution. This system is based on the PILATUS3 photon-counting detector, developed by DECTRIS Ltd., and is integrated into a pinhole camera setup. It features a temporal resolution of 2 ms, a spatial resolution ranging from 1 to 15 mm at $Z = 0$, and an x-ray sensitivity range covering approximately 2 to 30 keV. A distinctive characteristic of this detector is its capability to independently set a lower-energy threshold on each of its ~ 100 k pixels, that can be used to obtain a high energy resolution < 1 keV [1] across the detector range.

Previous applications of this diagnostic, including a deployment on the WEST tokamak, have demonstrated some of its capabilities for impurity transport studies and electron temperature measurements [2]. Building on this foundation, its integration into TCV offers a new opportunity to explore impurity dynamics and transport for many plasma scenarios.

This contribution presents the design, integration, and first experimental results obtained during the 2025 internal campaign at TCV. Additionally, emission profile inversions [3] will be discussed.

This work was supported in part by the Swiss National Science Foundation

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Poster Session MCF 4 - T

4 P 285 - Design process for the DNBI duct of the RFX-mod2 experiment

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ABSTRACT TEXT

The performance of the RFX-mod Diagnostic Neutral Beam Injector (DNBI) has not always been optimal and, now, with the advent of RFX-mod2 and the plan to implement Charge Exchange Recombination Spectroscopy (CXRS) and Motional Stark Effect (MSE) diagnostic systems, addressing this issue has become critically important.

The DNBI, designed to accelerate H⁺ ions up to 50 keV, was originally intended to provide an equivalent current of 2.6 A. Nevertheless, its actual output has never exceeded 0.8 A. Such discrepancy has lead to investigations being conducted on the possible sources of losses, which have revealed, through analysis of beam H α emissions during dry shots, some gas accumulation inside the DNBI duct that could be the cause of beam reionization.

This work motivates the reionization hypothesis and reports the steps that have been made towards the production of a more efficient duct, with a focus on the models used for describing steady-state gas pressure profiles and beam particles reionization.

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Poster Session MCF 4 - T

4 P 286 - Development of a GEM detector prototype with remote front-end electronics system for high-radiation environments

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ABSTRACT TEXT

We present a novel Gas Electron Multiplier (GEM) detector prototype candidate for integration into the ITER Radial X-ray Camera[1]. Triple-GEM detectors have demonstrated excellent performance in soft X-ray diagnostics, providing high sensitivity, broad dynamic range, and robustness against neutron/gamma backgrounds [2–5]. However, the high neutron flux expected in ITER poses challenges for front-end electronics reliability. Tests performed at the Frascati Neutron Generator (FNG) showed that the front-end electronics failed at 14 MeV neutron fluxes of $1.6 \cdot 10^5$ n/cm²·s, while the GEM detector remained operational up to 1.4×10^7 n/cm²·s, the highest flux achievable currently at FNG[6]. To address this limitation, we developed a new front-end electronic system that can be displaced via micro-coaxial cables (20–200 cm). A custom PCB with a 16×16 pad grid (6×6 mm² per pad) interfaces with the coaxial connectors and the new 64d GEMINI chips managed via FPGA boards. Laboratory tests have been performed using a pulse generator to simulate X-ray irradiation and to assess the signal quality transmitted via cables of different lengths. The studies showed that signal resolution degrades with the increase of the cable length but also revealed that a 100 cm cable maintains optimal spectroscopic performance with the applied threshold significantly below the upper limits of the device. The detector prototype consists of two aluminum GEM foils and a single copper foil to reduce X-ray background noise. It features a 20×3 mm² side window enabling X-ray absorption measurements up to 50 keV (Ar-CO₂) or higher with Xe/Kr, utilizing the full 10 cm gas depth. The detector's response to 5.9 keV X-rays from a ⁵⁵Fe source confirmed its promising performance, demonstrating the feasibility of GEM detectors with remote front-end electronics connected via 100 cm cables in high-radiation environments. Relocating the front-end electronics 1 m away not only reduces neutron flux exposure but also enables more effective shielding, significantly improving system resilience in harsh operational conditions.

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Poster Session MCF 4 - T

4 P 287 - Reflectometry in RFX-mod2: system upgrades and expected capabilities

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ABSTRACT TEXT

The RFX-mod device ($R = 2.0$ m, $a = 0.459$ m), in operation until 2016, was equipped with an ultrafast five-band (Ka, U, V, W1, W2) O-mode reflectometer. This system was designed to monitor the electron density profile from edge to core within the expected RFX-mod density range when operating in the Reversed Field Pinch (RFP) configuration. However, improved confinement RFP regimes were found at an average density below $4\text{--}5 \times 10^{19} \text{ m}^{-3}$. Consequently, the reflectometer provided information on edge density dynamics using only the Ka, U, and V bands [1]. As part of the Nefertari project [2], which supports the major upgrade towards the RFX-mod2 device, the reflectometry system has been re-structured to better match the new plasma scenarios. In particular, two distinct systems will be installed: a three-band (K, Ka, U) density profile reflectometer (DPR) and an innovative single-band (K) plasma position reflectometer (PPR). The DPR, as a direct evolution of the previous RFX-mod reflectometer, will operate in O-mode with a single equatorial line-of-sight, enabling high-frequency edge density profile measurements in RFP discharges. The PPR is a novel system with four lines-of-sight (outer and inner midplanes, top, and vertical ports), primarily designed to test a reflectometry-based plasma position control algorithm in Tokamak configuration. In RFP mode, PPR could still provide valuable insights into the complex interplay between density and magnetic structures at different poloidal angles.

This contribution presents the main characteristics of the two systems, focusing on their development progress, procurement status, and bench tests of the components. Particular attention will be given to the expected measurement capabilities and the diagnostic strategies being developed to optimize reflectometric data interpretation in the RFX-mod2 operational scenarios.

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Poster Session MCF 4 - T

4 P 288 - First data from a Balmer series-limit recombination spectrometer in the MAST-U divertor

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ABSTRACT TEXT

The suite of spectrometers monitoring the lower divertor [1] on MAST Upgrade has been extended before the start of the MU04 campaign. A new fiber bundle with good transmission in the near-UV was installed to increase the number of instruments viewing the same radial profiles in the divertor to a maximum of 4. This was done to accommodate a dedicated instrument to measure the Balmer series-limit recombination around 365 nm. From the ratio in the continuum above and below the recombination ‘edge’, one can derive the electron temperature for recombining plasmas [2]. Good signal-to-noise ratios have been obtained, but overlap with carbon lines can make it difficult to extract the continuum baseline from the spectra. The validity domain of the measurements will be discussed with comparisons to other temperature measurements in the divertor.

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Poster Session MCF 4 - T

4 P 289 - Radiated power density estimates from photon-counting measurements

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ABSTRACT TEXT

Multi-energy soft and hard x-ray pinhole cameras have been designed, built and operated at the Madison Symmetric Torus (MST), Alcator C-Mod, and the Tungsten Environment in Steady State Tokamak (WEST) and recently also at the Tokamak a Configuration Variable (TCV). Presented in this paper is a novel methodology to also estimate the local “filtered” radiated power density profiles [W/m^3] from photon-counting measurements [$\text{photons/m}^3\text{s}$] in several energy bands, which could become particularly useful for machines cladded with tungsten plasma facing components (PFCs) where the losses in the x-ray range can be a significant fraction of total radiated power. This novel application is possible since the pixel responsivity is well characterized by a complementary error function while the multi-energy measurements between adjacent energy-levels is described by a Probability Density Function (PDF) of a Gaussian distribution.

Poster Session MCF 4 - T

4 P 290 - Bayesian optimisation as a tool for solving the inverse problem with plasma diagnostics

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ABSTRACT TEXT

Plasma diagnostics observe complex interactions between high energy particles where there is often no simple relationship between measurement and plasma quantity. This complexity necessitates the use of an integrated diagnostic analysis which can combine measurements from a variety of diagnostics and use forward models of the diagnostic measurements to reconstruct plasma conditions. The challenge of this analysis lies in the ill-posed nature of reconstructions from forward models where multiple solutions can exist and are highly sensitive to noise and modelling error. Bayesian inference can help with this problem by enabling us to account for the uncertainty of models and measurements while providing a mathematical framework to combine heterogeneous data sources. A workflow called Bayesian Diagnostic Analysis (BDA) that uses Bayesian optimisation (BO) to solve the problem of Bayesian inference was developed and used for two different applications on the ST40 tokamak.

(1) The fitting of experimental ion temperature profiles, which is difficult due to a lack of radial resolution in the charge exchange recombination spectrometers (CXRS). Monotonic splines were used to constrain the profile shapes in conjunction with core temperature measurements from X-Ray Crystal Spectroscopy (XRCS) and radial profiles from CXRS. Ion temperature profiles were reconstructed that well matched the available CXRS and XRCS data while giving reasonable uncertainty quantification in the outer plasma regions which lacked measurements.

(2) A synthetic case study to determine the plasma composition given a mixture of low to high Z impurities and the relevant available diagnostic set; these are two soft x-ray cameras, a bolometer, XRCS and CXRS. Different impurity species and concentrations were trialled to determine how well they could be reconstructed. This study provides insight into what measurements are necessary on ST40 to determine plasma composition and where additional diagnostics or lines of sight may be needed for greater accuracy.

These applications of BO were benchmarked against more common Monte Carlo Markov Chain (MCMC) algorithms such as metropolis hastings and ensemble sampling [1][2]. This algorithm demonstrated a significant increase in convergence speed, more than 10 times faster than MCMC, while using orders of magnitude fewer total samples.

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Poster Session MCF 4 - T

4 P 291 - 3rd harmonic ECE for electron temperature monitoring in high-density plasmas at W7-X

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ABSTRACT TEXT

Achieving the fusion goal of the optimized superconducting stellarator Wendelstein 7-X (W7-X) requires high-beta plasma operation [1], where beta is the ratio of plasma pressure to magnetic pressure. Unlike tokamaks, stellarators are not subject to an inherent Magnetohydrodynamic-determined density limit, making increased plasma density (n) an attractive approach to raising beta (as beta scales with n). However, at high densities ($n \geq 1.2 \cdot 10^{20} \text{ m}^{-3}$), the well-established 2nd harmonic extraordinary mode (X2) electron cyclotron emission (ECE) diagnostic [2] employed to derive electron temperature (T_e) measurements becomes ineffective, due to the density preventing the propagation of these emissions in the plasma [3].

To address this limitation, a new radiometer dedicated to measuring X3 ECE was commissioned at W7-X during the last plasma operational campaign. This radiometer allows for T_e measurements at densities up to $n \approx 3.6 \cdot 10^{20} \text{ m}^{-3}$, since higher harmonic emissions have a higher cut-off density than lower harmonic emissions. This upgrade of the ECE diagnostic is essential for plasma operation at high-density conditions, as this diagnostic is best suited to derive high-resolution T_e measurements (2MHz sampling rate) for plasma monitoring. In this paper, we present initial measurements from the X3 ECE radiometer and assess its feasibility as a real-time monitoring tool for plasma density control. By incorporating the X3 ECE signal originating from the plasma core into a feedback control system, it can serve as a trigger to regulate the plasma edge density during operation. This regulation can be achieved via a gas injection actuator for plasma fueling purposes, activated when the core T_e drops below a predefined threshold. This approach has been successfully implemented employing X2 ECE signals as the trigger signal [4]. Such advancements in plasma diagnostics are crucial for supporting the operational demands of reactor-scale fusion experiments.

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Poster Session MCF 4 - T

4 P 292 - Developing a machine learning based plasma control system for ISTTOK

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ABSTRACT TEXT

Applying Machine Learning (ML) techniques to deal with complex systems/problems has, nowadays, become an increasingly used approach, which has already demonstrated significant improvements with respect to conventional methods. Therefore, demonstrating its applicability to nuclear fusion devices, such as tokamaks, as well as, learning and gaining experience on how to develop and implement it, are of utmost importance. ML based plasma control was successfully implemented and tested in DIII-D tokamak by NSF (Next Step Fusion) and DIII-D team [1] and it is now being implemented in ISTTOK, a significantly different tokamak with its own challenges.

ISTTOK is a large aspect ratio tokamak located in Portugal ($a = 8.5$ cm, $R = 46$ cm, $BT = 0.5$ T, $I_p = 4$ kA, $n_e = 5 \times 10^{18}$ m⁻³ and $T_e(0) \sim 120$ to 150 eV) and capable of operation with alternate (AC) discharges. Unlike most conventional tokamaks it has a particularly thick copper shell (conducting metallic structure) surrounding the vacuum vessel and operates with an iron core transformer.

This work aims to apply ML techniques for the plasma control system (PCS) of ISTTOK. The ML algorithms will be developed using the Reinforcement Learning (RL) technique, where a non-linear controller is trained by a trial-and-error approach in a simulation environment. The environment is therefore of crucial importance as it will represent the plasma response during the training phase of the Agent. The Agent is trained to sustain the desired plasma position and current. Developing such an environment that precisely reproduces plasma dynamics in the ISTTOK tokamak is, itself, a challenge due to the iron core and the thick copper shell.

NSF has created a digital model of ISTTOK plasmas to be used during the RL process. The model is based on NSFsim code, a free-boundary Grad-Shafranov and transport solver [2]. This paper presents the development and preparation of the model. Results of the model validation by comparing simulations with experimental data from vacuum pulses (dry runs) are also presented.

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Poster Session MCF 4 - T

4 P 294 - Leak detection and spatial localization inside fusion devices

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ABSTRACT TEXT

A fusion device, such as tokamaks, requires a high vacuum to create and sustain a high-performance plasma. The vacuum vessel pressure should be below 1×10^{-5} Pa to be in a suitable condition [1]. On the other hand, it is well known that leaks from different origins could occur. Even micro-metric leaks down to 10^{-6} Pa·m³·s⁻¹ of either air or water compromise the high-vacuum condition and could impede the operation of a fusion device [2]. Detecting the existence of a leak can be done using pressure gauges but identifying which component is leaking could take several weeks in present day tokamaks like ITER. Hence, there is a pressing need to develop methodologies for quick spatial localization of micro-metric leaks.

In fusion devices, glow discharge cleaning is a method of conditioning vacuum vessel walls using a low temperature unmagnetized plasma discharge [3]. This plasma excites and ionizes molecules and atoms of the gases coming from the plasma walls, particularly those resulting from a leak. This leads to the emission of electromagnetic waves that could be in the visible domain. Our approach for the spatial localization of the leak(s) is to image the inside of the vacuum chamber and by applying adequate image processing deduce the location of the leak. To demonstrate the feasibility of our approach, experiments are carried out on the glow discharge device, which is vacuum chamber at the IRFM dedicated to study glow discharges and equipped with diagnostics such as pressure gauges, a visible camera, and a visible spectrometer. This contribution presents the experimental setup as well as the first encouraging results of the experiments.

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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Poster Session MCF 4 - T

4 P 295 - Simulation and analysis of optical efficiency for tangential Thomson collection optics system in KSTAR

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ABSTRACT TEXT

Thomson scattering (TS) has been a standard diagnostic technique for the measurement of electron temperature (T_e) and density (n_e) profiles in various Tokamaks, including the Korea Superconducting Tokamak Advanced Research (KSTAR). In KSTAR, a tangential TS system was developed several years ago to measuring T_e and n_e during plasma discharge [1][2].

Tangential TS system on KSTAR consists of a laser guiding system, collection optics with a cassette system and data acquisition system. The laser guiding system was utilized a Nd:YAG laser from Continuum with specific parameters (wavelength: 1064 nm, pulse energy: 2.5 J, repetition rate: 20 Hz). The laser beam is directed into the tokamak chamber via the L-port and subsequently directed to a laser beam dump at the B-port. The collection optics with a cassette system that collects the light emission induced by the interaction between the plasma and a laser beam are key components for the TS system [3]. The collection optics with a cassette system was positioned at the N-port and consisted of the lens module and mirror for light collection and the optical fiber bundle for delivery of the collected light to the polychromator. For the collection optics system of the KSTAR tangential TS system, a system was chosen to measure two plasma regions, each with two types of light collection optics; one for the core plasma region and the other for the edge plasma region.

The collected light from collection optics with a cassette system, which is then transmitted through optical fiber bundle arrays to polychromators, which are equipped with five channels for different wavelengths. The collected light is finally detected by avalanche photodiodes (APDs). This study presents the results of image simulations of collected light in the plasma region. The results of these simulations are then discussed, along with an analysis of the optical efficiency after the collected light passes through the collection optics system.

This work was supported by Ministry of Science and ICT under KFE R&D Program of “KSTAR Experimental Collaboration and Fusion Plasma Research(KFE-EN2501)”.

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Poster Session MCF 4 - T

4 P 296 - High and medium Z impurity concentration determination with InDiCa in JET

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ABSTRACT TEXT

Knowledge of low-Z (up to Ne), mid-Z (Fe, Ni and first row elements) and high-Z (such as W) impurity profiles are important for integrated core modelling, studies of tungsten screening in the plasma, and determination of seed impurity compression. Whilst low-Z density profiles can be directly measured from Charge-Exchange Recombination Spectroscopy (CXRS), mid-Z and high-Z impurities must be inferred from combined analysis of multiple independent diagnostics.

Mid-Z and high-Z profiles have previously been inferred on JET using methods developed by Pütterich et al [1] and Sertoli et al [2]. These were iterative methods starting with tungsten concentration from the 5nm feature using vacuum ultra-violet (VUV) spectroscopy, and profile shape based on the vertical Soft X-Ray (SXR) camera to capture poloidal asymmetry. A low-Z and mid-Z element were then added to match Zeff and total radiation. This was the standard technique used before data from the vertical SXR camera and VUV Spectrometer became unavailable as a result of deuterium-tritium operations in DTE2, requiring development of a new analysis tool.

This contribution presents use of the analysis software InDiCa (Integrated DiagnostiC Analysis) [3, 4] for determination of mid-Z and high-Z impurity profiles, details of the process, and how the diagnostic challenges were overcome. Unlike previous methods, this uses a forward model-based approach driven by functional descriptions of impurity profiles (low-Z, mid-Z and high-Z). Initial assumptions for these are made, then optimised by comparison of synthetic diagnostic data with associated experimental measurements. This allows for simultaneously optimising all impurity profiles to ensure self-consistency, as well as flexibility depending on the measurements available. Additional sources of information were utilised to constrain the profiles, such as analysed concentrations from a VUV spectrometer measuring the 100–1000 Å region, tomographic reconstructions from bolometry, and more CXRS measurements.

InDiCa is being used to determine mid-Z and high-Z impurity content in the JET-ITER baseline [5] to address the questions of whether the W concentration increases with increasing Neon-seeding rate, and whether there is a change from D to D-T operation.

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Work completed with assistance from the EUROfusion Tokamak Exploitation Team (see the author list of E. Joffrin Nuclear Fusion 2024) and JET Contributors (see the author list of CF. Maggi et al., Nucl. Fusion 2024).

Poster Session MCF 4 - T

4 P 298 - Real-time plasma profile evaluation with multi-point Thomson scattering at Wendelstein 7-X

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ABSTRACT TEXT

We present results from the initial operation of a scalable, real-time, multi-point Thomson scattering evaluation system during the 2024–2025 operational phases at the Wendelstein 7-X (W7-X) stellarator. This system is designed to acquire and evaluate measurements of Thomson-scattered spectra at a target frequency of 100 Hz, informed by the nominal repetition rate of the probe lasers. During its initial run, the system evaluated signals from eight scattering volumes within the plasma, inferring T_e and n_e profiles within milliseconds of the interrogating laser pulse. We compare the software performance of different evaluation methods within this real-time framework as well as the accuracy of inferred profiles relative to standard post-processing routines. This system can be integrated with future density profile control schemes to optimize experiments at W7-X with the eventual goal of turbulence reduction and discharge length extension.

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For full W7-X team list, see O. Grulke et al. 2024 Nucl. Fusion 64 1120023.

Poster Session MCF 4 - T

4 P 299 - Neural Estimation of Plasma Distributions from Imaging through Synthetic Data

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ABSTRACT TEXT

In this work, we demonstrate a neural network that can learn the non-linear mapping from the Visible Imaging and Thomson Scattering (TS) measurement space to the distributions of neutrals density, electron density and electron temperature. Unlike prior work on inverting images [10, 5, 8, 15, 12, 4, 7, 2, 13, 3] through physically motivated estimation and approximation, we explore the use of synthetic modelling of plasma distributions in the Mega Ampere Spherical Tokamak (MAST) as a method of generating sufficiently large and diverse datasets for the training of a neural model, and Mixture Density Networks (MDNs) [1] for fine-tuning on physical data. Building on prior work [11], we demonstrate a novel data model that closely follows the qualitative behaviour of the magnetic potential in the core and near the edge which allows us to consider distributions of the neutrals density, electron density and electron temperature as functions of the magnetic potential. With a suitable path-tracing pipeline [6] and the Photon Emissivity Coefficients [14] we demonstrate that a dataset of 80,000 samples can be generated in half a week using only 64 A100 GPUs. We show that an encoder-decoder model with two encoders for mapping both the image and TS measurements to a common latent space, and a decoder that maps to the synthetic data space can effectively predict the plasma distributions. To overcome the domain gap between our synthetic data model and physical data such as SOLPS simulation data, we utilise MDNs to sample SOLPS-like neutrals distributions by learning the ionisation fraction as a function of the magnetic potential. We show that our model trained on a much larger dataset can be fine-tuned to predict physically realisable configurations of plasma. Compared to prior work, our method is able to predict interpretable plasma parameters in milliseconds such as minor radius, ellipticity, and triangularity, and the full distributional cross-sections in hundreds of milliseconds including the neutrals density.

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Poster Session MCF 4 - T

4 P 300 - The role of x-ray spectroscopy in the development and understanding of high-performance scenarios in Wendelstein 7-X

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ABSTRACT TEXT

Measurements from x-ray imaging crystal spectrometers (XICS), have played a critical role in the development of high-performance turbulence-reduced scenarios in the Wendelstein 7-X (W7-X) stellarator. They have also played a key role in the characterization of performance and understanding of the underlying physics of these plasmas. The versatile role of the x-ray spectrometers in providing profiles of ion-temperature, electron-temperature, plasma flow, radial electric field, and impurity transport will be reviewed in the context of experimental demonstration of high-performance discharges in the most recent W7-X experimental campaign. The reliability and robustness of the measurements will be discussed, along with a discussion of the importance of complementary measurements and diagnostic cross-comparisons. Future directions for analysis at W7-X will be presented including prospects for parallel velocity measurements and real-time analysis. Finally, the experience of using XICS at W7-X will be considered in the context of diagnostic development for future burning plasma devices.

Poster Session MCF 4 - T

4 P 301 - Application of autoencoders to electron density and temperature profiles for denoising, anomaly detection and automatic database construction in nuclear fusion

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ABSTRACT TEXT

Plasma physics and nuclear fusion are among the most complex fields of science. Studying the multifaceted phenomena in these domains requires the integration of a broad range of diagnostics with algorithms that are efficient, reliable, and capable of exploiting to the full the information content of the measurements. In this context, machine learning and deep learning algorithms have the potential to play a pivotal role. AI-based approaches enable highly accurate data analysis, allowing for the extraction of valuable insights with minimal manual intervention.

This work focuses on applying autoencoders based on unsupervised neural network architectures to analyse electron density and temperature profiles from various experimental campaigns conducted at the Joint European Torus (JET) tokamak. Autoencoders are powerful deep learning tools that compress input data into a lower-dimensional latent space, enabling several advanced applications. Specifically, we demonstrate how autoencoders applied to kinetic profiles can: (1) Automatically denoise measurements, including the removal of outliers; (2) Provide advanced anomaly detection indicators for early identification of electron temperature instabilities, such as hollowness and edge cooling; (3) Facilitate automatic building of databases through clustering algorithms applied to latent space representations.

This preliminary study aims at paving the basis for the development of innovative algorithms that, by using a multi diagnostic approaches, may allow for powerful and innovative ways to derive physically meaningful information from plasma measurements.

KEYWORDS

Autoencoders, Plasma Diagnostics, Anomaly Detection, Denoising, Database Construction

Poster Session MCF 4 - T

4 P 302 - Development of the Absolute Calibration System for the D-alpha Diagnostic for divertor

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ABSTRACT TEXT

D-alpha measurement is an important diagnostic used in many tokamak devices.

The D-alpha monitoring system for KSTAR is a diagnostic device that to measure visible light emitted from plasma using a filterscope. In 2023, when upgrading to the tungsten diverter, the filterscope was manufactured and installed to monitor the diverter region. The filterscope consists of nine channels, with four channels are designed to observe X-POINT and five channels are designed to observe the outer strike point. For plasma analysis, absolute calibration of the D-alpha signal is essential. To achieve this, a dedicated calibration device for work in the KSTAR tokamak was developed and work of absolute calibration was performed before the 2024 experimental campaign.

In this paper, we describes the device developed for the absolute calibration of the D-alpha monitoring system for divertor and presents the results of the calibration process.

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Poster Session MCF 4 - T

4 P 303 - Thomson scattering system for extreme plasma-surface interaction studies in QSPA

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ABSTRACT TEXT

Plasma-surface interactions (PSI) under extreme heat and particle loads are critical concerns for fusion reactor development. Quasistationary plasma accelerators (QSPAs) offer a unique platform for simulating disruption- and ELM-like conditions with high energy densities relevant to ITER and DEMO [1]. To study PSI in such extreme environments, ongoing efforts focus on adapting Thomson Scattering (TS) diagnostics for high-density, low-temperature, and fast plasma discharges of the QSPA Kh-50 and QSPA-M facilities.

The QSPA-tailored system under development aims to accurately measure electron density and temperature in the near-surface plasma, with a spatial resolution of less than 2 mm. The system will utilize a frequency-doubled Nd:YAG laser at 532 nm. A significant challenge addressed during the development is managing stray light, which is expected to reach extremely high levels due to the ablation and evaporation of sample material induced by high heat loads (up to 1.2 MJm^{-2} for tungsten) delivered to a surface. To mitigate this, a stray light-blocking system, similar to the one used in Magnum-PSI [2–3], is being implemented. The detection branch of the diagnostic system includes a high-etendue spectrometer with a transmission grating and an ICCD camera with fast gating capabilities to minimize background light and accurately resolve rapid phenomena. The conceptual design and key features of the diagnostic system adapted to the QSPA experimental conditions are currently under active development.

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Poster Session MCF 4 - T

4 P 304 - Correlation Electron Cyclotron Emission radiometry and imaging development on the stellarator Wendelstein 7-X

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ABSTRACT TEXT

A radial correlation radiometer diagnostic has been developed for electron temperature fluctuation measurements on the Wendelstein 7-X (W7-X) stellarator [1]. The system is designed to measure 2nd harmonic Electron Cyclotron Emission (ECE) originating on the low field side of the magnetic-axis of W7-X between 127–137 GHz. The microwave frontend consists of a focusing profiled antenna [2], an overmoded transmission line, and a pair of heterodyne radiometers. During the first operational phase of W7-X with a water-cooled divertor (OP2.1) the microwave backend consisted of 14 intermediate frequency (IF) channels, and the correlation between adjacent channel pairs was used to measure both coherent and broadband electron temperature fluctuations. In the last operation phase of W7-X (OP2.2/2.3), the system was expanded to allow radial correlation length measurements by adding a radially scannable 16-channel backend similar to the “ZOOM Device” [3] on W7-X. This is achieved with a pair of secondary mixing stages and remotely controllable local oscillators connected to a second heterodyne radiometer that extends the measurement range across the plasma minor radius, between 128–156 GHz, allowing for the possibility of cross-phase measurements with a nearby Doppler reflectometer and high-field side CECE measurements. Additionally, a delay-line and set of identical backend channels was developed and successfully operated as a test time-delay decorrelation radiometry system.

A new correlation ECE Imaging project has been launched on W7-X in order to study small-scale drift wave like turbulence and characterize the turbulent electron heat flux. A preliminary design based on the astigmatism of spherical mirrors [4] is under consideration, with an optical view that has overlapping measurement volumes with a proposed Heavy Ion Beam Probe diagnostic.

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Content of Oral & Poster Presentations

O 077 - Two decades of non-thermal plasma applications based on dedicated and optimized high voltage pulsed power supplies (Innovation Prize Winner)	5
O 002 - Astrophysical Shock Waves in the Violent Universe (Early Career Prize Winner)	6
O 003 - Advances in the physics understanding of transient thermal and runaway electron impact on tokamak plasma-facing components	7
O 004 - Magnetic reconnection in space plasma	8
O 005 - Perspectives on inertial fusion energy research at European XFEL	9
O 006 - Turbulent transport in stellarators: New insights from global gyrokinetic simulations	10
O 007 - Reduction or enhancement of stellarator turbulence by impurities	11
O 008 - Effective transport barriers without H-mode bifurcation in DIII-D negative triangularity plasmas	12
O 009 - Effect of the magnetic geometry on Trapped Electron Modes instability: comparison between theory and gyrokinetic simulations	13
O 010 - Dependencies of the transition into regimes of suppressed anomalous impurity transport in W7-X and implications for stellarator reactors	14
O 011 - Relevance of stochastic transport in spherical tokamaks	15
O 012 - Acceleration of unstable particles in laser-plasma accelerators using structured light	16
O 013 - Nanofoams in action: a versatile tool for laser-plasma interaction experiments	17
O 014 - Photon acceleration of high-intensity vector vortex beams into the extreme ultraviolet	18
O 015 - Visualizing Plasmons and Ultrafast Kinetic Instabilities in Laser-Driven Solids using X-ray Scattering	19
O 016 - Multi-stage simulations of nanowire ablation and proton acceleration in petawatt laser interactions	20
O 017 - A novel hybrid-target injector for high-charge laser-driven electron acceleration: understanding the injection process	21
O 018 - Process control in low pressure capacitive radio frequency plasmas based on kinetic simulations	22
O 019 - Production of reactive species in non-equilibrium hydrogen plasmas	23
O 020 - ExB plasmas generated by e-beams and non-thermal electrons for materials processing and aerospace applications	24
O 021 - Hydrogen production via combined dry reforming of ethanol with steam using 915 MHz microwave plasma at atmospheric pressure	25
O 022 - Complex dynamics in laser-produced high-entropy plasma: advances in controlling thin film growth with plasma diagnostic	26
O 023 - Investigating sources of coherent radio emissions from neutron star magnetospheres by particle-in-cell kinetic simulations	27
O 024 - Pevatrons and ultra-high energy cosmic rays as messengers of extreme astrophysical plasma	28
O 025 - Topology as a cornerstone feature of the magnetic fields	29
O 026 - PIC and PIC-MHD Simulations of Electron-Positron induced streaming Instability	30
O 027 - Evolution of an electrostatic collisionless shock created by a blast shell and formation of a mixing layer in Particle-In-Cell simulations	31
O 028 - Interplay of electromagnetic turbulence, global MHD modes, fast particles, and Alfvénic instabilities in fusion plasmas	32
O 029 - Jumping out of the thermal bath at interplanetary shocks in Solar Cycle 25	33
O 030 - Ion motion and self-modulation suppression in a plasma wakefield accelerator	34
O 031 - The SPARC and ARC tokamaks: Predictive results and open physics questions on the path to a commercial fusion power plant	35
O 032 - The Tokamak Exhaust Designer: a new tool for enhanced divertor control on MAST-U	36
O 033 - High-fidelity physics Integrated Modeling in support of ITER and burning plasma research	37
O 034 - Experimental validation of momentum transport theory in the core of the ASDEX Upgrade tokamak	38
O 035 - Long pulse achievements in the WEST tokamak	39
O 036 - Magnetic configuration effects on pellet fuelling in stellarators	40
O 037 - Electromagnetic QED cascades: How close are we to getting showers, avalanches and pair plasmas in the laboratory?	41
O 038 - QED cascades in extreme focusing	42
O 039 - Electromagnetic showers in matter: towards e ⁻ -e ⁺ pair plasmas	43
O 040 - Challenges and perspectives of efficient gamma-ray production in near-critical targets with PW-level high-intensity lasers	44
O 041 - Ion acceleration using high order PW helical beams at ELI-NP	45
O 042 - Chemical reactivity induced in liquids by non-equilibrium atmospheric plasma	46
O 043 - Possibilities for upscaling atmospheric pressure plasma systems for treatment of liquid samples	47
O 044 - Role of Streamers and Bubbles in the Plasma Assisted Production of Hydrogen	48
O 045 - Low-Temperature Plasma Diagnostic in Dielectric Capillaries for Laser Wakefield Acceleration	49
O 046 - Nitric oxide diagnostics in plasma heated gas using laser absorption spectroscopy	50
O 047 - Experimental characterization of stimulated Raman side-scattering in the context of the direct-irradiation approach to Inertial Fusion Energy ..	51
O 048 - Laser-driven Electromagnetic Pulses for the manipulation of charged particle beams	52
O 049 - Effect of spectral bandwidth on the stimulated scattering of a spatially smoothed laser beam in plasma	53

O 050 - Experimental study of laser plasma instabilities driven by 527 nm laser pulses with narrowband and broadband spectra	54
O 051 - A comprehensive study of laser-plasma experiment between sub-relativistic and relativistic intensities	55
O 052 - Divertor Tokamak Test Facility Physics Basis	56
O 053 - Power exhaust and detachment in LSN with varying outer leg length using multi-species turbulence simulations and experiments designed for validation	57
O 054 - EIRENE Interpretation of Divertor Deuterium Emission in DIII-D constrained by 2D Divertor Thomson Scattering and Langmuir Probe Measurements	58
O 055 - Addressing the power exhaust challenge with double-null configurations	59
O 056 - X-point target radiator regime in tokamak divertor plasmas	60
O 057 - X-point radiation and up-down asymmetry in detached plasmas of Wendelstein 7-X	61
O 058 - Recent implosions experiments in the compressive regime at the Laser MegaJoule facility	62
O 059 - Implosion and illumination designs for laser driven fusion energy	63
O 060 - First demonstration of improved yield with reduced adiabat and increased compression in high-performance implosions on the National Ignition Facility	64
O 061 - Strongly magnetized cylindrical implosions in inertial confinement fusion experiments	65
O 062 - 3D rad-hydro modelling on the NIF: effect of low-mode asymmetries on capsule implosions and use of foams for symmetry control*	66
O 063 - Piecewise omnigenous fields: a radically new family of optimized magnetic fields for stellarator reactors	67
O 064 - 3D plasma-wall interaction simulations: Advances and challenges for ITER and Wendelstein 7-X	68
O 065 - Efficient single-stage optimization of islands in finite- β stellarators	69
O 066 - Systematic study of CXRS ion flow measurements in W7-X stellarator towards a validation of neoclassical theory	70
O 068 - Geometry landscape for zonal flow activation in turbulent plasmas	71
O 069 - Magnetic field amplification induced by cosmic-ray pressure at non-relativistic shocks	72
O 070 - Cosmic-ray transport and acceleration in astrophysical plasmas	73
O 071 - On the width of a collisionless shock and the index of the cosmic rays it accelerates	74
O 072 - Sapphire++ – MHD: A finite element MHD code for astrophysical plasmas with energetic particles	75
O 073 - PIC Simulation of Oblique Whistler Waves from Gradient Drift Instability at a Low-Beta Subcritical Perpendicular Shock	76
O 074 - Routes to high-performance operation in Wendelstein 7-X (W7-X): turbulence suppression with shaping of the density profile	77
O 075 - Application of Non-Thermal Plasma for the Treatment of Selected Types of Foods and Conditioning of Biological Material	78
O 076 - The physics of gaseous diffractive optics for high-power lasers	79
O 078 - Development of a high-current, high fusion performance scenario on JET: physics insights and operational challenges	80
O 079 - Role of plasmoid drift in the efficiency and reliability of shattered pellet injection	81
O 080 - Validation of tungsten erosion and transport simulations in tokamaks	82
O 081 - Full-discharge simulations of TCV using the Fenix flight simulator	83
O 082 - Time evolved current drive modelling of solenoid-free microwave start-up in tokamaks	84
O 083 - Thermal quench induced heat fluxes on ASDEX Upgrade	85
O 084 - Direct Imaging of Wakefields Generated by Structured Light	86
O 085 - Highly efficient laser wakefield accelerator and gamma/neutron sources	87
O 086 - Radiative betatron losses drive phase-space shaping and hollow beam formation in wakefield acceleration	88
O 087 - Self-modulated laser wakefield acceleration of μC -level relativistic electron beams at the LMJ-PETAL facility	89
O 088 - A new facility dedicated to laser-plasma accelerator based very-high-energy-electron radiotherapy	90
O 089 - Laser-driven radiation sources for cultural heritage: laser-driven PIXE and XRF on historical and archaeological artifacts	91
O 090 - Annihilation gamma spectra of magnetically confined positrons scattering, forming positronium, and cooling	92
O 091 - Plasma surface interaction at objects with floating potential	93
O 092 - Modelling the evaporation of vacuum arc macroparticles by a beam of energetic electrons	94
O 093 - Phase separation and scaling laws in binary strongly coupled plasma	95
O 094 - Study of re-deposition dynamics of thin film in rear ablation geometry	96
O 095 - Universal fluctuation spectrum of Vlasov–Poisson turbulence	97
O 096 - Data-driven modelling of collisional kinetic plasma dynamics	98
O 097 - Universal equilibria, phase-space structure of collisionless plasma systems, and turbulence in non-Maxwellian plasmas	99
O 098 - Phase-space electron-hole dynamics in 1D-1V kinetic plasma	100
O 099 - Quantum numerical scheme for multidimensional transport equations	101

O 101 - Insights from JET high fusion power scenario in the final D-T campaign	102
O 102 - Quantum computing for plasma simulations: Opportunities and challenges	103
O 103 - Plasma electrification: A promising route for sustainable production of fuels and chemicals	104
O 104 - Building a path towards a negative triangularity fusion reactor with gyrokinetic simulations and experiments on TCV	105
O 105 - Characterization of edge modes in different confinement regimes	106
O 106 - Observation of sheared turbulence structure during edge-localized mode suppression with lower hybrid waves on EAST tokamak	107
O 107 - A high-confinement, no-ELM regime in JET: the EDA H-mode	108
O 108 - Progress in the understanding of edge transport in the QCE regime on TCV	109
O 110 - High-intensity laser-driven collisionless electrostatic shock formation and ion acceleration in a multicomponent plasma	110
O 111 - Formation of differentially rotating free-boundary plasmas with x-ray driven plasma flows at the MAGPIE facility	111
O 112 - Simulations and Experiments of Shocks in Weakly Collisional Plasmas	112
O 113 - Study of magnetic field compression in plasma for laboratory astrophysics	113
O 114 - Axisymmetric eigenmodes driven by positive energy gradients in the alpha particle distribution function in JET D-T plasmas	114
O 115 - Microturbulence is suppressed when Alfvén eigenmodes are excited	115
O 116 - Electromagnetic instabilities in global gyrokinetics and their interaction with energetic particles	116
O 117 - Simulation-driven first experimental observation of shear Alfvén wave caused by ion cyclotron resonance heating in stellarator plasmas	117
O 118 - Spatial structure of NBI-driven shear Alfvén waves in the TJ-II stellarator: modeling vs. experimental results	118
O 120 - Multi-GeV electron bunches obtained via direct laser acceleration for high-energy photon and pair production	119
O 121 - On measuring stimulated photon-photon scattering using multiple ultraintense lasers	120
O 122 - Predictive tool for Nonlinear Compton and Radiation Reaction scattering experiments	121
O 123 - Self-aligned Compton photon source from multi-GeV LWFA electron beam	122
O 124 - Coherently enhanced radiation friction	123
O 125 - Laser-Plasma Accelerators for Strong-Field QED Studies	124
O 126 - Radial Impurity Transport in the Pedestal of reactor-relevant Tokamak Operation Regimes	125
O 127 - ‘Density cliff’ formation near the separatrix of high density H-modes at JET and its role for the H-mode density limit	126
O 128 - Experimental characterization of ELM precursor oscillations on MAST-U and comparison with ELITE simulations	127
O 129 - Detection and characterization of intra-ELM modes in Type-I ELMy scenarios at TCV using the Thermal Helium Beam diagnostic	128
O 130 - A gyrokinetic analysis of turbulent transport in the pedestal region of the MAST-U tokamak	129
O 131 - Pedestal density prediction for tokamaks	130
O 132 - An internally consistent model for high energy density material properties	131
O 133 - X-ray spectroscopic diagnosis of core conditions in highly magnetized cylindrical implosions	132
O 134 - From X-ray phase contrast imaging to coherent diffraction for inverse problem solving in laser-driven experiments	133
O 135 - Characterizing shock dynamics in foams with Talbot interferometry	134
O 136 - Relaxation pathways in X-ray Free Electron Laser heated Iron	135
O 137 - From non-thermal plasma to cultural heritage: Tailored Atomic Oxygen Generation for non-contact cleaning sensitive works of art	136
O 138 - Plasmas for in-situ resource utilisation on Mars	137
O 140 - Global plasma model of a Microwave Electrothermal Thruster (MET) for self-consistent performance calculations	138
O 141 - Numerical design and experimental characterization of an innovative ‘plasma-shaped’ cavity realized in AM for ECR Ion Sources	139
O 142 - Relativistic plasma dynamics around astrophysical compact objects	140
O 143 - Fully kinetic simulations of magnetorotational turbulence in astrophysical compact-object accretion flows	141
O 144 - A visual approach to MHD accretion disk instabilities	142
O 145 - Laboratory experiments at accelerator and laser facilities to probe high-energy astrophysical processes	143
O 146 - Exhaust control in the WEST tokamak, in preparation of ITER tungsten divertor operation	144
O 147 - Advancing the Energy Frontier of Plasma-Based Proton Acceleration with Petawatt Lasers	145
O 148 - Parametric decay instabilities in fusion plasmas: Consequences and new possibilities	146
O 149 - 3D turbulence simulations in detached conditions and their implications for the mean-field modelling of divertor regimes	147
O 150 - Confinement transitions and large-scale mode activity in magnetic configurations with internal islands in the Wendelstein 7-X stellarator	148
O 151 - Integrated PIC-fluid modeling of the melting experiments of the WEST tokamak monoblocks	149
O 152 - Towards continual learning surrogates for transport solvers	150
O 153 - First experiments on alternative divertor configurations in ASDEX Upgrade	151

O 154 - Single-Shot, All-Optical Measurements of Laser-Produced Plasmas	152
O 155 - 11B-p fusion reaction with energetic- nanosecond- lasers: in-target and pitcher-catcher schemes for applications in inertial confinement fusion schemes	153
O 156 - ELIMAIA beamline: a user-oriented platform for repetition-rate ion acceleration and applications	154
O 157 - Ion acceleration by super-intense laser interaction with optically shaped gaseous targets in the near critical density plasma regime	155
O 158 - Quasi-monochromatic carbon ion beams using the “peeler” acceleration scheme	156
O 159 - A high yield, continuously operating fast neutron source driven by a table-top 10 Hz laser	157
O 160 - 3D non-linear MHD simulations of the flux pumping dynamo for sawtooth control at realistic experimental parameters	158
O 161 - Magnetic topology dynamics during reconnection events in RFX-mod	159
O 162 - Linear extended MHD in ASDEX Upgrade and Wendelstein 7-X	160
O 163 - JOREK simulations of radiation collapses and their magnetic signatures in ITER start-up limiter plasmas	161
O 164 - Resonant Layer Responses to Non-Axisymmetric Magnetic Perturbations in Two-Fluid, Drift-MHD Regimes	162
O 165 - Alfvén Mode Excitation by ITG Turbulence	163
O 167 - Turbulence and preferential heating in astrophysical plasmas	164
O 168 - Quasi-periodic pulsations in solar and stellar flares: automated detection and insights into electric current systems in coronal plasmas	165
O 169 - Spectrum of high-altitude blue auroral emissions observed with hyperspectral camera for auroral imaging (HySCAI) during astronomical twilight	166
O 171 - Wave conversion and heating in a two-fluid partially ionized atmosphere	167

Content of Poster Presentations

1 P 001 - Spectroscopic characterization of directly-driven spherical implosions using artificial neural networks	169
1 P 002 - Design of compact Thomson parabola spectrometer with high energy resolution	170
1 P 003 - Probing the density evolution of borane plasma by a multi-frame interferometer	171
1 P 004 - Foam-based targets for stable laser-driven fusion energy	172
1 P 005 - Surrogate modelling of electron acceleration in near-critical density QED plasmas at ultra-high intensities	173
1 P 006 - Quantum-accelerated simulation of electron-positron pair production in Extreme Laser-Plasma interactions	174
1 P 007 - Equation of motion of uniformly accelerating charged particles including radiation reaction effect	175
1 P 008 - Amplifying strong field signatures with flying focus pulses	176
1 P 009 - Modeling and theoretical description of extreme laser-matter interaction	177
1 P 010 - Investigating the competition between kinetic plasma instabilities in Earth's magnetosheath using the semi-implicit Particle-In-Cell method	178
1 P 011 - Nonlinear modulation of dispersive fast magnetosonic waves in an inhomogeneous rotating solar low- β magnetoplasma	179
1 P 013 - The use of imaging plates for proton radiography in laser-driven experiments	180
1 P 014 - Modeling of the ion dynamics in a bounded low-temperature plasma with moment methods	181
1 P 015 - Study on power efficiency for hydrogen production by methane decomposition using AC plasma	182
1 P 016 - A fully coupled Pressure-Based Method for the Electron Fluid Model in Hall-Effect Thrusters	183
1 P 017 - Optical emission spectroscopy of tungsten cathodic arc plasma at different argon and nitrogen pressure	184
1 P 018 - Numerical and experimental investigation of an atmospheric pressure DC corona discharge	185
1 P 019 - Plasma synthesis of nanogold for SERS detection of trace explosives	186
1 P 020 - Preliminary results from magnetic measurement by using hall sensors in the KSTAR tokamak	187
1 P 021 - Tungsten content quantification in Wendelstein 7-X plasmas	188
1 P 022 - Utilizing ECE for precise measurement of the Shafranov shift and plasma equilibrium assessment	189
1 P 023 - Fast visible imaging of X-point radiator regime in WEST	190
1 P 024 - Magnetic measurement under the environment with lower tungsten divertor in KSTAR tokamak	191
1 P 025 - Design of a hybrid polychromator for Thomson scattering diagnostic system on KSTAR	192
1 P 026 - Preliminary design of a Mirror-Type Thomson Scattering System in KSTAR	193
1 P 027 - Characterization of magnetic fluctuations in Reversed-Field Pinch plasmas	194
1 P 028 - Investigation of possible solutions for the Grad-Shafranov equation by using Bayesian inference	195
1 P 029 - Mirnov coil-based plasma state classification with deep learning methods	196
1 P 030 - Full Data Streaming Infra-Red Video Bolometer (IRVB) of Korea Superconducting Tokamak Advanced Research (KSTAR)	197
1 P 031 - Upgrade of APD and amplifier circuit in the polychromator of the KSTAR Thomson scattering diagnostic system	198
1 P 032 - Radial measurements of core hydrogen isotope ratios in ASDEX Upgrade	199
1 P 034 - Off-axis neutron camera design for the MAST Upgrade	200
1 P 035 - Development of an Integrated Data Analysis Platform for the VEST Tokamak	201
1 P 036 - MHD instabilities in benign termination of runaway electron beams in the JET tokamak	202
1 P 037 - Intrinsic momentum transport driven by magnetic topology in tokamak plasmas	203
1 P 038 - Dynamics of zonal structures and ion temperature gradient modes in the presence of energetic particles	204
1 P 039 - Non-gyrokinetic high-frequency mode instability for tokamak edge like gradients	205
1 P 040 - Transport model surrogates via Gaussian process regression with neural network kernels	206
1 P 041 - Self-consistent gyrokinetic simulations of magnetic islands in tokamaks	207
1 P 042 - Energy balance for ion temperature gradient driven modes in 6D kinetic Vlasov simulations	208
1 P 043 - Measurements of the intrinsic torque driven by up-down asymmetric L-mode plasmas in TCV	209
1 P 044 - Turbulence Regulation and Zonal Flow Dynamics in Magnetically Confined Plasmas	210
1 P 045 - A collisional 6-moment gyro-fluid model	211
1 P 046 - Recent results of Doppler reflectometry systems operated at Wendelstein 7-X	212
1 P 047 - State transitions in turbulent eddies as captured by information entropy	213
1 P 048 - The ITER baseline scenario on JET in D-T with Neon seeding	214

1 P 049 - Initial Experiments Utilizing the Langmuir Probe on Tungsten Divertor of KSTAR	215
1 P 050 - Divertor-core integration in high-performance, negative triangularity plasmas on TCV	216
1 P 051 - Tungsten erosion and re-deposition studies utilizing ultraviolet spectroscopy in DIII-D and W7-X	217
1 P 052 - A novel method for treating MAR in EMC3-EIRENE, and first applications to W7-X	218
1 P 053 - Optimizing interpretative SOLPS-ITER simulation with an advanced Bayesian inference workflow	219
1 P 054 - Development of divertor scenarios for quasi steady-state operation of Wendelstein 7-X	220
1 P 055 - Combining total flux expansion and strong baffling: initial observations on the X-point target divertor on MAST-U	221
1 P 056 - A tightly baffled long-legged divertor for TCV	222
1 P 057 - Experimental observation of edge plasma transport characteristics after boronization on Wendelstein 7-X	223
1 P 058 - Flexible grids for complex tokamak topologies	224
1 P 059 - Assessing wall heat fluxes in the Quasi-Continuous Exhaust regime at ASDEX Upgrade	225
1 P 060 - The marginally stable state of runaway electrons controlled by self-excited waves	226
1 P 061 - Evaluating energy fluxes during COMPASS disruptions	227
1 P 064 - Kinetic modelling of runaway electron momentum distributions for the EU-DEMO tokamak	228
1 P 065 - Magnetic stochasticity and runaway electron dynamics in vertically unstable plasmas during tokamak disruptions*	229
1 P 066 - Kinetic modelling of hot tail runaway electron generation during plasma disruptions using the JOREK code	230
1 P 067 - DECAF disruption avoidance and cross-device analysis of mode locking forecasting	231
1 P 068 - 3D MHD simulations of runaway electron avalanche in ITER mitigated disruptions	232
2 P 069 - Integrated Radiation-Magneto-Hydrodynamic simulations of magnetized burning plasmas	233
2 P 071 - New developments in the laser-plasma interaction code HERA: broadband lasers and MHD	234
2 P 072 - First experiment using an hydrodynamic growth radiograph platform at LMJ	235
2 P 074 - Ultra relativistic Weibel-like instabilities investigated with a Semi-Lagrangian adaptive mesh refinement method	236
2 P 076 - A simulation pipeline for short-pulse laser-driven hydrodynamics	237
2 P 077 - Scaling of Stimulated Raman Side-Scattering with focal spot size and density scale length in inhomogeneous plasmas	238
2 P 078 - Laser-matter interaction in magnetized plasmas: x-ray diagnosis of enhanced hot electron energy deposition	239
2 P 079 - Self-consistent laser dynamics in the ponderomotive acceleration of dense electronic beams	240
2 P 080 - A canonical view on particle acceleration by electromagnetic pulses	241
2 P 081 - Impact of High-Power q-Gaussian laser Beam Propagation in Collisionless Magneto Plasma	242
2 P 082 - Occurrence of Landau damping close to the Sun: Kinetic simulations and field-particle correlation	243
2 P 083 - MHD wave modeling with Q-variables	244
2 P 084 - Advancements in GPU-accelerated particle-in-cell simulations with iPIC3D	245
2 P 085 - Onset of driven magnetic reconnection and plasmoid formation in relativistic magnetized plasmas	246
2 P 086 - Void closure in complex plasmas in microgravity with the future complex plasma facility COMPACT	247
2 P 087 - Ion energy distribution and double layer formation in magnetized surface wave plasma (surfatron)	248
2 P 088 - Plasma Assisted Supersonic Jet Deposition for thin film growth	249
2 P 089 - Exploiting the synergy of a broad spectrum of light & surface dielectric barrier discharge (SDBD) plasma for ozone (O ₃) production	250
2 P 090 - Gyrokinetic particle-in-cell turbulence simulations with an evolving background	251
2 P 091 - An Improved Analytical Theory Model for Ion Temperature Gradient Instability in Tokamak Plasmas	252
2 P 092 - Numerical simulations of scrape-off layer plasma turbulence: evidence in support of stochastic modeling	253
2 P 093 - Tungsten and high-Z impurity transport analysis using x-ray spectroscopy at Wendelstein 7-X	254
2 P 094 - Enhancement of nonlinearly driven particle fluxes triggered by turbulence spreading in tokamak plasmas	255
2 P 095 - Full-f gyrokinetic simulations of a linear plasma device based on the gyromoment approach	256
2 P 096 - A constant flux surface average electron model for BSL6D	257
2 P 097 - Neoclassical Effects on Turbulent Transport in Tokamak Devices	258
2 P 098 - Reducing turbulent transport in tokamaks by combining intrinsic rotation and the low momentum diffusivity regime	259
2 P 099 - Investigation of the observed edge toroidal rotation acceleration due to Resonant Magnetic Perturbations on MAST-U	260
2 P 100 - Gyrokinetic simulations of negative triangularity plasmas in ASDEX Upgrade using GX	261
2 P 101 - Study on the dispersion relation and the discrete spectrum of drift wave turbulence	262
2 P 033 - Multi-diagnostic plasma equilibrium reconstruction with Physics-Informed Neural Networks (PINNs) for tokamak applications	263
2 P 062 - Scalable simulation-based inference framework for large-scale model validation in fusion	264

2 P 103 - Modelling type-I ELM detachment burn-through for SPARC	265
2 P 104 - Effect of vibrationally-resolved D2 on detachment in SOLPS-ITER simulations of MAST-Upgrade	266
2 P 105 - Stellarator divertor optimisation for a Stable Quasi-Isodynamic Design (SQulD): magnetic topology, divertor plates and baffle design	267
2 P 106 - Spectroscopic investigation of main impurity flows under magnetic field reversal in the TCV divertor	268
2 P 107 - Transient-divertor interaction studies in the MAST-U super-X divertor	269
2 P 108 - Study on poloidal field configuration effect to electron cyclotron wall cleaning in KSTAR	270
2 P 109 - Neural network surrogate model trained on EMC3-EIRENE database for rapid prediction of edge plasma parameters from experimental measurements	271
2 P 110 - Upgrade glow discharge cleaning system on the Uragan-2M stellarator	272
2 P 111 - The construction and experiment of divertor target biasing system (DTB) on J-TEXT tokamak	273
2 P 112 - 3D nonlinear MHD modeling of detachment, burn-through and the X-point radiator regime with kinetic neutrals and impurities	274
2 P 113 - Optimizing fuelling pellet injection geometry for COMPASS Upgrade using HPI2	275
2 P 114 - Characterization of gas flow in the JET sub-divertor	276
2 P 116 - Theory and simulation of phase space transport in burning plasmas	277
2 P 117 - The effect of strong plasma rotation on nonlinear ideal MHD instabilities and associated sustainment of sawtooth-avoiding magnetic configurations	278
2 P 118 - Magnetic equilibria during enhanced plasma performance phases in Wendelstein 7-X stellarator	279
2 P 119 - Observation of Helically-Trapped Energetic Particle Transport Induced by Energetic-Ion-Driven Resistive Interchange Mode using Imaging Neutral Particle Analyzer in LHD	280
2 P 120 - Magnetic topology of phase-locking driven Plasma-Wall Interaction in RFX-mod RFP discharges	281
2 P 121 - The recent development of the ASCOT code	282
2 P 122 - Hysteresis of amplitude-frequency relationship of MHD instabilities and its modeling in toroidal magnetically confined plasmas	283
2 P 123 - B-field dependency of high-beta plasmas at Wendelstein 7-X stellarator	284
2 P 124 - A multi-machine study of the interaction between locked modes and plasma rotation	285
2 P 125 - Progress on [N]TM modelling and control in the ITER Plasma Control System design	286
2 P 126 - First evaluation of gamma-ray emission from alpha-boron reactions in the ITER tokamak with a tungsten wall	287
2 P 127 - Simulations of trapped electron clouds in gyrotron electron guns and comparison with experimental data	288
2 P 128 - Improved calibration of the high-resolution tunable ECE system for power deposition and transport studies in Wendelstein 7-X	289
2 P 129 - Tomographic Reconstructions in RFX-mod via neural networks	290
2 P 130 - AI Tools for Plasma Diagnostics by X-ray Imaging and Spectroscopy in the PANDORA Project Frame	291
2 P 131 - Calibration of Thomson scattering density measurements at ASDEX Upgrade	292
2 P 132 - Machine learning surrogate model for peeling-ballooning pedestal MHD stability	293
2 P 133 - Reproducing edge localized modes mitigation by RMPs using neural networks on JET	294
2 P 134 - Electron-temperature-gradient mode evolution in the presence of a corrugated electron temperature gradient in the tokamak pedestal	295
2 P 135 - Investigating Fueling Location and Transient Fueling Effects on Scrape-Off Layer Transport in MAST-U	296
2 P 136 - Impact of the divertor conditions on L-H transition in KSTAR	297
2 P 137 - Experimental discovery of micro-tearing modes in the pedestal of MAST-U	298
2 P 139 - Ideal and Non-Ideal Pedestal Stability of Seeded Plasmas, Cross-Device Analysis	299
2 P 140 - Machine learning methods for modelling local, linear gyrokinetic simulations of MAST-U pedestal turbulence	300
2 P 141 - Effect of diamagnetic flow stabilization on pedestal stability in JET and its importance for isotope mass effects	301
2 P 142 - Comparisons between edge turbulence in EDA and QCE plasmas using the CECE diagnostic at ASDEX Upgrade	302
2 P 143 - Development of high plasma performance scenarios with small/no ELMs on HL-3	303
3 P 144 - Study on Polarized Emission and its effect on Laser Induced Breakdown Spectroscopy	304
3 P 145 - A Stark broadening line profile library for spectroscopic modeling of warm dense plasma	305
3 P 146 - Investigation of strongly coupled and weakly degenerate plasmas in supercritical fluid mixtures	306
3 P 147 - XUV imaging of electron heating and density changes femtosecond laser heating of solid titanium	307
3 P 148 - Transport and focusing of ultrashort electron bunches	308
3 P 149 - Simulating the focusing of laser-plasma accelerated proton beams	309
3 P 150 - High Energetic Proton Acceleration and Alpha Particle Generation from Laser-driven Proton-Boron nuclear reaction	310
3 P 151 - Effect of Parabolic Plasma Channel Shaping on Electron Acceleration and Betatron X-ray Emission	311
3 P 228 - X-Ray Sources for Non-Destructive Testing (NDT) Using Laser-Plasma Acceleration	312

3 P 152 - Measurement in Koopman Von Neumann approach	313
3 P 153 - Thin-target bremsstrahlung of plasmas with high-Z impurities	314
3 P 154 - Light dragging in moving magnetized plasmas*	315
3 P 155 - Characterization of pure electron plasmas in APEX-LD using an electron beam diagnostic	316
3 P 156 - Evidence of energy transfer from Helium metastables to Hydrogen in CCRF plasma: An Optical Emission Study	317
3 P 157 - Generation of Multiple Double Layers and Ion Beam in RF expanding plasma	318
3 P 158 - A non-destructive method for plasma blob trajectory estimation using capacitive probe arrays for non-neutral plasma diagnostics	319
3 P 159 - Fluid V-state dynamics through magnetized electron plasmas	320
3 P 160 - Mode conversion and parametric decay instabilities in electron cyclotron resonance heated helium and hydrogen plasmas in TOMAS	321
3 P 161 - Modelling current and pressure evolution in Gauss Fusion stellarator power plant	322
3 P 162 - ASCOT-RFOF modelling of JET and ITER distribution functions of energetic particles accelerated by ion cyclotron heating within the IMAS framework	323
3 P 163 - Turbulence-inclusive modelling of electron-cyclotron wave-plasma dynamics in Tokamaks	324
3 P 164 - Towards Steady-State Fusion: Demonstration of a Stable, Integrated High-Performance Scenario in the W7-X Stellarator	325
3 P 165 - Towards high performance long pulse operation with combined LHCD and ECCD in WEST	326
3 P 166 - Impact of turbulent tokamak edge plasma on ion cyclotron wave propagation: A stochastic 1D model in a DTT plasma scenario	327
3 P 167 - First experiments on ICRF plasma start-up at Wendelstein 7-X	328
3 P 168 - DTT Hybrid scenario development with ASTRA-TGLF predictive modelling	329
3 P 169 - Alya4fusion: Advancing plasma equilibrium and electromagnetic wave propagation modelling for fusion reactor simulations	330
3 P 170 - A workflow integrating simplified physics and engineering models for an initial design of the new DEMO Low Aspect Ratio baseline	331
3 P 172 - NSFSim code for machine design and scenario development	332
3 P 173 - Cascaded parametric amplification of lower hybrid waves using microwave beams	333
3 P 174 - Establishing a new operation point for Wendelstein 7-X at 1.8T with third harmonic electron cyclotron heating	334
3 P 175 - Effect of stray magnetic fields on particles in the Wendelstein 7-X neutral beam box	335
3 P 176 - Development of high-performance scenarios and H-mode operation on the ST40 tokamak	336
3 P 177 - Crayon: a flexible, fully relativistic ray tracer for electron Bernstein wave heating and current drive	337
3 P 179 - Fast scoping of fusion power plant parameter space using the new OD system code DOFUS	338
3 P 181 - Tokamak GOLEM for fusion education — chapter 16: plasma edge, transport barrier, fast ion temperature, spectroscopy, magnetic islands, MHD stability	339
3 P 182 - Fusion Twin Platform: an innovative tool for fusion research and education	340
3 P 183 - Compact shunts for the upper divertor of ASDEX Upgrade	341
3 P 184 - Tokamak GOLEM for fusion education – chapter 16: Bayesian discharge optimization, Artificial Neural Network tomography, runaway electrons, lithium evaporator, impurities	342
3 P 185 - Efficient pinpointing of mode-particle resonances and transport barriers in realistic tokamak equilibria	343
3 P 186 - Robust solver for MRxMHD equilibria	344
3 P 188 - Initial simulations of core instabilities in MAST-U with the non-linear code JOREK	345
3 P 189 - Convolutional Neural Network driven analysis of Strike Point Splitting in MAST-U	346
3 P 191 - Neutral Beam Injection in a high-field reactor-like stellarator	347
3 P 192 - Study of kinetic effects on the 1/1 internal kink mode using the hybrid kinetic MHD spectral code VENUS-KMHD	348
3 P 193 - Auburn University CTH and W7-X Research Progress and Plans*	349
3 P 194 - Testing the modes coupling effect on flux pumping in plasmas	350
3 P 196 - Benchmarking pressure stabilisation of neoclassical tearing modes in a spherical tokamak using the reduced MHD implementation of the JOREK code	351
3 P 197 - Simulation study of magnetohydrodynamic instabilities in Variable Symmetry Torus	352
3 P 198 - Analytic and numerical investigation of global ideal magnetohydrodynamic instabilities driven by strong toroidal rotation in tokamaks	353
3 P 199 - Spectroscopic diagnostics for the plasma edge of RFX-mod2 device	354
3 P 200 - Investigation of mode structure from BES signals in MAST Upgrade	355
3 P 201 - Enhancement of the TCV radio frequency antenna for detection of plasma instabilities by runaway electrons and electron cyclotron waves	356
3 P 203 - Spatiotemporal investigation of visible radiation distribution around attachment-detachment transition on Wendelstein 7-X	357
3 P 204 - Electron density and temperature profiles from spectroscopy in the upper divertor plasma of ASDEX Upgrade	358
3 P 205 - TWINTOK: a digital twin approach for refined comparison between experimental data and plasma simulations	359

3 P 206	Real-time Bayesian inference from TCV bolometry data	360
3 P 207	First results from LIBS characterization of plasma facing components in ADITYA-U Tokamak	361
3 P 208	Leveraging neural networks for real-time beam emission inference	362
3 P 209	Modeling electron cyclotron emission for investigation of ECE – Thomson Scattering discrepancy in Alcator C-Mod	363
3 P 210	Overview of the optical emission analysis of the hydrogen gas puff experiments in the linear plasma device PSI-2	364
3 P 211	Real-time pellet ablation radiation monitoring for a refined plasma core density control in ASDEX Upgrade	365
3 P 212	Upgrade of the TJ-II passive-spectroscopy system to improve estimations of carbon ion temperatures	366
3 P 213	A neural network approach to real-time electron density reconstruction from alkali beam emission spectroscopy data at W7-X	367
3 P 214	Conditional averaging of overlapping pulses — a method to characterize large-amplitude fluctuations in the SOL	368
3 P 215	Projecting stellarator reactors based on empirical scaling: uncertainties, risks and implications for the international stellarator research	369
3 P 216	Comparison of iota scan experiments in different experimental campaigns of the Wendelstein 7-X stellarator	370
3 P 217	Piecewise omnigenous stellarator magnetic fields with zero bootstrap current	371
3 P 218	Study of the density limit physics for stellarator devices by means of an energy balance model	372
3 P 219	Analyzing flows in high-performance pellet discharges at W7-X	373
3 P 220	Characterisation of the pellet cloud drift in stellarators	374
3 P 221	A physics basis for the Gauss Fusion 1 GWe stellarator fusion power plant	375
3 P 222	Can turbulent transport in optimized stellarators be as low as in tokamaks?	376
3 P 223	Modeling transport in stellarator island divertors in the presence of magnetic chaos	377
3 P 224	Fast-ion density measurements with FIDA spectroscopy in Wendelstein 7-X	378
3 P 225	Designing ALPES: an Adaptable Lab for Plasma Experiments in Stellarators at university scale	379
4 P 226	Simultaneous Transverse Radiography of a Dynamic Event Using Short-Pulse Laser-Generated Beams	380
4 P 227	Complex characterization of hot electron emission from laser produced plasma on thin foil targets	381
4 P 230	Real-Time Detection and Characterization of Ion Beams in Laser-Plasma Interactions	382
4 P 232	Quasilinear theory from first principles: reinstating the ponderomotive forces	383
4 P 233	A Quantum Algorithm for Simulating Dissipative Processes in Hot Plasma	384
4 P 234	Impact of phase shift and magnetic field configurations on BiGyM design	385
4 P 235	APEX-LD and EPOS: companion HTS devices for e+e- pair plasmas	386
4 P 236	Development of the Persistent Actor Framework (PAF) version of the European Transport Simulator (ETS)	387
4 P 237	Efficient uncertainty quantification in plasma micro-instability simulations with mode transitions	388
4 P 238	Effects of Neon seeding on density profiles and particle sources in the Integrated Scenario at the Joint European Torus	389
4 P 239	Investigating the pedestal intrinsic torque at the ASDEX Upgrade tokamak	390
4 P 240	Investigation of cross-scale interaction between high-k and low-k turbulence in Large Helical Device (LHD)	391
4 P 241	T3ST code: Turbulent Transport in Tokamaks via Stochastic Trajectories	392
4 P 243	Particle Transport and Turbulent Cascade Rate in the Scrape-Off Layer	393
4 P 244	Utilizing dynamic heat transport simulations to extract information out of measured ELM frequencies	394
4 P 245	Predictions of gyrokinetic turbulent transport in proton-boron plasmas on EHL-2 spherical torus	395
4 P 246	Density fluctuation measurements during confinement transitions in Wendelstein 7-X by phase contrast imaging	396
4 P 248	Investigating Density Pump-out and Wall Conditioning in RFX-mod Reversed Field Pinch Plasmas	397
4 P 249	Exposure of ultra-high temperature ceramics to scrape-off layer plasma in the WEST tokamak	398
4 P 250	Characteristics and Control of Tungsten Impurity Transport in KSTAR	399
4 P 251	Development towards integrated modeling of the X-point radiator in ASDEX Upgrade with JINTRAC	400
4 P 252	Influence of magnetic configuration on scrape-off layer drift effects in the Wendelstein 7-X stellarator	401
4 P 253	Investigation of limiter ramp-up phase of WEST discharge with integrated core-edge fluid transport code SolEdge-HDG	402
4 P 254	Ultrashort pulse series of electron cyclotron resonance heating for wall conditioning at Wendelstein 7-X	403
4 P 255	Integrated modelling of coupled free-boundary equilibrium and core-edge-SOL transport with improved conservation of plasma quantities during 2D edge-SOL grid evolution	404
4 P 256	Blob motion and flattened far-SOL profiles in Alcator C-Mod: evidence in support of stochastic modeling	405
4 P 257	Inner wall limiter startup experiments in WEST on bulk tungsten tiles	406
4 P 258	Numerical modelling of underexplored edge plasma scenarios in tokamaks using the SOLPS-ITER code	407
4 P 259	Improvement of helium exhaust on STEP by divertor design	408

4 P 260 - Deuterium Fulcher Band measurements in WEST tokamak	409
4 P 261 - Study of the divertor pumping capability in V-Shaped JT-60SA divertor	410
4 P 262 - Fast-ion model validation for He plasmas in W7-X	411
4 P 263 - Nonlinear Control Strategies for Divertor-Safe Burning Operation in ITER	412
4 P 264 - Direct reconstruction of density fluctuations observed by Alkali Beam Emission Spectroscopy	413
4 P 265 - Simulations of tungsten dust transport and survivability in DEMO	414
4 P 266 - Numerical study of the X-point radiator regime in WEST	415
4 P 267 - The NSTX-U Research Program: closing the gaps towards a Fusion Pilot Plant	416
4 P 268 - On the analysis and calculation of loop voltage involving tokamak inductance variations	417
4 P 269 - Two-dimensional kinetic full wave analysis in plasmas using integral form of dielectric tensor	418
4 P 270 - 3D full-wave simulations of the O-SX mode conversion process in MAST Upgrade	419
4 P 271 - Integrated plasma scenario analysis of the EHL-2 spherical torus	420
4 P 272 - Flight simulator development for the COMPASS-Upgrade Tokamak	421
4 P 273 - Overview of progress in establishing the plasma basis of STEP	422
4 P 274 - Simulation study of ECH multiple resonance heating and energetic electron generation in the QUEST spherical tokamak	423
4 P 275 - Developing plasma scenarios for the updated STEP design point	424
4 P 276 - Next-Generation TRANSP: Enabling High-fidelity Fusion Simulations with IMAS and GPU Optimization	425
4 P 277 - Nonlinear microwave physics at the upper hybrid layer in MAST-U	426
4 P 278 - Reinforcement learning-based magnetic control on the DIII-D tokamak	427
4 P 279 - Theoretical and experimental comments on rf current drive phenomenon	428
4 P 280 - Numerical investigation of the O-X mode conversion in the TCV device	429
4 P 281 - Family of phase space rays tracing model for RF heating	430
4 P 282 - A multi-synthetic diagnostic framework for SOL/edge plasma density studies on the W7-X stellarator	431
4 P 283 - Latest results from a multi-energy soft x-ray diagnostic for Te measurements and W transport studies on the WEST tokamak	432
4 P 284 - Energy-resolved soft x-ray camera in the TCV tokamak: First data	433
4 P 285 - Design process for the DNBI duct of the RFX-mod2 experiment	434
4 P 286 - Development of a GEM detector prototype with remote front-end electronics system for high-radiation environments	435
4 P 287 - Reflectometry in RFX-mod2: system upgrades and expected capabilities	436
4 P 288 - First data from a Balmer series-limit recombination spectrometer in the MAST-U divertor	437
4 P 289 - Radiated power density estimates from photon-counting measurements	438
4 P 290 - Bayesian optimisation as a tool for solving the inverse problem with plasma diagnostics	439
4 P 291 - 3rd harmonic ECE for electron temperature monitoring in high-density plasmas at W7-X	440
4 P 292 - Developing a machine learning based plasma control system for ISTTOK	441
4 P 294 - Leak detection and spatial localization inside fusion devices	442
4 P 295 - Simulation and analysis of optical efficiency for tangential Thomson collection optics system in KSTAR	443
4 P 296 - High and medium Z impurity concentration determination with InDiCA in JET	444
4 P 298 - Real-time plasma profile evaluation with multi-point Thomson scattering at Wendelstein 7-X	445
4 P 299 - Neural Estimation of Plasma Distributions from Imaging through Synthetic Data	446
4 P 300 - The role of x-ray spectroscopy in the development and understanding of high-performance scenarios in Wendelstein 7-X	447
4 P 301 - Application of autoencoders to electron density and temperature profiles for denoising, anomaly detection and automatic database construction in nuclear fusion	448
4 P 302 - Development of the Absolute Calibration System for the D-alpha Diagnostic for divertor	449
4 P 303 - Thomson scattering system for extreme plasma-surface interaction studies in QSPA	450
4 P 304 - Correlation Electron Cyclotron Emission radiometry and imaging development on the stellarator Wendelstein 7-X	451

Author Index

A

Abate, D. 4 P 268
 Abbasi, S. 3 P 181, 3 P 184
 Abrams, T. 1 P 051
 Abreu, P. O 033
 Acerbi, L. 2 P 062
 Adamek, J. 3 P 181
 Adams, J. 1 P 005
 Adishev, E. 4 P 292, 4 P 278
 Adulsiriswad, P. O 117
 Agarwal, S. 2 P 077, 2 P 078, 4 P 227, O 051
 Agostini, M. 2 P 120, 3 P 199, O 129, O 161
 Aiba, N. O 131
 Aich, S. 3 P 207
 Akella, V.S. O 093
 Akers, R. 4 P 299
 Åkerstedt, H. O 046
 Akos, K. 4 P 282
 Álamo Calderón, R.M. 4 P 291
 Alarcron, T. 4 P 294
 Albert, C. 3 P 225
 Albert, F. O 087
 Albertazzi, B. O 134
 Alberti, S. 2 P 127
 Alder, K. O 132
 Alekos, S. O 157
 Alessandro, M. O 140
 Alex Panera, A. 3 P 211
 Alexandre, T. 3 P 179
 Aleynikov, P. 1 P 046
 Aleynikova, K. 2 P 123
 Allen, N. 3 P 193
 Almeida, R. O 012
 Almukhametov, D. 3 P 182
 Alonso, A. 3 P 215, 3 P 218,
 3 P 219, 4 P 300, O 066
 Alvarez Laguna, A. 1 P 014
 Alves, E.P. O 096
 Amador, D. 3 P 212
 Amar, T. 3 P 228
 Amaro, Ó. 1 P 009, O 125, 1 P 006, O 122
 Amato, A. O 045
 Ambrogioni, K. O 013, O 089
 Ambrosino, R. O 104
 Amendt, P. O 062
 Amjad, I. 2 P 088
 Anastassiou, G. 3 P 185
 Anda, G. 4 P 264
 Anders Henry, N. 4 P 282
 Anders, A. O 092
 Andreas, K. 4 P 282
 Andrebe, Y. 1 P 056
 Andreeva, T. 3 P 216, O 150
 Andrew, Y. 3 P 176

Andrianaki, G. O 157
 Andriyash, I. O 084
 Andronic, M. O 085
 Angioni, C. 4 P 239, 4 P 244, O 011, O 034,
 O 126, O 152
 Ansia, L. O 136
 Antar, G. 4 P 294
 Antici, P. O 113
 Antlitz, F. 3 P 188
 Antoine, J. 3 P 205
 Antoine, M. 2 P 074
 Antonenas, Y. 3 P 185
 Antulio, T. 4 P 259
 Antunes, S. 3 P 147
 APEX Collaboration 4 P 235
 Araudo, A.T. O 024
 Arjmand, S. O 045
 Armbruster, L. 3 P 213
 Arnold, M. 3 P 149
 Artaud, J. 3 P 165
 Arthur, A. 3 P 160
 Artola Such, F.J. 1 P 065, 1 P 066,
 1 P 068, O 163
 Arun, P. 4 P 252
 Arvanitou, M. 1 P 022, 2 P 128, 4 P 291
 Asaturuv, A. 3 P 182
 Ascasibar, E. O 118
 ASDEX Upgrade Team. O 148, 1 P 032, 4 P 251
 Ashton-Key, T. 3 P 176
 Asunta, O. 3 P 176
 Asztalos, Ö. 3 P 208, 4 P 264, 3 P 213, 4 P 282
 Attiyah, D. O 154
 Auclair, T. 3 P 179
 AUG team 3 P 211
 Auriemma, F. 3 P 168, O 101
 Austin, M. 3 P 209, O 008
 Ayeab, A. 3 P 228

B

B R, G. 3 P 144
 B. Carvalho, B. 4 P 292
 Babjak, R. O 120
 Babucić, N. O 043
 Bacchini, F. 2 P 084, 2 P 085, O 143
 Bachmann, B. O 060
 Baciero, A. 3 P 212, 3 P 218
 Baczewski, A. O 132
 Badiali, C. O 012
 Badziak, J. 2 P 078
 Bae, K.H. O 125
 Baehner, J. O 150
 Bagnoud, V. O 050
 Bahk, S. O 121
 Bähner, J.P. O 165, 4 P 246, 4 P 300

Bähtz, C. O 005
 Baillo, A. O 065
 Bailly-Grandvaux, M. 1 P 001, O 061, O 133
 Baiocchi, B. 3 P 168
 Bak, J. 1 P 020, 1 P 024, 1 P 049, 1 P 067
 Baker, J.L. O 032, 2 P 103
 Balazs, P. 3 P 200, O 128
 Balbinot, L. 4 P 261, O 151
 Baldzuhn, J. 3 P 164, 3 P 220, 4 P 300, O 036
 Balestri, A. 2 P 098, O 104
 Balkovic, E. 3 P 186, O 065
 Ball, J. 1 P 037, 1 P 043, 2 P 098, 2 P 134, O 104
 Ballinger, S. 4 P 252
 Banerjee, S. 3 P 207
 Bang, E. 1 P 049, 2 P 108, 4 P 250
 Bannmann, S. 4 P 246, O 010
 Bañon Navarro, A. O 006, 1 P 046
 Baptiste, B. 3 P 179
 Baránková, H. O 044
 Barbante, P. 1 P 018
 Barbisan, M. 4 P 285
 Barbosa, B. 1 P 009
 Barbui, T. 4 P 283, 4 P 284
 Bardos, L. O 044
 Bardsley, O. O 032
 Barlow, D. O 059
 Barnes, M. 4 P 277, O 095
 Barni, R. 2 P 088, 2 P 089
 Baron, D. 2 P 110
 Barr, J. 4 P 278
 Batani, D. 2 P 077, O 087
 Batha, S. 4 P 226
 Batool, F. O 093
 Baumann, C. O 064
 Bayer, V. 3 P 155
 Bayer, V.C. 4 P 235
 Baylor, L. 3 P 164
 Beckley, C. 2 P 124, O 032
 Becoulet, M. O 008
 Beg, F. 1 P 001, O 133
 Begelman, M.C. O 143
 Begishev, I. O 121
 Beidler, C. 3 P 219
 Beidler, C.D. 4 P 300
 Belyaev, M. O 062
 Ben Slimane, T. O 138
 Benacek, J. O 023
 Benincasa, G. O 050
 Benracassa, S. O 084
 Berger, A. 1 P 014
 Bergmayr, R. 2 P 104
 Berkery, Jack 2 P 137
 Bernert, M. 3 P 183, 4 P 251, O 127, O 146
 Bernhard, P. 3 P 211
 Bessard, N. 3 P 193

Bharti, A. 2 P 062
 Biancalani, A. 1 P 038, 2 P 090, O 028
 Bianconi, D. O 141
 Bielajew, R. 2 P 100, 2 P 142, 3 P 209
 Bilbao, P.J. O 086
 Bin, W. 3 P 201, 4 P 234
 Bindsvlev, H. 1 P 032
 Bingham, R. O 062
 Birkenmeier, G. 3 P 225, O 105
 Biro, B. O 159
 Biswas, B. 3 P 177
 Blackman, D. O 049
 Blackmore, S. 2 P 099, 2 P 137
 Blancard, C. O 134
 Blanchot, N. O 087
 Bleotu, G. O 085
 Block, D. O 091
 Boboc, A. O 127
 Bock, A. 3 P 211, O 160
 Bodner, G. O 079
 Body, T. 2 P 103
 Boeyaert, D. O 064
 Bolzonella, T. 2 P 099, 3 P 162
 Bonanomi, N. 2 P 142
 Bonciarelli, A. 1 P 021, 1 P 057
 Bonfiglio, D. O 079
 Bong, S. 1 P 049
 Borchardt, M. O 165
 Bordón, A. 1 P 001, O 061, O 133
 Börner, P. 2 P 114, O 054
 Bott, A. O 113
 Bottino, A. 1 P 038, 1 P 041, 2 P 090, 2 P 116,
 O 028, O 116
 Bott-Suzuki, S. O 135
 Bouchard, G. 2 P 071, O 049
 Bouffetier, V. O 135
 Bourdelle, C. 1 P 048, 3 P 165, 3 P 179, O 101
 Bourdon, A. 1 P 014
 Boutoux, G. O 087
 Bowman, C. 1 P 055
 Bozhenkov, S. 3 P 164, 3 P 175, 3 P 216, 4 P 246,
 4 P 300, O 074
 Bradley, J. 2 P 107
 Brambrink, E. O 005
 Brandt, C. 2 P 118, 2 P 123, O 150
 Braud, A. 3 P 154
 Braun, J. 1 P 032
 Braunmüller, F. 2 P 127
 Breizman, B. 1 P 060
 Breslau, J. 4 P 276
 Bret, A. O 071
 Brezina, T. 3 P 181
 Brezinsek, S. 1 P 057, 2 P 109, 3 P 160, 3 P 210,
 4 P 254, O 064
 Brida, D. 1 P 059, O 055, O 056

Brix, M. 3 P 200, O 128
 Brochier, M. 2 P 072
 Brotankova, J. 3 P 184
 Brown, B. 1 P 056, O 056
 Brughmans, N. O 144
 Bruncrona, A. 2 P 062, 2 P 132, 2 P 140, O 152
 Brunner, K.J. 3 P 164, 4 P 254, 4 P 298, 4 P 300
 Brunner, S. 1 P 037, 2 P 098, 2 P 134, 3 P 192
 Bryant, J. 2 P 104
 Brynjulfsen, S. 2 P 092
 Bucalo, E. 2 P 129
 Buermans, J. 3 P 160
 Bueschel, C. 2 P 123
 Bufferand, H. 4 P 266, O 149
 Bulanov, S. O 038
 Buratti, P. 3 P 201
 Burch, J.L. O 004
 Burckhart, A. O 160
 Burian, T. 4 P 227
 Burke, W. 2 P 142
 Burton, L. 1 P 022
 Büschel, C. 2 P 118, O 165
 Bussiahn, R. 3 P 220
 Bustos, A. 3 P 218
 Bustos-Ramirez, G. 1 P 067
 Buttenschön, B. 1 P 021, 1 P 051, 1 P 057,
 2 P 093, 2 P 123, 4 P 300
 Buxton, P. 4 P 290
 Buzás, A. 3 P 203, 3 P 220
 Buzas, E. O 159
 Byrka, O. O 051

C

Caetano De Sousa, M. 1 P 001, O 061, O 133
 Cai, J. 2 P 109, 2 P 133
 Califano, F. O 167
 Calio, G. 1 P 018
 Callahan, K. O 115
 Calvo, I. 3 P 215, 3 P 217, O 007, O 063
 Campos, A. 4 P 249
 Cannarile, F. 2 P 129
 Cano-Megias, P. 4 P 239
 Cao, S. O 076
 Capasso, M. 4 P 253
 Capdessus, R. 2 P 071, O 049
 Cappa, Á. 3 P 218, O 118, O 165
 Caprin, E. 4 P 294
 Carannante, G. 2 P 125
 Card, A. 3 P 155, 4 P 235
 Cardinali, A. 3 P 166, 3 P 201
 Carleton, D. 2 P 077
 Carpenter, J. 3 P 188
 Carpita, M. 2 P 106, O 056

Carralero, D. 1 P 046, 4 P 282, 4 P 300, O 066,
 Carraro, L. 3 P 199
 Carrotte, J. 3 P 177
 Carvalho, D. O 096
 Casey, D. O 062
 Casiraghi, I. 4 P 234
 Casner, A. 4 P 249, O 135
 Casson, F. 4 P 255, 4 P 273, 4 P 275, O 011
 Castaldo, A. 3 P 168
 Castaldo, C. 3 P 201
 Castaño-Bardawil, D.A. 3 P 167
 Catalano, R. O 045
 Cathey, A. 2 P 112, 2 P 141
 Cavalier, J. 1 P 023
 Cavazzana, R. 1 P 027, 4 P 248, 4 P 268, 4 P 287
 Cavedon, M. 1 P 059
 Cayzac, W. 2 P 072, O 087
 Cazabonne, J. 3 P 163, 3 P 165, O 035
 Ceconello, M. 1 P 034, 3 P 188
 Cecrdle, J. 3 P 184
 Cernaianu, M. O 041
 Cerovsky, J. 2 P 113
 Cervenak, M. 2 P 078, O 051
 Chakraborty, M. 3 P 157
 Chalker, M. 3 P 221
 Chalupsky, J. O 051
 Chandra Joshi, H. 3 P 156
 Chandra, R. O 054
 Chandrarajan Jayalekshmi, A. 2 P 134
 Chang, C. O 008
 Chapelant, G. 3 P 228
 Chattopadhyay, P.K. 3 P 158
 Chaturvedi, N. O 111
 Chaudhary, N. 1 P 022, 2 P 128, 3 P 216,
 4 P 291, 4 P 293
 Chellai, O. 4 P 283, 4 P 284
 Chen, C. 2 P 101
 Chen, L. 2 P 116
 Chen, S. 2 P 091
 Chen, X. O 138
 Chen, Y. 2 P 101
 Chen, Z. 2 P 111
 Chertopalov, S. O 022
 Chien-Chung, H. 2 P 091
 Chimier, B. O 061
 Chlum, J. 3 P 184
 Chodukowski, T. 2 P 078, 4 P 227, O 051
 Choi, J. 1 P 015
 Choi, W. 4 P 278
 Chopineau, L. O 134
 Chopra, N. O 020
 Christos, K. O 157
 Chulu-Chinn, N. O 011
 Ciardi, A. O 112
 Cichocki, F. O 151

- Cichoń, S. O 022
 Cikhardt, J. 2 P 078, 4 P 227, O 051
 Cikhardtova, B. O 051
 Cinnirella, L. 4 P 285
 Cipciar, D. O 150
 Cipelli, S. 4 P 234
 Ciraolo, G. 3 P 205, 4 P 253, 4 P 257,
 4 P 266, O 055, O 149
 Cirrone, G.A.P. O 045, O 155
 Ciupiński, Ł. 4 P 249
 Ciurlino, A. 2 P 126
 Claps, G. 4 P 286
 Clark, D.S. O 060
 Clark, J. O 154
 Clark, R. 4 P 278
 Clark, T. O 017
 Classen, I. 4 P 303
 Clod, A. O 148
 Coda, S. 1 P 050, 3 P 163,
 3 P 201, O 104, O 129, O 148
 Coelho, A. 3 P 161, 3 P 221
 Coelho, R. 4 P 236, O 033
 Coenen, J.W. 3 P 221
 Connor, J. O 131
 Consoli, F. O 048, O 155
 Conti, C. O 089
 Contré, C. 1 P 050, O 108
 Contributors, D. O 052
 Conway, G. 2 P 142
 Conway, N. 4 P 273
 Cooke, A. O 032
 Coosemans, R. 1 P 043, O 056, O 081
 Cordaro, L. 1 P 027, 4 P 248
 Cordella, F. 4 P 286
 Coriton, B. 2 P 126
 Corobean, B. O 158
 Corre, Y. O 151
 Corsaro, L. 2 P 103
 Cosculluela, A. 4 P 249
 Cosse, P. O 134
 Coster, D. 4 P 236, O 033
 Couedel, L. 2 P 086
 Courtois, C. 2 P 072
 Courvoisier, A. O 088
 Craciunescu, T. 2 P 033
 Creely, A. O 031
 Crisanti, F. O 052
 Cristofolini, A. 1 P 018
 Cristoforetti, G. 2 P 077, O 050
 Croci, G. 2 P 126
 Crombé, K. 3 P 160, 3 P 167
 Cruz-Zabala, D.J. O 104, 2 P 098, 4 P 239
 Csedreki, L. O 159
 Cseh, G. 3 P 203, 3 P 220, O 057
 Cu Castillo, H. O 006
 Cummings, N. 3 P 165
 Cunningham, G. 2 P 124, 3 P 189
 Cvelbar, U. 1 P 019
 Cziegler, I. O 128
 Czykowski, D. O 021
- ## D
- Da Ros, A. O 061
 Dalla Rosa, M. 2 P 126
 Damizia, Y. 2 P 135
 Daniel, G. 2 P 085
 Danielson, J.R. 4 P 235
 David, P. 1 P 059, O 081
 David, Z. 3 P 205
 Davies, R. 2 P 105, 3 P 223
 Davoine, X. O 087
 De Chevron Villette, R. O 134
 De Falco, C. 1 P 018
 De Haas, M. 4 P 298
 De La Riva Villén, J. 3 P 219, 3 P 218, 3 P 212,
 4 P 300, O 118, O 066
 De Leo, V. 4 P 286
 De Lucca, B. O 053
 De Martino, B. 4 P 249
 De Masi, G. 4 P 287
 De Mollerat Du Jeu, R. O 087
 de Oliveira, D. O 053
 De Piccoli, C. 3 P 162
 de Sousa, M.C. O 133
 De Vries, P. 2 P 125
 de Witt, J.K. O 148
 Debbasch, F. 3 P 152, O 099
 Decker, J. 3 P 153, 3 P 163, 3 P 201
 Decyk, V. O 096
 Dedeler, P. O 076
 Dedrick, J. O 019
 Deka, P. 2 P 084
 Del Sarto, D. 2 P 074
 Del Valle, M.V. O 069
 Delabie, E. 2 P 124, 4 P 288
 Delgado-Aparicio, L.F. 4 P 283, 4 P 289, 4 P 284
 Dellasega, D. O 013
 Deller, A. 3 P 155, 4 P 235, O 090
 Delpech, L. 3 P 165
 Deltev, R. 1 P 052
 Depierreux, S. O 058, O 062
 Deriaz, E. 2 P 074
 Devi, P. O 051
 Devin, E. O 020
 Devlaminck, E. 3 P 163
 Dhard, C. 1 P 021, 4 P 254
 d'Humières, E. O 027, O 113, O 158
 Di Giannatale, G. 2 P 090, O 104
 Di Piazza, A. 1 P 008, O 121
 Di Siena, A. O 006
 Diamond, P.H. O 008
 Diaz, R. O 087
 Dickinson, D. O 130
 Dieckmann, M.E. O 027, O 073
 Diez, M. O 146
 Dikan, V. 3 P 172
 Dill, E. O 121
 Dima, R. O 141
 Dinklage, A. 3 P 164, 3 P 219, 4 P 300
 Dior, L. 2 P 076
 Divol, L. O 060
 Djordjevic, B. 2 P 069
 Dlouhy, J. 3 P 181
 Dmitriev, A. 2 P 087
 Do, A. O 060
 Dodin, I. 4 P 232
 Dolui, S. 3 P 207
 Domański, J. 2 P 078
 Domingo, H. 3 P 169
 Donald, M. O 157
 Dong, J. 4 P 245, 4 P 271
 Donnel, P. O 009
 Döppner, T. O 060
 Doria, D. O 041, O 123, O 158
 Dormido-Canto, S. 3 P 212
 Dorris, R. 3 P 193
 Dostal, J. 4 P 227
 Dove, A. 2 P 086
 Dozias, S. O 077
 Drabinskiy, M. 4 P 292
 Draeger, S. O 057
 Dreher, J. 2 P 082
 Dreval, M.B. O 118
 Drevlak, M. 2 P 105
 Du Toit, E. O 082
 Du, H. 4 P 245
 Du, X. 2 P 119, O 115
 Dubrov, M. 4 P 255, O 033, O 163
 Ducker, R. 2 P 106, O 056
 Dudžák, R. 4 P 227, O 051, 2 P 078
 Düll, R. O 149
 Dumont, R. 3 P 165, 4 P 283, O 035
 Dunai, D. 2 P 137, 3 P 200, 4 P 264,
 4 P 282, O 128
 Dunne, M. O 107, O 108, O 162
 Dunsmore, J. O 131
 Dupre, P. 2 P 072
 Duran, I. 1 P 020
 Durr-Legoupil-Nicoud, G. 1 P 050, O 056
 Dutta, D. 3 P 157
 Duval, B. 1 P 043, 1 P 056, 2 P 106, 3 P 206,
 4 P 284, O 034, O 056
 Dux, R. 3 P 204, 4 P 239, O 034, O 126

E

Ebihara, Y. O 169
Edgard, Z. 4 P 285
Edlund, E. 4 P 246, O 150
Edwards, M. O 076
Effenberg, F. O 064
Eich, T. 2 P 103, O 083
Eidietis, N. O 079
Ejiri, A. 4 P 240
Ekedahl, A. O 035
Ekmark, I. 1 P 064
Elaian, H. 1 P 056
Elekes, Z. O 159
Elian, H. 4 P 284
Eliasson, B.E. 4 P 270
Ellerbrock, L. O 064
Elmore, S. 2 P 137, O 032
Emilio, B. 4 P 282
Ennis, D. 1 P 051, 2 P 093, 3 P 193, 4 P 252
Entler, S. 1 P 020
Eric, N. 3 P 179
Eric, S. 3 P 205
Erickson, K. 1 P 067
Eriksson, F. 4 P 275
Escoto, F.J. O 063
Estrada, T. 1 P 046, 3 P 218, O 066
Estrela, P. 3 P 147
Etchessahar, B. O 087
Ettel, D. 2 P 078, O 051
EUROfusion Tokamak Exploitation Team.
3 P 194
EUROfusion WPTE team. O 148
Evangelos, K. O 157
Ewart, R.J. O 095, O 097
Exploitation Team O 151

F

Fable, E. 4 P 239, O 034, O 081
Faitsch, M. 1 P 059, 2 P 142, O 083, O 107,
O 108, O 126
Fajardo, D. O 126
Fajardo, M. 3 P 147, O 136
Falchetto, G. 4 P 261
Falessi, M.V. 1 P 038, 2 P 090, 2 P 116, 3 P 185,
O 052
Fantz, U. 2 P 104
Farcas, I. 4 P 237
Fedeli, L. O 017
Federici, F. 1 P 055
Fedorczak, N. 1 P 023, 3 P 205, 4 P 253,
4 P 257, 4 P 266, O 055, O 146
Fedotov, A. O 124
Fefeu, N. 1 P 001, O 061, O 133

Fegan, C. O 113
Felici, F. O 081
Feng, Y. 1 P 052, 2 P 105, 2 P 109, O 057
Fenyvesi, A. O 159
Fernandes, H. 4 P 292
Fernández Pacheco, V. 1 P 061
Fernando, D. O 006
Ferrari, G. 1 P 061
Fevre, L. 1 P 023
Février, O. 1 P 050, 1 P 056, 4 P 258, O 055,
O 056
Ficker, O. 1 P 036, 1 P 061, 3 P 184
Field, A. 2 P 098
Figini, L. 3 P 168
Figueiredo, H. 4 P 292
Finocchiario, G. 2 P 130
Fischer, M. O 050
Fischer, R. 1 P 059, 3 P 208, 3 P 211
Flanagan, J. 2 P 107
Florido, R. 1 P 001, O 061, O 133
Folini, D. O 073
Fonghetti, T. 3 P 165, O 035
Ford, O. 1 P 051, 3 P 219, 3 P 224, 4 P 300,
O 010, O 066
Fox, P. 4 P 255
Francalanza, V. 3 P 166
François, M. O 027
Frank, A. 2 P 125
Franz, P. 2 P 129
Frassinetti, L. 1 P 043, 1 P 048, 2 P 099, 2 P 132,
2 P 140, 2 P 141, O 127, O 131
Frederic, C. 3 P 205
Frederic, S. 3 P 205
Fredon, T. 3 P 152, O 099
Freethy, S. 3 P 177, 4 P 270, 4 P 273,
4 P 277, O 082
Frerichs, H. 1 P 052
Friling, T. O 088
Fuchert, G. 2 P 109, 2 P 131, 3 P 164, 3 P 216,
4 P 246, 4 P 298, 4 P 300
Fuchs, J. O 113
Fugazza, S. 2 P 126
Fujisawa, A. 1 P 028
Fukumoto, M. 2 P 108
Fukuyama, A. 4 P 269
Fülöp, T. 2 P 062
Furno, I. 4 P 234
Fusaro, A. 2 P 071
Futtersack, R. 4 P 251, 4 P 255, 4 P 259, O 033

G

Gabriellini, S. 1 P 048
Gajdoš, P. 3 P 148, O 051, 2 P 078
Galatà, A. O 141

Galbiati, M. O 013, O 039, O 040
Galdón-Quiroga, J. 3 P 200
Gallardo-Díaz, E. 1 P 001, O 133
Gallart, D. 3 P 169
Gallego, J. 3 P 218
Galli de Magistris, M.S. O 013
Gallo, A. O 141
Gallo, C.S. O 141
Galperti, C. O 081
Galtier, E.C. O 135
Gambrioli, M. 2 P 124, 3 P 189
Gao, Y. 1 P 054, 2 P 109,
3 P 164, 4 P 252, O 057
Gao, Y. 2 P 133
Garbet, X. O 098
Garcia, O.E. 2 P 092, 3 P 214, 4 P 256
García-Cortés, I. 3 P 218, 3 P 220
García-Munoz, M. O 104, 4 P 262
Garcia-Regaña, J.M. O 007
Garkusha, I. 4 P 303
Garzotti, L. 1 P 048, O 011, O 078
Gaspar, J. O 035, O 146
Gatti, F. O 013, O 089
Gatto, R. 1 P 048
Gaudio, P. 2 P 033, 4 P 301
Geethika B R, G. O 094
Geiger, J. 1 P 022, 2 P 105, 3 P 216, O 150
Gelfer, E. O 124
Gelfusa, M. 2 P 033, 4 P 301
Gemmell, M. 4 P 290
Genoud, J. 2 P 127
Geoffray, I. 2 P 072
Gerardin, J. O 151
Gerasimov, S. 1 P 036
Geulin, E. 1 P 023, 3 P 211, 4 P 257, O 146
Ghendrih, P. 4 P 253
Ghim, Y. 1 P 049
Ghizzo, A. 2 P 074, O 098
Ghosh, A. 4 P 299
Ghosh, D. O 076
Ghosh, J. 3 P 207
Giannone, L. 3 P 183
Gigosos, M. 1 P 001, O 133
Gil, L. 2 P 142, O 107
Gil, P. 4 P 235
Gillinger, T. O 159
Giroud, C. 1 P 048, 4 P 296
Giroud-Garampon, P. 2 P 127
Giruzzi, G. O 052
Giuffrida, L. 4 P 230, O 089, O 155, O 156
Gizzi, L.A. 2 P 077, O 050
Glasser, A. 3 P 205, 4 P 253
Gleason, A. O 135
Gleiter, T. O 126
Glize, K. 2 P 077, O 047, O 050

- Glovkin, I. 3 P 145
Gobbin, M. 2 P 120, O 161
Göde, S. O 005
Goel, Y. 3 P 156
Goliyad, M. 4 P 276
Golovanov, A. O 084, O 088
Gomez Miguez, M.M. O 171
Goncharov, A. O 092
Gonda, T. 2 P 093, 3 P 193, 3 P 219, 4 P 246,
4 P 300
Goodman, A. 2 P 105
Goodman, T. 2 P 127
Gorbunov, E.A. O 143
Goree, J. 2 P 086
Gorelenkova, M. 4 P 276
Goriaev, A. 3 P 160, 4 P 254
Görler, T. 4 P 237, O 105
Gospodarczyk, M. 3 P 201, 4 P 284
Gossard, D. 1 P 038
Goswami, R. 3 P 158
Graber, V. 4 P 263
Grace, E. O 154
Gadic, D. 2 P 109, 2 P 123, 3 P 164, 3 P 167
Grahl, M. 3 P 216
Granier, C. 2 P 085
Granovsky, A. 4 P 278
Grassi, A. O 112
Grassi, E.M. O 089
Graßler, G.S. 2 P 099
Graves, J. 1 P 068, 2 P 117, 3 P 186, 3 P 192,
3 P 196, 3 P 198
Gravier, E. O 098
Grech, M. O 037, O 039, O 040
Gregori, G. O 062, O 145
Gren, P. O 046
Grenfell, G. O 105, O 105
Griener, M. O 105
Grillet, N. 4 P 249
Grishko, L. O 088
Grismayer, T. 1 P 009, O 039
Grosjean, A. 4 P 260, O 035
Groth, M. 2 P 114, O 054
Grulke, O. 1 P 046, 3 P 164, 3 P 174, 4 P 246,
4 P 304, O 150
Grumezescu, V. O 022
Gu, M. 3 P 145
Gu, X. 4 P 245
Guaitella, O. O 138
Guepin, C. O 026
Guerrout, R. 3 P 154
Guerra, V. O 138
Guerrero Arnaiz, J.F. 1 P 022, 2 P 128, 3 P 174,
4 P 291, 4 P 304
Guerrier, C. 2 P 072
Guilhem, D. 3 P 205, O 009
Guillemaut, C. 4 P 257, 4 P 260, O 146
Guillermin, B. 4 P 249, 4 P 257, 4 P 260
Guillevic, A. O 098
Guinchard, S. 3 P 153
Guittienne, P. 4 P 234
Gunn, J. 4 P 249, 4 P 257, 4 P 260,
O 146, O 151
Günter, S. O 160
Günter, T. 1 P 044
Guo, J. 2 P 111
Guo, Z. 2 P 101
Gupta, A. 1 P 049
Gurcan, O. 1 P 038
- H**
- Hachmeister, D. O 107
Hakola, A. 4 P 258
Hakosalo, J. 4 P 290
Halasz, Z. O 159
Hallatschek, K. 1 P 039, 1 P 042, 2 P 096
Ham, C. 3 P 188, 3 P 196
Hamm, D. 3 P 206, O 056
Hammond, K. 3 P 164, 4 P 252, 4 P 298
Hamstra, B. 3 P 175
Han, H. 1 P 067, 2 P 108, 2 P 136
Han, Y. 1 P 030
Hansen, C. 1 P 036
Hansen, S. O 132
Hansen, S.B. 1 P 032
Hansen, S.K. O 148
Happel, T. 2 P 100
Harrer, G.F. O 126
Harrison, J. 1 P 055, 2 P 104, 2 P 107
Harrison, J.R. O 055
Harting, D. 2 P 109
Hartmann, D. 3 P 167, 3 P 175
Hasegawa, M. 1 P 028, 4 P 274
Hatch, D. 2 P 134, 2 P 140, 4 P 237
Hausten, E.V. 2 P 118, 2 P 123
Havránek, A. 4 P 272
Hayes, S. 3 P 211
Hayward-Schneider, T. 1 P 038, 1 P 041,
2 P 090, 2 P 116, O 028, O 116
He, R. 2 P 101
Hečko, J. 1 P 053, 4 P 272
Hegde, B. 3 P 207
Hegedus, S. 3 P 200, O 128
Heidbrink, W. O 115
Held, M. 1 P 045
Helgeland, A. 4 P 256
Hender, T. 4 P 273
Henderson, M. 4 P 273, O 146
Henderson, S. 4 P 259, O 032, O 055
Henke, F. 1 P 051
Henneberg, S. 2 P 105
Hennequin, P. O 108, O 146
Henriques, R. 4 P 292
Hentschel, T. O 132
Heo, C. 1 P 029
Herashchenko, S. 4 P 303
Herfindal, J.L. O 054
Hernández-Sánchez, J. O 036
Herrera Quesada, L.C. 4 P 270
Herschel, M. O 105
Higaki, H. O 090
Hill, K. 4 P 283
Hill, M. O 154
Hill, P. 1 P 058
Hindenlang, F. O 162
Hiret, P. 2 P 087
Hirsch, M. 1 P 022, 2 P 128,
3 P 216, 4 P 291, 4 P 304
Hizanidis, K. 4 P 233
Ho, D. 2 P 069
Hobirk, J. 4 P 257
Hoelzl, M. 1 P 068, 2 P 141, 3 P 188, O 079
Hoenen, O. O 033
Hogge, J. 2 P 127
Hohenberger, M. O 060
Holland, L. 3 P 177
Hollmann, E.M. O 054
Hölzl, M. 2 P 112, O 160
Honda, M. 1 P 040
Hong, R. O 115
Hopkins, C. 3 P 177
Hoppe, M. 1 P 064, 2 P 062, 3 P 201
Höppner, H. O 005
Hoque, I. 3 P 207
Horacek, J. 3 P 184
Horný, V. O 085, O 158
Horsten, N. 2 P 114
Howard, N. 3 P 209
Hromádka, J. 4 P 272
Hromasova, K. 1 P 053
Hruška, P. O 022
Hrycak, B. O 021
Hu, D. 1 P 066, O 079
Huang, K. 1 P 060
Huang, P. 2 P 101
Huang, X. 4 P 245
Huber, A. O 127
Hudec, L. O 051
Hudoba, A. 4 P 259
Hue, C. 3 P 191
Huebl, A. O 017
Hugenschmidt, C. 4 P 235
Hughes, J. 2 P 103, O 131
Huijsmans, G. O 008
Humbird, K.D. O 060

Hume, E. 2 P 077, O 050
 Humphries, O. O 005
 Huslage, P. 4 P 235
 Hussain, M. 3 P 147
 Hwang, J. 1 P 049, 4 P 250

I

I. Pokol, G. 1 P 064, 3 P 200
 Iaccarino, M. O 013
 Iaquina, S. O 062
 Ibrahim, M.S.A.A. 2 P 082
 Ichiguchi, K. 3 P 197
 Ida, K. 4 P 240, O 169
 Idei, H. 4 P 274
 Idouakass, M. O 117
 Igochine, V. O 160
 Illerhaus, J. 3 P 208
 Imada, K. O 128, O 131
 Imříšek, M. 1 P 061, 4 P 272
 Inagaki, S. 4 P 240
 Inigo Gamiz, L. 1 P 006
 Innocente, P. O 052
 Innocenti, M.E. 1 P 010, 2 P 082
 Ioan Hojbota, C. O 125
 Ioannis, F. O 157
 Ionescu, S. O 016
 Irimiciuc, S. O 022
 Isayama, A. 2 P 122
 Isernia, N. 1 P 061
 Ishida, Y. 4 P 274
 Ishizawa, A. 1 P 041
 Ivan, K. 3 P 205
 Ivanoff, A. O 046
 Izumi, N. O 062

J

Jachmich, S. 1 P 036, O 079, O 163
 Jadeja, K. 3 P 207
 Jäger, Z. O 159
 Jakubowski, M. 1 P 054, 1 P 057, 3 P 203,
 3 P 215, 4 P 252, 4 P 254, O 057
 Jalalvand, A. 3 P 208, 3 P 213
 Jang, J. 1 P 025, 2 P 108, 4 P 250, 4 P 302
 Janky, F. 3 P 176
 Jansen van Vuuren, A. 1 P 043, 3 P 201
 Jaouen, S. 2 P 071
 Jaroš, D. 1 P 002
 Järvinen, A. 2 P 062, 2 P 132,
 2 P 140, 4 P 237, O 152
 Jasiński, M. O 021
 Jaulmes, F. 2 P 113, 4 P 272
 Jean-François, A. 3 P 179
 Jean-Luc, D. 3 P 179

Jeanquartier, F. 3 P 192
 Jelínek, Š. O 051, 2 P 077
 Jena, P. 4 P 294
 Jenko, F. O 006
 Jennings, C. O 132
 Jeon, Y. 2 P 136
 Jepson, J. 1 P 067
 Jepu, I. 2 P 114
 JET Contributors. 3 P 194
 Jiang, X. 4 P 271
 Jirasek, V. O 042
 Jirka, M. O 038
 Jitsuk, P. 2 P 134
 John, C. O 157
 Johnson, C. 3 P 219, 4 P 260, 4 P 300
 Jonsson, T. 4 P 236, O 033
 Jordan, D. 2 P 062, 2 P 140, 4 P 237
 Joshi, H.C. 3 P 144, O 094
 Joshi, N. 2 P 089
 Joung, M. 2 P 108
 Jovanović, O. O 043
 Juan, F.R.-R. 3 P 200
 Juha, L. 2 P 077, 4 P 227, O 051, O 155
 Juhn, J.W. 2 P 108, 2 P 136
 Julien, Z. 3 P 152
 Jung, G. 1 P 016
 Juno, J. O 095
 Juras, V. O 051

K

Kabirov-Leontieva, D. 1 P 061
 Kalis, J. O 105
 Kallenbach, A. 3 P 183
 Kallmeyer, J.P. 3 P 167
 Kalvala, R. O 088
 Kamio, S. O 117
 Kanstein, C. O 050
 Kantarelou, V. O 089
 Kappatou, A. O 101, O 126
 Karácsonyi, M. 3 P 208, 3 P 213
 Karbstein, F. O 121
 Karnok, M. O 159
 Kasahara, H. O 117
 Kasuya, N. 2 P 094
 Kaye, S. 4 P 267
 Kazakov, Y. 3 P 167
 Kazuo, T. O 016
 Keeling, D. O 101
 Kembleton, R. 3 P 161, 3 P 221
 Kennedy, D. 2 P 098
 Keppens, R. O 144
 Kevin, O. O 009
 Khabanov, F. O 008
 Khaghani, D. O 135

Khairutdinov, E. 3 P 172, 3 P 182, 4 P 278,
 4 P 292
 Khan, S.A. 4 P 269
 Kharitonov, I. 3 P 172, 4 P 278
 Khieu, S. 2 P 072
 Khomenko, E. O 171
 Killer, C. 1 P 057, 3 P 216, 4 P 252, O 150
 Kim, C.M. O 125
 Kim, D.Y. O 125
 Kim, H. 1 P 020, 1 P 024, 1 P 025, 1 P 026,
 1 P 031, 1 P 049, 2 P 136, 4 P 295
 Kim, H.T. O 125
 Kim, J. 1 P 025, 1 P 026, 1 P 031, 1 P 067,
 2 P 108, 4 P 295
 Kim, K.T. O 125
 Kim, K.Y. O 125
 Kim, M. 1 P 067, 2 P 136
 Kim, S. 4 P 255, O 033
 Kim, Y. 1 P 025, 1 P 026, 1 P 031, 2 P 108,
 4 P 295
 King, B. O 121
 King, D.B. 1 P 048, O 101
 Kirjasuo, A. 1 P 043, 2 P 099
 Kirov, K. 2 P 124, 4 P 273, 4 P 275
 Kirschner, A. O 064
 Kit, A. 2 P 062, 2 P 132, 2 P 140, 4 P 237, O 152
 Kleiber, R. O 165, O 028
 Klein, K.G. 2 P 082
 Klimo, O. O 049, O 124
 Klinger, T. 4 P 304
 Knappek, C. 2 P 086
 Knauer, J. 3 P 164, 4 P 298
 Knieps, A. 1 P 057, 2 P 109, 2 P 133, 4 P 254
 Knight, P. 4 P 255
 Ko, J. 1 P 067
 Ko, W. 2 P 136
 Kobayashi, T. 4 P 240
 Kocan, M. 4 P 294
 Kochan, M. O 032
 Köchl, F. O 036
 Kocsis, G. 2 P 113, 3 P 203, 3 P 220, O 036
 Koechl, F. 4 P 251, 4 P 255, O 011, O 033
 Koenig, M. O 134
 Koester, P. 2 P 077
 Köhn-Seemann, A. 4 P 270, 4 P 280
 Kolotkov, D. O 168
 Kominis, Y. 3 P 185
 Komorowska, G. 4 P 249
 Kong, M. 1 P 068, O 079
 Könies, A. O 028, O 165
 Kononenko, O. 3 P 228
 Kononov, A. O 132
 Konopka, U. 2 P 086
 Kool, B. O 055
 Kopański, M. 3 P 209

Korkulu, Z.	O 159	Kur, E.	O 076	Lee, Y.	1 P 067, O 164
Kornejew, P.	1 P 057	Kurki-Suonio, T.	4 P 262	Lehe, R.	O 017
Korovin, V.	2 P 110	Kurzan, B.	2 P 131	Lelièvre, R.	O 113
Korsholm, S.B.	1 P 032	Kuti, I.	O 159	Lemoine, N.	1 P 023
Korving, S.	2 P 112, 4 P 251	Kwak, J.	2 P 108	Lemos, N.	O 154
Kos, D.	O 127			Lengyel, F.	1 P 064
Köster, P.	O 050	L		Lennholm, M.	4 P 273
Kotaro, Y.	1 P 028	La Bombard, B.	4 P 256	Leonardi, O.	O 141
Kotov, V.	3 P 210	La Cognata, M.	O 155	Leoni, C.	1 P 048, 4 P 238
Koukalova, K.	3 P 184	La Matina, M.	3 P 199, O 108, O 129	Leonov, S.A.	1 P 017
Koukoutsis, E.	1 P 006, 4 P 233	Labit, B.	1 P 043, 4 P 258, 4 P 284, O 056, O 107, O 108	Lerche, E.	3 P 162, O 101, O 107
Kousek, J.	3 P 181	Lachhvani, L.	3 P 158	Lesur, M.	O 098
Kovalev, A.	2 P 126	Lackner, K.	O 160	Levine, E.Y.	O 084
Kovalova, Z.	O 042	Lafay, A.	O 131	Li, F.	O 014
Kovtun, Y.	1 P 017, 2 P 110, 3 P 167, 4 P 254	Laffite, S.	O 058, O 059	Li, Y.	2 P 142
Kozachok, O.S.	O 118	Lafon, M.	O 058, O 059	Liang, Y.	2 P 112, 2 P 133, 4 P 245, 4 P 271
Kozlov, I.	3 P 182	Lahaye, R.	O 084	Liang, Y.	1 P 057, 2 P 109
Kozłowski, P.	O 135	Lampert, M.	2 P 137	Liao, L.	2 P 119
Krafft, F.	4 P 298	Lancia, L.	O 039, O 040, O 076	Liberatore, S.	O 058
Kragh Nielsen, S.	O 148	Lancok, J.	O 022	Lieberman, A.	O 084
Krajcz, I.	O 159	Landen, O.	O 060, O 062	Lin, Z.	3 P 222
Krämer-Flecken, A.	3 P 216	Lang, P.	3 P 211	Lindl, H.	3 P 204
Krasa, J.	4 P 227, O 051, O 155	Langenberg, A.	2 P 093, 3 P 164, 3 P 219, 4 P 246, 4 P 300	Lipschultz, B.	1 P 055
Krasiuk, O.	2 P 110	Langlois, J.	3 P 154	Liska, R.	O 051
Krebs, I.	O 160	Lanti, E.	3 P 186	Litherland-Smith, E.	4 P 296
Kremeyer, T.	O 057	Lantuéjoul, I.	O 087	Litovko, I.	O 092
Kreter, A.	3 P 210	Laqua, H.	3 P 164, 3 P 174, 4 P 254	Liu, B.	4 P 245, 4 P 263
Krier, L.	3 P 164	Larreur, H.	2 P 077	Liu, C.	2 P 091, 2 P 101
Kriete, D.M.	1 P 021, 1 P 051, 3 P 193, 4 P 252, O 057	Laso Garcia, A.	O 005	Liu, D.	2 P 119
Kripner, L.	4 P 272	Lattuada, D.	O 155	Liu, S.	O 106
Kritcher, A.	O 062	Lauber, P.	1 P 038, 2 P 116, O 028, O 116	Liu, W.	4 P 271
Kritcher, A.L.	O 060	Lauriola, M.	O 140	Liu, Y.	2 P 099
Kroupp, E.	O 084, O 088	Lawson, K.	1 P 048, 4 P 296	Loarte, A.	1 P 065, 4 P 251
Krupka, A.	2 P 083	Lazerson, S.A.	2 P 118, 3 P 161, 3 P 175, 3 P 221, 4 P 262	Lobko, L.	3 P 184
Krupka, M.	2 P 077, 2 P 078, 4 P 227, O 051	Lazzaro, E.	4 P 234	Lo-Cascio, G.	O 098
Krûs, M.	2 P 077, 3 P 148, 4 P 227, 2 P 078	Le Bars, G.	2 P 127	Loch, S.	1 P 051
Krychowiak, M.	1 P 057, 3 P 164	Le Deroff, L.	2 P 072	Loiseau, P.	2 P 071, O 049
Kryjak, M.	2 P 103	Le Pape, S.	O 059	Loizu, J.	2 P 127, 3 P 186, O 065
Ku, S.	O 008	Lebedev, S.	O 111	Lomanowski, B.	4 P 288, O 127
Kuang, A.	4 P 256	Leblanc, A.	O 017	Lomas, P.J.	O 107
Kubelka, R.	3 P 184	Lecherbourg, L.	O 134	Lombardo, J.	3 P 168, O 101
Kudashev, I.	4 P 253	Lee, H.	1 P 049, 1 P 067, 4 P 250	Longman, A.	O 154
Kudlacek, O.	3 P 211	Lee, H.H.	2 P 108	Lonigro, N.	1 P 055
Kulik, M.	4 P 303	Lee, H.J.	O 135	López Rodriguez, L.D.	3 P 160, 3 P 167
Kulla, D.	3 P 224, 4 P 262	Lee, J.	1 P 025, 1 P 025, 1 P 031, 1 P 035, 2 P 108, 3 P 146, 4 P 255, 4 P 295	Lopez, N.	3 P 173, 4 P 277
Kulyk, Y.	4 P 254	Lee, J.H.	1 P 026	López-Miranda, B.	3 P 212, 3 P 218
Kumar R, R.	3 P 144	Lee, J.W.	1 P 020	Lorenzini, R.	3 P 168, O 101
Kumar Sharma, V.	3 P 156	Lee, K.	1 P 050, O 056	Losada, J.M.	4 P 256
Kumar, A.	3 P 207	Lee, S.	1 P 035	Losada, U.	1 P 051
Kumar, U.	O 108	Lee, S.K.	O 125	Loureiro, N.	O 099, O 102
Kumawat, A.	3 P 207			Lovell, J.	2 P 135, O 055
Kumpulainen, H.	O 064, O 080			Lu, Z.	1 P 038
Kunimoto, Y.	4 P 253			Luca, C.	2 P 085
Kuprin, O.	1 P 017			Luda di Cortemiglia, T.	4 P 244
				Luda, T.	O 131

Ludovica, D.G. O 009
 Lukes, P. O 042
 Lunt, T. 1 P 059
 Luo, Y. 2 P 109, 2 P 133
 Lvovskiy, A. 1 P 036

M

Ma, T. O 154
 Maaziz, N. 3 P 223
 MacGowan, B. O 062
 Macha, P. 3 P 181
 Maciej, K. 2 P 109
 MacLaren, S. 2 P 069
 MacLeod, A. O 121
 Madurkay, M. 3 P 184
 Maero, G. 3 P 159
 Maeyama, S. 1 P 040, 4 P 240
 Maffini, A. O 013, O 089
 Maget, P. 3 P 165, 4 P 257, O 035
 Maggi, F. O 140
 Magin, T. 1 P 014
 Mahieu, B. O 087
 Maiden, F. 3 P 177, O 082
 Maier, D. 2 P 086
 Mailloux, J. O 101
 Maj, O. 3 P 163
 Makarov, S. 3 P 223
 Makhlai, V. 4 P 303
 Makhov, M. 2 P 110
 Makita, M. O 135
 Malaca, B. O 012
 Malakhov, M. O 124
 Malec, Š. 3 P 184
 Malka, G. 2 P 077
 Malka, V. O 084, O 085, O 088
 Mallimaci, C. O 013
 Manas, P. 3 P 165, 4 P 253, 4 P 257,
 O 035, O 146
 Mancelli, D. 2 P 077
 Mancini, D. O 053
 Mancini, R. 1 P 001, O 133
 Mandal, D. O 098
 Manna, C. O 045
 Mantica, P. 2 P 100, 3 P 168, O 052, O 104
 Mantsinen, M.J. 3 P 169
 Manuel, S.D. 3 P 205
 Manyer, P. 3 P 169
 Manz, P. O 105
 Manzini, D. O 167
 Maragkoudakis, E. O 066
 Marandet, Y. O 149
 Maraschek, M. 3 P 183, O 083
 Marcer, G. 2 P 126
 Marchioni, S. 4 P 272

Marchiori, G. 4 P 268
 Marchuk, O. 3 P 210
 Marcowith, A. O 026
 Marcucci, M.F. O 004
 Mareš, J. 1 P 003
 Marešová, E. O 022
 Margarone, D. O 156, O 089, O 155
 Marholt, R. 4 P 277
 Mariani, A. O 104
 Mariano, G. 2 P 126
 Maricle, S. O 154
 Marin, M. O 101
 Marini, S. 2 P 079, 2 P 080
 Maris, D. 2 P 112
 Mariscal, D. O 154
 Markevičius, T. O 137
 Marković, A. O 043
 Markovic, T. 3 P 181
 Marot, L. 2 P 087
 Marques, J. O 040
 Marrow, K. O 111
 Marsden, S. 4 P 275
 Martin, P. 3 P 189, O 026, O 052
 Martin, V. 4 P 294
 Martinez Gomez, D. O 171
 Martinez, B. 1 P 009
 Martinez-Fernandez, J. O 118
 Martinović, M.M. 2 P 082
 Martín-Solís, J.R. 1 P 065
 Martseniuk, Y. 2 P 110, 4 P 254
 Mascali, D. 2 P 130, 3 P 166, O 045, O 141
 Masillo, S. 4 P 284
 Maslov, M. O 101
 Masse, L. 2 P 072, O 134
 Masson-Laborde, P. 2 P 071, 2 P 077, O 049
 MAST Team. 4 P 299
 Mastrogirolamo, A. 4 P 258
 Matsunaga, G. 2 P 122
 Matsuoka, S. O 068
 Matthew, T. 1 P 067
 Matthieu, P. O 009
 Matveeva, E. 1 P 061
 Maurer, D. 2 P 093, 3 P 193, 4 P 252, 4 P 300
 Mauro, G.S. O 141, O 045, 3 P 166
 Maviglia, F. 3 P 170
 Maznichenko, S. 2 P 110
 Mazon, D. 2 P 033, 4 P 249, 4 P 294
 Mazzucconi, D. O 089
 McCarthy, K.J. 3 P 212, 3 P 220,
 3 P 218, O 036, O 118
 McClements, K. 4 P 273
 McDermott, R. 1 P 043, 2 P 124, 4 P 239, O 034,
 O 083, O 126
 McGibbon, B. O 149
 McIlvenny, A. O 113

McKay, K. 4 P 239, 2 P 104
 McKee, G. O 115
 McLean, A. 1 P 051
 McLean, A.G. O 054
 McMillan, B.F. O 011, O 116
 McNamara, S. 3 P 176
 McNeely, P. 3 P 175
 Medina Roque, D. 1 P 021, 2 P 093, 3 P 220
 Medina, F. 3 P 218
 Meigs, A.G. O 127
 Mele, A. O 081
 Melzer, A. 2 P 086
 Mencke, J. 2 P 095
 Mendes, S.V. 2 P 118
 Mendonça, D. 3 P 225
 Meng, G. 2 P 116
 Menkovski, V. O 152
 Menmuir, S. 1 P 048, 2 P 124, 4 P 288
 Merle, A. O 081
 Merlini, S. O 111
 Merlo, G. O 006
 Merten, L. O 070
 Meshkani, S. 3 P 181
 Meyer, E. 2 P 087
 Meyer, H. 4 P 273, 4 P 275
 Michael, C. 2 P 099, 2 P 137
 Michael, T. O 157
 Michel, P. O 076
 Michishio, K. O 090
 Mier, J.Á. 1 P 065
 Miklos, V. 4 P 282
 Militello Asp, E. O 033
 Miller, A. O 131
 Miller, K. O 014
 Milovich, J. O 062
 Miotk, R. O 021
 Mirabella, S. O 155
 Mirani, F. O 013, O 089
 Mireille, S. 3 P 205
 Miron, G. 3 P 194
 Mirzaie, M. O 125
 Mishchenko, A. 1 P 038, 1 P 041, 2 P 090,
 2 P 116, O 028, O 116, O 165
 Mishchenko, M. O 005
 Mishra, B. 2 P 130, 3 P 166, O 141
 Misra, A.P. 1 P 011
 Mitchell, N. 3 P 221
 Mitteau, R. 4 P 257
 Miyamoto, R. 2 P 094
 Modic, M. 1 P 019
 Mohacsi, Á. O 159
 Mohammed, A. 4 P 298, O 036
 Mohr, D. 2 P 086
 Moiraf, D. O 055
 Moiseenko, V. 2 P 110, 3 P 167, 4 P 254

Molisani, S. 1 P 027
 Molnár, B. 3 P 208, 4 P 264, 3 P 213
 Moloney, P. O 133
 Mombelli, F. 4 P 258
 Momo, B. 4 P 248
 Mongaretto, G. 1 P 018
 Moody, J. 2 P 069
 Morace, A. O 051
 Morales, J. 3 P 165, O 055, O 146
 Morales, R.B. O 127
 Mordijk, S. 2 P 135
 Moreau, P. 4 P 294, O 035
 Morel, E. 3 P 228
 Morel, P. 1 P 038
 Morent, R. O 137
 Moresco, M. 4 P 287
 Morgan, R. 1 P 050, O 056
 Mori, W. O 014
 Morris, J. 3 P 188, 3 P 196, 4 P 273
 Morten, L. 2 P 124
 Moseev, D. O 148
 Moulton, D. 2 P 104, 4 P 259
 Mukherjee, A. 3 P 157
 Mundy, T. O 111
 Munoz, M. 2 P 098
 Munzar, V. 2 P 078
 Murakami, S. 4 P 274
 Murari, A. 2 P 033, 4 P 301
 Murugesan, V. 1 P 022, 2 P 128, 4 P 291
 Mutinelli, V. 2 P 129
 Myatra, O. 2 P 137, 4 P 259, O 055
 Myatt, J. 2 P 077
 Mykytchuk, D. 1 P 056, 2 P 106

N

Na, Y. 1 P 029, 2 P 108, O 164
 Nagashima, Y. 4 P 240
 Nagler, B. O 135
 Nagy, D. 4 P 264
 Nair, V. 4 P 304
 Nakamura, R. O 004
 Nakamura, T. 1 P 007
 Nakano, T. 2 P 108, 4 P 261
 Nakata, M. 1 P 047, 4 P 240, O 068
 Nakatsutsumi, M. O 005
 Nakeva, Y. 2 P 139
 Nalbaru, L. 3 P 149
 Nam, C.H. O 125
 Nam, G. 1 P 035
 Nam, Y.U. 2 P 108, 2 P 136
 Napoli, F. 3 P 201
 Nardon, É. 1 P 068, 2 P 062, O 079, 1 P 066
 Narita, E. 1 P 040
 Narnhofer, M. 3 P 225

Naselli, E. 2 P 130
 Nastac, M. O 095
 Nasu, T. 4 P 240
 Naujoks, D. 1 P 021, 1 P 054, 3 P 164, 4 P 254
 Nava, M. O 140
 Navarro, M.X. O 064
 Naydenkova, D. 3 P 181
 Nektarios, P. O 157
 Nelson, A.O. O 008
 Neretti, G. 1 P 018
 Newton, S. 4 P 259
 Nicholls, C. O 130
 Nicolai, P. 2 P 077, O 061
 Nicolas, R. O 146
 Nicotera, G. O 039, O 040
 Nielsen, A.H. 3 P 208, 3 P 213
 Nielsen, S.K. 1 P 032, 3 P 173, 4 P 277
 Niemelä, A. 2 P 062, 2 P 140, 4 P 237
 Nikiforov, A. O 137
 Nilsen, R. 3 P 214
 Nishiura, M. 4 P 240
 Nishizawa, T. 1 P 028
 Nißl, S. 4 P 235, O 090
 Nocente, M. 2 P 126, O 101
 Noh, H. 1 P 029
 Nora, R.C. O 060
 Nosek, K. 3 P 181
 Nouailletas, R. O 035, O 146
 Novak, D. 3 P 184
 Novimir, P. 4 P 283
 Nuehrenberg, C. 3 P 216
 Nuga, H. 2 P 119
 Nührenberg, C. O 028
 Nuno, L. 3 P 152
 Nurgaliev, M. 3 P 172, 3 P 182, 4 P 278
 Nyström, H. 2 P 132, 2 P 141

O

O. Silva, L. O 096
 Oberth, N. 3 P 225
 Oblak, M. 3 P 225
 Odstrčil, T. O 126
 Ogawa, K. 2 P 119, O 117
 Oh, S. 1 P 016, 1 P 030, 4 P 250
 Olasz, S. 1 P 064
 Olde, C. 4 P 275
 Olenik, J. 1 P 019
 Oliva, D. O 045
 Oliver, J. O 114
 Ollus, P. 4 P 262
 O'Mullane, M. 4 P 296
 Onchi, T. 4 P 274
 Onderka, R. 3 P 184
 O'Neill, S. 1 P 010

Ong, J.F. O 016
 Ongena, J. 3 P 167
 Onjun, T. 2 P 119
 Oosterbeek, H. 4 P 291
 Ordyna, P. O 015
 Orecchia, D. O 013
 Orlandi, L. 2 P 129
 Orlov, D. 3 P 182, 4 P 278
 Osawa, R. 4 P 259
 Osvay, K. O 159
 Otte, M. 4 P 264
 Ou, K. O 076
 Oudin, A. O 076
 Ozturk, E. 4 P 299

P

Pablant, N. 2 P 093, 3 P 219, 4 P 246, 4 P 300
 Pacella, D. 4 P 286
 Paenthong, W. 2 P 119
 Pahari, S. 3 P 158
 Pak, A. O 060
 Palade, D. 2 P 097, 4 P 241
 Palastro, J. O 014, 1 P 008
 Palermo, F. O 011
 Palodhi, L. O 073
 Pamela, S. 4 P 299
 Pan, O. 4 P 251
 Panadero, N. 2 P 113, 3 P 218, 3 P 220, O 036
 Pandey, A. O 057
 Pankin, A. 4 P 276
 Papagiannis, P. 4 P 233
 Pappalardo, A.D. O 045
 Paraskevopoulos, C. 3 P 201
 Parisuaña, C. O 135
 Park, G. 1 P 025, 1 P 026, 1 P 031, 2 P 136, 4 P 295
 Park, J. 1 P 035, O 164
 Parra, F. O 007, O 063
 Pârvu, M. O 085
 Pasch, E. 4 P 246, 4 P 298, 4 P 300
 Pasley, J. 2 P 076
 Passoni, M. 4 P 258, O 013, O 089, O 140
 Pastore, F. O 056
 Patel, B. 2 P 137, O 032
 Patel, M. 3 P 156
 Pathak, V.B. O 125
 Pau, A. 3 P 189
 Paulo, A. 3 P 205
 Pautasso, G. 1 P 064
 Pawelec, E. 4 P 260
 Pawlat, J. O 075
 Paz-Soldan, C. 1 P 036, O 008
 Pearce, R. 4 P 294
 Pedersen, A.C. 3 P 173

Pedrini, M.	O 056	Puač, N.	O 043	Reimold, F. ...	2 P 093, 3 P 164, 3 P 223, 4 P 252, 4 P 300, O 010, O 057
Peers, P.	4 P 299	Pucella, G.	1 P 048	Reinhart, M.	3 P 210
Pelka, A.	O 005	Puchmayr, J.	O 162	Reinoso, T.	3 P 184
Pelkner, M.	2 P 096	Puel, L.	1 P 066	Reiter, D.	2 P 109, 2 P 114, O 054
Pepato, A.	O 141	Pueschel, M.j.	2 P 134	Ren, J.	1 P 041
Perek, A.	1 P 050, 2 P 106, O 056	Puetterich, T.	2 P 124	Ren, P.	1 P 057
Perez Von Thun, C.	O 127	Pukhov, A.	O 158	Renner, O.	2 P 077, 2 P 078, O 051
Pérez-Callejo, G. ...	1 P 001, O 061, O 133, O 135	Pütterich, T.	2 P 093, O 034	Retino, A.	O 004
Perez-Ramirez, V.	O 076	Qin, X.	O 008	Reux, C.	1 P 036
Peri, B.	2 P 130	Qinghu, Y.	2 P 111	Reveille, T.	O 098
Perseo, V.	3 P 203, 4 P 252	Qiu, Z.	2 P 116	Reville, B.	O 072
Petersen, K.	1 P 032	Quadri, V.	O 149	Reyner-Viñolas, A.	4 P 262
Peterson, B.	1 P 030	Quantrill, M.	3 P 196	Ribeyre, X.	O 027
Petringa, G.	O 155			Ribotte, L.	O 087
Petrov, Y.	4 P 303	R		Riccardi, C.	2 P 088, 2 P 089
Peysson, Y.	3 P 153	R M, A.K.	3 P 150	Ricci, D.	4 P 234
Philippe, G.	3 P 205	R S, A.	3 P 151	Ricci, P.	2 P 095, O 053
Picciotto, A.	O 155	R, R.K.	O 094	Riconda, C.	O 039, O 040, O 076
Pidatella, A.	2 P 130, 3 P 166, O 045, O 141	Radovanovic, L.	2 P 142	Ridgers, C.	1 P 005, 2 P 103
Piehler, E.	4 P 298	Raeth, M.	1 P 039, 1 P 042	Riemann, J.	O 028, O 165
Pierce, J.	O 014	Ragazzi, F.	1 P 018	Rienacker, S.	O 108
Pierotti, G.	1 P 018	Ragona, R.	3 P 160, 3 P 201, O 148	Rigamonti, D.	O 101
Pigatto, L.	2 P 099	Rahbarnia, K. ...	O 165, 2 P 118, 2 P 123, 3 P 216, 4 P 300, O 150	Rigoni, A.	2 P 129
Pinches, S.	4 P 251, 4 P 255, O 033	Raitses, Y.	O 020	Rinderknecht, H.	O 121
Pira, C.	O 141	Raj, H.	3 P 207	Riquezes, J.	1 P 067
Piron, C.	3 P 189, O 129	Rajesh, H.	O 076	Riquier, R.	O 058
Piron, L.	2 P 124, 2 P 129, 3 P 189	Ralph, J.E.	O 060	Rivals, N.	1 P 023, 4 P 266, O 055, O 149
Pisarczyk, T.	2 P 078, 4 P 227, O 051	Ram, A.	4 P 233	Rizzato, F.	2 P 079, 2 P 080
Pitts, R.A.	4 P 251, 4 P 257, O 064, O 163	Ramaiya, N.	3 P 207	Roach, C.	2 P 098, 4 P 273, O 011
Plaum, B.	3 P 174	Ramakrishna, B.	3 P 150, 3 P 151	Robert, E.	O 077
Plotnikov, I.	O 026	Ramasamy, R.	O 160	Robert-Dautun, G.	O 017
Plunk, G.	2 P 105	Ramisch, M.	1 P 044, 4 P 280	Rode, S.	O 064
Podesta, M.	2 P 127	Ramsey, D.	1 P 008	Rodríguez, E.	3 P 223
Pokol, G.	3 P 208, 3 P 213	Rashid, M.M.	2 P 089	Rodríguez-Fernandez, P.	2 P 100
Pokorny, M.	3 P 181	Rasmussen, J.	1 P 032, O 148	Rofman, B.	1 P 038, O 028
Pola, A.	O 089	Räb, L.	4 P 239	Romadanov, I.	O 020
Polei, N.S.	2 P 123, 3 P 174	Räth, M.	2 P 096	Romagnani, L.	O 040
Polevoi, A.	2 P 126	Rathouit, P.	2 P 072	Romane, H.	2 P 071
Poli, E.	1 P 041, 2 P 090, 3 P 163, O 028	Ratynskaia, S.	2 P 086, 4 P 265, O 003	Romano, F.	2 P 127, O 089
Poli, F.	2 P 125, 4 P 236, O 033	Rauschenberger, A.	2 P 142	Romazanov, J.	O 064
Pölöskei, P.	3 P 224, 4 P 246, O 010	Ravan, E.L.	O 089	Romba, T.	2 P 093, 3 P 224, 4 P 246, O 010, O 066
Pomârjanschi, L. M.	2 P 097, 4 P 241	Razzaq, J.	O 159	Romé, M.	3 P 159
Pons Villalonga, P.	O 118, O 165	Rebai, M.	2 P 126	Roméo, B.	O 009
Popoli, A.	1 P 018	Rebesan, P.	O 141	Ronchi, G.	1 P 051, O 054
Popovic, Ž.	1 P 051	Redl, A.	1 P 059	Rosenthal, M.	3 P 225
Poradzinski, M.	O 101	Redshaw, C.	O 076	Rosinski, M.	O 051, O 155
Porcu, P.	2 P 120, O 161	Refy, D.I.	4 P 264	Rossi, R.	2 P 033, 4 P 301
Porkolab, M.	4 P 246, O 150	Regal-Mezin, X.	O 035	Rostami, Z.	3 P 181
Porth, O.	O 142	Reich, M.	2 P 125	Roth, I.	O 025
Poupouzas, M.	O 137	Reichle, R.	4 P 294	Roth, M.	O 050
Pouyez, M.	O 039, O 040	Reimerdes, H.	1 P 050, 1 P 056, 2 P 106, O 056, O 146	Rousseau, P.	3 P 228
Pozo, F.	2 P 098			Rousseaux, C.	O 061
Preston, T.	O 005			Rovere, E.	1 P 001, O 061, O 133
Prokofyev, I.	3 P 172				
Pshenov, A.	4 P 251				

Roy, D. 3 P 157
 Rubery, M.S. O 060
 Rubino, G. 3 P 168, 4 P 261, 4 P 268, O 151
 Rudakov, D. 1 P 051
 Rudolph, M. O 092
 Ruffini, F. 4 P 287
 Ruiz Gonzalez, S. 1 P 058
 Rusiniak, Z. 2 P 078, 4 P 227, O 051
 Russell, B. O 014
 Russo, F. O 141
 Russo, V. O 013
 Russman, F. 2 P 080
 Rust, N. 3 P 175
 Rutigliano, N. 2 P 033, 4 P 301
 Ruyer, C. 2 P 071, O 049
 Ryan, D. 2 P 099, 2 P 124,
 2 P 137, 3 P 189, O 032
 Ryan, P. 1 P 055

S

S, V. 3 P 156
 S. Duarte, A. 4 P 292
 Saarelma, S. 2 P 132, 2 P 140,
 4 P 273, O 128, O 131
 Sabbagh, S. 1 P 067
 Sackers, M. 3 P 210
 Saha, P.K. 3 P 157
 Sahraoui, F. O 167
 Saito, K. O 117
 Saitoh, H. O 090
 Sakawa, Y. O 110
 Salmi, A. 1 P 043, 2 P 099, O 034
 Salvia, C. 3 P 166
 Sama, J.N. 1 P 038
 Samulyak, R. O 079
 Sánchez, E. O 063
 Sanchis, L. 4 P 262
 Sandor, Z. 4 P 282
 Sangaroon, S. 2 P 119
 Sanpei, A. 1 P 028
 Santos, J.J. 1 P 001, O 061, O 133
 Särkimäki, K. 2 P 121, 4 P 262
 Sarkis, R. 1 P 044
 Sartori, E. 4 P 285
 Satake, S. 4 P 240
 Sato, M. 3 P 197
 Saura, R. 3 P 165
 Sauter, O. 1 P 043, 1 P 050, 2 P 125, O 056,
 O 081, O 104, O 108
 Savoye-Peysson, Y. 3 P 163, 3 P 165
 Scandurra, A. O 155
 Scannell, R. 2 P 107, 2 P 137
 Scarivaglione, L. 4 P 243
 Schaumans, C. 3 P 198

Schekochihin, A. O 095
 Schellpfeffer, J. 2 P 142
 Schennach, R. 3 P 225
 Schillaci, F. O 089
 Schilling, J. 3 P 225
 Schlisio, G. 4 P 254, O 057
 Schlossberg, D.J. O 060
 Schmidt, G. 3 P 164
 Schmidt, J. 4 P 237
 Schmitz, L. O 008, O 115
 Schneider, M. 2 P 125, 3 P 162, 3 P 165
 Schneider, P. 1 P 032, 4 P 244
 Schramm, R. O 083
 Schreiber, J. O 121
 Schröder, T. 4 P 300, 4 P 304
 Schuler, T. 4 P 235
 Schulze, F. O 072
 Schuster, E. 4 P 263
 Schütt, S. 2 P 086
 Schwander, F. 4 P 253
 Schwarz, N. O 163
 Schween, N. O 072
 Scionti, J. 4 P 234
 Sciortino, F. 2 P 093, O 126
 Sciscio, M. O 155
 Scotti, F. O 054
 Scotti, L. 1 P 059
 Scotto d'Abusco, M. 4 P 253
 Sebastien, H. 3 P 205
 Sedmidubský, V. 3 P 181
 Seebarruth, T. O 112
 Seidl, J. 1 P 053, 3 P 181
 Seki, R. 2 P 119, 3 P 197, O 117
 Seki, T. O 117
 Sellmair, G. 3 P 211
 Senstius, M. 4 P 277, O 148
 Senstius, M.G. 3 P 173
 Seo, D. 1 P 025, 4 P 250, 4 P 302
 Seo, G. 1 P 035
 Seon, C. 4 P 250
 Sepman, A. O 046
 Sepulveda, V. 3 P 184
 Sergienko, G. 3 P 210, O 127
 Sergio, S. 4 P 243
 Serre, E. 4 P 253, 4 P 266, O 149
 Sertoli, M. 4 P 290
 Shapoval, A. 1 P 017, 2 P 110
 Sharma, N. 3 P 157
 Sharma, R. 1 P 034
 Sheehan, F. 1 P 067
 Sheffield, F. O 105
 Sheikh, U. 1 P 036, 3 P 201,
 3 P 206, 4 P 284, O 079
 Shen, H. 4 P 278
 Shevchenko, V. O 082, 3 P 173

Shevchuk, P. 4 P 303
 Shi, Y. 4 P 245, 4 P 271
 Shibata, Y. 2 P 122
 Shiokawa, K. O 169
 Shirin T, A. O 072
 Shvalya, V. 1 P 019
 Siccino, M. 2 P 125, O 101
 Siddiki, M. 4 P 252
 Sieglin, B. 2 P 124, 3 P 211, O 153
 Silburn, S. 1 P 055, 2 P 062,
 2 P 107, 3 P 189, O 127
 Silva de Freitas, C. O 061, O 133
 Silva, C. O 107
 Silva, L.O. O 086
 Silva, M. 3 P 201
 Silva, T. O 012, O 086, O 138
 Silvagni, D. O 127
 Simonovsky, M. 1 P 020
 Simons, L. 3 P 201, 3 P 206, O 056
 Singapulli, D. 2 P 077
 Singh, D. O 076
 Singh, K. 3 P 207
 Singh, R. O 008
 Singh, S. 2 P 077, 2 P 078, 4 P 227, O 051, O 155
 Singh, T. 2 P 081
 Singha, K. 3 P 158
 Sipilä, S. 3 P 162
 Sissonen, J. 2 P 121
 Škoro, N. O 043
 Slaby, C. O 165
 Sladek, P. 1 P 020
 Sladkov, A. O 113
 Smartsev, S. O 084
 Smets, R. O 112
 Smidl, V. 1 P 053
 Smiet, C. 2 P 105, 3 P 186, O 065
 Smith, H. 2 P 093, O 066
 Smolyakov, A. O 020
 Smoniewski, J. 4 P 235
 Snicker, A. 2 P 121
 Soba, A. 3 P 169
 Sobota, A. O 137
 Solano, E.R. O 107
 Soldat, S. 1 P 053
 Somosköi, T. O 159
 Song, Y. O 137
 Sorokin, D. 4 P 278
 Sousa, T. 2 P 087
 Sow, K. O 121
 Sozzi, C. 4 P 261
 Spagnolo, S. 4 P 248
 Speirs, D. 3 P 177
 Spizzo, G. 2 P 120, 2 P 129, O 161
 Sripati Venkata, R. O 005
 Srivastav, P. 3 P 156

Stack Formanek, M. 1 P 008
 Stagni, A. O 129
 Stancar, Z. 4 P 255, 4 P 275
 Stanek, L. O 132
 Stange, T. 1 P 054, 2 P 123,
 3 P 164, 3 P 174, 4 P 254
 Stefanoska, B. 1 P 061
 Steinbrunner, P. 4 P 235
 Steinwender, E. 3 P 225
 Stenger, L. O 053
 Stenson, E. 3 P 155, 4 P 235, O 090
 Stepanov, I. 3 P 167
 Stephens, C. 4 P 237
 Stern, M. 4 P 298
 Stewart, I. 1 P 036
 Stewart, S. O 008
 Stilianos, P. O 157
 Stober, J. O 148
 Stoneking, M. 3 P 155, 4 P 235
 Strand, P. 4 P 236, O 033
 Stratton, B. 4 P 283
 Stroth, U. 3 P 225, O 034, O 105, O 126
 Strozzi, D. 2 P 069
 Strucka, J. O 111
 Strumberger, E. O 162
 Stuhl, L. O 159
 Suarez Lopez, G. 4 P 255, O 033
 Suarez, J. O 045
 Subbotin, G. 3 P 172, 3 P 182, 4 P 278
 Sun, H. 1 P 043, 2 P 098
 Sung, H. 1 P 016
 Sung, J.H. O 125
 SureshKumar, S. O 149
 Surko, C.M. 4 P 235
 Suttle, L. O 111
 Suttrop, W. 2 P 124, O 126
 Svetnicka, P. 3 P 184
 Svoboda, J. 1 P 023
 Svoboda, V. 3 P 181, 3 P 184
 Sweeney, R. O 083
 Szepesi, T. 2 P 113, 3 P 203, 3 P 220, O 036
 Szűcs, M. 2 P 112

T

T.T. 3 P 201
 Taccogna, F. O 151
 Takemura, Y. 2 P 122, 3 P 197
 Tala, T. 1 P 043, 2 P 099, O 034
 Tamain, P. 4 P 266, O 149
 Tamburrino, A. 4 P 286
 Tamura, N. 2 P 093, 3 P 164,
 3 P 220, 4 P 300, O 036
 Tan, M. 4 P 245
 Tanaka, K. 4 P 240

Tang, W. O 079
 Tanna, R. 3 P 207
 Tarabova, B. O 042
 Tardini, G. 4 P 239, 4 P 244, O 034, O 152
 Tardocchi, M. 2 P 126
 Tassin, V. O 058
 Tata, S. O 084
 Tatarakis, M. 2 P 077
 Taylor, D. 4 P 255
 Tazes, G. O 157
 Tchorz, P. O 155
 TCV Team. O 081, O 148
 Team, A.U. O 126
 Team, C. 1 P 061
 Team, D. O 054
 Team, E.T.E. 2 P 104, O 126
 Team, M.U. 2 P 104
 Team, W. O 151
 Tenaglia, A. O 081
 Terranova, D. 2 P 120, O 161
 Terry, J. 4 P 256
 Terzolo, L. 1 P 035
 Thaur, C. 3 P 228, O 084
 Theiler, C. 1 P 050, 1 P 056, 3 P 206, O 053,
 O 055, O 056, O 129
 Theobald, W. O 050
 Theodorsen, A. 3 P 214
 Thienpondt, H. O 007, O 063
 Tholerus, E. 4 P 259, 4 P 275
 Thoma, M. 2 P 086
 Thomas, A. O 014
 Thomas, B. O 127
 Thomas, C. O 015
 Thomas, H. 2 P 086
 Thomas, J. 3 P 144, 3 P 156, O 094
 Thomas, K. O 015
 Thomas, P. 3 P 176
 Thomas, S. 2 P 135, 2 P 137, 3 P 200, O 128
 Thome, K. O 008
 Thomsen, H. 2 P 118, 2 P 123,
 3 P 167, 3 P 216, O 150, O 165
 Tichit, Q. O 151
 Ticos, C. 3 P 149
 Tikhonchuk, V. 2 P 071, O 049, O 051
 Tillinghast, G. 1 P 067
 Tiwari, S.K. O 093
 TJ-II Team. O 036, 3 P 220
 Todo, Y. 3 P 197, O 117
 Tokuda, S. 1 P 028
 Tokuzawa, T. 4 P 240, O 117
 Told, D. O 105
 Tomarchio, V. 4 P 261
 Tomasina, E. 2 P 099
 Tomassini, P. O 085, O 158
 Tomes, M. 1 P 053

Tommasini, R. O 062
 Toncian, T. O 005
 Tonel, A. 2 P 124
 Tonello, E. 1 P 050, 2 P 106, 4 P 258, O 056
 Tookey, A. 3 P 189, O 127
 Torrisi, G. 3 P 166, O 141
 Tóth, L. O 159
 Tóth, S. O 159
 Tovar, G. 4 P 280
 Trauchessec, V. 2 P 072
 Treutterer, W. 3 P 211
 Trieu, S. 4 P 298
 Trimino Mora, H. 4 P 304
 Tritthart, M. 3 P 225
 Trotta, D. O 029
 Truong, D.D. O 054
 Tsampas, M. O 138
 Tsikouras, A. 3 P 164
 Tsironis, C. 4 P 233
 Tsui, C.K. O 054
 Tu, X. O 103
 Tubman, E. 1 P 013
 Tudisco, S. O 155
 Tunkl, M. 3 P 184
 Turi, J. 1 P 011
 Turner, M. O 030

U

Uccello, A. 4 P 234
 Uehara, K. 4 P 279
 Ugoletti, M. 3 P 199, O 129
 Ulrich, S. O 015
 Ur, C.A. O 158
 Uras, A. O 111
 Ursescu, D. O 085
 Uzdensky, D.A. O 143

V

v. Stechow, A. 2 P 123
 Vabek, J. O 038
 Vagkidis, C. 4 P 280
 Vahala, G. 4 P 233
 Valcarel, D. 4 P 273
 Valdetaro, L. 1 P 018
 Valdivia, M.P. O 135
 Valek, M. 3 P 184
 Valenzuela Villaseca, V. O 111
 Vallis, D. 4 P 233
 van de Sanden, R. O 138
 van der Meiden, H. 4 P 303
 Van Eester, D. 3 P 162
 Van Ham, L. 3 P 175
 Van Marle, A.J. O 026

Van Rossem, M. O 108, O 129
 Van Tol, D. 3 P 193
 Van Zeeland, M. O 115
 Vann, R. 3 P 177, 4 P 270, O 082
 Vannini, F. 1 P 064
 Vanovac, B. 2 P 100, 2 P 142, O 162
 Vanthieghem, A. O 002
 Varadarajan, N. 4 P 257, O 149
 Varela, J. O 118
 Varini, N. O 053
 Varje, J. 3 P 176
 Varmazyar, P. O 159
 Vasilios, D. O 157
 Vasquez, C. 3 P 184
 Vatavu, S. O 022
 Vauzour, B. O 087
 Vavassori, D. O 013
 Vavrik, M. 2 P 113, 3 P 203, 3 P 220, O 036
 Vay, J. O 017
 Vaz Mendes, S. 2 P 123, 3 P 216, O 150, O 165
 Vécsei, M. 4 P 264, 3 P 213
 Vega, J. 3 P 212
 Velarde, P. O 136
 Velasco, J.L. 3 P 217, O 063, O 066
 Velyhan, A. 4 P 230, O 155
 Vengust, D. 1 P 019
 Veranda, M. 2 P 120, O 161
 Verdier, T. 1 P 032
 Verdoolaege, G. 1 P 053
 Verhaegh, K. 1 P 055, 2 P 104,
 2 P 107, 4 P 288, O 055, O 056
 Verma, N. O 094
 Vernimmen, J. 4 P 303
 Verona, C. O 155
 Verstraeten, M. 3 P 167
 Vervier, M. 3 P 167
 Vesa, A. 2 P 114
 Vescovi, M. O 135
 Vezinet, D. 4 P 283, 4 P 284
 Viala, D. 1 P 004, O 059
 Vianello, N. 1 P 027, 1 P 048, O 127
 Viegas, P. O 138
 Vieira, J. O 012
 Viezzer, E. 2 P 098, 4 P 239, O 104, O 108
 Vignitchouk, L. 4 P 265
 Villalobos, E. 3 P 164, 3 P 220, O 036
 Villard, L. 1 P 038, O 028, O 116
 Villone, F. 1 P 061
 Vincent, B. 1 P 043, 1 P 050, 1 P 056
 Vincent, C. O 032, 2 P 124
 Vincenti, H. O 017
 Vincenzi, P. 3 P 162
 Vinci, T. O 113
 Vinciguerra, F. O 045
 Vine, G. 4 P 294

Vinkler, V. 3 P 184
 Virginie, G. O 009
 Vlad, G. O 052
 Vogel, G. 3 P 184
 Volcokas, A. 1 P 037
 Volfova, L. O 022
 Volkova, Y. 4 P 303
 Von Der Linden, J. 4 P 235, O 090
 von Stechow, A. 4 P 246, 4 P 252, 4 P 300,
 O 150, O 165
 Vondracek, P. 1 P 061
 Votta, L. 3 P 163
 Vranić, M. 1 P 009, O 122, O 125, 1 P 006
 Vu, A.T. 2 P 125

W

W. Moloney, P. O 061
 W.T. 3 P 224, O 064, 3 P 201
 W7-X Team 1 P 021, 1 P 022, 1 P 046, 1 P 051,
 1 P 054, 2 P 093, 2 P 118, 2 P 123, 3 P 164,
 3 P 167, 3 P 174, 3 P 203, 3 P 216, 3 P 220,
 4 P 246, 4 P 252, 4 P 254, 4 P 282, 4 P 291,
 4 P 298, 4 P 300, O 010, O 036, O 148
 Walder, R. O 073
 Walia, K. 2 P 081
 Walkden, N. 2 P 135
 Walsh, C. 1 P 001, 2 P 069, O 061, O 133
 Walsh, J. 1 P 019
 Waltenspiel, T. O 113
 Wampler, W. 1 P 051
 Wang, C. 1 P 068
 Wang, E. 1 P 057, 2 P 109, 2 P 133, O 064
 Wang, H. O 054, O 117
 Wang, J. O 117
 Wang, L. O 018
 Wang, X. 1 P 038, 2 P 100, 2 P 101, 4 P 245,
 4 P 271, O 028
 Wang, Y. 2 P 077, 2 P 087, 2 P 101, 2 P 111,
 4 P 245, O 053, O 056, O 108, O 129
 Wappl, M. 3 P 216
 Ward, I. 4 P 263
 Warren, M. O 096
 Wasser, F. O 050
 Watanabe, K. 2 P 122
 Watkins, J.G. O 054
 Wauters, T. O 064
 Waybright, J. O 164
 Weber, C. 2 P 069
 Weber, S. O 049, O 124
 Wegner, T. 1 P 021, 2 P 093, 2 P 123, 3 P 164,
 3 P 220, 4 P 300
 Wei, G. 2 P 116
 Weiland, M. 1 P 032
 Weinzettl, V. 3 P 181

Weir, G. 2 P 128, 4 P 291, 4 P 304
 Welch, E. O 154
 Werner, G.R. O 143
 WEST Team O 035
 Westerberg, L. O 046
 Wheeler, J. 3 P 228
 White, A. 3 P 209
 White, A.E. 2 P 100
 Widmer, F. 1 P 041, O 028
 Wiesen, S. 1 P 048, 4 P 251, O 152
 Wiesenberger, M. 1 P 045
 Wigram, M. 2 P 103
 Wiinika, H. O 046
 Wilcox, R.S. O 054
 Wilks, S. O 154
 Willensdorfer, M. O 105, O 126
 Willett, H. 4 P 290
 Williams, G. 3 P 147, O 136
 Wilms, F. 1 P 046, O 006
 Wilson, T. 3 P 177, 4 P 270, 4 P 275
 Windisch, T. 1 P 046, 4 P 304, O 066
 Winters, V. 3 P 223, 4 P 252
 Wisitsorasak, A. 2 P 119
 Wohlfahrt, S. O 091
 Wolf, R. 1 P 022, 2 P 128,
 3 P 164, 3 P 224, 4 P 291
 Wolfrum, E. 2 P 131, 3 P 208, O 105
 Wood, J. 4 P 290
 Woolsey, N. 2 P 077, O 050
 Worth, L. 4 P 294
 WPTE Team 4 P 251
 Wu, H. 2 P 103
 Wunderlich, D. 2 P 104
 Wurden, G. 3 P 216, O 150
 Wyss, I. 4 P 301

X

Xanthopoulos, P. 2 P 105
 Xavier, G. O 009
 Xiang, L. 4 P 259
 Xiao, C. 2 P 101
 Xiao, G. 2 P 143
 Xie, H. 4 P 245, 4 P 271
 Xie, P. 2 P 133
 Xu, J. 4 P 245
 Xu, S. 2 P 109, 2 P 133, O 064
 Xu, T. 2 P 101
 Xu, X. 2 P 111

Y

Yadav, K. 3 P 207
 Yadykin, D. 4 P 236, O 033
 Yagi, M. 2 P 094

Yamada, I.	1 P 025, 1 P 026	Yu, L.	1 P 057	Zhao, X.	2 P 077, 2 P 101, O 050
Yamaguchi, H.	2 P 119, 3 P 197	Yun, G.	3 P 146	Zhdankin, V.	O 143
Yan, X.	2 P 133	Yun, H.S.	1 P 035	Zhong, W.	2 P 143
Yanagihara, K.	4 P 281			Zhou, T.	2 P 101
Yanai, R.	4 P 240	Z		Zhu, Y.	2 P 143
Yang, D.	4 P 271			Zhurba, A.	3 P 182
Yang, G.	4 P 271	Zähler, Ş.	O 050	Ziegler, T.	O 147
Yang, H.	4 P 266, O 149	Zaka, H.	2 P 088	Zimmerman, G.	2 P 069
Yang, X.	2 P 101	Zamkovska, V.	1 P 067	Zimmermann, C.F.B.	1 P 036, 1 P 043, 4 P 239, O 034
Yanick, S.	3 P 179, O 009	Zanini, M.	3 P 224, O 010	Zimmermann, M.	4 P 304
Yanovskiy, V.	1 P 061	Zaniol, B.	4 P 285	Zito, A.	4 P 258
Yao, W.	O 113	Zanisi, L.	2 P 062, O 152	Zocco, A.	1 P 038
Yatomi, G.	1 P 047	Zanon, F.	2 P 129	Zohm, H.	O 083, O 160, O 162
Yelisseyev, D.	4 P 303	Zastrau, U.	O 005, O 135	Zoletnik, S.	4 P 264
Yevsiukov, O.	2 P 110	Zeng, L.	O 008	Zonca, F.	1 P 038, 2 P 090, 2 P 116, O 028, O 116
Yildiz, C.	3 P 201	Zenz, P.	2 P 131	Zotta, V.K.	1 P 048
Yoo, C.	2 P 142	Zepf, M.	O 121	Zou, X.	2 P 143
Yoo, M.	2 P 108	Zeraouli, G.	O 154	Zuin, M.	1 P 027, 2 P 120, 3 P 199, 4 P 248, O 161
Yoon, J.	4 P 250	Zestanakis, P.	3 P 185	Zurita, M.	1 P 050, O 056, O 108
Yoon, J.W.	O 125	Zhang, D.	1 P 021, 3 P 203, 4 P 252, O 057	Zylberman, J.	O 099
Yoshimura, Y.	4 P 240	Zhang, H.	O 160		
Yoshinuma, M.	4 P 240, O 169	Zhang, X.	3 P 176, O 067		
Young, C.V.	O 060	Zhang, Y.	2 P 101		