Alya4fusion: Advancing plasma equilibrium and electromagnetic wave propagation modelling for fusion reactor simulations

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Abstract Fusion reactor design requires advanced simulation tools for coupled multi-physics problems. Alya, a finite-element high-performance computing (HPC) framework, has been extended through the Alya4Fusion project to address the needs of fusion reactor modelling design. This work presents two key modules developed within Alya4Fusion. First, EQUILI solves the Grad–Shafranov equation using a level-set based CutFEM approach, enabling accurate computation of magneto-hydrodynamic equilibrium configurations with free-boundary conditions. Second, EMWAVE solves the time-harmonic Maxwell's wave equation in magnetised plasmas under the cold plasma approximation, allowing the simulation of radio-frequency wave propagation in realistic tokamak cross-sections. The integration of these modules supports consistent multi-physics coupling, as demonstrated by their application to simulate second harmonic ion cyclotron resonance frequency (ICRF) heating of tritium in ITER.

Introduction The design and operation of nuclear fusion reactors involve inherently complex and strongly coupled multiphysics processes. In particular, plasma physics simulations require resolving wave–particle interactions, turbulence, kinetic effects, and edge-localised modes (ELMs), which are governed by nonlinear, high-dimensional, and tightly coupled equations. Capturing these phenomena accurately demands advanced numerical techniques and massive computational power to resolve the multiscale dynamics of magnetised plasmas efficiently [1].

To address these challenges, we present Alya4Fusion, a dedicated project built upon Alya [2], the Barcelona Supercomputing Center's (BSC) high-performance, finite element-based multiphysics framework. Alya has demonstrated excellent scalability on large supercomputing infrastructures, with near-linear performance up to 100,000 cores. Its modular design allows for the coupling of specialised solvers in complex three-dimensional geometries, making it a suitable foundation for integrated fusion reactor simulations.

Alya4Fusion extends Alya's capabilities to meet the specific needs of nuclear fusion research. It is structured into two main components: a plasma solver and an engineering solver. The plasma solver currently includes the modules EQUILI [3], for computing magnetohydrodynamic equilibrium configurations and EMWAVE [4], for simulating radio-frequency (RF) wave propagation in magnetised plasmas by solving Maxwell's equations. Future plasma-oriented modules include PTRANS, for simulating plasma transport, and NEBEAM, which is intended to model neutral beam injection (NBI).

The engineering solver leverages existing Alya modules for thermal, structural, and fluid dynamics, and incorporates fusion-specific tools such as MAGNET [5], for simulating current distribution and magnetic fields in high-temperature superconductive (HTS) magnets, and NEUTRO [6], for neutron transport. In essence, the coupling between solvers is handled by PTRANS, which provides temperature profiles and, more importantly, the neutron source term to NEUTRO, which computes the transport of fusion-born neutrons.

Modelling of plasma equilibrium The EQUILI module provides the plasma shape and the flux surfaces to the rest of the modules in the plasma solver of Alya4fusion. It uses the Grad–Shafranov equation which models the equilibrium between plasma pressure and magnetic confinement. As a result, the poloidal magnetic flux field ψ is used to determine the shape of the magnetically confined plasma cross-section. To solve this equation, a numerical CutFEM [7] scheme is employed.

CutFEM is a branch of FEM characterised by an unfitted computational mesh, where geometries and domains are not aligned with mesh nodes but instead lie embedded. This makes it well-suited for problems where interfaces undergo large deformations or resizing. Interfaces and boundaries are parametrised using level-set functions. While the currents and positions of the tokamak's confining magnets can be adjusted to accommodate a variety of plasma pressure and current profiles, the current carried by the plasma depends on its cross-sectional shape, which is in turn influenced by the self-induced magnetic field generated by the plasma current. This coupling implies that the problem must be solved with a plasma boundary that is not fixed, but free to iteratively adapt to the force balance and evolve toward the equilibrium configuration.

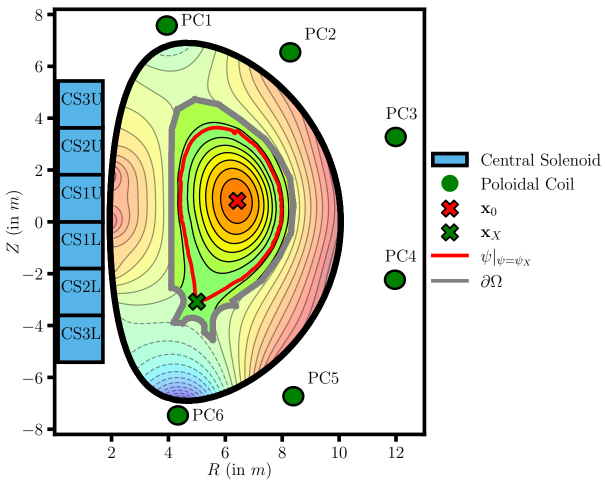

Figure 1: Axisymmetrical plasma equilibrium problem layout for ITER. External magnets (poloidal coils PC_i and central solenoids CS_j [8]) with fixed current lie outside the tokamak's cross section.

As mentioned earlier, EQUILI is integrated into Alya's framework, but a standalone version of the code also exists, developed in Python. EQUILIPY has been validated against analytical solutions [8] for fixed conditions, and tested for the ITER configuration [9] in the free-boundary case. The simulation layout and its results are shown in fig. 1.

Modelling of electromagnetic wave propagation EMWAVE is an electromagnetic wave solver designed to model the propagation of radio-frequency (RF) waves in magnetised plasmas. Currently, EMWAVE solves the wave propagation in the cold plasma model approximation, which is sufficient for assessing wave accessibility across the entire plasma region. Work is underway to implement the hot tensor. The code solves the time-harmonic Maxwell's equations in the frequency domain, assuming invariance in one spatial direction (typically the toroidal or axial direction), which reduces the problem to a 2D cross-sectional geometry. The wave equations can be decoupled into two scalar Helmholtz-like equations: one for the extraordinary mode and another for the ordinary mode. The solver can handle both finite external sources and incident plane waves, distinguishing between incident and scattered fields in the latter case.

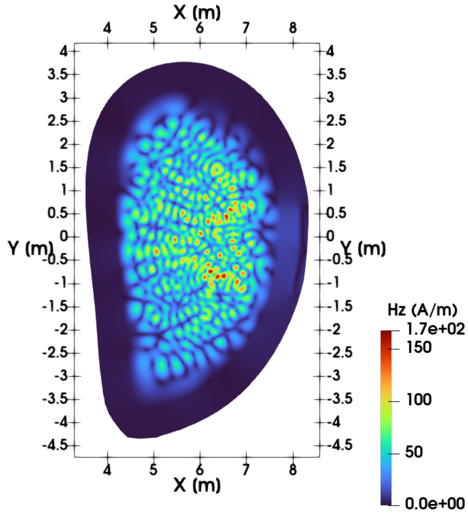

Figure 2: Magnetic field component H_z for 2nd harmonic ICRF heating of tritium in ITER as given by EMWAVE. Radiation is emitted from an antenna with current of arbitrary value. The plasma shape was obtained from EQUILI.

From a numerical standpoint, EMWAVE uses a Galerkin finite element method. To truncate the computational domain and avoid artificial reflections, both absorbing boundary conditions (ABCs) and perfectly matched layers (PMLs) are implemented. Several test cases have been reproduced and compared against bibliographic references [10] and well-established codes such as ERMES [11], both showing excellent agreement with EMWAVE [4]. The code exists both as a standalone application and as an integrated module within Alya.

A relevant case study involves an ITER scenario of 53 MHz wave frequency, a 5.3 T central magnetic field, and a 50%:50% deuterium–tritium mixture. This configuration corresponds to second harmonic ICRF heating of tritium, which is expected to be one of the main heating sources in ITER [12]. The plasma geometry was extracted from the last closed magnetic surface computed by EQUILI, and embedded in the mesh geometry of the domain. This demonstrates the first coupling between different modules within Alya4Fusion's plasma solver, since previous coupling between engineering modules has also been proved successful [13]. The magnetic field component H_z is shown in fig. 2, confirming the good accessibility of the wave. Second-order absorbing boundary conditions and finite sources were used for this simulation. Notice that perfect electric conductor (PEC) boundary condition should be applied to the walls in the near future to take into account reflections on the first wall.

Conclusions In this work, we have presented Alya4Fusion, a specialised initiative within the Alya HPC framework aimed at addressing the simulation needs of nuclear fusion research. By leveraging Alya's multi-physics capabilities, Alya4Fusion provides a modular and scalable platform suitable for integrated modelling of plasma physics and reactor engineering. We have described two key modules currently under development. EQUILI solves the Grad–Shafranov equation using a level-set-based CutFEM scheme, allowing for the computation of plasma equilibria with free-boundary conditions. EMWAVE addresses the simulation of RF wave propagation in magnetised plasmas under the cold plasma approximation, solving Maxwell's equations in the frequency domain and enabling analysis of wave accessibility.

The successful coupling of EQUILI and EMWAVE within a single simulation environment illustrates the potential of Alya4Fusion to perform consistent multi-physics studies. In particular, we have demonstrated this integration through a case involving ITER-relevant conditions, where plasma's equilibrium shape was used to produce the corresponding mesh geometry for the wave accessibility assessment. These developments mark a significant step towards establishing a comprehensive and efficient simulation tool for fusion reactor design, taking full advantage of modern HPC resources. Future work will focus on extending the plasma model to include transport effects and additional heating mechanisms, as well as strengthening the coupling with engineering modules for structural, thermal, and neutronic analysis.

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