Fast-ion transport in advanced tokamak scenarios with qmin close to two at ASDEX Upgrade

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Steady-state operation of tokamaks is demanding since the toroidal plasma current needs to be sustained by non-inductive means [1]. Although external current drive sources are available, their extensive use would yield an unacceptably high recirculated power fraction in future fusion power plants. High fractions of the intrinsic bootstrap current are needed that can be obtained in discharges with off-axis current distributions (low central poloidal fields) and internal transport barriers (strong gradients). Such advanced discharge conditions are, however, difficult to maintain since they are prone to impurity accumulation [2] and ideal ideal magnetohydrodynamic (MHD) modes[3].

Here, high q95 operation (high values of the safety factor q at 95% of the toroidal flux) is beneficial since this reduces the poloidal field (maximizes the bootstrap current) and a reduced tendency for impurity accumulation is observed. In the past, those high q95 scenarios were unattractive because high plasma currents are necessary for high enough confinement to meet the lawson criteron. The limited toroidal field strenght of present day magnets thus imposed operation at low q95 values. Nowadays, high-temperature superconductors might allow one to build steady-state fusion devices with a sufficiently high plasma current and simultaneously at high q95 [4], possible due to the higher toroidal fields B_t. This might provide an easier access to the non-inductive tokamak operation since the boostrap faction will be increased. The fast-ion transport, however, has not yet been studied in detail under such conditions since fast-ion transport studies are typically performed at high currents and low magnetic fields (low q95). Operation at high q95 values, instead, implies large banana orbits and thus increased neoclassical transport. Moreover, mitigation of edge-localized modes (ELMs) by resonant magnetic perturbation (RMP) coils, as well as MHD activity might have a stronger effect on the fast-ion confinement than during low-q95 experiments.

ASDEX Upgrade is very well suited for advanced scenario research as it is equipped with a flexible and powerful heating system. Moreover, the recent installation of a massive tungsten divertor has made high power experiments with low densities possible such that e.g. fully non-inductive discharges using co-electron cyclotron current drive (ECCD) could be demonstrated [5]. Here we extend these studies using co- neutral beam current drive (NBCD) in combination with counter ECCD in the plasma center for a q-profile shape that further increases the bootstrap current fraction.

Current-hole experiments at ASDEX Upgrade

Time traces of a representative discharge with a central toroidal field of -2.49 T and a plasma current of 600 kA (q95 = 7.5) are shown in figure 1. NBI heating starts early at 0.35 s using the on-axis source NBI Q3, which is required by charge exchange recombination spectroscopy (CXRS), motional Stark effect (MSE) and fast-ion D-alpha (FIDA) measurements. Early NBI

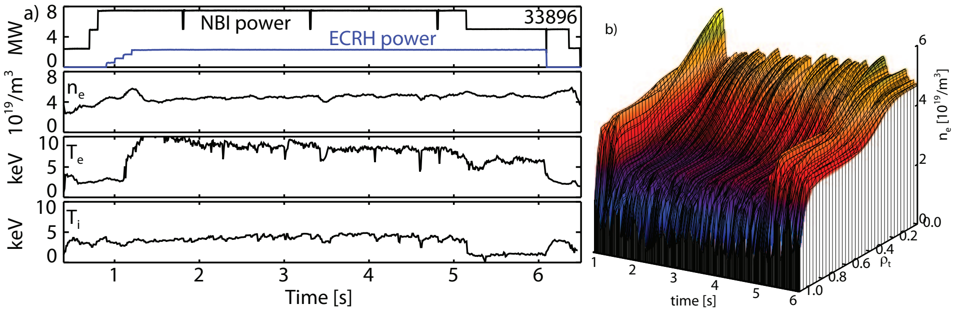

Figure 1: a) Representative time traces of discharge in #33896 showing the applied heating power, the core electron density and the core electron and ion temperatures. b) Electron density as a function of time and normalized radius.

heating reduces the plasma resistivity during the current ramp such the induced current cannot quickly penetrate into the plasma center and, thus, avoids centrally peaked current profiles. To further increase the off-axis current character of the discharge, two off-axis sources (NBI Q7 and NBI Q6) are turned on at 0.7 s and 0.8 s. Finally, counter ECCD is applied in the plasma center from four gyrotrons between 0.9 s and 1.2 s, with a total heating power of 2.3 MW and RMPs (n=2) are applied between 1.5s and 5.0s. The density pump-out imposed by the RMPs can be clearly seen in figure 1b.

As consequence of the application of counter ECCD and off-axis co-NBI, a current hole develops in the plasma center [6] that is associated with a strong shear region and a transport barrier visible in the electron and ion temperature. Central electron temperatures of up to 10 keV and ion temperatures in the range of 4 keV are observed. When looking a the evolution of the electron temperature in the strong gradient region (see figure 2), sawtooth-like crashes become visible. These crashes are followed by reversed shear Alfvén eigenmodes (RSAEs), as visible in spectrogram of a central soft X-ray channel (see figure 2 middle row). At the plasma edge, toroidicity-induced Alfvén eigenmodes are present that have been detected in an edge channel of the soft X-ray diagnostic.

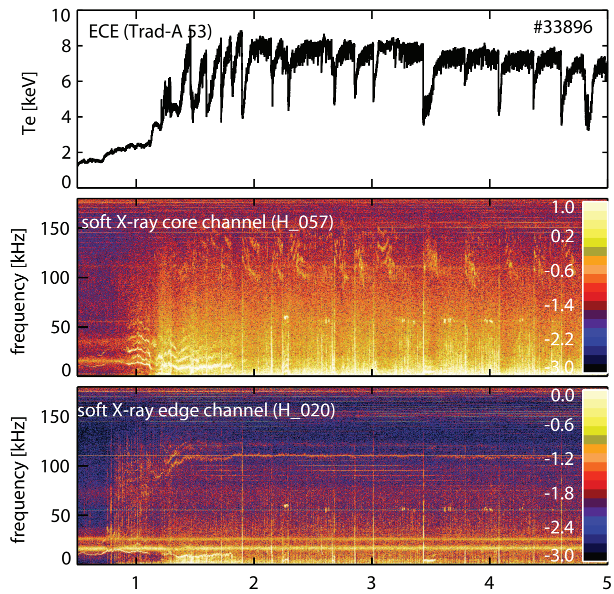

Figure 2: *Temperature in the strong gradient region, measured by the ECE diagnostic, magnetic spectrogram from an soft X-ray channel crossing the core and a channel intersecting the edge region, only.*

Measurement vs. modeling

TRANSP [7] modeling has been performed to compare fast-ion and current-profile measurements with neo-classical expectations which allows us to assess whether the applied perturbations or MHD modes have an impact on the fast-ion distribution function or not. The TRANSP

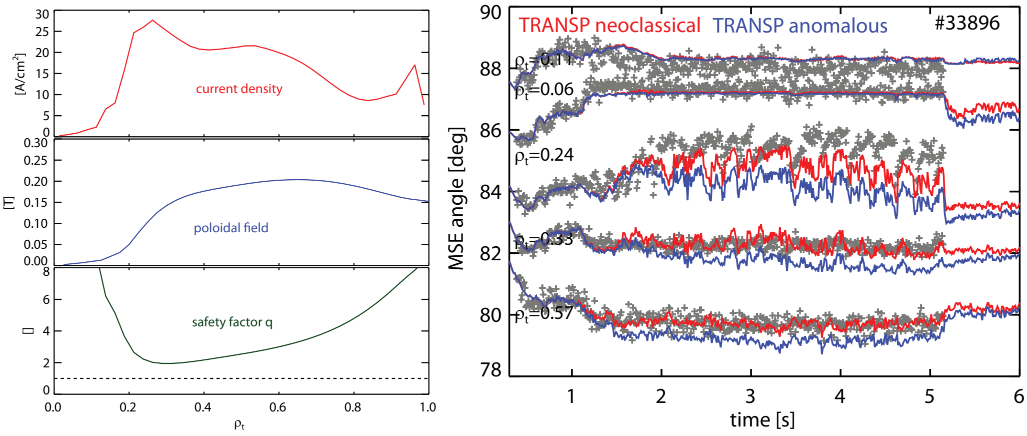

Figure 3: a) Current, poloidal field and q-profiles as predicted by TRANSP. b) Measured MSE angles compared with TRANSP predictions.

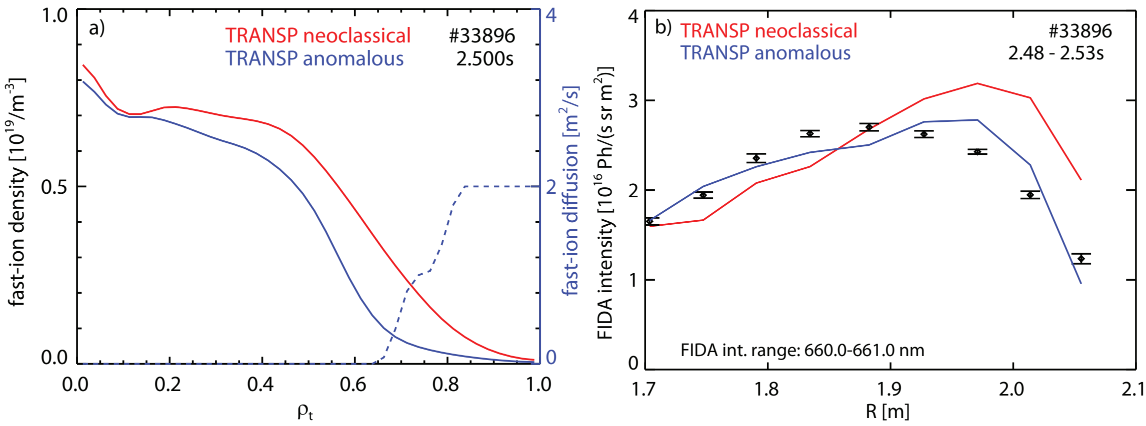

Figure 4: Radial fast-ion density profiles from TRANSP compared with the applied profiles of anomalous diffusion. b) Radial FIDA profiles compared with TRANSP/FIDASIM results.

predicted current profile is plotted in figure 3 together with the poloidal magnetic field and the q-profile. As expected, the current is close to zero in the plasma center which yields a very low poloidal field and thus high values of the q-profile (reaches the upper boundary of q0=8, as defined in the TRANSP namelist). Together with the high electron and ion temperatures, input to TRANSP, a the predicted bootstrap current fraction reaches up to 62% and the discharge is almost non-inductive despite the application of counter ECCD. The predicted evolution of the current profile agrees well with MSE measurements, shown in figure 3b for five radially distributed channels. During the formation of the current hole around 1.5 s, the MSE angles of the channel at ρ=0.24 move closer to the channel above. This indicates that the variation of the poloidal magnetic field between the two radially separated channels becomes smaller, i.e. less current is flowing between the measurement locations. This behavior is expected when considering a current hole and is well reproduced by the neo-classical TRANSP prediction in red. When instead assuming an ad-hoc anomalous fast-ion diffusion profile, as plotted in figure 4a, the agreement between the measurement and the simulation (blue) becomes worse.

However, the assumption of this anomalous diffusion profile is necessary to explain radial profiles of the fast-ion D-alpha diagnostic, shown in figure 4b. The radial profiles correspond to horizontally viewing lines of sight and red-shifted wavelengths and provide information on co-rotating fast ions above 30 keV. When comparing the measured profiles with synthetic profiles from FIDASIM [8] that represent the neoclassical fast-ion distribution function from TRANSP (red), a clear difference is observed close the plasma edge. Instead, the assumption of the anomalous diffusion profile (blue) yields better agreement.

This requirement of anomalous fast-ion diffusion obviously disagrees with the MSE measurement. Possibly, a velocity space dependent transport is present here which is strong for the bulk fast-ion distribution function (observed by FIDA spectroscopy) but does not affect the high energetic fast-ions which drive most of the plasma current. Such velocity space dependent fast-ion transport is for instance caused by the magnetic field perturbation induced by RMPs. In fact, modeling results of the RMP-induced fast-ion transport using LOCUST [9], which are based on perturbed 3D equilibria from VMEC [10], show a dominant redistribution of low-energetic fast-ions. The predicted effect on the FIDA profiles gives the right trend and amplitude. However, LOCUST does not simulate charge exchange losses which have been found to be significant in this discharge scenario as well. The reduced the edge-collisionality due to the RMP-induced density pump-out yields longer fast-ion slowing down times. Thus, additional transport channels such as charge exchange losses or mode-induced diffusion have more time to affect the fast-ion distribution function. In the TRANSP simulations presented here, the charge-exchange losses are already 0.6 MW during the RMP phase (compared with 7.5 MW of NBI heating) which dominantly affect low-energetic fast ions due to the energy-dependence of the cross-section. The uncertainty of the prediction is, however, large since the 1D neutral code FRANTIC is applied in TRANSP while it is well known that the neutral density has strong poloidal dependence. The actual level of losses might be even higher. However, even losses in the range of 1 MW cannot fully explain the observed effect on the FIDA profiles. Finally also the MHD activity present in the discharge might redistribute fast-ions. While the core localized modes appear in bursts which would, if a strong transport was involved, result in a temporal variation of the fast-ion density which is not observed, the TAE modes might additionally redistribute the fast particles. First analysis results using LIGKA [11] show that the mode structure is, indeed, edge-localized as observed by the soft X-ray system. An impact of these modes on the low energetic fast-ions will be analyzed by forward modeling of the expected redistribution.

References

[1] ZOHM, H., Fusion Science and Technology **58** (2010) 613.
[2] DUX, R. et al., Nuclear Fusion **44** (2004) 260.
[3] WESSON, J. et al., Nuclear Fusion **25** (1985) 85.
[4] SORBOM, B. et al., Fusion Engineering and Design **100** (2015) 378 .
[5] BOCK, A. et al., Physics of Plasmas **25** (2018) 056115.
[6] FUJITA, T. et al., Nuclear Fusion **43** (2003) 1527.
[7] HAWRYLUK, R. et al., Physics of Plasmas Close to Thermonuclear Conditions **1** (1980) 19.
[8] HEIDBRINK, W. et al., Commun. Comput. Phys. **10** (2011) 716.
[9] AKERS, R., IAEA Fusion Energy Conference - Kyoto (2016).
[10] HIRSHMAN, S. P. et al., The Physics of Fluids **26** (1983) 3553.
[11] LAUBER, P. et al., Journal of Computational Physics **226** (2007) 447 .