Fast-ion response to externally applied 3D magnetic perturbations in ASDEX Upgrade H-mode plasmas


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Abstract. The fast-ion response to externally applied 3D Magnetic Perturbations (MPs) has been investigated on ASDEX Upgrade (AUG) in H-mode plasmas with a wide range of collisionalities / densities and MP spectra. MPs have little effect on kinetic profiles, including fast-ions, in high collisionality plasmas with mitigated ELMs while a strong plasma (including fast-ions) response is observed in H-mode regimes with low collisionality / density and low q95. Multiple, absolutely calibrated, fast-ion loss detectors (FILDs) [1] located at different toroidal and poloidal positions measure significant changes in escaping ion phase-space when MPs are applied. Fast-ion losses can be up to an order of magnitude larger with MPs than the nominal NBI prompt losses measured without MPs. The application of the 3D fields is followed by a rapid rise (within ms) of the associated fast-ion losses while the measured fast-ion losses exhibit a slow decay, ~100 ms, down to the nominal NBI prompt loss level, after the MP coils are switched off. The heat load associated to the MP induced fast-ion losses have been measured with infrared cameras imaging the divertor as well as FILD and the surrounding first wall. The measured heat load can be up to 6 times larger with MPs than without MPs. The impact the 3D fields have on the confined fast-ions have been monitored by means of Fast-Ion D-Alpha (FIDA) spectroscopy. FIDA measures an enhancement of the fast-ion content in plasma with a visible impact on the gradients of the fast-ion profiles when MPs are applied and density pump-out is observed. A strong fast-ion response is typically accompanied by an apparent displacement of the outboard separatrix, 1-3 cm, as measured by Beam Emission Spectroscopy (BES) that modifies significantly the NBI deposition profile. The accurate fast-ion measurements presented here are used to test models of 3D fields using full orbit simulations. The perturbed equilibria are calculated in vacuum, using the 3D free boundary VMEC / NEMEC code as well as including the plasma response with the M3D-C1 and MARS-F.
1. Introduction.
Edge localized modes (ELMs) are inherent to high confinement regimes in tokamak plasmas. The energy and particle release associated with the large ELM crash are likely be intolerable in future fusion devices such as ITER; therefore, several mitigation techniques have been developed during the last years. Among others, externally applied resonant magnetic perturbations (MPs) are one of the most promising techniques [2–5]. However, the impact of the externally applied MPs on energetic particles still needs to be assessed experimentally. This is of special importance for future burning plasmas with a large content of MeV-ions with relatively long slowing-down times. Numerical simulations of fast-ion losses induced by ELM mitigation coils in ITER [6–10] have shown that, under certain conditions, up to 20% of the neutral beam injection (NBI) power can be lost due to the 3D fields created by the ELM mitigation coils. First experiments at AUG and DIII-D have shown that under certain conditions MPs can cause significant fast-ion losses in L [11] and H-mode [12] plasmas. An experimentally validated model for the plasma response is, however, needed to improve our abilities to make realistic predictions for ITER as the plasma can shield or even amplify some components of the externally applied MPs leading to a complex 3D background equilibrium [13].

In this paper, measurements of fast-ion losses induced by ELM mitigation coils in H-mode plasmas are presented. The experiments discussed here have been carried out in a rather low collisionality ($\nu_e \leq 1$), density ($n_e \leq 6.5 \times 10^{19} \text{ m}^{-2}$) and $q_{95} \leq 3.85$ plasma with static $n = 2$ MPs applied by the 16 ELM mitigation coils that have been recently installed in the ASDEX Upgrade (AUG) tokamak [5]. The fast-ion losses are measured by two absolutely calibrated scintillator based fast-ion loss detectors (FILDs), located at different toroidal positions but at the same poloidal position ($\approx 30$ cm above the mid-plane). The MHz bandwidth of the detectors allows a high temporal resolution of the intra-ELM fast-ion losses. Indeed, several fast-ion bursts are typically observed almost simultaneously within a single ELM by both FILD systems. Externally applied MPs have little effect on plasma profiles, including fast-ions, in high collisionality plasmas with mitigated ELMs. A strong impact on the plasma rotation, density (with a pump-out of up to 25% of the core line integrated density) and fast-ion population is observed, however, in low-collisionality and low-$q_{95}$ plasmas with externally applied MPs and partially mitigated ELMs. Orbit simulations are used to test different models for 3D field equilibrium reconstruction, including the vacuum representation, the free boundary NEMEC code [14, 15] and the MHD codes M3D-C1 [16] and MARS-F [17]. In order to account for modifications of the NBI prompt loss pattern due to perturbed density profiles with density pump-out, the perturbed NBI birth distribution has been calculated using the FIDASIM code [18] using measured kinetic profiles with and without MPs. The deeper beam deposition achieved during the MP phase due to the lower density indicates that the perturbation fields are likely affecting fast-ions that would be well confined in an unperturbed equilibrium. This paper is organized as follows. In section 2 the experimental observations including the response to the 3D fields of the background plasma and of the fast-ions are described in detail. The modeling strategy is presented in section 3, with emphasis on the perturbed NBI birth distributions and 3D fields. Finally, some conclusions are given in section 4.
2. Experimental observation.

The experiments presented here have been carried out in H-mode plasmas with a toroidal magnetic field, \( B_t = -1.7 \text{T} \); a plasma current, \( I_p = 0.8 \text{ MA} \); 1.4MW of ECRH to avoid impurity accumulation; 5MW of NBI heating as main fast-ion source; and an externally applied \( n = 2 \) static MP. The current of the coils was set to \( I_{\text{coil}} \approx 1.2 \text{ kA} \cdot \text{t} \). The discharge is divided in three phases that have been heated with three different beams (with different injection geometries) to vary the dominant pitch-angle of the fast-ions in the plasma as well as the plasma rotation, i.e. possible plasma shielding. All three NBI phases have a 500 ms phase with the ELM mitigation coils ON. The NBI#3 source was kept ON during the entire discharge for diagnostic purposes.

An overview of the most relevant signals is shown in Fig. 1. The time traces of the whole fast-ion losses (integrated in velocity-space) measured by the FILD1 and FILD2 CCD cameras are shown in Fig. 1-(a). The strongest losses appear in FILD1 and are clearly correlated with the application of the \( n = 2 \) MP during the first NBI phase. There are striking differences in the overall evolution of FILD1 and FILD2 signals with MP-induced fast-ion losses concentrated in FILD1 signals. While FILD1 signals rise dramatically with the external MPs, the fast-ion losses on FILD2 seem to vanish. FILD1 signals exhibit two clear characteristic times in the temporal response to the ELM mitigation coils as the rise and decay time of the losses are quite different in all three coil phases but most pronounced in the first coil phase. ELM induced fast-ion losses are clearly visible in both detectors.
The temporal evolution of the core line integrated density is shown in Fig. 1-(b), together with the timing of the NBI sources. Density pump-out is observed in all MP phases with a clear density/collisionality dependence, i.e. as the discharge evolves, the density rises and so the density pump-out becomes smaller. The same behavior is observed in FILD1 signals, i.e. the lower the density, the larger the density pump-out and the stronger the fast-ion losses measured in FILD1. The discharge exhibits a marginal ELM mitigation with the externally applied MPs that becomes more evident as the plasma density increases in time; see Fig. 1-(c). At t = 1.5 s, the coils are ramped up and the dc component of the fast-ion losses rises quickly up to a level that is ≈7–8 times the NBI prompt loss level without the external perturbation. After the coils are switched off at t = 2.0 s, FILD1 signals decay slowly with a characteristic time much longer (a few times the fast-ion slowing-down time) than the rise time observed during the coil ramp up. Indeed, as the coils are switched on, the maximum in FILD signals is achieved within 10 ms while FILD signals are back to the nominal prompt loss level after switching off the coils in ≈200 ms. The velocity-space of
the escaping NBI ions measured by FILD identifies unequivocally the orbits of the ions that are most affected by the perturbation fields. In Fig. 2, the gyroradii (energies) and pitch-angles of the escaping ions measured by FILD1 with and without the MP coils during the different NBI phases are shown. Fig. 2-(a), coils off, and (b), coils on, correspond to the NBI#3 + #8 phase. Fig. 2-(c), coils off, and (d), coils on, correspond to the NBI#3 + #7 phase and Fig. 2-(e), coils off, and (f), coils on, to the NBI#3+#5 phase. Fig. 2-(a), -(c) and -(e) give an overview of the NBI prompt losses, with ≈93 keV, measured by FILD1.

The different pitch-angles of the measured NBI prompt losses are a direct measure of the NBI injection geometry, and so radial beams (Fig.2-(a) and (e)) cause prompt loss with larger pitch-angles than tangential beams (Fig.2-(c)). In addition to the NBI prompt losses, Fig. 2-(b), (d) and (f) show the new velocity-space areas covered with fast-ion losses due to the MP coils. In all cases, fast-ion losses with gyroradii ≈30–40 mm and pitch-angles ≈60° appear only when the MP coils are on. Figures 2-(b) and -(d) show, in addition, other energies and pitch-angles that without the MPs would be well confined. According to the FILD2 time traces shown in Fig. 1-(a), the CCD frames of FILD2 show the velocity-space of the NBI prompt losses together with the bursting ELM-induced fast-ion losses before the coils are switched on. However, as soon as the coils are switched on, all signals in FILD2 disappear indicating that the losses may be quite localized toroidally and poloidally.

3. Modelling

The modeling activities carried out here are focused on the two time points presented in Fig. 2-(a) and (b). To properly model the fast-ion losses induced by externally applied MPs, realistic NBI birth profiles and 3D perturbation fields need to be taken into account. The MP perturbed NBI birth profiles have been calculated using the FIDASIM code with measured kinetic profiles and 2D magnetic equilibria. The measured electron density profiles, ne, perturbed and unperturbed, used to calculate the density of NBI deposited ions, are shown in Fig.3-(a). A 1D density of the resulting NBI deposited ions can be seen in Fig.3-(b) as a function of the major radius, R. As expected from the BES measurements, the
higher density at the edge in the unperturbed phase leads to a higher NBI birth density at the edge, while during the perturbed phase, the NBI birth density is lower at the edge and higher in the core. Fig. 3-(c) and -(d) show the 2D density of deposited fast-ions on a R–z plane. Intuitively, the higher NBI birth density at the edge at $t = 1.42$ s should lead to stronger losses than the NBI birth density at $t = 1.61$ s. However, stronger losses are observed at $t = 1.61$ s due to the applied 3D fields. The NBI birth profiles calculated here are used as input for the orbit following codes.

Figure 4. AUG discharge #28061. MARS-F simulation, including plasma response, of the $\delta B_r$ (a) and $\delta B_z$ (b) components of the n=2 RMP fields in AUG. In both figures the black curve is the equilibrium plasma surface, and the magenta curve is a virtual surface on which the MP coil currents are defined.

The perturbed 3D fields are calculated using the vacuum field representation, the free boundary NEMEC code [11, 12] and the MHD two fluid M3D-C1 and one-fluid MARS-F codes. NEMEC calculates the corrugation of flux surfaces due to the 3D fields assuming nested flux surfaces and including toroidal field (TF) ripple. The one fluid MARS code simulates the plasma response to externally applied MPs taking into account resistivity, rotation and realistic toroidal geometry. Fig. 4-(a) and -(b) show the $\delta B_r$ and $\delta B_z$ plasma
response to the perturbation fields on an AUG poloidal cross section. The plasma response clearly affects not only the resonant but also the non-resonant surfaces. A 3D Poincaré plot of magnetic field lines calculated with the LOCUST code in MARS-F fields is shown in 3D in Fig.5-(a) and in a poloidal cross-section around the x-point at phi=0 in Fig.5-(b) showing the characteristic X-point lobe structure introduced by the 3D MPs. The two-fluid model in M3D-C1 predicts an efficient shielding in the plasma core, though resonant field amplification at rational surfaces with negligible electron rotation causes a stochastic layer in the pedestal due to island overlap. In these calculations, the last closed flux surface is treated as a free boundary, and both the plasma and vacuum regions are treated self-consistently as resistive plasmas. The amplification of islands is typically not seen in the one-fluid model because the $E \times B$ frequency (and hence the electron rotation frequency) generally crosses zero either near the last closed flux surface (where the tearing drive is small due to low pressure and current density), or not at all. This is in contrast to the two-fluid case, where the electron diamagnetic term tends to cause the electron rotation to cross zero well within the plasma, where tearing modes are closer to marginal stability and hence easier to drive to finite amplitude. Fig.6-(a) shows a 3D visualization of the perturbed fields calculated with the M3D-C1 code. Orbit simulations are conducted in 3D fields calculated using the vacuum representation, the free boundary VMEC / NEMEC code as well as the MHD codes M3D-C1, and MARS-F. Fig.6-(b) shows the effect of the 3D fields calculated with the M3D-C1 code on a typical banana orbit, which is well confined without 3D fields but escapes the plasma in a few poloidal bounces as soon as the external 3D fields are applied. The largest losses are predicted in the 3D fields calculated with the VMEC / NEMEC code including the entire MP spectra as well as the TF ripple. Indeed, a clear synergy between the static MP and the TF ripple is observed in the calculated fast-ion heat load, see Fig.7. Simulations reproduce some key observations though they still show some important deviations with respect to experiments, e.g. absolute values and velocity-space dependence.


The effect that the 3D fields arising from the ELM mitigation coils have on fast-ions has been studied in the AUG tokamak both experimentally and in simulations. Static n=2 MPs have a strong impact on fast-ions in low-collisionalility and $q_{95}$ discharges causing fast-ion losses that are localized in both real and velocity-space. Modelling of the fast-ion losses in 3D fields calculated using the vacuum representation, the free boundary NEMEC model as well as taking into account the plasma response with the 1 fluid MARS-F and the 2 fluids M3D-C1 codes has been carried out. The largest losses are predicted in the 3D fields...
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References

Figure 7. GOURDON simulations. Fast-ion heat load on a 2D AUG first wall computed with the full orbit GOURDON code in a NEMEC 3D equilibrium. The patterns of the $n=2$ MP and of the TF ripple are clearly visible.