Fast-ion first orbit displacement induced by externally applied magnetic perturbations in the ASDEX Upgrade tokamak

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Introduction

The so called H-mode of operation is considered as a possible candidate for future fusion reactors. Inherent to the H-mode, instabilities known as edge localized modes (ELM) appear in a cyclic fashion expelling energy and particles from the confined region to the walls of the machine. These instabilities can cause excessive heat loads to the plasma facing components, and therefore must be avoided. One of the most explored avoidance techniques is the ELM control using externally applied magnetic perturbations (MP) [1]. However, it has been observed both experimentally and numerically, that these 3D applied MPs can have a deleterious impact on fast-ion confinement [2, 3]. Therefore, a good understanding of the mechanisms responsible for the associated fast-ion transport is required to develop optimized MP configurations and to validate our numerical tools for reliable predictions. In this work we present an experimental study at the ASDEX Upgrade tokamak (AUG) of fast-ion first orbit displacement induced by externally applied MPs as a function of the applied spectrum by means of the so-called light ion beam probe technique (LIBP) [4]. Experimentally we control the applied MP spectrum via the phase between upper and lower set of MP coils ($\Delta\Phi_{ul}$) installed at AUG. The LIBP technique allows to infer the fast-ion orbit displacement from the modulation of the fast-ion loss detector (FILD) signal. In the case of experiments dealing with 3D perturbations, a generalization of the LIBP formula [4] is needed:

$$\sum_{n=1}^{\infty} \xi_n^{FI} \cdot \cos(n \cdot \phi + \beta_n) = L_{n_e}(\vec{r}_{birth}) \cdot \left[\frac{F - \langle F \rangle}{\langle F \rangle} \right] - \sum_{n=1}^{\infty} \xi_n^{pl} \cdot \cos(n \cdot \phi + \alpha_n) \quad (1)$$

where ϕ is the toroidal coordinate, n is the toroidal mode number of the applied perturbation, ξ^{FI} is the fast-ion orbit displacement induced by the MPs, ξ^{pl} is the plasma boundary displacement, L_{n_e} is the density scale length evaluated at the birth position of the probe ions measured by FILD, F is the FILD signal and $\langle F \rangle$ is the FILD signal averaged over a full MP cycle. Here, the term in the left hand side is what we want to infer, while the terms in the right hand side are obtained from experimental measurements.

Experimental measurements

These experiments were carried out in ELM mitigated H-mode plasmas at $B_t = -1.8$ T and $I_p = 0.8$ MA, in lower single null configuration with low triangularity, characterized with an edge density of $\sim 2-2.7 \cdot 10^{19}\ m^{-3}$, a plasma $\beta \sim 2-2.5$, $q_{95} = 3.85$ and $Z_{eff} \sim 1.4$. All the shots followed the same structure: 2.7 MW of ECRH power were used, together with 2.5 MW of NBI source Q3, in the background, for diagnostic purposes. On top of this, phases of $\sim 2s$ of 2.5 MW of the corresponding probe beam were applied. A rigid rotation at 1 Hz of an n=2 MP configuration was applied with a fixed $\Delta\Phi_{ul}$, which was modified on a shot-to-shot basis. For each case the plasma boundary displacement (PBD) at the outer midplane is measured using the lithium beam emission spectroscopy diagnostic (Li-BES), following the same procedure as in [5]. The correction due to the plasma control system was taken into account. The fast-ion orbit displacement is inferred using the FILD signal and applying Eq.1. The correction due to the effect of the 3D plasma boundary displacement on the FILD signal is taken into account.

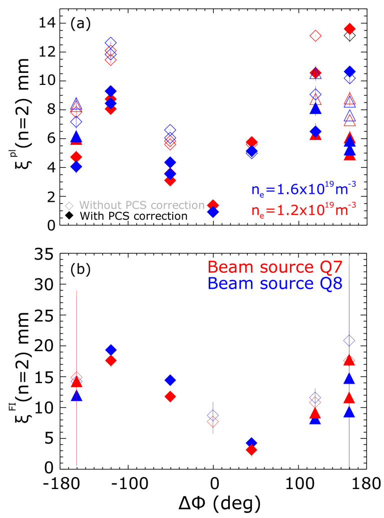

Figure 1: *(a) Plasma boundary displacement as measured by the Li-BES diagnostic. (b) Fast-ion orbit displacement inferred by the application of the LIBP technique. The measurement associated to the fast-ion population of NBI source Q7 is plotted in red. In blue, the same for Q8.*

The results are shown in Fig.1. In (a) the PBD is plotted against $\Delta\Phi_{ul}$. In (b) the inferred fast-ion orbit displacement is plotted against $\Delta\Phi_{ul}$, for NBI source Q7 (in red) and Q8 (in blue). It can be seen that the PBD ranges from 2-10 mm, while the fast-ion orbit displacement ranges from 3-20 mm. Within experimental errorbars, there is no difference between NBI sources Q7 and Q8. Interestingly, there is a shift between both curves: the minimum of the PBD appears at $\Delta\Phi_{ul} \sim 0^o$, while the minimum of the fast-ion orbit displacement appears at $\Delta\Phi_{ul} \sim 50^o$. This shift suggests that the effect of MPs on ELM control could be decoupled from the MP induced fast-ion transport. A similar experiment was carried out where the MP coil current I_{MP} was scanned from 0 to 1.2 kA, also at a fixed MP spectrum. Two cases were studied: an n=2 perturbation at $\Delta\Phi_{ul} = -120^o$ and 45^o, corresponding to the values of maximum and minimum fast-ion orbit displacement found on Fig.1(b). Again, both NBI sources Q7 and Q8 were used as probing beams. The results are shown in Fig.2, where only the case corresponding to $\Delta\Phi_{ul} = -120^o$ is shown, for NBI source Q8 in (a) and Q7 in (b). In both cases, it can be seen that the intensity of the FILD signal scales almost linearly with the applied current. In the case of NBI source Q7, a clear threshold of the onset of the fast-ion losses is obsvered at a coil current of ~ 0.3 kA. Such a clear threshold is not observed for NBI source Q8. There is also no clear evidence of a threshold for the saturation of the FILD signal, as was observed in KSTAR experiments [6].

Modelling

Modelling of these experiments has been carried out with the orbit following code ASCOT. In the first place, the impact of the perturbed 3D kinetic profiles on the FILD signal was evaluated, independent from the MP induced fast-ion orbit displacement, by carrying out simulations in a 2D magnetic equilibrium and shifting the kinetic profiles accordingly. It was found that for a plasma boundary displacement of ± 1 cm, consistent with the experimental observations, a modulation of the FILD signal of up to $\frac{\Delta F}{\langle F \rangle} \sim 0.5$ can be obtained. This justifies the need to include a correction due to the plasma boundary displacement to the LIBP formula in Eq.1. In a second step, the first-orbit fast-ion displacement induced by the MPs has been evaluated. The simulations are done by using a magnetic configuration with a fixed $\Delta\Phi_{ul}$ and following markers with fixed initial position (R,Z) and pitch angle ($\lambda = \frac{v_\parallel}{v}$), and scanning the initial toroidal coordinate ϕ from $0 - 2\pi$. The markers are followed during $\sim 30\mu s$, corresponding to a couple of poloidal transits, and the radial displacement is evaluated at the outer midplane. An example is illustrated in Fig.3. In (a) the FILD signal for AUG shot 37620 is shown, corresponding to $\Delta\Phi_{ul} = 120^o$ and beam source Q8. In (b) the results from an ASCOT simulation using $\Delta\Phi_{ul} = 120^o$ (including the plasma response) and an initial pitch angle $\lambda = 0.40$ (consistent with the pitch angle range measured by FILD) is shown. In (c) the fourier decomposition of both signals is plotted. In both cases it can be seen that the n=2 component is clearly dominant. However, it is worth to note that other components such as the n=4 and n=6 also show up, both in the experimental measurement and in the ASCOT simulation. This suggests that, in addition to the main toroidal mode number of the applied MP, including

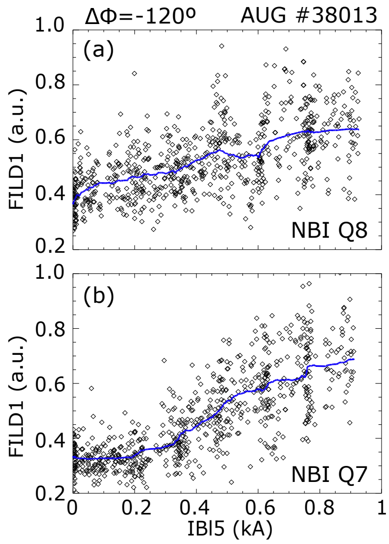

Figure 2: *(a) Evolution of the FILD signal as a function of the applied MP coil current in AUG shot 38013 for NBI source Q8 (a) and Q7 (b).*

the additional sidebands might be important for reliable predictions towards future experiments. The toroidal phases corresponding to the maximum and minimum fast-ion orbit displacements predicted by ASCOT seem to be consistent with the experimental trend.

Summary and outlook

In this work the first-orbit fast-ion displacement induced by externally applied MPs has been measured for two different NBI sources as a function of $\Delta\Phi_{ul}$ by means of the LIBP technique in the AUG tokamak. The measured displacements range between 3-20 mm, being the minimum at $\Delta\Phi_{ul} \sim 50^o$. No difference is observed between NBI sources Q7 and Q8, within experimental errorbars. This is compared to the plasma boundary displacement at the outer midplane, inferred from Li-BES measurements. The PBD ranges from 2-10 mm, being the minimum at $\Delta\Phi_{ul} = 0^o$, which is consistent with previous observations [7]. The shift between the minimum in the fast-ion orbit displacement and the PBD at the outer midplane suggests that the MP induced fast-ion transport could be decoupled from the ELM control, thus opening the possibility for the optimization of the applied MP configuration. A scan of the fast-ion losses as a function of the intensity of the applied MP reveals a threshold for the onset of fast-ion losses for NBI source Q7, similar to what was reported in KSTAR [6]. The FILD signal scales roughly linearly with the applied MP coil current. No clear evidence of saturation of fast-ion losses is observed.

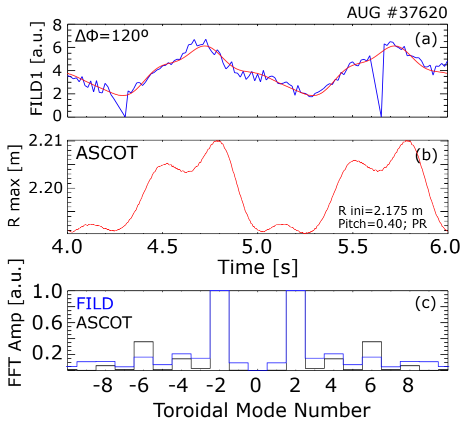

Figure 3: *(a) Experimental modulation of FILD signal during AUG shot 37620 for beam source Q8. (b) Simulated modulation of FILD signal with ASCOT. (c) Fourier transform of the signals shown in (a) and (b).*

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