Fast ion wall loads in ASDEX Upgrade in the presence of magnetic perturbations due to ELM mitigation coils

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Abstract. Neutral beam injected (NBI) particles were simulated in ASDEX Upgrade (AUG) discharge #26476 plasma with the fast particle following Monte Carlo code ASCOT. Three neutral beams were used in the discharge, one at a time and each both in the presence and in the absence of the magnetic perturbation induced by the eight newly installed in-vessel coils. The perturbation due to the in-vessel coils was seen to have an effect on the fast particle confinement. Most notably, the losses from the parallel neutral beam Q6 were quadrupled due to the perturbation. The wall loads were focused below (or at) the upper set of coils. This was particularly the case of the parallel beam Q6, whereas for the perpendicular beams studied in this work (Q5 and Q8) also the protruding wall elements such as the limiters carried significant power loads. Preliminary comparisons between experimental and simulated Fast Ion Lost Detector (FILD) signals showed good correspondence. The synthetic signal did, however, include and aditional feature not seen in the experimental one. The lack of this feature in the experimental signal can be at least partly explained by the geometrical limitations of the detector.

1. Introduction

Mitigation of edge localized modes (ELMs) is vital for successful high-confinement mode (H-mode) operation of ITER [1]. To investigate the effect of magnetic perturbations on the behaviour of ELMs, 24 in-vessel saddle coils will be installed on ASDEX Upgrade (AUG) [2]. So far, eight coils have been installed and their locations are shown in Figs. 1(b) and 3. Running a current in the coils in the positive (negative) direction creates a magnetic field mainly in outward (inward) radial direction. First experiments using the coils showed clear mitigation of ELMs, but left plasma performance (e.g. stored energy and pedestal top density) unaffected [3].

While the magnetic perturbation created by the in-vessel coils has been found to have the desirable effect on ELMs, it might be harmful for the fast ion confinement. Indeed, the local perturbation due to tritium breeding test blanket modules (TBMs) projected for ITER has been found to cause increased and more localized fast ion losses [4].

In this work, the effect of the magnetic perturbation created by the in-vessel coils on the confinement and losses of fast particles was studied. Neutral beam injected (NBI) particles were simulated in AUG discharge #26476 plasma in the presence and absence of the said magnetic perturbation. The simulations were done with the test particle orbit following Monte Carlo code ASCOT [4, 5] and the results were compared with those of the fast ion loss detector (FILD) [6].

The structure of the paper is as follows: ASCOT-code is presented in Sec. 2 along with the simulated discharge. Section 3 discusses the changes in wall loads induced by the in-vessel coils, whereas in Sec. 4 the simulations are compared with fast ion lost detector (FILD) measurements.

2. ASCOT simulations

ASCOT [4, 5] is able to take into account the full 3D structures of both the magnetic field and the first wall of the device, which makes it an ideal tool for modelling fast ion wall loads, particularly in non-axisymmetric magnetic fields. In this work, the most recent 3D wall structure of AUG, updated to include the modifications for the 2010–2011 experimental campaign, and the magnetic fields from AUG discharge #26476 (B_t = 1.8 T, I_p=0.8 MA), were used. Six different cases were studied; three neutral beams Q5, Q6, and Q8 (all 93 keV and 2.5 MW) were simulated individually, each with both I_coil=0.0 kA, and $I_\mathrm{coil} = \pm 0.95$ kA current in the in-vessel coils. The coils were used in the odd parity configuration creating an n=2 perturbation (cf. Fig. 3). The effect of the in-vessel coils on the magnetic field can be seen on the ripple maps shown in Fig. 1.

The density and temperature profiles for the six cases are presented in Fig. 2. The electron temperature measurements for all the cases were within each other's error margins and, therefore, a constant T_e profile was used. In the simulations it was assumed that $T_i = T_e$. The variation in electron density between the six cases was also very

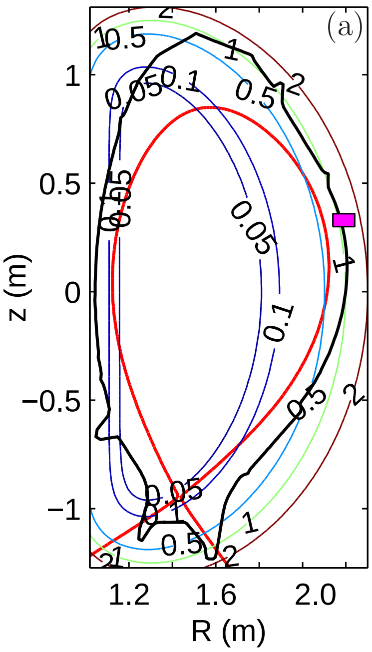

Figure 1. Ripple maps depicting $\delta = \frac{B_{\max} - B_{\min}}{B_{\max} + B_{\min}}$ in #26476 with (a) $I_{\rm coil}$=0.0 kA, and (b) $I_{\rm coil}$=0.95 kA current in the in-vessel coils (indicated by red bars on the outboard side of (b)). The magenta square marks the FILD location.

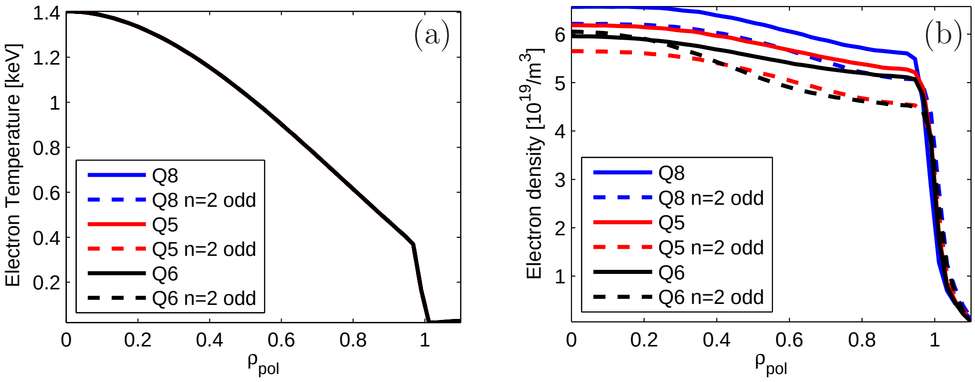

Figure 2. (a) Temperature and (b) density profiles used for the six simulated cases.

small but, since it seemed to have a clear trend (i.e. the density dropped when the coil current was on), this variation was taken into account in the simulations by using different profiles for each case. A quasineutral plasma of deuterium with carbon impurity (Z_{eff}=1.05) was used.

For every simulation, 200000 NBI test particles were generated using ASCOT NBI [7]. Their guiding-centres were then followed until they either hit a material surface or had cooled down to twice the local energy of the thermal ions. For wall hits, full-orbit collision model was used, i.e. close to material surface the particles' full Larmor-orbits, instead of their guiding-centre orbits were followed [8]. ASCOT is also capable of following the particles' full orbit throughout the simulation [9]. This is, however, computationally much (tens of times) more expensive and should therefore be used only when absolutely necessary. To check the validity of the guiding-centre results, the parallel beam Q6 was simulated using the full-orbit following and a limited number (20000) test particles.

3. Simulated wall loads due to in-vessel coils

The simulated NBI wall loads for the three neutral beams (Q5, Q6, and Q8) are plotted in Fig. 3; on the left-hand column without the magnetic perturbation, and on the right-hand column with the perturbation. The effect of the perturbation seems to vary strongly for different beams; for the more perpendicular beams the perturbation increases the losses only a little (Q5 in Figs. 3(a) and (b)), or even reduces them (Q8, Figs. 3(e) and (f)), whereas for the parallel current drive beam (Q6, Figs. 3(c) and (d)), that has the least losses to begin with, the losses increase drastically. The total losses without (with) the perturbation are approximately 5% (8%), 2% (8%) and 3% (5%) of the total beam power for the beams Q5, Q6, and Q8, respectively.

For the perpendicular beams Q5 and Q8, protruding wall structures, such as the limiters, collect the majority of the heat load both with and without the magnetic perturbation. For the current drive beam Q6, in addition to the divertor loads that are prominent in all the cases, the majority of the loads are located close to the upper set of coils where the plasma is closest to the wall. This is particularly the case in the presence of the magnetic perturbation.

Using complex 3D magnetic fields, there is always a risk that following the particles' guiding-centres washes out some of the effects that the magnetic field causes to the real particle orbits. To ensure the validity of the guiding-centre simulation results presented above, beam Q6 was simulated (both with I_{coil}=0.0 kA and I_{coil}=0.95 kA) also using the full-orbit following.

Because the full-orbit simulations are computationally very expensive, they were done with ten times less test particles than the guiding-centre simulations (20000 vs. 200000). That is why the full-orbit wall loads presented in Fig. 4 look smaller than the results from the corresponding guiding-centre simulations (3(c) and (d)). In reality, the seemingly lower losses are only due to poorer statistics and total losses are equal to the guiding-centre simulations: 2% (8%) of the total NBI power when the current in the in-vessel coils was 0.0 kA (0.95 kA). Also the locations, as well as the levels, of the peak loads are the same in the two sets of simulations.

4. Experimental vs. simulated FILD

FILD measurements are normally dominated by ELMs. Because modelling ELMs is outside the scope of ASCOT, it is important to find the inter-ELM periods and use them as the basis for modelling. Hence, the plasma profiles used in simulations are

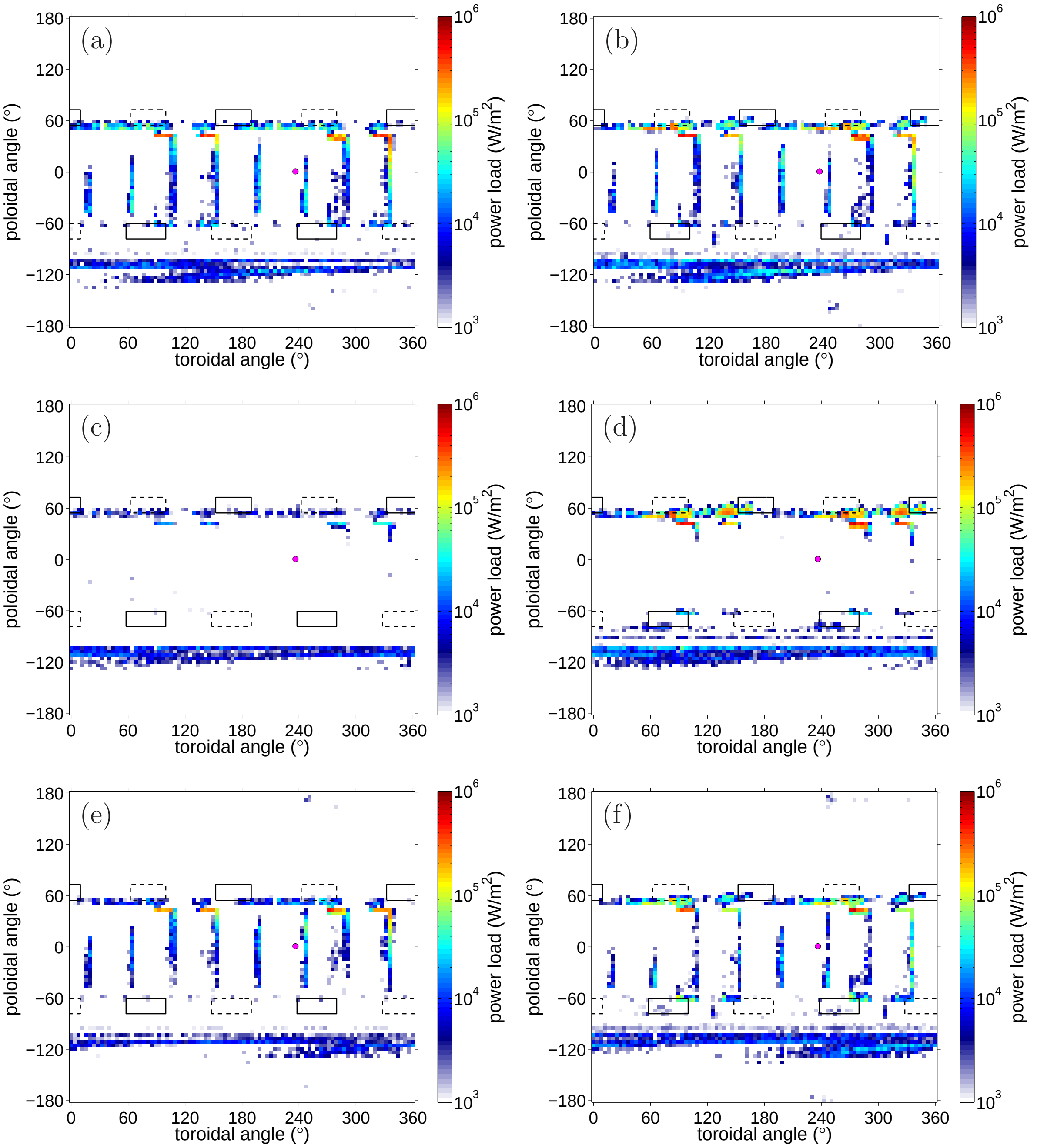

Figure 3. Simulated fast ion wall loads for: (a) Q5 with I_{coil}=0.0 A (b) Q5 with I_{coil}=0.95 kA (c) Q6 with I_{coil}=0.0 A (d) Q6 with I_{coil}=0.95 kA (e) Q8 with I_{coil}=0.0 A (f) Q8 with I_{coil}=0.95 kA. The location of the FILD is marked with a filled magenta circle, and the in-vessel coils are drawn as squares with solid (negative current) and dashed (positive current) black line.

achieved by averaging the $T_e$and n_e measurements over inter-ELM periods. Similar averaging of FILD signal makes it comparable to simulation results.

Unfortunately, when the ELMs are suppressed they do not disappear entirely, but their amplitude is decreased and frequency increased, making inter-ELM averaging

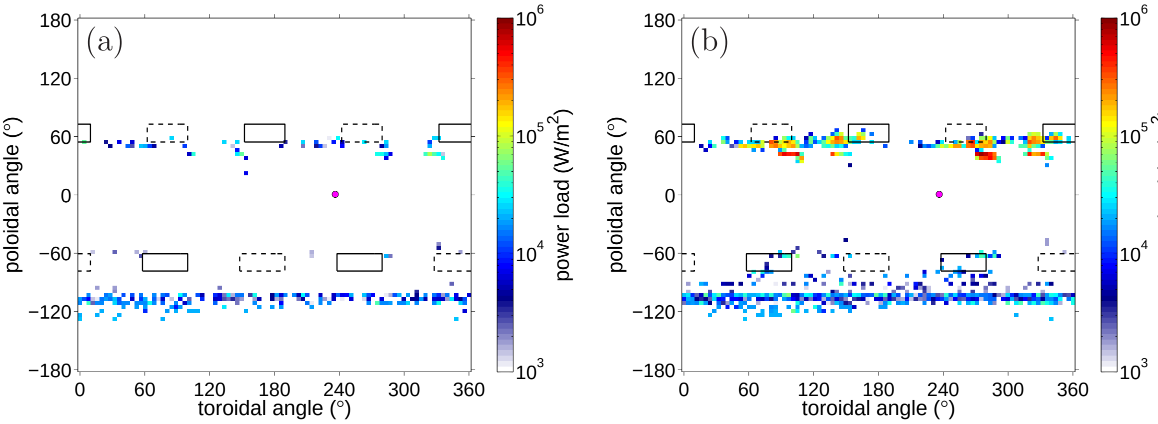

Figure 4. Simulated fast ion wall loads for the parallel beam Q6 with (a) I_{coil}=0.0 A, and (b) with I_{coil}=0.95 kA when following the full Larmor-orbits of 20000 test particles.

impossible. Therefore, for the AUG discharge of interest (#26476), good data for experimental versus synthetic FILD diagnostic comparison only exists for the time when beam Q5 was used because in that phase ELM suppression was not achieved.

The experimental results and the results from a synthetic FILD diagnostic in ASCOT are shown in Fig. 5. There is a good correspondence in the particle pitch angle ($\xi = v_{\parallel}/v$) between the measured and the simulated signal; both are centered around ξ=70°. The gyroradii of the particles seen by FILD suggest that most of them are prompt losses. This might, however, not be the case since losses induced by the magnetic perturbation may have similar pitches. Besides, the gyroradii given by FILD are not be read as absolute truth due to issues in calibration. ASCOT synthetic diagnostic on the other hand registers a broad distribution of gyroradii (i.e. energy).

Another difference between the experimental and synthetic FILD signals is the second stripe of deposition seen by ASCOT at around ξ=30°. This feature is caused by neutral beam particles ionised at the inboard side of the device and promptly (within half a millisecond) lost. Most of it is not visible in experimental data because losses with pitch angles between 0° and 30° are blocked by the FILD collimator or by other protruding first wall structures can, therefore, not be detected by FILD. Part of the difference could be due to the synthetic FILD (R=2.14–2.24 m, z=0.30–0.36 m) being deeper in the plasma than the real one. Judging from these preliminary results it seems that the in-vessel coils have a small effect on the experimental and synthetic FILD signals. However, further experiments are planned in order to collect more data to isolate the effect of the coils on the FILD signal and, hence, enable drawing the final conclusions on their effect on fast ion confinement.

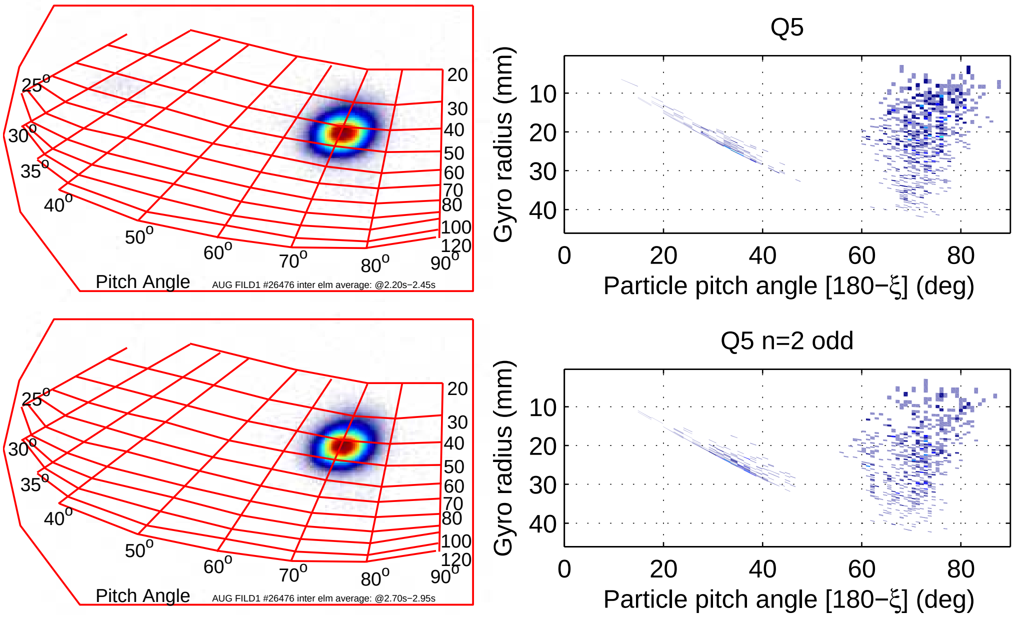

Figure 5. Comparison between experimental (left) and synthetic (right) FILD measurements for beam Q5 without (upper) and with magnetic perturbation (lower). Fast ion flux (indicated by color) is in arbitrary units in all the figures. Here $\xi = v_{\|}/v$.

5. Future work

In the future, fast particles will be simulated in a similar discharge (#26475), including the observed β-driven neoclassical tearing mode (NTM) islands. The combined effect of NTM islands and the magnetic perturbation due to the in-vessel coils are expected to increase the amount of lost particles and, therefore, the particles seen by the FILD, thus improving the statistics. In order to better isolate the effect of in-vessel coils on FILD signal, also more experiments are needed. One obvious follow-up for this work is to simulate the ELM-mitigation coils designed to ITER and their effect on confinement and losses of ITER NBI as well as fusion-born alpha-particles.

Acknowledgements: This work was partially funded by the Academy of Finland projects No. 121371 and 134924. This work, supported by the European Communities under the contract of Association between Euratom/Tekes, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The supercomputing resources of CSC - IT center for science were utilized in the studies.

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