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Abstract. Mitigating the effect of edge localized modes (ELMs) in ITER is a key issue for the integrity of the plasma facing surfaces and the longevity of the components. Introducing resonant magnetic perturbations in the magnetic field using ELM control coils is an experimentally proven method for mitigating ELMs, but the perturbations simultaneously increase energetic particle losses and resulting wall loads. Criteria for sufficient mitigation have been established in a vacuum approximation. However, the inclusion of the plasma response can change both the total losses as well as their spatial distribution, possibly resulting in unsafe peak loads. This letter presents recent results of fusion alpha and NBI ion losses in the ITER baseline scenario in a realistic magnetic field including the effect of plasma response. The plasma response was found to increase NBI losses, with up to 4.5% of the injected power being lost. Additionally, some of the load in the divertor was shifted away from the target plates, possibly exposing unprotected divertor structures to unsafe levels of heating.

1. Introduction

Operating a high performance plasma in the H-mode often results in edge localized modes (ELMs) which are violent relaxation processes of the edge pedestal region that rapidly deposit large amounts of energy in the divertor. The high power loads from ELMs are expected to be the primary driver for the erosion of the target plates in ITER, limiting the lifetime of the divertor cassettes [1]. Thus suppression or mitigation of ELMs is a critical part of the design and operation of ITER. One of the leading mitigation methods is the application of resonant magnetic perturbations (RMPs) on the plasma using an array of in-vessel ELM control coils (ECCs) [2]. While RMPs reduce the severity of the ELMs, the non-axisymmetric perturbations also reduce the confinement of energetic particles, resulting in increased fast ion losses and wall loads, both on the divertor and the blanket.

Results from experiments in DIII-D have yielded criteria associating the vacuum magnetic perturbation to ELM mitigation effectiveness [3]. The width of the region with overlapping magnetic islands, corresponding to the region of perturbation-induced stochasticity, should extend sufficently far in from the separatrix. This criteria has further been linked to the formation of a transport-enhancing island on top of the edge pedestal [4]. The DIII-D criteria have been applied to ITER, and sufficient coil currents for ELM mitigation have been determined for several ITER operating scenarios [5].

The effect of ECCs on fast ion losses has previously been modelled in the vacuum approximation [6, 7], where it was presumed that plasma would respond to the applied RMP field by dampening the penetration of the perturbations and reducing losses. Recent simulation results [8] suggest this is not generally the case, as the plasma response can increase stochasticity near the edge, even while hindering island formation deeper inside the plasma. Also of interest is the effect on the distribution of losses, where the response may diffuse or concentrate the particle flux on the plasma facing components, possibly resulting in hotspots with high peak loads.

In this letter, the effect of ECCs and plasma response on fusion alpha and NBI ion losses was studied in the ITER 15 MA Q=10 baseline scenario, in the presence of magnetic perturbations from ferritic components.

2. Model and methods

The simulations of the wall loads in this study extend the methods previously applied to the 15 MA baseline and 7.5 MA half-field cases with ferritic components [8, 9]. The particles were followed using the Monte Carlo orbit-following code ASCOT [10] in a realistic 3D magnetic field, including perturbations caused by the ripple-mitigating ferritic inserts and three pairs of European test blanket modules, which also contain ferritic components.

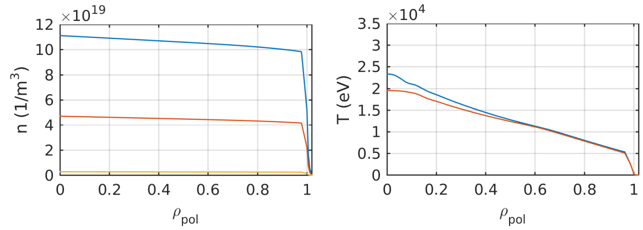

Figure 1. Electron, ion and carbon impurity densities (left) and electron and ion temperatures (right) in the 15MA baseline scenario.

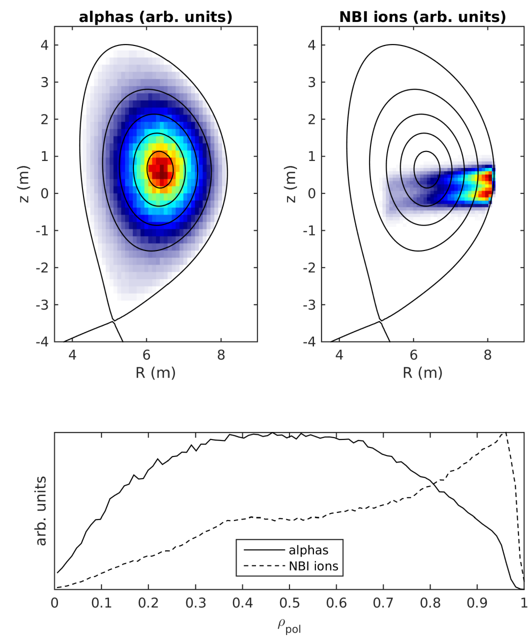

Figure 2. Initial distributions for the fusion alphas and NBI ions in the poloidal cross section (top) and as a function of the radial coordinate $\rho_{\text{pol}} = \sqrt{(\psi - \psi_{\text{axis}})/(\psi_{\text{sep}} - \psi_{\text{axis}})}$ (bottom).

The plasma equilibria (Figure 1) were prepared using a combination of 1.5D transport codes and free-boundary equilbrium codes [11]. The plasma profiles in the baseline scenario still include carbon as an impurity species, but its effect on fast ion losses has been found negligible [9]. The fusion alpha test particles were initialized uniformly in the plasma volume and weighted according to thermal fusion reactivity at their birthplace. Total fusion alpha power in the baseline scenario was 85 MW. NBI ions were generated for both injectors in both on-axis and off-axis alignment with

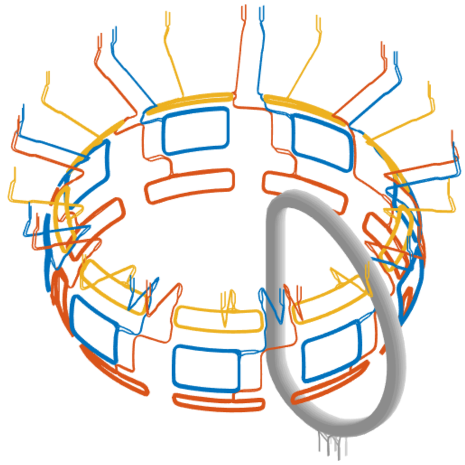

Figure 3. Upper, equatorial and lower ELM control coils and their current leads used in the calculation of the RMP field, together with an example of the TF coils.

total heating power of 33 MW. An ensemble of 600 000 test particles was used for the fusion alphas and 300 000 test particles for the NBI ions in both configurations (Figure 2).

The magnetic perturbations caused by the ferritic components were computed with the finite-element solver COMSOL [12]. In the first step, magnetization of the components was computed from the magnetic fields produced by the poloidal and toroidal coils and the plasma current. In the second step, the magnetic perturbations resulting from the magnetization were computed and added to the equlibrium magnetic field together with the toroidal field ripple. The RMP field produced by the ECCs was computed from a detailed coil geometry (Figure 3) using the Biot-Savart integrator BioSaw [6]. The coil currents were set according to the reference case for a 4.5 keV pedestal temperature baseline plasma, with an n=3 mode 45 kAt maximum current and phase shifts of 86°, 0° and 34° for the upper, equatorial and lower coil rows respectively [5].

The response of the plasma to the magnetic perturbations was computed using the resistive MHD code MARS-F [13]. Response in the toroidal modes n=1 through n=6 was included, as the contribution from the higher n modes was found to be negligible. The original vacuum approximation was used for the higher modes. As shown in the poincare plots in Figure 4, the effect of the plasma response is to significantly reduce the width of the islands near the edge of the plasma. However, the response increases the stochasticity close to the edge ($\rho_{\mathrm{pol}} > 0.95$), resulting in an increase in the lost field lines that intersect the wall. A shift of approximately 60-70 degrees in the toroidal island location can be seen, which is consistent with results in a similar study for ASDEX [14].

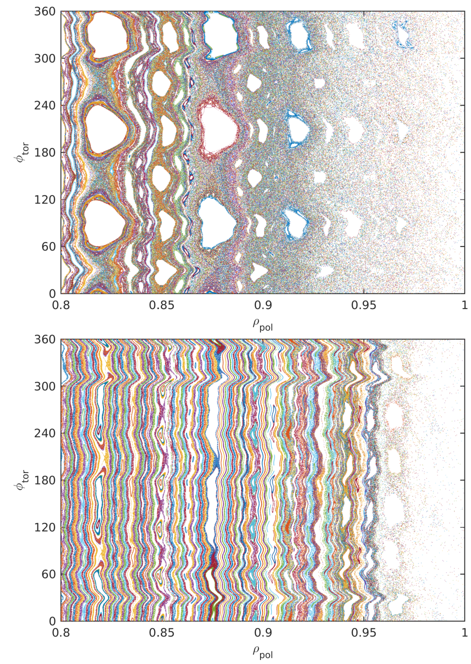

Figure 4. Poincare plots of the magnetic field line structure close to the last closed flux surface on the outer midplane. Field lines were followed from the outer midplane until they intersected the wall or completed 5000 toroidal orbits.

Table 1. Total fast ion losses, with non-ECC results from [9].

	No ECC	With ECC	
		Vacuum	Response
Alphas			
Wall	40 kW	50 kW	70 kW
Divertor	130 kW	1900 kW	1270 kW
NBI ions (on-axis)			
Wall	7 kW	1 kW	1 kW
Divertor	1 kW	1125 kW	1530 kW
NBI ions (off-axis)			
Wall	7 kW	3 kW	3 kW
Divertor	1 kW	904 kW	1250 kW

To accurately determine the particle strike points on the first wall, a 3D wall model was included in the simulations. The wall model is based on a CAD design of the first wall and divertor, which were simplified using a ray-tracing method and smoothing to approximately 300 000 triangles with a mean size of 25 cm^2.

3. Fast ion losses

Both the fusion alpha particles as well as NBI ions have previously been found to be well confined in the baseline scenario without ECCs [9]. Including the perturbations from the ECCs has negligible effect on

Table 2. Fast ion losses to the divertor separated by strike point location.

	Inner target	Outer target	Divertor dome	Below dome
Alphas				
Without response	840 kW	870 kW	178 kW	18 kW
With response	520 kW	320 kW	380 kW	54 kW
NBI ions (on-axis)				
Without response	810 kW	240 kW	40 kW	30 kW
With response	260 kW	120 kW	1060 kW	100 kW
NBI ions (off-axis)				
Without response	640 kW	210 kW	30 kW	20 kW
With response	170 kW	160 kW	840 kW	90 kW

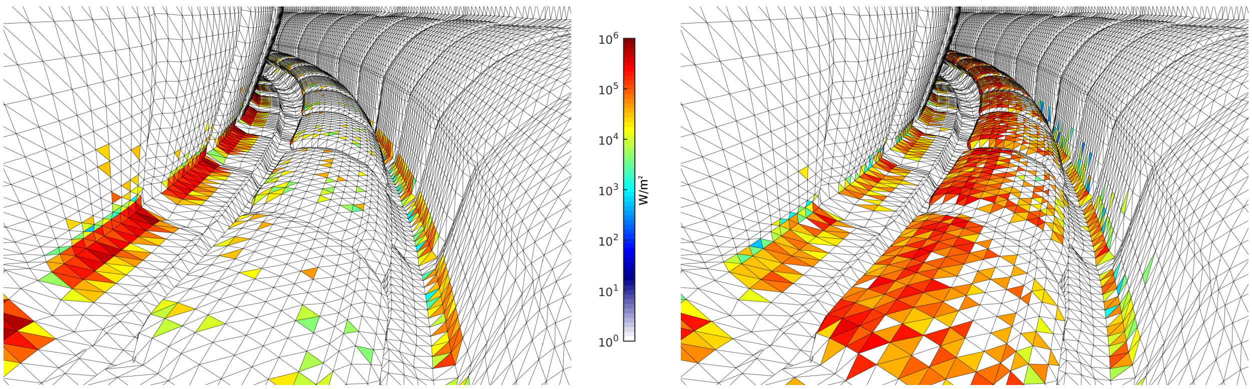

Figure 5. Peak loads due to NBI ions on the divertor targets and dome without plasma response (left) and with plasma response (right). Losses can also be observed on elements on the underside of the dome.

the energetic particle losses to the blanket (Table 1). The losses to the divertor increase dramatically, as the ECC-enhanced stochasticity rapidly depletes the particles produced or ionized near the edge.

Including the plasma response reduces fusion alpha losses by 34% due to the shielding effect in $\rho_{\mathrm{pol}} < 0.95$, as few alphas are born further out. However, the NBI ion losses increase by 36% with the plasma response, since their birth profile is peaked closer to the plasma edge where the stochasticity is enhanced. For the alpha particles, the losses represent 1.5% of the total fusion alpha power. The NBI ion losses in the off- and on-axis configurations represent 3.8% and 4.6% of the total injected NBI power, respectively. The difference between the on-axis and off-axis losses is due to the off-axis injection trajectory being located below the midplane, where the particles can reach spatially further inwards before encountering high density plasma.

Without plasma response, 94% of the power loss from NBI ions impinges on the target plates (Table 2). Upon application of the plasma response, the load is shifted to the divertor dome, which then receives 67% of the losses. The peak fluxes in the divertor are approximately 1 $\mathrm{MW/m^2}$ in both cases (Figure 5), which is within the design limits both for the targets as well as the divertor dome [15]. Of concern, however, are the fast ion losses on the underside of the divertor dome. While the simulation results show losses an order of magnitude less under the dome compared to the top of the dome, if localized, they may cause damage to the unprotected structures and cooling systems under the dome.

4. Discussion

Based on the simulation results, it is apparent that the effect of the plasma response cannot simply be assumed to be shielding, but it depends on the operating scenario, plasma profiles and the source of energetic particles. While the effect on the alpha particle losses is benign, the NBI losses approach a significant fraction of the total NBI heating power. The losses are less than predicted in previous studies where full 90 kAt coil current was applied, but even the case presented here can noticeably reduce the available heating power margin and possibly limit the plasma performance. Redistribution of the losses due to the plasma response can also expose poorly protected areas to fast ion fluxes, jeopardizing the integrity of the structures.

While including the effect of plasma response represents a step forward in the fidelity of ECC-induced fast ion loss analysis, further study is still called for. With plasma response, the shielding and amplification of the perturbations is represented in the magnetic field structure, but the equilibrium and the plasma profiles are still modelled in the vacuum approximation. The lost field lines near the edge likely cannot support as steep pedestal profiles as those resulting from the vacuum approximation. A self-consistent plasma equilibrium, including the effect of the perturbations and the plasma response, would thus be required.

With the wall model and the number of test particles used in the presented simulations, the peak loads on the divertor target plates represent reasonable estimates. Modelling the peak heat load on the structures under the divertor dome, however, would require more detailed wall geometry that includes the cooling systems and support structures, to identify any localized heating that could damage the components.

Acknowledgements

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