The Effect of Plasma Response on Losses of Energetic Ions in the Presence of 3D Perturbations in Different ITER Scenarios

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Abstract:

Large quantities of energetic particles, including fusion alphas and NBI and ICRH accelerated ions, will be present in ITER plasmas. Their confinement is vital both for fusion performance as well as machine protection. Past analyses of the fast ion confinement have primarily been restricted to vacuum approximation This approach does not take into account the dynamic response of the plasma to external perturbations produced by, e.g., ferritic components inside the vessel, or the ELM control coils. For long, neglecting plasma response has not been considered an issue because it was assumed that the plasma response simply shields the plasma from external perturbations. However, some recent simulation results suggest this is generally not the case, and the plasma response can in some cases increase the edge stochasticity and corresponding fast ion losses. In this contribution we employ magnetic backgrounds where the plasma response has been included as calculated by the MARS-F code. The Monte Carlo orbit-following code ASCOT is used to simulate the fast particles in a full 3D magnetic configuration with plasma response and a 3D wall. The analyses cover all major operating scenarios of ITER. Comparing the present simulation results to the ones obtained in vacuum approximation shows that with only ferritic components, the plasma response increases the small total load by up to 10-15%. However, when the perturbation due to ELM control coils is included, the plasma response brings about significant changes in the power deposition and, in some cases, even increases it.

1 Introduction

The new physics introduced by ITER operation, of which there is very little prior experience, is related to the very energetic (3.5 MeV) alpha particles produced in large quantities in fusion reactions. These particles not only constitute a massive energy source inside the plasma, but also present a potential hazard to the material structures that provide the containment of the burning plasma. In addition, the negative neutral beam injection (NBI) produces 1 MeV deuterons which have to be well confined to ensure successful operation of ITER.

In ITER the confinement of energetic ions is compromised by a variety of components breaking the axisymmetry of the magnetic field. The periodic magnetic perturbation due to the finite number of toroidal field (TF) coils (18 in ITER) is mitigated by ferritic inserts (FI), and the magnetic field at the edge is further perturbed by test blanket modules (TBM), made of ferromagnetic material and installed to test tritium breeding. Finally, in-vessel ELM control coils (ECC) introduce a strong periodic magnetic perturbation.

Past analyses of the fast ion confinement have typically been restricted to vacuum approximation [1, 2, 3]. This approach does not take into account the dynamic response of the plasma to the external perturbations due to FIs, TBMs and ECCs. For long, this has not been considered an issue because it is known that the plasma response tends to shield the plasma from external perturbations.

However, recent simulation results [4] suggest this is not generally the case. While hindering island formation deep inside the plasma, the plasma response can increase stochasticity at the very edge of the plasma. If the source of energetic ions does not vanish in this region, the stochastic field lines can transport these ions to the walls very rapidly and, thus, with very high energy.

In this contribution we present a comprehensive study of the effect of plasma response, as calculated by the MARS-F code, on fast ion losses simulated with the ASCOT code. The analyses cover all major operating scenarios of ITER, including the non-nuclear 7.5 MA half-field and half-current scenario, the 15 MA baseline scenario, the 12.5 MA hybrid scenario and the 9 MA steady-state scenario. All scenarios include the perturbations due to the ferritic components. In addition, the effect of ECCs was studied in the 9 MA and 15 MA scenarios.

2 Model and methods

The energetic ion losses were simulated using the Monte Carlo orbit-following code ASCOT [5]. The alpha population was generated according to the fusion reactivity, given by the density and temperature profiles corresponding to the stationary flat-top phases of the different operating scenarios using the ASCOT fusion source integrator AFSI. The NBI population was generated by following neutrals from the injector until ionization with the BBNBI code [6]. The particles were followed until they were thermalized or intersected a 3D wall based on CAD design of the ITER first wall.

The magnetic field was constructed from an axisymmetric equilibrium field into which the various perturbations were added. The ripple due to the 18 toroidal field coils was computed from accurate coil geometry using the Biot-Savart integrator BioSaw [7]. The

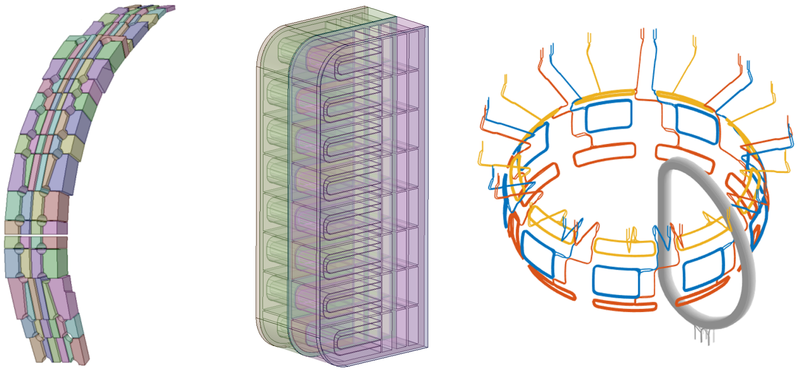

FIG. 1: The basic ITER components contributing to the structure of the magnetic field in this study: The ferritic inserts (left), test blanket modules (middle) and ELM control coils (right).

perturbations due to the magnetization of the ferritic components were computed with the FEM-solver COMSOL using simplified geometries of the ferritic inserts and test blanket modules (Figure 1 left and middle). For the 9 MA steady-state and 15 MA baseline scenarios, also cases with ELM control coils (Figure 1 right) were simulated. The RMP field was also computed from the realistic coil geometry, with currents and phasings according to criteria developed at DIII-D and applied to ITER [8].

The plasma response to these perturbations was computed using the resistive MHD code MARS-F [9]. The plasma response to high toroidal mode numbers ($n > 4$) was found to be very weak and, therefore, the MARS-F analysis was carried out only for modes $n = 1 - 6$. The process consisted of providing MARS-F with the amplitudes of the relevant toroidal modes of the magnetic field and then using the new amplitudes calculated by MARS-F to replace the original ones in our magnetic field while keeping the rest of the components untouched.

3 Results

As seen in Poincare plots of the magnetic field in the 7.5 MA hybrid scenario (Figure 2), the plasma response effectively shields the perturbations inside the plasma, reducing the width of magnetic islands. However, the stochasticity close to the separatrix is actually increased. The same effect was observed also in the other scenarios. The effect of the plasma response on the fast ion losses was, however, found to be small in most cases without ELM control coils (Table I). The divertor loads are generally increased, indicating that particles on passing orbits are most affected by the plasma response. Of particular note is the 12.5 MA hybrid scenario, in which the losses are the highest. This was found to be due to the shape of the plasma in this scenario, where the higher triangularity brings the separatrix closer to the wall.

The effect of the plasma response changes dramatically with the inclusion of the ELM

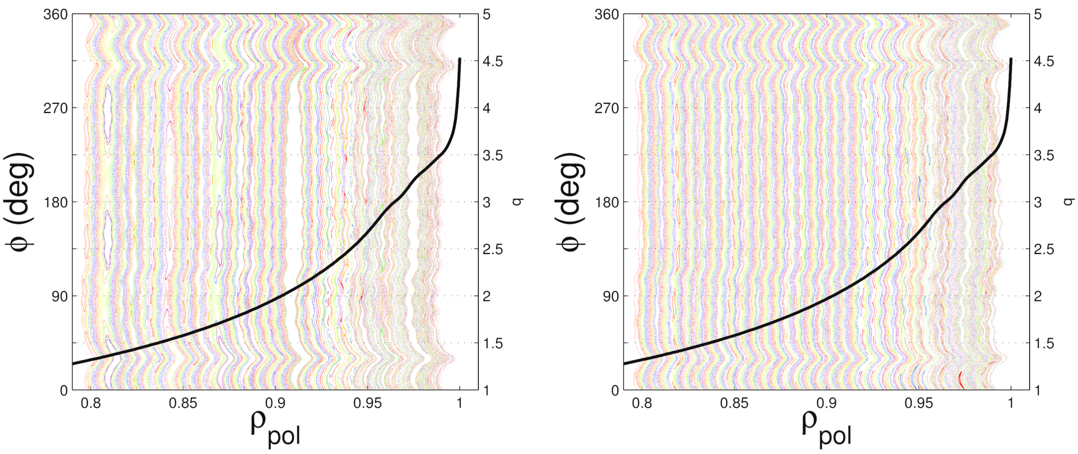

FIG. 2: Poincare plots at the outer midplane of the magnetic field edge in the 7.5 MA scenario, with (right) and without plasma response (left) and the q profile depicted in black.

TABLE I: Total fast ion losses with and without plasma response.

	Alphas		NBI ions	
	Vacuum	Response	Vacuum	Response
7.5 MA half-field scenario				
Wall			19 kW	19 kW
Divertor			0 kW	3 kW
9 MA steady-state scenario				
Wall	250 kW	270 kW	15 kW	14 kW
Divertor	130 kW	180 kW	2 kW	9 kW
12.5 MA hybrid scenario				
Wall	580 kW	640 kW	7 kW	8 kW
Divertor	190 kW	210 kW	1 kW	3 kW
15 MA baseline scenario				
Wall	39 kW	42 kW	7 kW	0 kW
Divertor	110 kW	130 kW	1 kW	0 kW

TABLE II: Total fast ion losses with ELM control coils in the 9 MA and 15 MA scenarios.

	Alphas		NBI ions	
	Vacuum	Response	Vacuum	Response
9 MA scenario with ECC				
Wall	340 kW	394 kW	14 kW	14 kW
Divertor	950 kW	580 kW	1038 kW	778 kW
15 MA scenario with ECC [10]				
Wall	70 kW	157 kW	5 kW	5 kW
Divertor	1925 kW	1343 kW	1150 kW	1279 kW

control coils (Table II). As previously reported in [10], the alpha losses in the 15 MA baseline scenario are reduced compared to the vacuum approximation case, as they are primarily born deeper inside the plasma, whereas the NBI ions, born closer to the edge in the region of increased stochasticity, are more rapidly lost. The situation is different in the 9 MA steady-state scenario with the ELM control coils included. The alpha losses decrease as in the 15 MA scenario, but also the NBI ion losses are reduced with plasma response. This is explained by the different birth profiles of the NBI ions, as the particles can penetrate deeper into the plasma before ionization in the lower density of the 9 MA scenario and thus avoid the increased stochasticity near the edge. The peak wall loads (Figure 3) remain below 500 kW/m^2, with the losses primarily concentrated at the outer midplane and near the upper ELM coil row.

4 Conclusions

The confinement of energetic particles was not found to be dangerously compromised with the inclusion of the plasma response. However, while the effect of the plasma response remains small in most of the studied scenarios, the dramatic effect in the ELM control coil cases demonstrates the importance of including the response in future fast ion studies.

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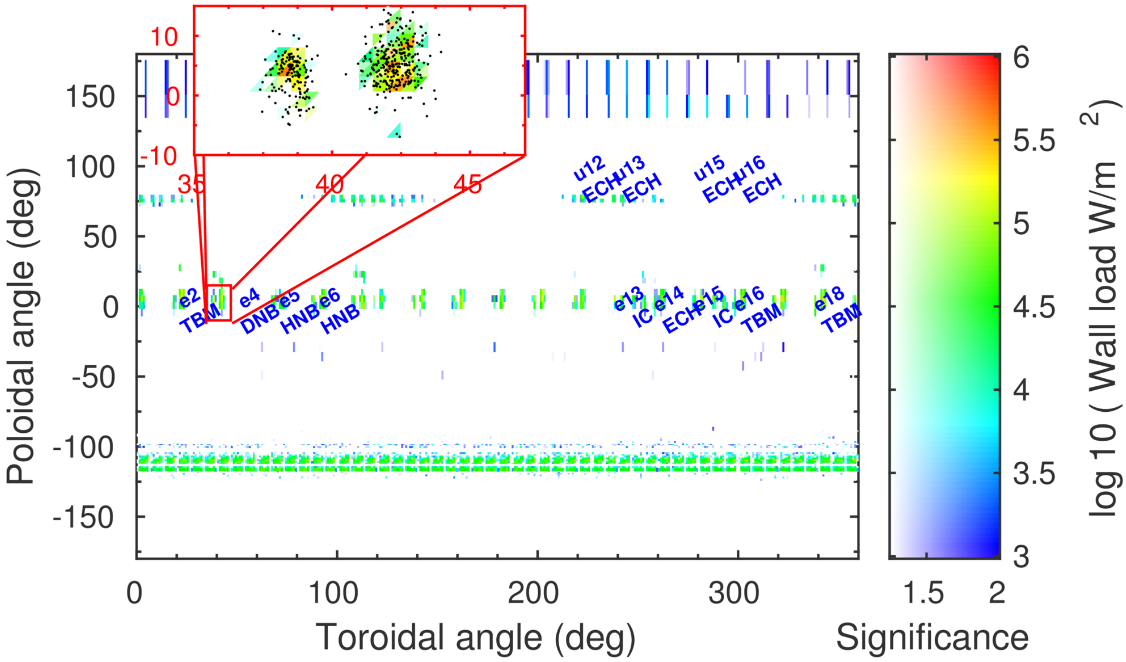

FIG. 3: Wall loads in the 9 MA scenario with ELM control coils and plasma response.

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