Mechanics of ELM control coil induced fast particle transport in ITER

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Abstract

Using the orbit-following code ASCOT, we have modelled fast ion transport in ITER under the influence of ELM control coils (ECCs), toroidal field ripple, and test blanket modules, with emphasis on how the plasma response (PR) modifies the transport mechanisms and fast ion loads on the divertor. We found that while PR shields the plasma by healing broken flux surfaces at the plasma periphery, it also opens a new loss channel for marginally trapped particles: PR causes strong toroidal variation of the poloidal field near the X-point which leads to de-localisation of banana tips and collisionless transport. The reduction in passing particle losses and the increase in marginally trapped particle losses shift divertor loads from targets to the dome and under-the-dome structures. The plasma response was calculated by both MARS-F and JOREK codes. The new transport mechanism was stronger for PR calculated by JOREK which, unlike MARS-F, explicitly includes the X-point.

Keywords: ELM control coils, ITER, fast ions, plasma response

1. Introduction

ITER will be equipped with ELM control coils (ECCs) to mitigate the detrimental effects of edge localized modes (ELMs). Their application further compromises the axisymmetry of ITER and creates a stochastic field line region at the edge, thus possibly deteriorating the confinement of fast ions. Understanding the ECC-induced fast-ion transport has mostly relied on models using the so-called vacuum approximation where the plasma response (PR) has been ignored [1–3]. Lately, modelling of PR with MHD codes has progressed rapidly [4, 5], and ECCs have gained renewed interest in the fast ion community [6–10]. Plasma response ‘heals’ part of the stochastic region and, thus, the vacuum approximation is expected to give a conservative estimate on total losses. This was indeed the case when losses in vacuum approximation were compared to losses including PR for ITER [11]. However, PR was found to redistribute the loads on the divertor: dome and under-the-dome structure loads were higher than they were with the vacuum approximation, while target loads were lower. Furthermore, the ions were lost at higher energy. The redistribution of divertor loads is relevant mainly from the fast-ion diagnostics point-of-view [12] but also because the under-the-dome structure holds cooling pipes whose maximum allowed heat load is much smaller than that of other divertor components [13].

To understand why the redistribution of losses occur, and whether this is true in general, we continue the work reported in [11]. We aim to identify dominant loss mechanisms in the presence of ECCs and PR by modelling alpha particle and beam ion transport with an orbit-following code. Because ITER-relevant ECC-induced fast-ion simulations involving PR are a relatively new topic, we seek to verify the results by comparing the fast ion transport when PR is provided by two different MHD codes.

The paper is organized as follows. Section 2 gives an overview of the orbit-following and MHD codes used in this work along with a brief description of simulations and methods. In section 3, we use the simulation results to identify the transport mechanisms causing the alpha particle losses. In section 4,
we show how these mechanisms lead to a redistribution of divertor losses. We find that the redistribution is partly due to a new loss mechanism caused by PR, and we discuss this finding in section 5. The beam results are analyzed separately in section 6. Finally, section 7 explores how the loss dynamics are affected when the current in ECCs is chosen so that the minimum or maximum plasma response is achieved.

2. Overview of the models used to evaluate the plasma response and fast ion losses

The slowing-down simulations are carried out using the methods established in [14]. We simulate markers representing fast ion population until they either thermalize or come in contact with a material surface. The simulations are carried out with the orbit-following code ASCOT [15]. ASCOT supports an arbitrary 3D magnetic field, given on a cylindrical Rzø-grid, and as such it can model transport processes arising from a stationary non-axisymmetric magnetic field in addition to neo-classical transport.

The simulations correspond to the ITER baseline \( I_p = 15 \text{ MA H-mode scenario} \) where ECCs are operated with \( n = 3, I = 45 \text{ kA} \). Two different MHD codes are used to calculate the plasma response: MARS-F [16] is a one-fluid, linear (each \( n \) solved independently) code solving the full resistive MHD equations in toroidal geometry. JOREK [4] is a two-fluid, non-linear code solving the reduced MHD equations in toroidal geometry which (unlike for MARS-F) includes the divertor and X-point. JOREK recalculates equilibrium, which is used in corresponding ASCOT simulations. For ECCs, the toroidal phases, \([\Phi_U, \Phi_M, \Phi_L]\), for upper, middle, and lower coils were taken from [17]; \([86^\circ, 0^\circ, 34^\circ]\). However, different phases were used in JOREK; \([58^\circ, 0^\circ, 6^\circ]\).

The fast ion losses are known to depend on the phase-difference between the coils [7, 9], so we except some difference in results. But, as we shall report later on, the results are similar and the most distinct differences in the results can be attributed to the fundamental differences between the codes themselves. As such, the difference in coil phases does not play a significant role on the conclusions of this work. Another difference in the MHD simulations was the resistivity, which is the main factor in screening. In JOREK, \( S = 7 \times 10^9 \) (central Lundquist number) was used, and \( S = 1 \times 10^{11} \) in MARS-F.

To include PR in ASCOT magnetic field, the vacuum field given in cylindrical grid is decomposed into toroidal harmonics, and the \( n = 1-6 \) harmonics are used as an MHD code input. The results of the MHD code replace the original \( n = 1-6 \) harmonics in the vacuum field and give the full plasma response field. JOREK takes as an input the toroidal component of the vector potential whose Fourier coefficients are interpolated with splines from ASCOT (R,z)-grid to JOREK grid. To import data from JOREK to ASCOT, the magnetic field components are first calculated from the vector potential, then the coefficients are spline-interpolated to ASCOT grid, and, finally, inverse Fourier transformation is performed.

For MARS-F the procedure is similar with the exception that only magnetic field is used (not vector potential) and Fourier decomposition is done also in the poloidal direction. The MARS-F calculations are described in detail in [18].

3. Modification of the loss channels due to ECCs

Slowing-down simulations were done for four cases: no ECCs (OFF), ECCs included in vacuum approximation (VAC), and ECCs included with plasma response solved with JOREK (JPR) or MARS-F (MPR). All cases include also TF ripple, mitigated by ferritic inserts, and test blanket modules. The magnetic field structure in each case is illustrated with a Poincaré-plot in the top row in figure 1. Generally, the field structure can be divided into three domains: a closed field-line region with healthy flux surfaces, a stochastic region where field-lines are chaotic, and a laminar region which is otherwise similar to stochastic region but where field-lines intersect wall within a few poloidal orbits and as such appear as a sparse or empty area at the very periphery in Poincaré-plots. The stochastic and laminar regions are born when islands overlap radially. In VAC, the coils make the field stochastic down to \( \rho \approx 0.85-0.9 \), where \( \rho \) is the square root of the normalized poloidal flux, \( \rho = 1 \) at the separatrix. In ideal plasmas, the penetration of external fields would be completely screened by the plasma response. However, with finite resistivity, the plasma response heals only some of the flux surfaces and enhances the laminar region next to the separatrix. The enhanced stochasticity is partly due to lower screening caused by higher resistivity at the edge, but it is also possible that the plasma response amplifies the magnetic islands, via toroidal coupling to the so-called edge peeling response [19].

With JPR, the laminar region extends down to \( \rho \approx 0.97 \), followed by a narrow stochastic region. With MPR, the laminar region extends down to \( \rho \approx 0.98 \) and the stochastic region to \( \rho \approx 0.95 \).

One would expect that the depth of stochastic/laminar region correlates with passing particle losses. To see whether this is the case, we map the initial \((R, z, \phi, \xi = v|/v)\) position of the simulated markers to a \((\rho', \xi')\)-space where \(\rho'\) and \(\xi'\) are the values the marker would have at outer midplane (OMP). Because trapped particles have two points where they cross OMP, we choose the one where the signs of \(\xi\) and \(\xi'\) are same. The \((\rho', \xi')\) coordinates determine not only which particles are trapped but they are also a major factor in determining how a particle responds to the 3D field structure. We make use of the latter point in the middle row of figure 1 which shows the fraction of lost particles evaluated as a function of \((\rho', \xi')\). The regions where majority of particles are lost appear as yellow, and we refer to them as loss channels. These channels are caused by various transport mechanisms:

- \(|\xi'| \lesssim 0.2\). Direct-ripple and ripple-enhanced losses. Because ECCs only slightly increase magnitude of the TF ripple, this loss channel is similar in each case. In JPR, the losses are slightly smaller because the outer gap is somewhat larger in JOREK-calculated equilibrium.
- \(0.2 \lesssim |\xi'| \lesssim 0.6\). Stochastic ripple losses arise when trapped particle turning point location is in a region where the TF ripple is strong enough to cause orbit stochasticization.
As they depend on TF ripple magnitude, stochastic ripple losses are only slightly increased by the ECCs. No increase is seen between VAC and JPR cases nor it is expected due to JOREK using the reduced MHD model. However, there is an increase between VAC and MPR.

\[0.6 \lesssim |\xi'| \lesssim 0.7\]. Marginally trapped particles lost via yet unidentified mechanism(s). These are present in all cases, enhanced in VAC, and further increased in JPR and MPR.

\[0.7 \lesssim |\xi'|\]. Stochastic or open field-line losses. Nearly all passing particles are lost in regions where the field is stochastic or laminar.

The fraction of losses is asymmetric in \(\xi'\) because ones with \(\xi' < 0\) are born in counter-current direction and, thus, are moved outward by the gradient drift.

The bottom row of figure 1 shows the time during which particles were lost. Bounce time is approximately \(10^{-3}\) s, and so prompt losses correspond to roughly \(t_{\text{bou}} < 10^{-4}\) s. This is seen to correspond to parameter regime \((\xi' \approx -0.7 \text{ to } -0.6, \rho' \gtrsim 0.92)\) in all cases. These are marginally trapped particles whose orbits are wide enough for the particle to exit the plasma and cross material surface. Likewise particles at \((\xi' \approx -1.0 \text{ to } -0.7, \rho' \gtrsim 0.96)\) are passing particles that are lost due to the outward drift. Dark blue regions in the middle and bottom rows in figure 1 correspond to slowed-down particles that were not born inside a loss channel but have entered it collisionally.

The results show that VAC indeed gives a conservative estimate on losses but only with respect to passing particles. However, the large ’spikes’ around \(\xi' \approx -0.7\) to \(-0.6\), and smaller ones at \(\xi' \approx 0.6\) to \(0.7\), in figures 1(g), (h), (k) and (l) shows, once we neglect the prompt losses, that PR gives birth to a new loss channel affecting marginally passing particles. For convenience, we refer this new channel as perturbed banana transport (PBT). PBT features characteristics similar to the ripple transport: it penetrates into the plasma and causes rapid losses which indicates that PBT might also be due to a convective or resonant process.

Figure 1. Alpha loss dynamics for the different cases. Note that in all plots lower horizontal axis corresponds to \(\rho'\) (for field-lines \(\rho' = \rho\)) while upper axis shows the corresponding 
\(R\), i.e. the major radius, at OMP. The magnetic axis is at \(R = 6.20\) m and the separatrix at \(R = 8.16\) m except in JPR case where it is at \(R = 8.10\) m. (a)–(d) Field-line Poincaré-plot at OMP where colors indicate different field lines. Dotted red line shows approximately the boundary between the closed field line and stochastic regions while the dashed red line marks the boundary between stochastic and laminar regions. (e)–(h) Fraction of particles lost, \(N_{\text{lost}}/N\), where \(N = N(\rho', \xi')\) is the number of particles whose initial location corresponds to \((\rho', \xi')\). White regions correspond to no losses. The dashed black lines roughly show the trapped-passing boundary. (i)–(l) Mean loss time as a function of markers’ initial position.
4. Re-distribution of the divertor loads

Figure 2 shows how the losses are distributed among three different divertor subregions: target consisting of inner and outer target plates, dome umbrella, and the unprotected under-the-dome cooling pipes. In the absence of ECCs, the loads are almost non-existent. Introducing the ECCs in vacuum approximation increases loads on all components. Including PR decreases the loads on target but increases dome and under-the-dome loads. The total alpha particle losses were OFF: 0.2 MW, VAC: 2.0 MW, JPR: 1.2 MW, and MPR: 1.5 MW. The heat loads to first wall are not shown in figure 2 but also they see a slight increase when PR is included.

To understand the shift in divertor loads, one must first identify the type of particles contributing to it. The target loads are mainly due to passing particles, but also marginally trapped particles with trajectories falling below the X-point can contribute. However, losses of marginally trapped particles are predominantly on the dome. Particles that miss the dome but encounter a second reflection before reaching the target can end up on the pipes. The divertor loads are shifted because PR decreases passing particle transport while increasing the marginally trapped particle transport. The dome and under-the-dome loads are higher in JPR compared to MPR because PBT was stronger in the former.

5. Mechanism responsible for the marginally trapped particle losses

The mechanism responsible for PBT is not the stochastic ripple diffusion because it arises also in JOREK case where the toroidal field stays invariant. There is a difference in toroidal field with MARS-F plasma response, as figure 3 shows, but this difference does not extend to the high-field side where the marginally trapped particles have their turning points. As such, this difference in toroidal field is unlikely to be the cause of PBT. However, we point out that the increased toroidal field variation near separatrix in MPR case could be the cause of increased transport of particles with $0.2 \lesssim |\xi'| \lesssim 0.6$ (figure 4) whose turning points lie in the affected region and that are known to experience the stochastic ripple transport.

The mechanisms behind PBT appears to be due to the toroidal variation of the poloidal magnetic field strength near the X-point. Figure 4 shows how PR both enlarges the area of significant poloidal field variation and strengthens it locally, in particular near the X-point. The same marker alpha, chosen from the $(\rho', \xi')$ region affected by PBT, is simulated for each case and the resulting trajectories are also shown in figure 4. The marker shows no radial transport in the OFF case, again eliminating the TF ripple as a possible mechanism. In VAC, the banana tips wander, but only in MPR and JPR these changes are strong enough for the marker to exit the plasma even without experiencing any collisional scattering. The changes in the banana tip location are strongest in JPR which also has the strongest poloidal field variation.

Figure 2. Origin of the lost alpha power, $P_{\text{lost}}$, to the divertor. Illustration of (a) the first wall and (b) the divertor components: target (blue), dome (orange), and under the dome cooling pipes (purple). In (a), the poloidal flux contours shows the region where majority of the losses originate in $R_z$-plane. The solid trajectories in (b) illustrate how particles end up to the different components. The origin of the lost power, in $(\rho, \xi')$-space, is shown in (c)–(e). Note the white horizontal stripes in (c) are due to all particles being lost on or under the dome. Power load to different divertor components is given in (f)–(h), with red bars indicating the Monte Carlo error.

Figure 3. Contours of toroidal field ripple $\delta B_\phi = \left(\langle B_\phi \rangle_{\text{max}} - \langle B_\phi \rangle_{\text{min}}\right) / \left(\langle B_\phi \rangle_{\text{max}} + \langle B_\phi \rangle_{\text{min}}\right)$ where the brackets indicate toroidal maximum or minimum, on an $R_z$-plane with and without MARS-F plasma response. The first wall (solid curve) and the separatrix (dashed) are also shown.
The observed behaviour can be explained by noting that the poloidal field strength near the X-point has a large effect on how much the $V B$-drift contributes to the orbit width. If the poloidal field is weak, the particle travels longer almost toroidally. The poloidal field around the X-point is small and the poloidal field is weak, the particle travels longer almost toroidally. Even a weak perturbation there has a noticeable effect on the particle trajectory. When the poloidal field varies toroidally, the trajectories would not extend beyond the X-point, and for higher $\rho$, the trajectories would not extend beyond the X-point, while for higher $\omega_{bnc}$, the trajectories would be trapped if the resonance condition is satisfied for 1 $\times$ 10$^{-3}$ s with collisions disabled.

If this explanation is correct, it would explain why we observe PBT for alphas with $|\xi'| \approx 0.6$–0.7. If $|\xi'|$ were to be smaller, the trajectories would not extend beyond the X-point, while for higher $|\xi'|$ values the alphas are already on passing orbits. However, as shown in figure 5, these orbits also meet the resonance condition $k = n\omega_{bnc}/\omega_{bnc}$, where $\omega_{bnc}$ is the toroidal precession frequency, $\omega_{bnc}$ is the bounce frequency, and $n$ is toroidal mode of the perturbation (for ECCs $n = 3$). Orbits resonate with the perturbation if $k = 1, 2, 3, \ldots$ and, therefore, it is possible that the $k = 1$ resonance enhances the PBT mechanism for alpha particles. There is no such resonance for beam particles, whose results we study in the next section.

6. Beam ion losses

Beam ions are deuterium with birth energy of 1 MeV. They are born on co-passing orbits at the edge and thus are well-confined (total losses less than 10 kW) in the absence of ECCs. Losses in the presence of ECCs are collected in table 1 which shows a major increase, with practically all losses ending up to the divertor. The plasma response calculated with JOREK was simulated for $\rho'$ = 0.91 as a function of OMP pitch value.


![Figure 4. Poloidal field, $B_\theta$, variation along the toroidal direction in different cases. The contours show the normalized variation, $\delta B_\theta = \left( \langle B_\theta \rangle_{max} - \langle B_\theta \rangle_{min} \right) / \left( \langle B_\theta \rangle_{max} + \langle B_\theta \rangle_{min} \right)$, on an R-$\rho$-plane. The red curves show the trajectory of a sample 3.5 MeV alpha marker with initial location $(\rho) = 0.9$, $(\xi') = -0.65$. The marker was simulated for $1 \times 10^{-3}$ s with collisions disabled.](image)

The most distinct feature in PR cases is that the origin of the losses moves towards the separatrix. This happens because the stochastic layer no longer penetrates as deep into the plasma, and so less particles get scattered into the stochastic field-line transport region. Even though the loss region is smaller in PR cases, locally the fraction of markers lost is greater, and, in some regions, particles are lost at sub-collisional time scales.

We can identify that three mechanisms contribute to the losses: the stochastic field-line transport, PBT mechanism, and stochastic ripple transport. The stochastic field-line transport affects passing particles ($\xi' > 0.7$) with $\rho' > 0.95$ in both JPR and MPR cases (figure 6), but this channels is stronger in MPR because the stochastic region is wider. The decrease in trapped particle loss time in region $0.7 > \xi' > 0.3$, $\rho' > 0.95$ is due to PBT mechanism in JPR case. The PBT mechanism is not as distinct here as it was for the alpha particle simulations, and this could be due to the smaller orbit width or the lack of resonance (recall figure 5). In MPR case, the presence of PBT mechanism is hard to confirm in region $\xi' \approx 0.7$ although it seems to be present at $\xi' \approx -0.7$. On the other hand, the trapped particle transport is increased overall which indicates enhanced stochastic ripple transport.

![Figure 5. Resonance condition $k = n\omega_{bnc}/\omega_{bnc}$, where $n = 3$, for trapped particles at $\rho' = 0.91$ as a function of OMP pitch value. Shaded region shows the location of the transport channel at $\xi' \approx -0.7$ to $-0.6$ in figure 1. The resonance condition is shown at $\rho' = 0.91$ because it excludes first-orbit losses, and also because $(\rho' = 0.91, \xi' = -0.6)$ 1 MeV deuterium markers correspond to those at $(\rho' = 0.99, \xi' = -0.6)$, i.e. where the actual beam ions are born.](image)

Table 1. Beam ion power loads by case assuming full beam power of 33 MW.

| Case | Target (kW) | Dome (kW) | Pipes (kW) | Total (MW) |
|------|------------|-----------|------------|------------|
| VAC  | 920        | 170       | 40         | 1.2        |
| JPR  | 190        | 680       | 80         | 0.9        |
| MPR  | 400        | 770       | 80         | 1.3        |

* Includes wall loads.

Beam results are displayed in figure 7 which shows that the beam birth population (for particles born at the edge) is localised at the region $0.5 < \xi' < 0.7$.

In VAC case, there is no strong transport mechanism present in this region and, as such, the particles are lost only after being scattered by collisions. The fraction of particles lost is larger at higher $\xi'$ values which indicates that particles are lost when collisions have scattered them to the stochastic field-line transport region ($\xi' > 0.8$).

The most distinct feature in PR cases is that the origin of the losses moves towards the separatrix. This happens because the stochastic layer no longer penetrates as deep into the plasma, and so less particles get scattered into the stochastic field-line transport region. Even though the loss region is smaller in PR cases, locally the fraction of markers lost is greater, and, in some regions, particles are lost at sub-collisional time scales.

We can identify that three mechanisms contribute to the losses: the stochastic field-line transport, PBT mechanism, and stochastic ripple transport. The stochastic field-line transport affects passing particles ($\xi' > 0.7$) with $\rho' > 0.95$ in both JPR and MPR cases (figure 6), but this channels is stronger in MPR because the stochastic region is wider. The decrease in trapped particle loss time in region $0.7 > \xi' > 0.3$, $\rho' > 0.95$ is due to PBT mechanism in JPR case. The PBT mechanism is not as distinct here as it was for the alpha particle simulations, and this could be due to the smaller orbit width or the lack of resonance (recall figure 5). In MPR case, the presence of PBT mechanism is hard to confirm in region $\xi' \approx 0.7$ although it seems to be present at $\xi' \approx -0.7$. On the other hand, the trapped particle transport is increased overall which indicates enhanced stochastic ripple transport.
This analysis confirms the redistribution of the divertor loads (table 1): reduced stochastic field-line transport decreases the target loads while the appearance of PBT mechanism in JPR case increases the dome loads. For MPR case, the increased dome loads cannot be clearly attributed to PBT and the stochastic ripple transport might have a larger role. This is difficult to confirm based on these results as the mean loss time is 0.01 s–0.1 s, meaning the collisional scattering can change particle’s initial orbit topology before it is lost. The target loads in MPR are a factor of two greater than in JPR, which is why the total loads between these two cases were different. The greater target loads can be attributed to the wider stochastic layer in the MPR case.
7. Simulations with minimum and maximum plasma response

So far our analysis has been limited to ECC current configurations that are considered for an actual ITER operation. Repeating the analysis for several different configurations would help us to establish the relative importance of the PBT mechanism and increase the confidence in results. Unfortunately, the orbit-following simulations are rather expensive to perform so we limit our additional simulations to two cases: one with minimum and one with maximum plasma response. A series of MARS-F calculations has been performed in [21] from which we choose the minimum and maximum cases—the figure of merit being the displacement of the X-point due to the plasma response. We do not repeat these simulations with JOREK and use only the MARS-F to compute the plasma response. Furthermore, in order to facilitate these simulations, we only include the $n=3$ component of the ECC perturbation. We also increase the coil current to $I=90$ kAt to see whether this affects the relative importance of different transport mechanisms.

Both beam and alpha particle slowing down simulations were done for the minimum (MIN) and maximum (MAX) cases; first with vacuum approximation (VAC) and then with the plasma response (PR). The corresponding toroidal phases are $[115^\circ, 0^\circ, 23^\circ]$ (MIN) and $[56^\circ, 0^\circ, 77^\circ]$ (MAX).

### Table 2. Fast ion power loads in cases with minimum and maximum MARS-F calculated plasma response.

| Fast-ion species | Case   | Target (MW) | Dome (kW) | Pipes (kW) | Total (MW)$^a$ |
|------------------|--------|-------------|-----------|------------|----------------|
| Alpha            | MIN-VAC| 0.15        | 60        | 10         | 0.3            |
|                  | MIN-PR | 0.47        | 250       | 40         | 0.9            |
|                  | MAX-VAC| 3.4         | 440       | 110        | 4.0            |
|                  | MAX-PR | 1.4         | 310       | 120        | 3.6            |
|                  | MIN-VAC| 0           | 0         | 0          | 0.01           |
|                  | MIN-PR | 0.3         | 120       | 61         | 0.5            |
|                  | MAX-VAC| 2.6         | 290       | 130        | 3.0            |
|                  | MAX-PR | 2.1         | 930       | 50         | 4.5            |

$^a$ Includes wall loads.

Figure 8. Alpha loss dynamics for the maximum and minimum plasma response cases. (a)–(d) Field-line Poincaré-plots. The $n=3$ mode is made more visible by the stronger ECC current and the omission of other ECC related $n$ modes. (e)–(h) Fraction of particles lost. (i)–(l) Mean loss time as a function of markers’ initial position.
The resulting losses are collected in table 2 while the field structure and loss dynamics (for alpha particles) are shown in figure 8.

For alpha particles, the total losses are higher in MAX compared to MIN both with and without plasma response. Overall results are in line with previous observations: plasma response reduces stochastic field line transport while increasing open-field line, stochastic ripple, and PBT transport. PBT transport is clearly higher in MAX case compared to MIN, as expected. In MIN case, both divertor target and dome loads increase with dome losses increasing more in proportion. In MAX case, there is a decrease in total divertor loads, but again the proportion of the divertor loads ending up to the dome grows. Interestingly, the stochastic ripple transport becomes the dominant mechanism in MAX-PR case which results in half of the losses ending up to the wall instead of the divertor. This increase in stochastic ripple transport is due to the toroidal field perturbation near the separatrix (recall figure 3) which is stronger here than in the previously analysed case. Here JOREK results would differ dramatically from MARS-F since JOREK, being a reduced MHD code, would omit the toroidal field perturbation completely.

For beam particles, there are few losses overall in MIN-VAC case but they are increased when plasma response is introduced. In MAX case, the losses are also increased with PR and the losses shift from the dome to the target. However, the under-the-dome losses decrease while the wall losses increase. In both MIN and MAX cases, divertor target receives highest loads which further confirms that the beam ions are sensitive to the magnetic field stochasticity at the edge.

8. Conclusions

The inclusion of plasma response to ECCs is essential for an accurate modelling of fast ion transport mechanisms and power loads. While plasma response heats flux surfaces, thus reducing the transport of passing particles, it also introduces a new transport mechanism that increases the transport of marginally trapped particles. This results in a shift in divertor loads (from the target to the dome) and could even lead to greater total losses, as was the case for beam ions in [11]. Therefore, assuming that the vacuum approximation gives a conservative estimate on losses can be misleading.

To summarize, ECCs affect the fast ion transport by following mechanisms. With vacuum approximation, the main transport mechanisms are the stochastic and open field-line transport. With plasma response, the stochastic field-line transport is reduced while the open field-line transport might increase at the very edge. These mechanisms affect the passing particle transport but plasma response affect also the trapped particles: the new mechanism increases marginally trapped particle transport, and, if the plasma response includes the toroidal field component, the stochastic ripple transport is increased. The relative importance of these mechanisms depends on the ECC current configuration and which code is used to compute the plasma response.

The new transport mechanism induced by the plasma response was identified to result from the toroidal variation of the poloidal field strength, in particular near the X-point. This mechanism was prominent for alpha particles possibly because they were in resonance with the ECC-induced perturbation. The higher transport of marginally trapped alpha particles seen with JOREK-based plasma response can be attributed to the fact that JOREK model contains X-point geometry. For beam particles, the effect of the PBT mechanism was also more clear with JOREK plasma response than with MARS-F. On the other hand, the MARS-F plasma response includes the toroidal magnetic field component which led to increased stochastic ripple transport. Since these differences are due to the fundamental differences in the codes, we expect them to hold in general. On the other hand, the passing particle transport was reduced irrespective which MHD code produced the plasma response. The width of the remaining stochastic layer determined the magnitude of the passing particle losses. The stochastic layer was higher in MARS-F case which was the reason why the beam losses were higher in with MARS-F than JOREK.

As for the effect of the additional ECC-induced fast ion losses, the highest power deposited to the divertor was 4 MW of the investigated cases. Since radiative power deposited to ITER divertor is expected to be around 70 MW [22], it is unlikely that the additional fast ion loads due to ECCs will be an issue. Even the cooling pipes received loads less than 0.15 MW, and so are probably well below the radiative loads. The exact fast ion loads can be investigated more thoroughly with codes including accurate divertor geometry such as LOCUST [8]. On the other hand, the redistribution of divertor loads remains interesting from the fast ion diagnostics point of view [12]. However, the values reported here are not certain to be the highest possible as the losses depend on the ECC current configuration, and the highest fast ion losses do not necessarily correspond to maximum plasma response.

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