ASCOT simulations of neoclassical tearing mode effects on fast ion losses

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Introduction

In present-day fusion devices and in ITER, fast particles play a significant role. They appear as fusion-born alpha particles or as NBI and ICRH generated fast ions. On one hand, the fast particles are crucial for plasma heating and current drive (CD). On the other hand, the plasma facing components may be damaged due to fast ion losses (FIL). Moreover, the interaction between the fast particles and MHD instabilities may adversely affect the fast ion confinement leading to higher FIL and decreased CD.

The Monte Carlo orbit-following code ASCOT has been used to quantitatively analyse FIL for several existing experiments, and ITER as well [1, 2]. So far ASCOT has neglected the effect of MHD instabilities. In this work, ASCOT is enhanced to include a magnetic perturbation causing magnetic island structures. A numerical model for neoclassical tearing modes (NTM) is presented and verified. Preliminary simulation results are presented for ITER scenario 2.

Numerical model and implementation

We have used a relativistic Hamiltonian formalism in derivation of the equation of motion in magnetic coordinates. The effect of magnetic islands is added as a magnetic vector potential perturbation as in [3]. The perturbation describing NTM's is given by [4]

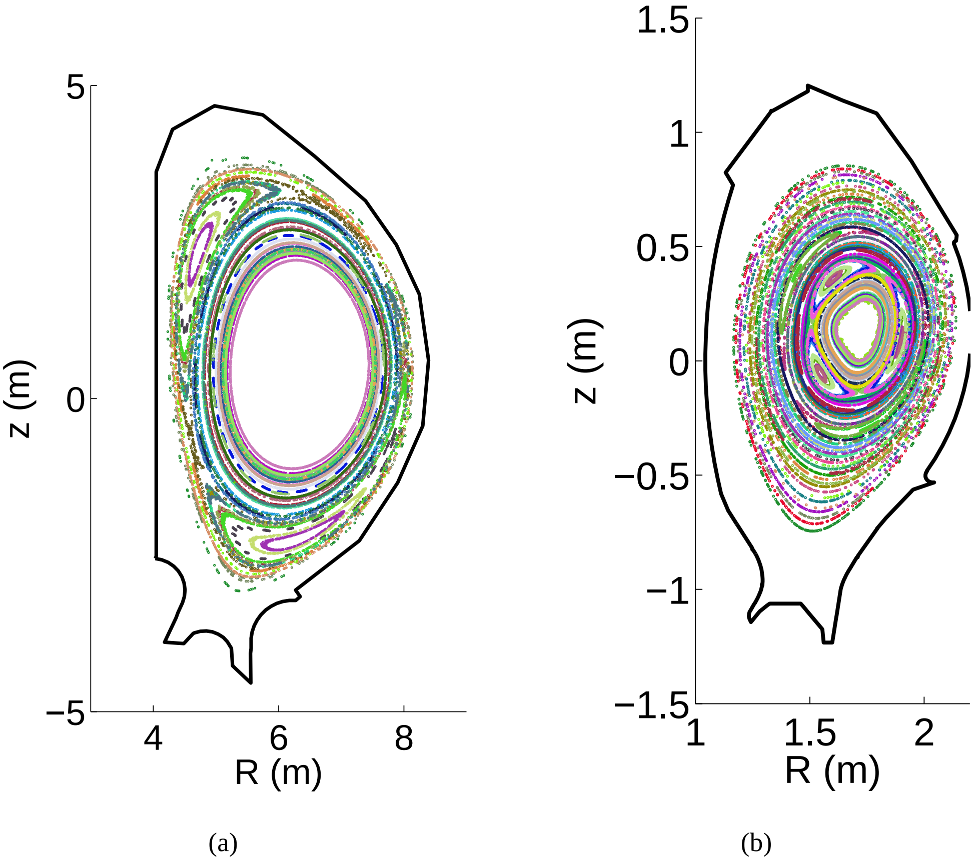
$$\alpha(\chi,\theta,\zeta,t) = \sum_{n,m} A_{m,n}(\chi)\cos(m\theta - n\zeta)\,, \tag{1}$$

where the amplitudes $A_{m,n}$ for different perturbations can be functions of the radial coordinate χ, m is the poloidal mode number and n is the toroidal mode number. In ASCOT, we use a normalized poloidal flux ψ_n as a radial coordinate. For the radial profile $A_{m,n}$ we use a theory-based parametrization [5] describing resistive modes

$$\begin{aligned} A_{m,n}(\chi) =& \rho_{m,n}\alpha\left(\frac{\chi}{\chi_{m,n}}\right)^{m/2}\left(1-\beta\left(\frac{\chi}{\chi_{m,n}}\right)^{1/2}\right) \text{ ,for } \chi \le \chi_{m,n} \\ A_{m,n}(\chi) =& \rho_{m,n}\frac{\alpha(1-\beta)-\gamma+\gamma\left(\frac{\chi}{\chi_{m,n}}\right)^{1/2}}{(\chi/\chi_{m,n})^{(m+1)/2}} \text{ ,for } \chi > \chi_{m,n}. \end{aligned} \tag{2}$$

The parameters $\rho_{m,n}$, α, β and γ are fixed so that the island width, measured by electron cyclotron emission (ECE) or motional Stark effect (MSE), the island position (ECE or MSE) and the radial perturbation field strength (Mirnov coils) correspond to the ones obtained from experimental data.

Verification studies



(a) (b)

Figure 1: *Magnetic islands in tokamaks. (a) A Poincaré plot of a (2,1) perturbation in ITER and (b) a Poincaré plot of a (3,2) and (2,1) perturbation with a constant amplitude* $A_{m,n}$ *in ASDEX Upgrade.*

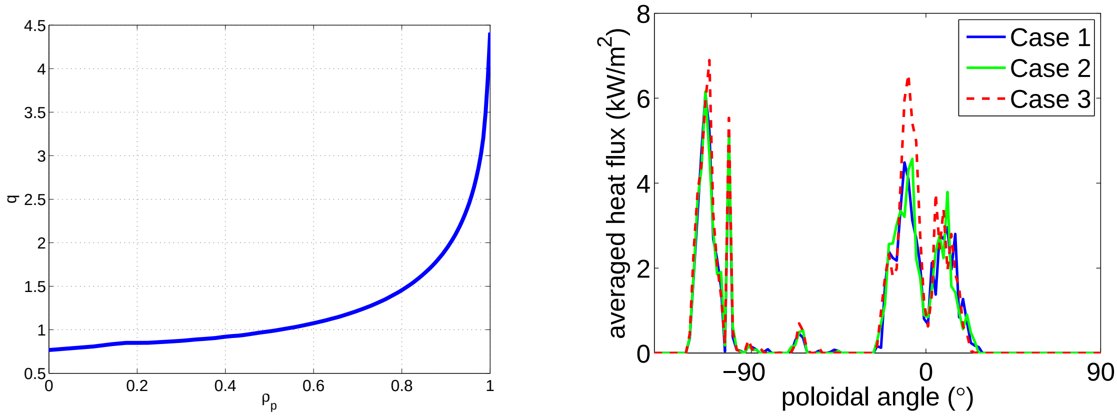
To be sure that the model has been implemented correctly, the following tests were made:

- Islands should be evident when a particle field-line trace is made (Poincaré plot)
- A deformation of the flux surfaces near the core should appear when the perturbation is modelled with a constant amplitude $A_{m,n}$
- The island width should be proportional to the square root of the perturbation amplitude
- Overlapping islands should form a stochastic magnetic field in the overlapping region.

The formation of islands is shown in Fig. 1(a) and the deformation of the flux surfaces near the core is shown in Fig. 1(b). The other tests were also carried out, and the implementation was verified to produce physical results.

Preliminary simulation results

A wall load simulation for an axisymmetric ITER scenario 2 was made by tracing the orbits of some 20 000 fusion-born alpha particles, with spatially even initial distribution weighted by the local fusion reaction rate, and recording the wall hits. At this stage, we did not have a magnetic ripple included in the simulation. Three different cases were studied. The first, from now on Case 1, is a standard ASCOT run without any field perturbations. This was done for comparison. The second one, Case 2, was a (3,2) NTM discharge. The island width was adjusted to be 10 cm at the outer midplane, which is the critical size for mode locking of the (2,1) island according to Ref. [6], and, therefore, it acts as a upper limit. The resonance surface is deep in the plasma, see Fig. 2(a), and hence, without the ripple effects, the alpha particle wall load distribution should resemble the one obtained in Case 1. Finally, Case 3 is a (2,1) NTM discharge with the resonance surface very close to the separatrix as shown in Fig. 2(a). Hence, even without the ripple channelling a clear difference in the wall loads due to NTM activity is expected. The perturbation amplitude $A_{m,n}$ is kept the same as in Case 2 and, therefore, due to the higher magnetic shear at the edge, the island width is smaller in the Case 3.



(a) (b)

Figure 2: *(a) The safety factor* q_s *of ITER scenario 2 vs. radial coordinate* $\rho_p = \sqrt{\chi_n}$. *The q=3/2 resonance surface is situated rather deep in the plasma, while the q=2/1 resonance surface extends close to the separatrix. (b) Comparison of the toroidally averaged wall load as a function of the poloidal angle. Blue: no perturbation. Green: NTM deep in the plasma. Red: NTM near separatrix.*

Even though the wall distribution is slightly different in Cases 2 and 3, the differences in the 2D wall loads are too small to be shown. However, the differences are more easily seen in the ϕ-averaged wall loads shown in Fig. 2(b). Case 1 and 2 differ only in the limiter region, around $\theta=0$, where the deep NTM slightly increases the wall load. On the other hand, the NTM at the edge, Case 3 shown in red, clearly increases the wall loads. This effect is expected to be even more severe when magnetic field ripple is included in the simulation. Even the deep NTM of Case 2 might channel the particles to the ripple well region and, thus, increase FIL significantly.

Discussion and future work

The newly added model for magnetic islands in ASCOT was used to simulate wall load distributions of alpha particles in ITER in the presence of MHD modes. It was observed that the NTM activity near the edge of the plasma will increase the wall load even without magnetic ripple, while the loads from deep-lying NTM case hardly differ from the non-perturbed case.

In the near future, a more detailed study of the wall load distribution caused by the interplay of magnetic field ripple and NTM activity will be made. Furthermore, the magnetic island model will be applied to study the redistribution of fast ions and, in particular, current drive by neutral beam ions during NTM activity. Moreover, a detailed validation study against ASDEX Upgrade experiments is under way.

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