Role of increased magnetic field stochasticity due to test blanket modules on radial transport of thermal particles

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Introduction

ITER will feature three pairs of test blanket modules (TBMs) required for tritium breeding endeavours. Each TBM contains more than a ton of ferritic material, and as such they produce a significant perturbation to the magnetic field. This ripple of the field lines near the TBMs has been a concern for the confinement of fast ions but recent studies have alleviated this concern [1]. However, thermal particle confinement has received less attention. One way TBMs could affect the particle confinement, in addition to the localised perturbation, is through the increase in the width of the stochastic region at the plasma edge. This increase could then result in inward displacement of the pedestal depending on how strongly the stochastic region increases the radial transport. Thermal particle losses due to TBMs have been studied before [2] but the transport due to field stochasticity was not investigated explicitly, and the main TBM based loss mechanism was attributed to displacements of banana tips due to toroidal asymmetry. In this work, we aim to quantify the stochastic layer's contribution to thermal electron transport in the baseline ($I_p = 15$ MA) and steady-state ($I_p = 9$ MA) ITER scenarios. We will carry out orbit-following simulations using the code ASCOT to measure the field stochasticity and particle transport. Comparing these two results shows to which extent the transport is enhanced by the stochastic field.

Evaluation of the particle transport

The transport is studied with and without TBMs in magnetic fields that also include contribution from ferritic inserts (designed to reduce the toroidal ripple) and the plasma response [3]. The magnetic field structure of the four cases being investigated are shown in Fig. 1, where the increase in stochastic layer width when TBMs are introduced is clearly seen in both scenarios. Inside $\rho_{\mathrm{pol}} = 0.95$ the TBMs have less dramatic effect on the field topology, and we will not study the transport there. The pedestal top is located at $\rho_{\mathrm{pol}} = 0.98$ in both scenarios.

In order to measure the level of stochasticity with test particle simulations, we will use electrons with pitch $v_\parallel/v = 0.999$, and omit collisions. These electrons are strongly passing and,
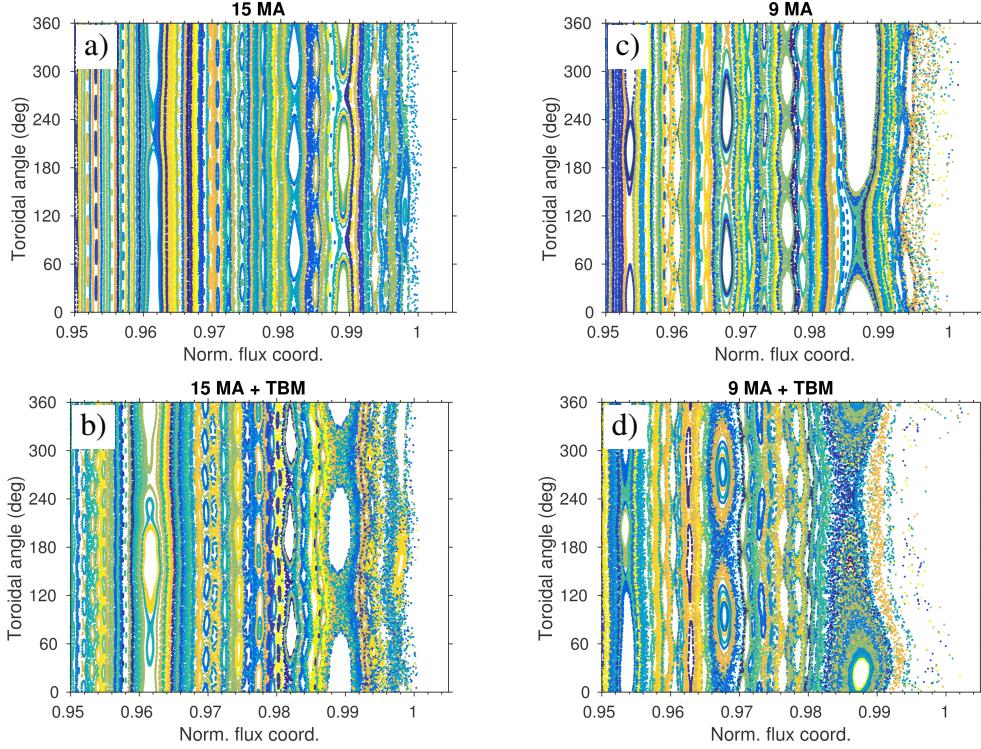
Figure 1: *The magnetic field Poincaré plots of the investigated cases. The plots show the field structure at inner midplane (IMP) with different colors corresponding to different field lines. The normalized flux coordinate, ρ_{pol}, is evaluated from axisymmetric equilibrium.*

as such, they provide a measure for the stochastic field line transport alone, and not other collisionless transport mechanisms (e.g. ripple well transport). We will refer to this population as *passing*. The particle ensemble referred as *thermal* electrons have a uniform pitch distribution, experience pitch collisions and are used to evaluate the particle transport. Electron energy is chosen to be the local electron thermal energy. At a given ρ_{pol}, a population of 1000 markers is initialized toroidally uniformly, after which they are simulated for 50 poloidal orbits, lasting roughly 0.6 ms (several collision times). The radial coordinate is stored each time the particle crosses the outer midplane (OMP) which gives us the time-evolution of the radial profile. The radial profile at $t = 0$ is a Dirac delta function and, therefore, it evolves according to

$$f(\rho_{\text{pol}}, t) = \frac{1}{\sqrt{4\pi Dt}} \exp\left[-\frac{(\rho_{\text{pol}} - \rho_0 - Kt)^2}{4Dt}\right],\tag{1}$$

where ρ_0 is the initial location, and K and D are advection and diffusion coefficients, respectively. Using Eq. (1), we can find the transport coefficients K and D from the simulation results. Both collisional and stochastic field line transport are diffusive processes so we only analyse the diffusion coefficient, although there might be advection arising, e.g., from magnetic islands and healthy flux surfaces as those form transport barriers for collisionless particles.
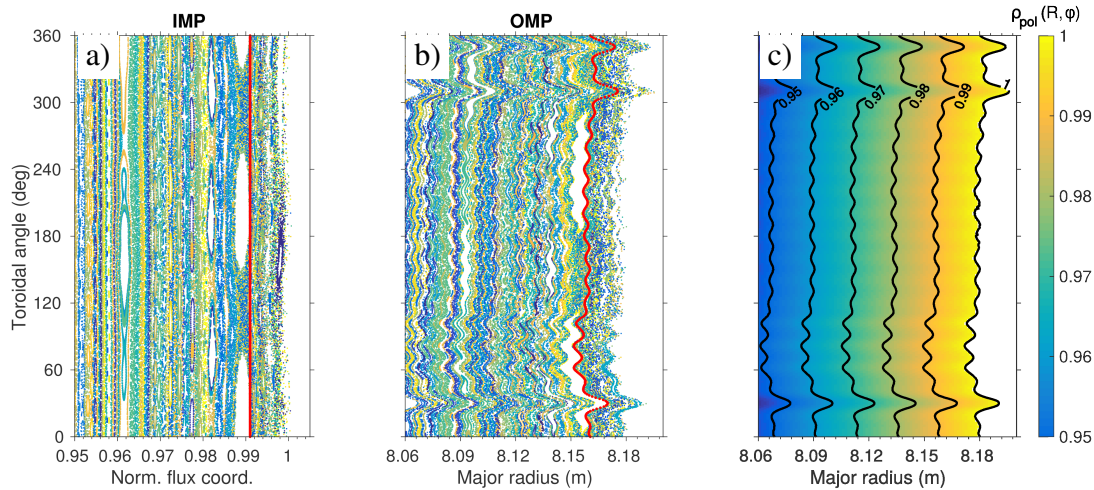
Figure 2: *Illustration of the mapping process in 15 MA+TBM case. (a) An axisymmetric population of field lines (red line) corresponding to a given ρ_{pol} value is chosen at the IMP where the external perturbation is weakest. (b) The field lines are followed for half a poloidal turn to OMP which results in the bent red curve that aligns with the field line Poincaré plot. This curve is assigned the ρ_{pol} value the field lines had at IMP. (c) Repeating the process for several ρ_{pol} values results in mapping $(R, \phi) \rightarrow \rho_{pol}$ at OMP.*

The particles are initialized at OMP since it corresponds to the only poloidal angle that is punctured even by the strongly trapped ones. The drawback is that the TBM perturbation is strongest there, and the flux surfaces are bent as a result. Axisymmetric initialization would lead to erraneous diffusion that results from particles being initialized effectively on different flux surfaces. We remedy this issue with a mapping method, illustrated in Fig. 2, which gives us ρ_{pol} at OMP as a function of major radius R and toroidal angle ϕ. This mapping is used both in particle initialization and when the particle state is stored.

Diffusion coefficient results and the role of the field stochasticity

The diffusion coefficient (Fig. 3) confirms what one would expect based on the Poincaré plots alone. For each simulated population the transport is higher when TBMs are present. The overall transport is roughly by a factor of 5 higher in the 9 MA scenario. While there is a growing trend towards the edge in all cases, the increase is not monotonic.

The non-monotonic features in the passing particle cases are connected to the field structure, e.g., the 9MA TBM case has a steep positive slope at $\rho_{pol} = 0.98$ which is where the magnetic field becomes clearly more stochastic. Therefore, we can use the passing particle result as a measure of the field stochasticity. However, the exact values should not be quoted since the transport barriers from healthy flux surfaces could mean the collisionless transport is non-diffusive, biasing the results.
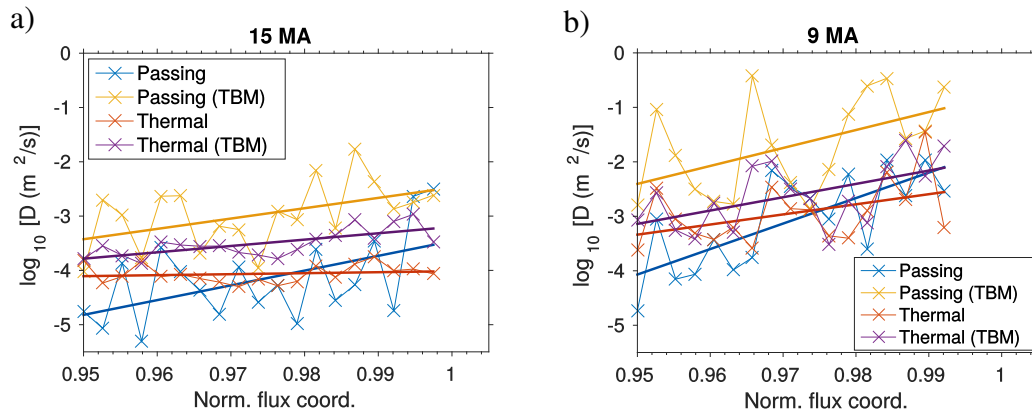
Figure 3: *The evaluated diffusion coefficient in different cases on a logarithmic scale. The evaluated values are marked with crosses and connected with broken lines that show the radial profiles. Also shown is the linear fit on each dataset which shows the general trend.*

In 15 MA scenario, there seems to be no clear connection between passing and thermal profiles, indicating that the field stochasticity is probably not a significant transport mechanism. According to the linear fit, thermal particle transport is 2.5×10^{-4} m^2/s at the pedestal top. Without TBMs, the diffusion coefficient is approximately the same as the neoclassical value of 4.6×10^{-5} m^2/s. *In 9 MA scenario*, the thermal profiles in both cases correlate with the corresponding passing profiles, therefore here the stochastic field has a significant role. The pedestal top has a value 4.0×10^{-3} m^2/s for thermal particle transport with TBMs, slightly higher than without, and even more higher than the neoclassical value 1.6×10^{-4} m^2/s.

Conclusions

We studied the electron transport in presence of the TBMs. The focus was on the transport resulting from the TBM caused increased magnetic field stochasticity at the edge. Of the two investigated ITER scenarios, baseline and steady-state, the TBM induced stochasticity was found to increase transport in the latter. There the transport was more than an order of magnitude larger than the neoclassical value at the pedestal top. Further research is needed to find whether this leads to a pedestal displacement.

References

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