# 3D orbit simulations of the fast-ion transport induced by externally applied magnetic perturbations with different poloidal spectra

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## I. Introduction

In ITER, Edge Localized Modes (ELMs) must be kept under control in order to avoid too high heat fluxes on plasma facing components. Externally applied Magnetic Perturbations (MPs) are routinely used in present tokamaks to mitigate or even suppress ELMs [1] . MPs can, however, cause significant fast-ion losses [2] threatening the integrity of future large devices. It has been observed experimentally that the impact of externally applied MPs on the ELM stability depends strongly on the poloidal spectra of the applied MP. In this paper, we present ASCOT [3] simulations of fast-ion losses induced by externally applied MPs with different poloidal spectra in the ASDEX Upgrade tokamak (AUG) using perturbed and unperturbed density profiles.

## II. ASCOT inputs

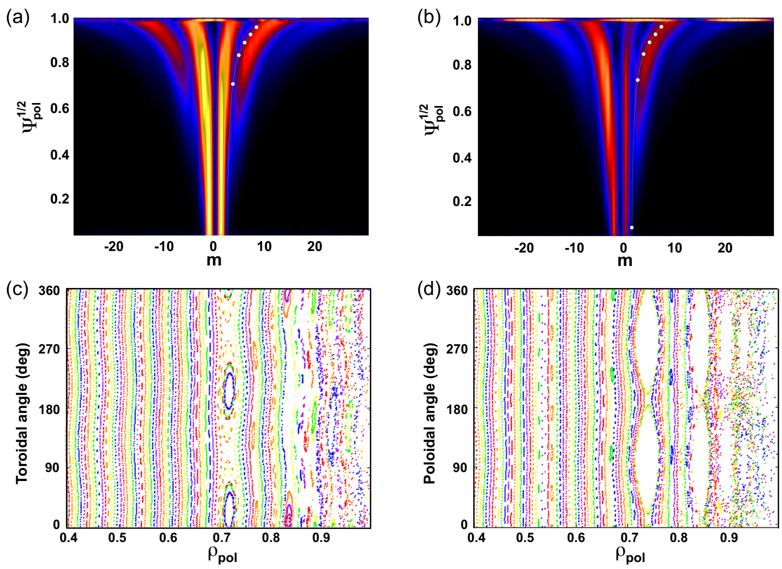


Figure 1: *AUG #33143. (a) MP poloidal spectra at t=2.25s. (b) MP poloidal spectra at t=2.55s. (c) Poincaré plot of the magnetic field including MPs and TFC ripple at t=2.25s and (c) t=2.55s.*

ASCOT simulations have been carried out for the low collisionality ($\nu_e^* = 0.2$) and $q_{95}$ ($q_{95}$=3.8) AUG shot #33143. A scan in the poloidal spectra of the applied MP was performed through a differential phase scan between the upper and lower sets of MP coils currents. Orbit simulations have been carried out for the two most extreme cases with minimum and maximum MP resonant configurations and kinetic profiles. The magnetic background includes the toroidal field coils (TFC) ripple and the 3D fields of the externally applied n=2 MPs calculated using the vacuum approach for each coils configuration. Figures 1 (a)-(b) show the poloidal spectra of the magnetic perturbation calculated with ERGOS for two MP configurations. The poloidal spectra indicates that at t=2.55s the MP configuration is most resonant with the magnetic field lines close to the separatrix and over a large plasma radius producing a broad stochastic area, see figures 1 (c)-(d).

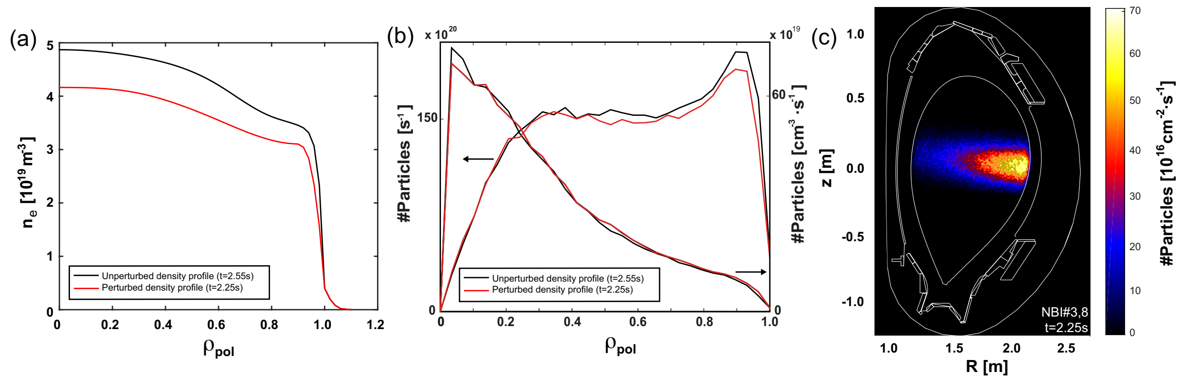


Figure 2: *AUG #33143. (a) Electron density profiles. (b) NBI birth profile. (c) Poloidal projection of NBI birth distribution for NBI 3 and 8.*

The impact the density pump-out, often observed ELM mitigated discharges, on final fast-ion losses has been studied using two different sets of kinetic profiles, see figure 2-(a). One corresponds to the perturbed density profile, affected by pump out, the other to a slightly higher (unperturbed) density profile during a different MP phase. Both sets have been used in order to determine which effect has a bigger impact on the final fast-ion losses: the change in the plasma profiles or the MP configuration. The initial fast-ion distribution generated by the Neutral Beam Injection (NBI) have been calculated for both sets of kinetic profiles. Figure 2-(b) shows the NBI birth profiles for both kinetic profiles while figure 2-(c) shows a poloidal projection of the NBI birth distribution for the unperturbed case. Two ASCOT simulations (using the perturbed and unperturbed kinetic profiles) have been carried out for each MP configuration. The guiding centers of 100k particles have been followed until they thermalize through Coulomb collisions or hit the wall.

## III. ASCOT simulation results

Figures 3-(a) and (b) show a 2D map of the wall heat loads produced by the MP induced fast-ion losses for two different MP poloidal spectra. The n=2 MP structure is clearly visible in the heat load pattern on the first wall around the midplane with the maximum heat loads in both cases being ≈ 1 MW/m$^2$. Significant changes in the wall load pattern in the divertor and midplane structures are clearly visible for both coils configurations.

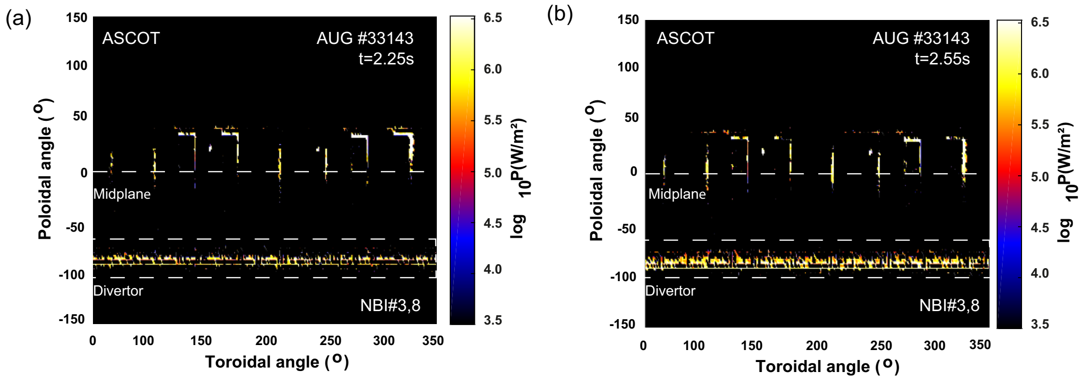


Figure 3: *AUG #33143. (a) 2D wall heat loads at t=2.25 using a perturbed $n_e$ profile. (b) 2D wall heat loads at t=2.55 using a unperturbed $n_e$ profile.*

The following table presents the distribution of fast-ion losses on the divertor and low field side wall for the two MP configurations shown in figure 3-(a) and (b) and both kinetic profiles.

| | MP config at t=2.25s | MP config at t=2.55s |
|---|---|---|
| Unperturbed $n_e$ profile (divertor) | 2.5 | 4.9 |
| Unperturbed $n_e$ profile (Midplane) | 3.3 | 2.4 |
| Unperturbed $n_e$ profile (Total) | **5.8** | **7.3** |
| Perturbed $n_e$ profile (divertor) | 2.7 | 1.9 |
| Perturbed $n_e$ profile (Midplane) | 2.7 | 5.2 |
| Perturbed $n_e$ profile (Total) | **5.4** | **7.1** |

Table 1: *MP driven fast-ion losses in % fot two MPs configurations using two density profiles.*

The velocity-space of the lost ions is shown in figures 4 (a)-(b). Most of the losses are observed at the injection energy (60 and 93keV) and pitch-angle though some lower energies and pitch angles are also visible. The fast-ion radial transport induced by the externally applied MPs has been investigated by looking at the changes in the toroidal canonical momentum $P_\phi = mRV_\phi - Ze\Psi_p$ as a function of the energy and radial position of the ions for our magnetic field configuration at t=2.25s and t=2.55s and main injection pitch-angle. The structures observed in figures 4 (c)-(d)) are aligned with the geometrical resonances $\omega_{pol}/\omega_{tor} = p/n$ with p/n indicated in each figure. Here, $\omega_{pol}$ and $\omega_{tor}$ are the poloidal and toroidal precession frequencies of the particles respectively.

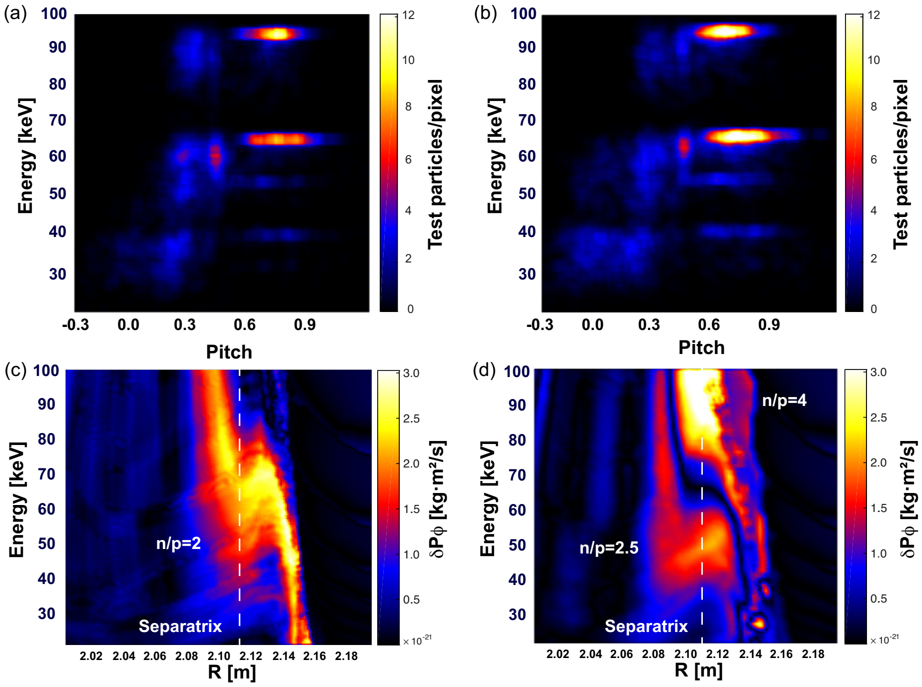


Figure 4: *AUG #33143. (a),(b) show the velocity-space of the total lost fast-ions at t=2.25s and t=2.55s. (c),(d) represent the variation of toroidal canonical momentum of fast-ions at z=0 and pitch=0.5 for different MPs configurations at t=2.25s and t=2.55s. The largest variation of $P_\phi$ corresponds to resonances that are identified indicating the quotient $n/p = \omega_{pol}/\omega_{tor}$.*

## IV. Conclusions

In the simulations presented here, the maximum fast-ion losses, 7.3%, are observed for the most resonant MP coils configuration and non-perturbed density profiles. The MP poloidal spectra has a stronger impact on the simulated losses than the observed variations in the density profiles due to density pump out. Maximum heat loads on the first wall are $\approx$ 1 MW/m$^2$. The geometrical resonances responsible for the MP induced fast-ion losses are clearly visible in the variations of the canonical angular momentum. A similar study will be carried out in the future taking into account the plasma response effect.

## V. Acknowledgements

This research was supported in part by the Spanish Ministry of Economy and Competitiveness (RYC-2011-09152, FIS2015-69362-P, ENE2012-31087 and BES-2013-065501), and the Marie Curie FP7 Integration Grant (PCIG11-GA-2012-321455).

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