Kinetic Modelling of ELM-induced Fast-ion Transport and Acceleration in the ASDEX Upgrade Tokamak

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Introduction

In magnetically confined fusion, fast-ion confinement is essential to achieve a good plasma performance, while fast-ion losses may damage the tokamak wall, endangering its integrity. In H-mode regimes, tokamaks exhibit explosive and repetitive magneto-hydro dynamic (MHD) instabilities driven in the plasma edge, known as Edge Localized Modes (ELMs) [1]. ELMs release a great amount of energy and particles to the tokamak wall that are believed to be intolerable in future devices [2]. Besides, recent experiments in the ASDEX Upgrade tokamak have observed accelerated fast-ion losses correlated with the ELM activity [3, 4, 5]. This work seeks to reproduce the main experimental observations in ASDEX Upgrade by first principle modelling and to characterize the fast-ion transport and acceleration mechanism during ELMs.

The ELM-induced fast-ion losses were experimentally observed and characterized in AUG using the Fast-Ion Loss Detector (FILD) [6, 7, 8]. The FILD diagnostic provides direct measurements of the fast-ion losses and gives information of their velocity space. The 5 FILDs in AUG enable the measurements in different toroidal and poloidal angles. Peaks in the FILD signals are seen to be correlated with the ELM activity, revealing different behaviours in the toroidally and poloidally displaced FILDs. This suggests a 3D nature of the fast-ion losses during an ELM crash. The intra-ELM velocity-space measurements of the fast-ion losses depict a population at

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energies tens of keV above the main NBI energy. A tomographic inversion of the measurement shows that this accelerated population is very localized in velocity space, suggesting a fast-ion acceleration induced by the ELM perturbation.

The AUG plasma is modelled with the MHD module of the hybrid kinetic-MHD code MEGA [9], with the aim to obtain the electromagnetic perturbation during an ELM. This perturbation will be employed as an input in the Monte-Carlo full-orbit code ASCOT5 [10] to study the ELM-induced fast-ion transport and acceleration with a newly developed module that accounts for the time-evolving electromagnetic perturbations. The MEGA simulations reproduce the main features of an ELM [11]. However, the perturbation is dominantly $n = 20$, well above the dominant $n = 3$ and $n = 5$ observed experimentally, and the growth rate of the perturbation is $\gamma = 10^5\,\mathrm{s}^{-1}$, an order of magnitude above that observed experimentally [12, 13]. Besides, the time scale of the perturbation have been adjusted to be above the orbital time scales with the aim to observe an interaction between the ELM perturbation and the fast ions. Thus, only qualitative comparisons between the modelled results and the experiments are adressed here.

Effect of ELMs on the NBI distribution

The transport and acceleration of the NBI-born fast-ion distribution in AUG are assessed by modelling the 8 beams with BBNBI [14]. BBNBI produces a distribution of 6 million markers for each beam. The markers are first tracked in an unperturbed field to filter out the NBI prompt losses. Then, the orbits of the confined fast ions are tracked during the ELM perturbation. Simulations with an axisymmetric wall show that the ELM-induced losses concentrate on the LFS near the midplane, following the high-n, field-aligned patterns of the ELM perturbation. This illustrates the strong impact of the ballooning perturbation on the fast-ion confinement. The NBI fast-ion energy distribution spreads over high energies during the simulation, forming a local maximum at 30 keV above the injection energy, resulting in a distinguishable accelerated population. The velocity space of the fast ions colliding with the FILD probes can be used as an estimate of the FILD signal. Figure 1 shows the velocity space of the NBI1 distributions colliding with FILD2. A high energy component, 30 keV above the injection energy, that converges to a narrow pitch angle range, can be observed.

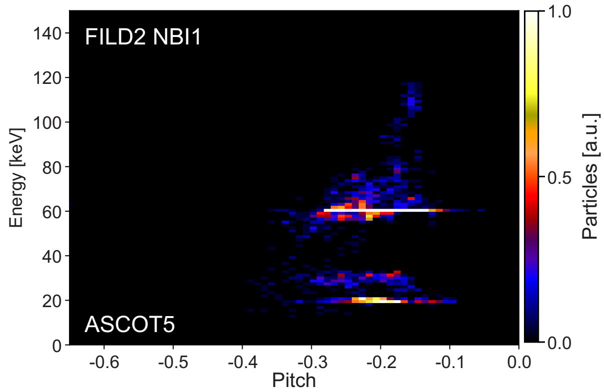

Figure 1: *Velocity space distribution of the ELM-induced fast-ion losses reaching FILD2 from NBI1, as estimated in ASCOT5.*

Modelled Transport and Acceleration Mechanism

The fast-ion transport and acceleration during the ELM perturbation is assessed by tracking the variation of the orbits constants of motion and adiabatic invariants. The variation of the toroidal canonical momentum (ΔP_φ) is associated with the particle radial transport, the variation of the kinetic energy ($\Delta\varepsilon$) with acceleration and the variation of the magnetic moment ($\Delta\mu$) with a variation of the perpendicular velocity in the cyclotron time scale. A set of markers is used as a representation of the particle phase-space, distributed in a grid with initial conditions $\varphi = 0$, $z = 0$, $\varepsilon = 80\,\mathrm{keV}$ and the initial radial position and pitch angle of the grid. The markers are followed during 10 poloidal turns. Besides, to evaluate a resonant interaction, the orbits resonance condition, expressed in terms of the fraction $\omega_{pol}/\omega_{tor}$ [15], are shown as white contour lines.

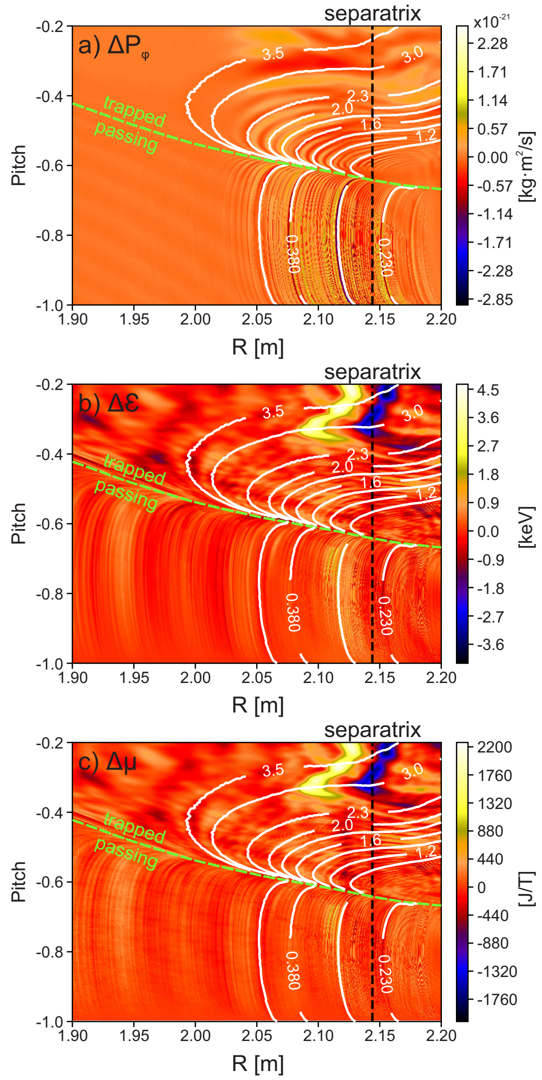

Figure 2: *(a) Variation of the toroidal canonical momentum , (b) the kinetic energy and (c) the magnetic moment.* $\omega_{pol}/\omega_{tor}$ *contour lines in white.*

A clear correlation between the ΔP_φ lines and the $\omega_{pol}/\omega_{tor}$ contour lines can be observed in figure 2(a). This suggests a resonant transport between the fast-ion orbits and the magnetic perturbation. Besides, it is observed that passing particles are affected by the chaotic field lines near the edge, even though the resonant transport is dominant. The patterns in figures 2(b) and 2(c) are different to those observed in figure 2(a). Nonetheless, they are analogous to each other, depicting that the energy variation is associated with a variation of the perpendicular velocity component in the cyclotron time scale. The electric field, which is calculated in MEGA by a simplified Ohm's law ($E = -v\times B + \eta J$), is dominated by the $v\times B$ term, while the resistive term has a negligible effect. Therefore, the electric perturbation is mostly perpendicular to the magnetic field lines in spatial scales below the gyroradius size. This produces a net variation in the magnetic moment, that is reflected in an acceleration due to an orbit drift resonance with the perpendicular electric field. This cannot be observed in a guiding center approach, as the perpendicular electric field is there interpreted as a drift in the fast-ion orbit. These results are in line with the proposed acceleration of energetic particles due to propagating plasma blobs [16], where vertically polarized blobs with sizes below the fast-ion gyroradius interact with the fast particle gyromotion thus producing a fast-ion acceleration.

Conclusions

The main observations in ASDEX Upgrade of accelerated fast-ion losses during ELMs have been qualitatively reproduced using MEGA and ASCOT5. MEGA is employed to resolve the electromagnetic perturbation during an ELM, while ASCOT5 is employed to trace the fast-ion orbits during the time-evolving perturbations. The results show field-aligned patterns of the losses on the wall near the midplane and have reproduced an accelerated population on the FILD probe very localized in phase space. The models reveal a resonant transport and acceleration in the fast-ion perpendicular velocity.

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References

[1] H. Zohm. Edge localized modes (ELMs). *Plasma Phys. Controlled Fusion*, 38(2):105, 1996.

[2] T. Eich et al. *Nuclear Materials and Energy*, 12:84–90, 2017.

[3] M. García-Muñoz et al. *Plasma Phys. Controlled Fusion*, 55(12):124014, 2013.

[4] J. Galdon-Quiroga et al. *Phys. Rev. Lett.*, 121:025002, 2018.

[5] J. Galdon-Quiroga et al. *Nucl. Fusion*, 59(6):066016, 2019.

[6] M. García-Muñoz et al. *Rev. Sci. Instrum.*, 80(5):053503, 2009.

[7] J. Gonzalez-Martin et al. *Rev. Sci. Instrum.*, 89(10):10I106, 2018.

[8] J. Gonzalez-Martin et al. *J. Instrum.*, 14(11):C11005–C11005, 2019.

[9] Y. Todo and T. Sato. *Phys. Plasmas*, 5(5):1321–1327, 1998.

[10] J. Varje, K. Sarkimaki, et al., 2019. preprint.

[11] G. T. A. Huysmans and O. Czarny. *Nucl. Fusion*, 47(7):659, 2007.

[12] F. Mink et al. *Plasma Phys. Control. Fusion*, 58(12):125013, 2016.

[13] F. Mink et al. *Nucl. Fusion*, 58(2):026011, 2018.

[14] O. Asunta et al. *Comput. Phys. Commun.*, 188:33–46, 2015.

[15] L. Sanchis et al. *Plasma Phys. Controlled Fusion*, 61(1):014038, 2018.

[16] V. S. Marchenko and S. N. Reznik. *Phys. Plasmas*, 25(8):084502, 2018.