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Acceleration of beam ions during edge localized modes in the ASDEX Upgrade tokamak

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Introduction. Acceleration of charged particles is ubiquitous in space, astrophysical and laboratory plasmas. However, it is not always straightforward to identify the physical mechanisms leading to the particle acceleration. In this sense, magnetically confined fusion plasmas with in-situ measurements are an ideal testbed to elucidate the physics underlying the different acceleration mechanisms [1]. In tokamaks, acceleration of electrons through runaway mechanisms is commonly observed during disruptions and poses a potential threat to the device integrity [2]. On the other hand, ion runaway has also been reported in the presence of internal magnetic reconnection events in MAST [3] and MST [4]. More recently, acceleration of electrons during edge localized modes (ELM) was inferred from measurements of bursts of microwave emission and soft X-ray [5]. In this contribution we present results of recent experiments in the ASDEX Upgrade tokamak which have revealed for the first time the existence of an accelerated beam-ion population during ELMs through the direct measurement of fast-ion losses [6].

Experimental results. These experiments were carried out in low collisionality plasmas ($\nu^* \leq 0.4$) with a normalized plasma to magnetic pressure ratio of $\beta_n \sim 2.5$. The only external source of fast-ions to the plasma were neutral beam injected (NBI) deuterium ions. Bursts of fast-ion losses correlated with the occurrence of ELMs are measured by means of scintillator based fast-ion loss detectors (FILD) [7], which are characterized by a filamentary-like behaviour showing multiple spikes of fast-ion losses within single ELMs. FILD detectors provide intra-ELM time resolved measurements of the velocity-space of fast-ion losses. An example of such a measurement is shown in Fig.1 (a). Here, two spots at gyroradius of ~ 4 cm and ~ 3 cm can be observed,

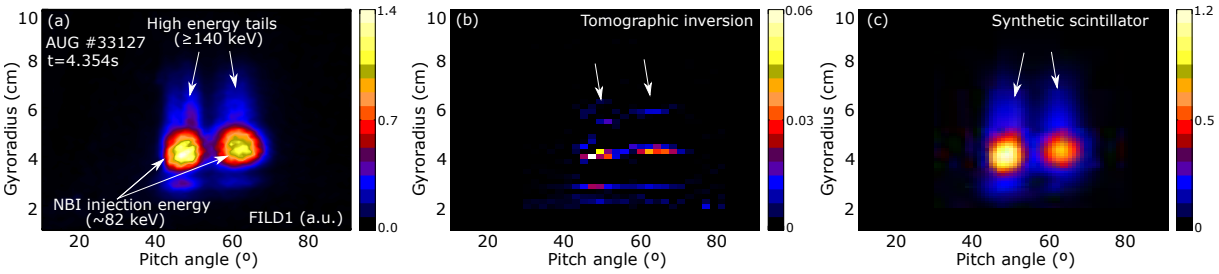

Figure 1: (a) Velocity-space measurement of fast-ion losses during an ELM. (b) Tomographic reconstruction of the undistorted velocity-space distribution reaching the detector pinhole. (c) Synthetic FILD signal obtained after the tomographic inversion.

corresponding to first orbit losses of NBI ions with the main and half injection energy, respectively. Additionally, a population at gyroradii larger than ~ 5 cm is also observed, corresponding to ions with energies well above the main NBI injection energy. In the following this is referred to as *high-energy feature*. The observation of this feature is correlated with the occurrence of ELMs and the onset of the NBI systems. Furthermore, it has been observed in a wide variety of scenarios with toroidal magnetic field and plasma currents ranging from $B_t = 1.8 - 2.5$ T and $I_p = 0.6 - 1.0$ MA, respectively.

The measurements shown in Figure 1 correspond to the ion loss pattern observed at the FILD scintillator. However, due to the finite resolution of the system, this pattern is a distortion of the velocity-space of the losses that reach the detector pinhole. In order to overcome this problem, a model for the instrument response of the FILD detector has been developed based on a weight function formalism [8]. With this model, tomographic inversion techniques can be applied to the FILD measurements in order to recover the undistorted velocity-space of the fast-ion losses reaching the detector pinhole. Figure 1 (b) shows the result of this analysis, revealing that the high-energy feature observed in the FILD measurements is well localized. Figure 1 (c) shows the corresponding synthetic FILD signal, which is in good agreement with the experimental measurement. Additionally, experiments carried out with different q_{95} values reveal multiple pitch angle structures in the high-energy feature. These well-defined velocity-space structures suggest that the acceleration results from a resonant interaction between the beam-ions and parallel electric fields emerging during the ELM filament eruption, when magnetic reconnection is believed to take place [6].

At the onset of ELMs, bursts are often detected in electron cyclotron emission and also in soft X-ray channels with lines of sight tangential to the plasma edge, consistent with the FILD measurements presented here. Similar bursts reported in the MAST spherical tokamak have

been attributed to electron acceleration [5]. Radiation transport modelling of these ECE measurements including broadening effects suggests that this emmission is originated at $\rho_{pol} > 0.92$ and is likely produced by the build-up of a non-thermal electron population with energies below 25 keV. The mechanism leading to the formation of this high-energetic electron population remains to be investigated.

Modelling. Full orbit following simulations have been carried out during a whole ELM crash including the 3D magnetic perturbation fields modelled with JOREK. The temporal evolution of the modelled fast-ion losses show a filamentary-like pattern, reproducing the same behaviour observed in the experiments. Additionally, simulations with the orbit following code ASCOT [9] have been carried out to calculate the variation of the toroidal canonical angular momentum (P_ϕ), which is used as a proxy for the radial transport of the ions [10]. These results are shown in Figure 2 (a), where multiple resonant structures are observed, which are different in the passing orbit region and the trapped orbit region.

In order to explore the viability of the proposed acceleration mechanism, simulations have been carried out including a test model of a parallel electric field:

$$\vec{E} = \vec{b}_{\parallel} \cdot A \cdot exp\frac{(\rho - \rho_0)^2}{2\sigma^2} \cdot \cos n\phi - m\theta^* + \alpha \tag{1}$$

where $\vec{b}_{\parallel}$ is a unitary vector in the direction of the magnetic field, A is the amplitude of the electric field, ρ is the radial coordinate, ρ_0 is the radial location of the perturbation, σ is related to the width of the perturbation, n is the toroidal mode number, m is the poloidal mode number, ϕ and θ^* are the toroidal and poloidal angles, and α is the phase of the perturbation. This simple model resembles the 3D character of the ELM perturbation and allows us to perform sensitivity scans on the different parameters.

In these simulations, a set of markers distributed in the radial coordinate and pitch angle is followed. Figure 2 (b) shows the result of a simulation with parameters of the parallel electric field model set to $A = 0.5$ kV/m, $n = 3$, $m = q \cdot n$, $\rho_0 = 0.9$ and $\sigma = 0.1$, and following the markers during 50μs. It can be observed that the maximum energy gain is of the order of tens of keV, while resonant structures are observed in the region corresponding to passing orbits ($\Lambda \leq -0.5$) which are different to the structures observed in the trapped orbit region ($\Lambda \geq -0.5$), similar to what is observed in Figure 2 (a).

A sensitivity study has been carried out by varying the parameters of the parallel electric field model within the range of values expected at AUG. The same qualitative behaviour is observed in terms of resonant structures. The trend shows that lower toroidal mode numbers lead

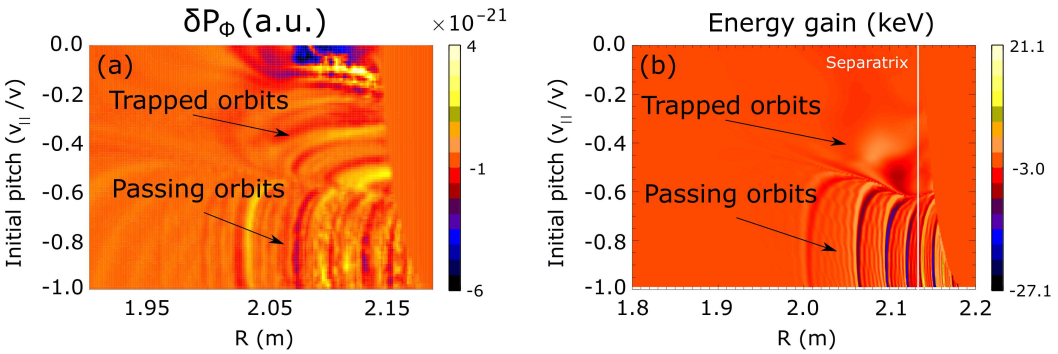

Figure 2: (a) Variation of P_{phi} in the presence of the 3D magnetic perturbation fields calculated with JOREK. (b) Energy gain in the presence of the test model for the parallel electric field.

to higher energy gains, while lower values of the electric field amplitude lead to lower energy gains, as expected.

Conclusions. The first experimental observation of an accelerated beam-ion population during ELMs in a tokamak has been presented. A resonant interaction between the beam-ions and parallel electric field emerging during the ELM is proposed as a mechanism to explain the beam-ion acceleration. These findings motivate the incorporation of a kinetic description of fast-particles in ELM models and may contribute to a better understanding of the role of fast-ions in ELM stability as well as in the overall energy and particle losses during the ELM cycle.

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