Simulation and analysis of fast ion dynamics in a JT-60SA tokamak plasma subject to pressure- and current-driven instabilities

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The resistive MHD-PIC hybrid code MEGA has recently been used to study the ramp-up phase of a high-β plasma in the JT-60SA tokamak as predicted by integrated simulations [1]. Here, we analyze the effects of MHD and fast-ion-driven instabilities observed in the MEGA simulations. The fast ions originate from powerful negative-ion-based neutral beams (N-NB), which are deposited off-axis and have energies up to 500 keV. Effects of $\boldsymbol{E} \times \boldsymbol{B}$ drifts and magnetic perturbations with long wavelengths (low toroidal mode numbers $n < 5$) are examined.

We report new results on the behavior of fast ions in the presence of reconnecting instabilities, whose magnetic perturbations evolve slowly compared to the fast ion motion. This was motivated by the possibility that off-axis N-NB injection in JT-60SA may produce nonmonotonic current and pressure profiles, whose gradients may destabilize multiple kink-tearing modes and cause minor internal disruptions. When such reconnecting instabilities develop in our simulations, we observe a flattening in the density profiles across the inner half of the plasma, both in the bulk and the fast ion components. When the underlying dynamics are examined using orbit-based resonance analysis combined with Poincarè maps, one can see that the flattening of the fast ion density profile cannot be explained with the formation and growth of magnetic islands, which influence only particles that closely follow magnetic lines of force. In contrast, in the case of fast particles that are subject to significant magnetic drifts — such as our energetic beam ions during current ramp-up [1], or relativistic electrons [2] — the radial redistribution is connected with the formation of resonant islands in canonical toroidal angular momentum space. These orbit islands have different existence conditions and, when projected into real space, they can be located in a different region of the plasma than the magnetic islands.

The insights won in this study may be used for the development of reduced models that will allow to incorporate the effects of MHD activity into integrated codes. The ability to simulate the complex interplay of processes such as MHD activity, fast ion transport, current drive, torque and heating using integrated codes is necessary for shedding light on feedback loops that may exist on multiple spatio-temporal scales, and for reliably predicting their effects in experiments.

[1] Bierwage *et al.*, Plasma Phys. Control. Fusion **59** (2017) 125008.

[2] de Rover *et al.*, Phys. Plasmas **3** (1996) 4468; Matsuyama *et al.*, Nucl. Fusion **54** (2014) 123007.