§4. Simulation Study of Beam Ion Loss Due to Alfvén Eigenmode Bursts

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The toroidicity-induced Alfvén eigenmodes (TAE) can be destabilized by fast ions which have velocities comparable to the Alfvén velocity. A decade ago recurrent bursts of TAEs were observed with drops in neutron emission during neutral beam injection (NBI) in the Tokamak Fusion Test Reactor (TFTR) [1] and DIII-D [2]. The drops in neutron emission have been recognized as a manifestation of TAE-induced beam ion loss. In the experiments cited multiple TAEs were destabilized during TAE bursts that took place at regular time intervals. The modulation depth of the drop in neutron emission in the TFTR plasma was typically ~10% (Fig. 4 of Ref. [1]). The most important result is that the beam confinement time is much shorter than the collisional slowing-down time. This means that TAE activity expels beam ions before their energy is absorbed by the core plasma. We report on the first simulation that reproduces all of these experimental aspects in the TFTR plasma. Simulation study of TAE bursts and beam ion loss is essential for the prediction of behaviors of Alfvén eigenmodes and alpha particles in the forthcoming burning plasmas.

The simulation is based on a perturbative approach similar to Ref. [3]. TAE spatial profile is assumed to be independent of mode amplitude. The amplitude and phases and the nonlinear fast-ion dynamics are followed self-consistently. The q-profile is taken to vary quadratically with minor radius from a central value of 1.2 to an edge value of 3.0. The major and minor radii are R=2.4 m and a=0.75 m. The magnetic field is 1.0 T on axis. The spatial structure and the real frequency of the eigenmodes are obtained from the MHD simulation [4]. The plasma density in the simulation is chosen for simplicity to be uniform. Both the core plasma ions and the beam ions are deuterium. Five eigenmodes (a) n=1/q=1.5, (b) n=2/q=1.25, (c) n=2/q=1.75, (d) n=3/q=1.5, and (e) n=3/q=1.83 are accounted for. The linear damping time of each mode is assumed to be constant at 0.17 ms. Beam ions are injected along the magnetic field at a constant energy of 110 keV which corresponds roughly to the Alfvén velocity. The beam has a Gaussian spatial profile with a width of 0.4a. The beam power is 10 MW. Any beam particle that reaches the loss boundary is removed. The beam slowing-down time is taken to be a typical value 100 ms. The number of particles in the simulations is 4 million.

In the TFTR experiments the inner toroidal limiter was employed. We consider only the co-injection (beam velocity parallel to the plasma current) and take the loss boundary at r=1.2a, since the beam-ion orbit excursion is ~0.2a. We start the simulation at time taken as t=0 when there are no beam ions. As time passes, energetic ions gradually accumulate due to the beam injection. Synchronized bursts of all the modes take place recurrently after t=2.0 ms at a burst interval that is roughly 2.5 ms which closely matches that of experimental value 2.2 ms. In Fig. 1 we show time history of stored beam energy and amplitude of the dominant n=3/q=1.83 mode. The modulational depth of the drop in the stored beam energy is 20% which is comparable to the inferred experimental value of 7%. In the relative units of this figure, the stored beam energy of the classical distribution which is established with only a particle injection source and slowing down saturates at relative level of 1.5, whereas that of the simulation saturates at a relative level of 0.15, namely, 10% of that of the classical distribution. This means that the beam confinement time is much shorter than the collisional slowing-down time. This is the first simulation that reproduces all of these experimental aspects. Figure 2 shows the Poincaré plot for the dominant n=3/q=1.83 mode with the maximum amplitude. Time evolution of the eigenmode is taken into account in the horizontal axis in order to see the resonance between the eigenmode and the beam ions. KAM surfaces disappear at the particle loss boundary (R/a=4.4). Disappearance of KAM surfaces leads to beam ion loss.

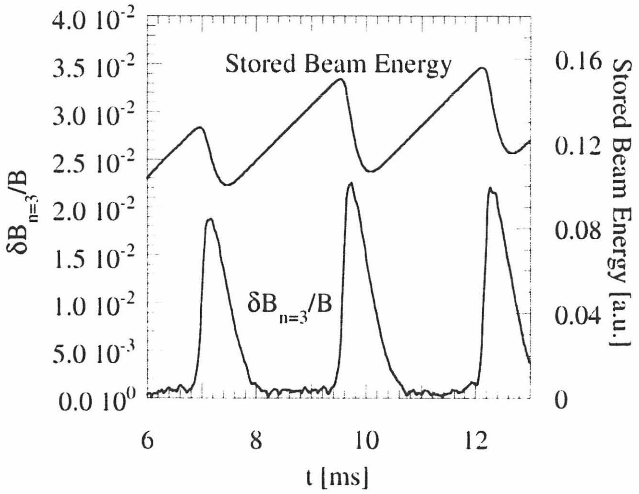

Fig. 1. Time history of stored beam energy and amplitude of the dominant n=3/q=1.83 mode.

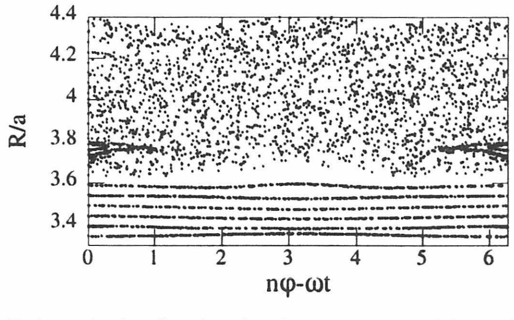

Fig. 2. Poincaré plot for the dominant n=3/q=1.83 mode with the maximum amplitude.

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