§1. Simulation of Alfvén Eigenmode Bursts Using a Hybrid Code for Nonlinear Magnetohydrodynamics and Energetic Particles

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The energetic-particle transport and losses enhanced by Alfvén eigenmodes are an important concern for burning plasmas. Computer simulation is a powerful tool to investigate the interaction between Alfvén eigenmodes and energetic particles. In our previous work[1], we performed the first numerical demonstration of toroidal Alfvén eigenmode (TAE) bursts with parameters similar to a TFTR experiment[2] and reproduced many of the experimental characteristics. These include: a) the synchronization of multiple TAEs, b) the modulation depth of the drop in the stored beam energy, c) the stored beam energy. It was demonstrated by surface of section plots that both the resonance overlap of different eigenmodes and the disappearance of Kolmogorov-Arnold-Moser (KAM) surfaces in phase space due to overlap of higher-order islands created by a single eigenmode lead to particle loss. However, the saturation amplitude $\delta B / B \sim 2\times10^{-2}$ in the simulation results is higher than the value $\delta B / B \sim 10^{-3}$ which we inferred from the plasma displacement that was measured at the plasma edge region with normalized radius $\rho > 0.8$. In the experiment, the plasma displacement (ξ) was estimated from the density fluctuation (δn) measurement assuming a relation $\xi \sim \delta n/(\partial n/\partial r)$ where $\partial n/\partial r$ is the radial gradient of the equilibrium density profile. In the region close to the plasma center, $|\partial n/\partial r|$ is too small and the error bars for the displacement becomes infinitely large. A possibility where the TAE saturation amplitude in the central region is larger than $\delta B / B \sim 10^{-3}$, which is the amplitude at the edge region, is not excluded.

We have extended the hybrid simulation code for nonlinear magnetohydrodynamics (MHD) and energetic particle dynamics, MEGA, to simulate recurrent bursts of Alfvén eigenmodes by implementing the energetic-particle source, collisions, and losses[3]. The Alfvén eigenmode bursts with synchronization of multiple modes and beam ion losses at each burst were successfully simulated with nonlinear MHD effects for the physics condition similar to the previous reduced simulation[1] for the TFTR experiment. It was demonstrated with a comparison between nonlinear MHD and linear MHD simulation results that the nonlinear MHD effects significantly reduce both the saturation amplitude of the Alfvén eigenmodes and the beam ion losses. Two types of time evolution were found depending on the MHD dissipation coefficients, namely, viscosity, resistivity, and diffusivity. The Alfvén eigenmode bursts take place for higher dissipation coefficients with roughly 10% drop in stored beam energy and the maximum amplitude of the dominant magnetic fluctuation harmonic $\delta B_{m/n} / B \sim 5\times10^{-3}$ at the mode peak location inside the plasma. For lower dissipation coefficients, the Alfvén eigenmodes amplitude is at steady levels $\delta B_{m/n} / B \sim 2\times10^{-3}$ and the beam ion losses take place continuously. The radial magnetic fluctuation evolution is shown in Fig. 1. Figure 2 shows quadratic dependence of beam ion loss rate on magnetic fluctuation amplitude for the bursting evolution in the nonlinear MHD simulation. The beam ion pressure profiles are similar among the different dissipation coefficients, and the stored beam energy is higher for higher dissipation coefficients.

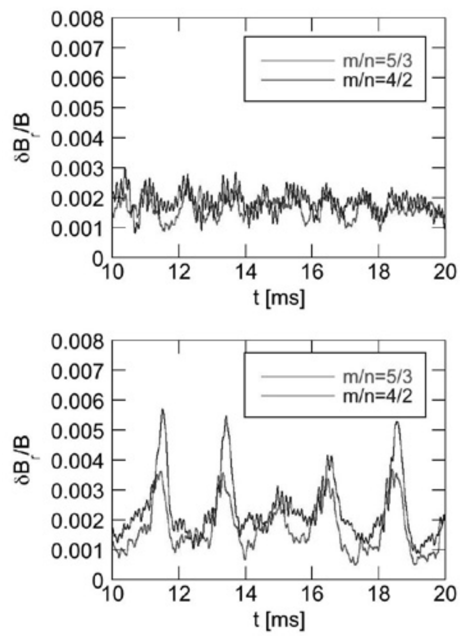

Fig. 1. Evolution of the dominant radial magnetic fluctuation harmonics with m/n=4/2 and m/n=5/3 at each peak location for nonlinear MHD run with $\nu = \nu_n = \eta / \mu_0 = 10^{-7} \mathrm{v}_A R_0$ (top) and and $5\times10^{-7} \mathrm{v}_A R_0$ (bottom).

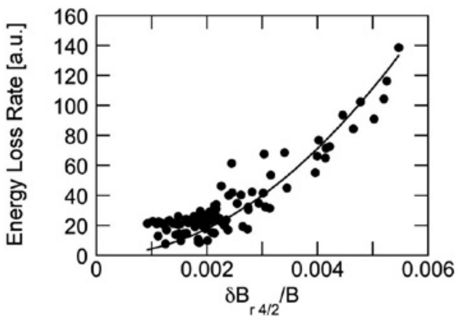

Fig. 2. Stored beam energy loss rate vs. radial magnetic fluctuation amplitude with m/n=4/2 at 10≤t≤20ms for nonlinear MHD run with $\nu = \nu_n = \eta / \mu_0 = 5\times10^{-7} \mathrm{v}_A R_0$. Data points are plotted every 0.1 ms. Solid line is a quadratic fit to the data.

1) Todo, Y. *et al.*: Phys. Plasmas **10** (2003) 2888.
2) Wong, K. L. *et al.*: 1991 Phys. Rev. Lett. **66** (1991) 1874.
3) Todo, Y. *et al.*: Nucl. Fusion **52** (2012) 033003.