§8. Reduced Simulation of Alfvén Eigenmode Bursts in LHD

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Computer simulation is a powerful tool to study self-consistent evolution of the system of energetic particles (EP) and Alfvén Eigenmodes (AE modes). Simulation methods of AE modes can be divided into two types. The first type is a hybrid simulation where full or reduced MHD equations are coupled with energetic-particle pressure or current density while energetic-particle orbits are followed in the MHD electromagnetic field. In the second type of simulation, the time evolution of AE mode amplitude and phase is followed in a way consistent with the energetic-particle evolution while the AE mode spatial profile is assumed constant [1,2]. This reduced simulation method has an advantage that the time step is not restricted by the Courant condition of the MHD equations and it suits simulation for long time-scale comparable to the EP slowing-down time.

A reduced version of the MEGA code has been newly developed to study the time evolution of energetic particles and AE modes in three-dimensional equilibria such as LHD [3]. Three-dimensional MHD equilibrium data calculated with the HINT code are used in the reduced simulation. In advance of the simulation, the spatial profile and frequency of Alfvén eigenmodes were analyzed with the AE3D code. The numerical algorithm how to calculate the time evolution of EP-AE system is the same as a reduced code for tokamaks [2].

The Alfvén eigenmode bursts in LHD plasma #47645 were simulated with neutral-beam injection (NBI) and collisions taken into account. The cylindrical coordinates (R,φ,z) with the number of grid points (128, 640, 128) were used. The equilibrium data calculated in the rotating helical coordinates with the HINT code was interpolated onto the cylindrical grid points. The two TAE modes with toroidal mode number n=1 were employed in the reduced simulation. The major four poloidal harmonics with toroidal mode number n=1 were mapped to the simulation region using the mapping of the Boozer coordinates (ρ,ϑ,ζ) to the cylindrical coordinates. The coordinate ρ is the square root of the normalized toroidal magnetic flux, and takes $\rho = 0$ at the plasma center and $\rho = 1$ at the plasma edge. The poloidal and toroidal angles in the Boozer coordinates are denoted as ϑ and ζ, respectively. The neutral beams in the experiment were injected onto the outboard side. The NBI deposition profile $I(\rho,\vartheta,\zeta)$ was simply modeled by a Gaussian profile

$$\begin{aligned} I(\rho,\vartheta,\zeta) &= I_0 \exp[-\rho_I^2/\Delta^2] \\ \rho_I^2 &= (\rho\cos\vartheta-\rho_C)^2+(\rho\sin\vartheta)^2 \end{aligned} \tag{1}$$

where $\rho_C = 0.3$, $\Delta = 0.4$, and I_0 is used to adjust the injection power. In the simulation run reported in this artilce, the injection power is 5 MW and the beam energy is 180 keV. The beam injection direction is tangential and the injection powers of the co- and counter-beams are respectively a half of the total injection power. For simplicity, the pitch-angles of the injected particles are assumed $v_{//}/v=1$ or -1. The slowing-down is taken into account in the simulation, while the pitch-angle scattering is neglected. The slowing-down time is assumed 100 ms and the damping rate of the TAE modes is taken to be 6% of the angular frequency of the lower-frequency TAE mode. The beam ion loss is modeled by removing the particles that reached the plasma edge $(\rho = 1)$.

The amplitude evolution of the two TAE modes in the simulation result is shown in Fig. 1. It is seen in the figure that the TAE bursts takes place and the behavior of the two TAE modes are synchronized. The synchronized bursts of the multiple TAE modes were also found in the simulation results of the TAE bursts in TFTR tokamak plasma [2]. The synchronization of the multiple TAE modes takes place through the nonlinearity of the energetic-particle dynamics, namely the resonance overlap [1]. The amplitude of the high frequency mode is greater than that of the low frequency mode. This can be explained by the fact that the resonance location of the high frequency mode is closer to the center of the beam injection profile. The time evolution of the stored beam energy was investigated. It was found that the losses of the co-injected beam ions take place associated with the TAE bursts. The time interval of the TAE bursts shown in Fig. 1 is roughly 2ms, which is shorter than the experimental value 9ms. More realistic beam injection profile including the spatial and pitch-angle distribution may be needed to reproduce the experimental results more closely. Also the particle loss condition needs a careful modeling, because the particles are not immediately lost when they reach the plasma edge. The TAE mode damping rate also should be chosen carefully to match the time interval of the bursts to the experimental results.

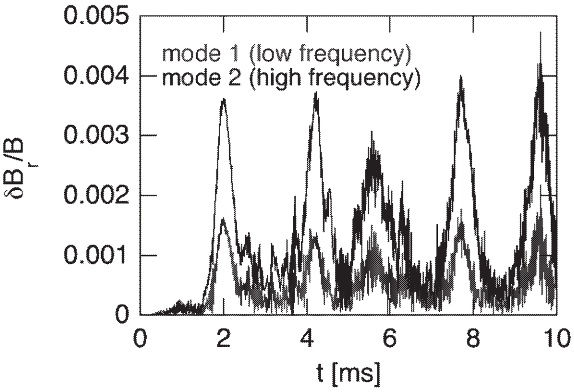

Fig. 1. Time evolution of the two toroidal Alfvén eigenmode amplitude. The amplitude is represented by the peak value of the radial magnetic field fluctuation inside the plasma.

1) Berk, H. L. et al.: Nucl. Fusion **35** (1995) 1713
2) Todo, Y. et al.: Phys. Plasmas **10** (2003) 2888
3) Todo, Y. et al.: Fusion Energy 2008, TH/P3-9