§8. Simulation Study of Energetic Ion Transport Due to Alfvén Eigenmodes in LHD Plasma

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The creation of hole and clump pairs in energetic ion energy spectra associated with the Alfvén eigenmodes was observed with the neutral particle analyzer (NPA) on LHD shot #47645[1]. The frequencies of the Alfvén eigenmodes are roughly 55 kHz and 68 kHz, respectively. Both of the Alfvén eigenmodes have toroidal mode number n=1. The hole and clump pairs are created around an energy of 150 keV. The difference in the slowing-down times between the holes and clumps suggests that the energetic ions were transported over 10% of the plasma minor radius.

The Alfvén eigenmodes with toroidal mode number n=1 in the LHD shot #47645 were analyzed with the AE3D code[2], which is based on a Galerkin approach using a combined Fourier mode (poloidal/toroidal angle) finite element (radial) representation in Boozer coordinates. An MHD equilibrium was constructed in the Boozer coordinates. Two toroidal Alfvén eigenmodes (TAE modes) were found with the eigen-frequencies of 42.7 kHz and 79.1 kHz. The eigen-frequencies are comparable to the Alfvén eigenmode frequencies observed in the experiment. The spatial profiles of electrostatic potential are shown in Fig. 1. The primary poloidal harmonics of both the two TAE modes are m=1 and m=2. The primary poloidal harmonics have the same sign for the TAE mode with frequency 42.7 kHz, while they have the opposite signs for the mode with frequency 79.1 kHz.

The energetic-ion orbits were calculated with different starting points on the NPA line-of-sight in an MHD equilibrium constructed with the HINT code. The energetic-ion energy is 150 keV at which hole and clump creation in energy spectrum was observed with the NPA. We found that energetic ions exist with the orbit frequencies 55kHz and 68kHz same as the Alfvén eigenmode frequencies observed in the LHD experiment[3].

We considered how far the energetic ions are transported by the finite amplitude eigenmodes[3]. To study this, we investigated Poincaré plots where only one eigenmode is taken into account and the amplitude of the eigenmode is at a constant value. We need a conserved variable to make Poincaré plots interpretable. In axisymmetric equilibria, we can find a conserved variable in the interaction of a constant amplitude wave with finite frequency. The phase space regions trapped by the eigenmodes appear as islands in the Poincaré plots. As island width depends on AE amplitude, we can determine the amplitude that is consistent with the energetic ion transport. Then, we investigate an axisymmetric equilibrium comparable to the LHD equilibrium. We would like to emphasize that this is the first attempt to understand the phase space structures in the LHD plasmas with finite amplitude waves. The Poincaré plots for TAE modes, whose spatial profile is shown in Fig. 1, are shown in Fig. 2. The radial width of the islands corresponds to the transport distance of the energetic ions. As island width depends on the Alfvén eigenmode amplitude, it was found that the Alfvén eigenmodes with amplitude $\delta B_r / B \sim 10^{-3}$ resulted in island widths at about 10% of the minor radius, in consistency with the experimental observations.

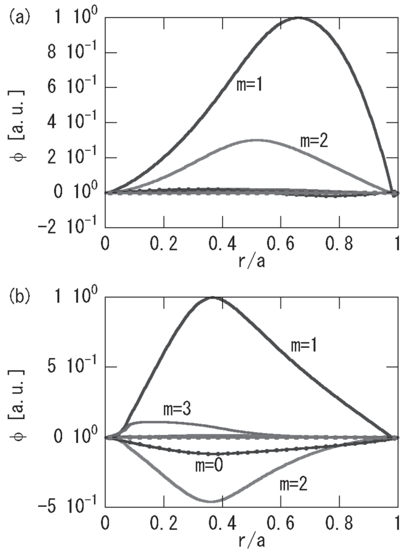

Fig. 1. Spatial profiles of the n=1 toroidal Alfvén eigenmodes analyzed with the AE3D code for the LHD shot #47645. The frequencies are (a) 42.7 kHz and (b) 79.1 kHz, respectively.

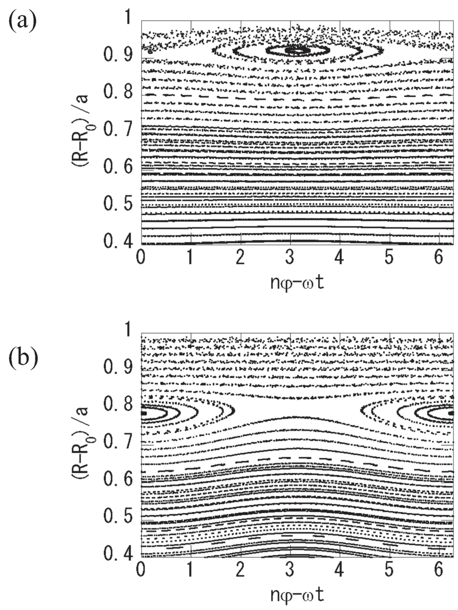

Fig. 2. Poincaré plots for (a) the TAE [Fig.1(a)] with amplitude $\delta B_r / B = 2 \times 10^{-3}$ and (b) the TAE [Fig.1(b)] with amplitude $\delta B_r / B = 10^{-3}$.

1) M. Osakabe et al., Nucl. Fusion **46**, S911 (2006).
2) D. A. Spong and Y. Todo, 49th APS-DPP (2007).
3) Y. Todo et al., to appear in Plasma Fusion Res. **3** (2008).