Simulation study of energetic ion transport due to Alfvén eigenmodes in an LHD plasma

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The creation of hole and clump in energetic ion energy spectrum associated with the Alfvén eigenmodes was observed with the neutral particle analyzer (NPA) on LHD shot #47645. The difference in slowing-down time between the hole and clump suggests that the energetic ions were transported for 10% of the plasma minor radius. The spatial profile and frequency of the Alfvén eigenmodes was analyzed with the AE3D code. The phase space structures of the energetic ions on the NPA line-of-sight were investigated in an axisymmetric equilibrium comparable to the LHD equilibrium with the Poincaré plots where one oscillating Alfvén eigenmode for each plot is employed. The phase space regions trapped by the Alfvén eigenmodes appear as islands in the Poincaré plots. The radial width of the islands corresponds to the transport distance of energetic ions. The island width depends on the Alfvén eigenmode amplitude. It was found that the Alfvén eigenmodes with amplitude $\delta B_r / B \sim 10^{-3}$ transport energetic ions for 10% of the minor radius.

Keywords: energetic ion transport, Alfvén eigenmode, Poincaré plot, LHD, neutral particle analyzer

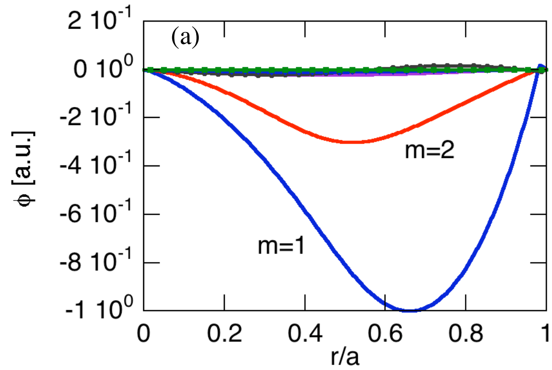
1. Inroduction

The creation of hole and clump in energetic ion energy spectrum 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 the Alfvén eigenmodes have toroidal mode number n=1. The hole and clump are created around energy 150 keV. The difference in slowing-down time between the hole and clump suggests that the energetic ions were transported for 10% of the plasma minor radius.

In this paper, we try to find the candidates of the Alfvén eigenmodes using the AE3D code [2]. We also investigate the Alfvén eigenmode amplitude consistent with the energetic-ion transport suggested by the NPA data. The Poincaré plots were made to investigate the phase space structures of the energetic ions on the NPA line-of sight. The phase space regions trapped by the Alfvén eigenmodes appear as the islands in the Poincaré plots. The radial width of the islands corresponds to the transport distance of energetic ions. As island width depends on Alfvén eigenmode amplitude, we can discuss the amplitude consistent with the NPA observation.

2. Analysis of Alfvén eigenmodes

The Alfvén eigenmodes with toroidal monde number n=1 in the LHD shot #47645 were analyzed with the



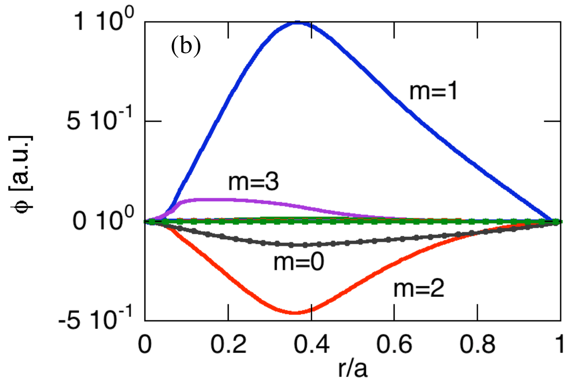


Fig.1 Spatial profiles of the n=1 toroidal Alfvén eigenmodes analyzed with the AE3D code for the LHD shot #47645. The frequencies are (a) 42.7 kHz and (b) 79.1 kHz, respectively.

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AE3D code where the Galerkin method is used in the Boozer coordinates. An MHD equilibrium was constructed in the Boozer coordinates. Two toroidal Alfvén eigenmodes (TAE modes) were found with The eigen-frequencies 42.7 kHz and 79.1 kHz. The eigen-frequencies are comparable to the Alfvén eigenmode frequencies observed at 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 sign to each other for the mode with frequency 79.1 kHz.

3. Analysis of energetic-ion orbit

The energetic-ion orbits were calculated with different starting points on the NPA line-of sight. The orbits were calculated in an MHD equilibrium constructed in the HINT coordinates [3]. The energetic-ion energy is 150 keV with which the hole and clump creation in energy spectrum was observed with the NPA. The pitch angle is determined by the direction of the NPA line-of-sight. The poloidal orbit-frequency is defined by $\omega_\theta = 2\pi / T_\theta$ where T_θ is the poloidal circulation time. The toroidal orbit-frequency is defined by $\omega_\varphi = \Delta\varphi / T_\theta$ where $\Delta\varphi$ is the toroidal angle which the energetic ion proceeds in T_θ.

The orbit frequency of the energetic ions is defined by

$$f_{m/n} = \left(n\omega_\varphi - m\omega_\theta\right)/2\pi,$$

where n and m are toroidal and poloidal mode nubers. We take n=1 and m=1 which are identical to the primary poloidal harmonic of the TAE modes shown in Fig. 1. In Fig. 2, the orbit frequency is shown versus the major radius of the starting point on the NPA line-of-sight. We see that there exist energetic ions with the same orbit frequency as the Alfvén eigenmode frequencies observed at the LHD experiment. These energetic ions resonate with the Alfvén eigenmodes.

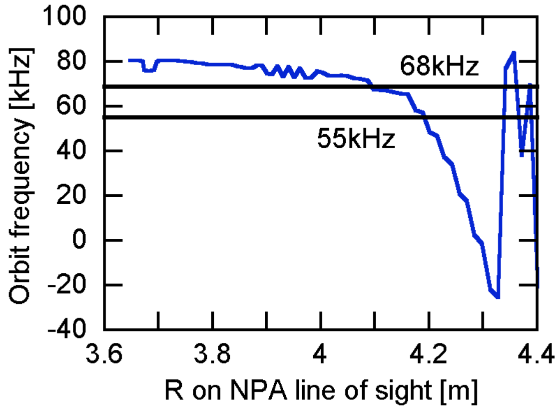

Fig.2 Blue curve represents energetic-ion orbit frequency with m/n=1/1 as a function of the starting point major radius on the NPA line-of-sight. Black lines denote Alfvén eigenmode frequencies observed in the LHD experiment.

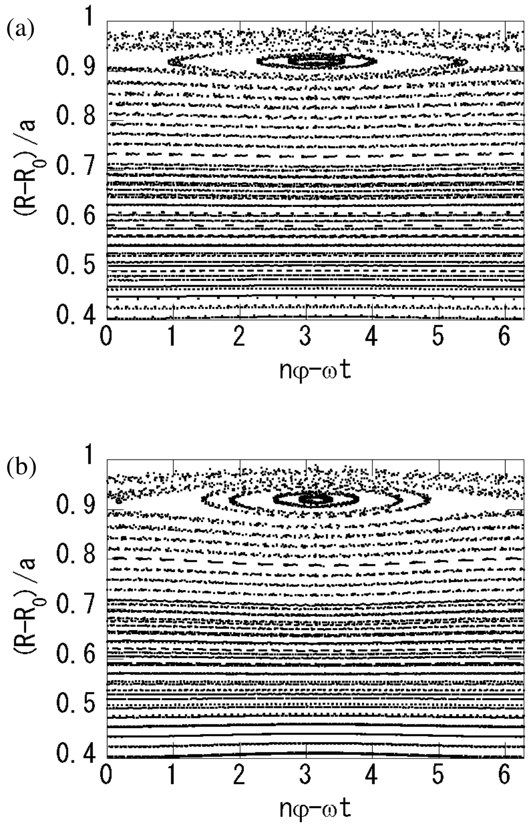

Fig.3 Poincaré plots for the lower frequency TAE with amplitude (a) $\delta B_r / B = 10^{-3}$ and (b) $\delta B_r / B = 2\times10^{-3}$.

4. Phase space structure of energetic ions

In axisymmetric systems, $E' = E - \omega P_\varphi / n$ is conserved in the wave-particle interaction. Here, E and P_φ are respectively the total energy and the canonical toroidal momentum of the particle. This enables to utilize Poincaré plots where the particles with the same E' are employed. The phase space structure associated with finite-frequency waves can be analyzed with the Poincaré plots. Furthermore, as the harmonics of the two TAE modes other than n=1 are negligibly small, we expect some similarities in phase space structure between the LHD equilibrium and axisymmetric systems.

Then, we investigate an axisymmetric equilibrium

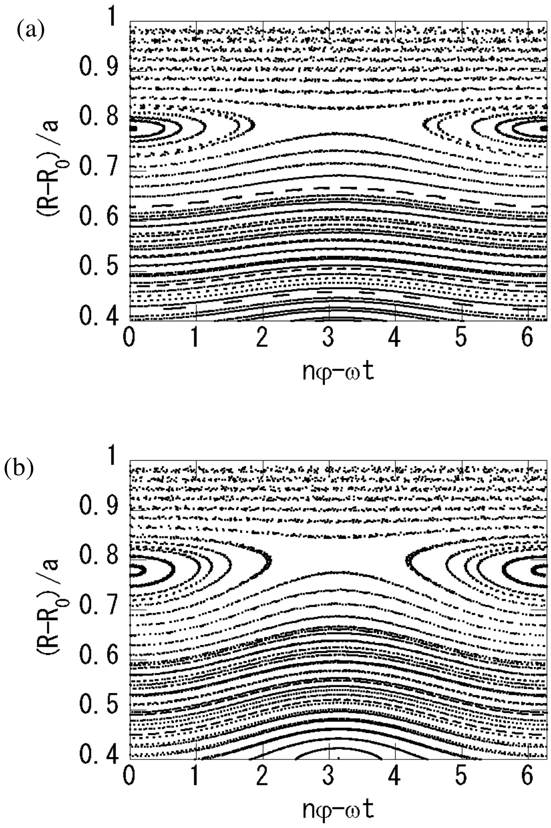

Fig.4 Poincaré plots for the higher frequency TAE with amplitude (a) $\delta B_r / B = 10^{-3}$ and (b) $\delta B_r / B = 2 \times 10^{-3}$.

comparable to the LHD plasma #47645. The parameters of the axisymmetric equilibrium are major radius 3.67m, minor radius 0.54m, toroidal magnetic field 0.5T, and safety factor profile $q(r) = 2.11 - 1.23(r/a)^2$. The value of E' is that of a particle with energy 150keV at $r = 0.7a$. The two TAE modes are mapped to the axisymmetric equilibrium. The frequencies are renormalized to the experimental values 55kHz for the lower frequency TAE shown in Fig. 1(a) and 68kHz for the higher frequency TAE shown in Fig. 1(b).

The Poincaré plots for the lower frequency TAE are shown in Fig. 3. The phase space regions trapped by the Alfvén eigenmodes appear as the islands in the Poincaré plots. The radial width of the islands corresponds to the transport distance of energetic ions. The island width depends on the Alfvén eigenmode amplitude. The lower frequency TAE with amplitude $\delta B_r / B = 2 \times 10^{-3}$ transports energetic ions for 10% of the minor radius. The phase space structures with the higher frequency TAE is analyzed in Fig. 4. Comparing Fig. 4(a) and (b), we see that the higher frequency TAE with amplitude $\delta B_r / B = 10^{-3}$ transports energetic ions for 10% of the minor radius.

4. Summary

The spatial profile and frequency of the Alfvén eigenmodes in the LHD shot #47645, where the creation of hole and clump in energetic ion energy spectrum associated with the Alfvén eigenmodes was observed, was analyzed with the AE3D code. The difference in slowing-down time between the hole and clump observed at the experiment suggests that the energetic ions were transported for 10% of the plasma minor radius. The phase space structures of the energetic ions on the NPA line-of-sight were investigated investigated in an axisymmetric equilibrium comparable to the LHD equilibrium with the Poincaré plots where an oscillating Alfvén eigenmode for each plot is employed. The phase space regions trapped by the Alfvén eigenmodes appear as the islands in the Poincaré plots. The radial width of the islands corresponds to the transport distance of energetic ions. The island width depends on the Alfvén eigenmode amplitude. It was found that the Alfvén eigenmodes with amplitude $\delta B_r / B \sim 10^{-3}$ transport energetic ions for 10% of the minor radius.

References

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