§1. Study on TAE-Induced Fast-Ion Loss Process in LHD

Ogawa, K., Isobe, M., Toi, K., Shimizu, A., Spong, D.A. (Oak Ridge National Laboratory), Osakabe, M., Yamamoto, S. (Kyoto Univ.), LHD Experiment Group

Much attention has been given to the effects of fast-ion-driven MHD instabilities such as toroidal-Alfvén eigenmodes (TAEs) on fast-ion transport and/or loss in magnetically confined fusion because those instabilities can potentially induce anomalous fast-ion losses. In Large Helical Device (LHD), recurrent bursts of TAEs have been often excited by super-Alfvénic ions produced by high-energy neutral beam (NB) injection, leading to anomalous fast-ion losses. A Mirnov coil array indicates that TAEs observed in LHD have a mode structure of m/n=~1/1 and are characterized by a relatively wide radial profile [1)].

Measurements of fast-ion losses induced by these TAE instabilities are conducted in NB-heated LHD plasmas having three magnetic axis positions at finite β, i.e. R_{mag}=3.75m (case A), 3.86 m (case B), and 4.00 m (case C). As R_{mag} becomes larger, fast-ion orbits tend to deviate largely from magnetic flux surfaces as shown in Fig. 1 (a). In this paper, r/a and B_{t} represent normalized minor radius and toroidal magnetic field strength, respectively. Note that the TAE gap becomes wider with larger R_{mag} compared with smaller R_{mag} since magnetic shear in LHD becomes weaker as R_{mag} becomes larger. Figure 1 (c) shows an increment of fast-ion loss flux due to the TAEs from the neoclassical orbit loss level ($\Delta\Gamma_{\mathrm{fast\ ion}}$) at the SLIP position normalized by fast-ion populations created by co-injected NB, i.e. $P_{\mathrm{NBco}}\times\tau_{\mathrm{s}}$ as a function of $b_{\theta\mathrm{TAE}}/B_{\mathrm{t}}$. Here, P_{NBco}, τ_{s}, and $b_{\theta\mathrm{TAE}}$ stand for co-injected NB power, the Spitzer slowing-down time, and poloidal magnetic fluctuation amplitude at the Mirnov coil position placed on the vacuum vessel, respectively. In case B, the dependence of the fast-ion loss flux on $b_{\theta\mathrm{TAE}}/B_{\mathrm{t}}$ changes at $b_{\theta\mathrm{TAE}}/B_{\mathrm{t}} \sim 7\times10^{-5}$. In the low $b_{\theta\mathrm{TAE}}$ regime, $\Delta\Gamma_{\mathrm{fast\ ion}}$ is proportional to $b_{\theta\mathrm{TAE}}$ whereas it scales as $\Delta\Gamma_{\mathrm{fast\ ion}} \propto b_{\theta\mathrm{TAE}}^2$ in the higher $b_{\theta\mathrm{TAE}}$ regime. According to a theory [2)], $\Delta\Gamma_{\mathrm{fast\ ion}}$ proportional to $b_{\theta\mathrm{TAE}}$ is suggested to be due to a convective type loss process whereas $\Delta\Gamma_{\mathrm{fast\ ion}}$ scaling as the square of $b_{\theta\mathrm{TAE}}$ is suggested to be due to a diffusive type loss process. The experimental result indicates that the fast-ion loss process changes from convective to diffusive in case B. On the other hand, in cases A and C, this change of loss processes has not been observed for these $b_{\theta\mathrm{TAE}}/B_{\mathrm{t}}$ ranges although the change may appear in unexplored regions.

Previous work modeling for axisymmetric tokamak predicts that the process of TAE-induced fast-ion transport changes from a convective type to a diffusive type according to $b_{\theta\mathrm{TAE}}$[3)]. To study fast-ion loss processes in a three-dimensional helical configuration precisely, simulations based on an orbit following model, DELTA5D[4)], have been performed. TAE magnetic fluctuation is modeled as $\boldsymbol{b}=\nabla\times(\alpha\boldsymbol{B})$, where α is given based on the eigenfunction of TAEs shown in Fig. 1 (b). The eigenfunction is calculated by an ideal MHD calculation code treating shear-Alfvén waves, AE3D[5)]. The dependence of $\Delta\Gamma_{\mathrm{fast\ ion}}/(P_{\mathrm{NBco}}\times\tau_{\mathrm{s}})$ on $b_{\theta\mathrm{TAE}}/B_{\mathrm{t}}$ obtained by simulation is shown in Fig. 2. In case A, the calculated dependence is similar to Fig. 1 (c) in the low $b_{\theta\mathrm{TAE}}$ regime. The change of the loss process to a diffusive nature appears at $b_{\theta\mathrm{TAE}}/B_{\mathrm{t}}$ of ~ 10^{-4} that is in unexplored regions of experiments. In case B, the change of the loss process from a convective type to a diffusive type is successfully reproduced. As described in Ref. 3, our calculation suggests that with a convective type loss process, the barely confined fast ions near the confinement/loss boundary are lost. On the other hand, the fast ions confined in the interior region of the plasma are lost with a diffusive type loss process. Experimentally observed phenomena are explained as follows. In the small $b_{\theta\mathrm{TAE}}$ region, the convective type loss is dominant. As $b_{\theta\mathrm{TAE}}$ increases, the diffusive type loss increases and exceeds the convective type loss at a certain $b_{\theta\mathrm{TAE}}$ level.

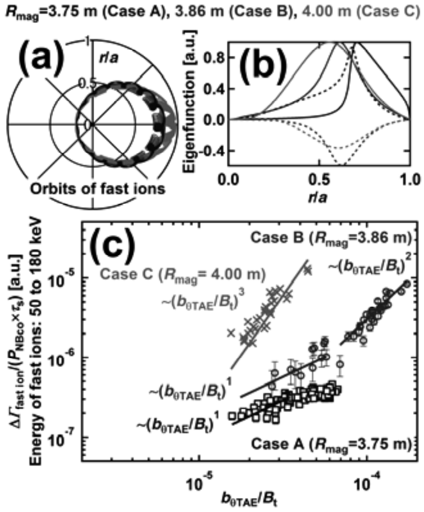

Fig. 1 (a) Co-circulating fast-ion orbits in cases A, B, and C on B_{t}= 0.6 T. (b) Eigenfunctions of TAE calculated by AE3D for cases A, B, and C. (c) $\Delta\Gamma_{\mathrm{fast\ ion}}/(P_{\mathrm{NBco}}\times\tau_{\mathrm{s}})$ as a function of $b_{\theta\mathrm{TAE}}/B_{\mathrm{t}}$. Dependence of fast-ion loss flux on $b_{\theta\mathrm{TAE}}/B_{\mathrm{t}}$ changes at $b_{\theta\mathrm{TAE}}/B_{\mathrm{t}}\sim7\times10^{-5}$ in case B.

1) Toi, K. et al. : Plasma Phys. Control. Fusion **53** (2011) 024008.
2) Heidbrink, W.W. et al., Phys. Fluids B **5** (1993) 2176.
3) Sigmar, D. et al. : Phys. Fluids B **4** (1992) 1506.
4) Spong, D. A. : Phys. Plasmas **18** (2011) 056109.
5) Spong, D. A. et al. : Phys. Plasmas **17** (2010) 022106.

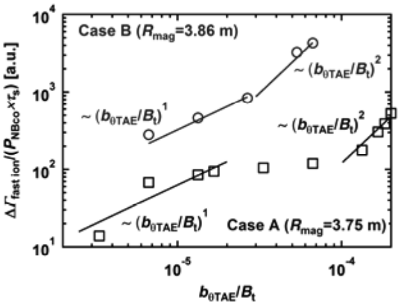

Fig. 2 $\Delta\Gamma_{\mathrm{fast\ ion}}/(P_{\mathrm{NBco}}\times\tau_{\mathrm{s}})$ as a function of $b_{\theta\mathrm{TAE}}/B_{\mathrm{t}}$ in calculations for cases A and B. The dependence is similar to that obtained in experiments in case A in the low $b_{\theta\mathrm{TAE}}$ regime. The change of the loss process from a convective type to a diffusive type is reproduced by simulation for case B.