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

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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. $P_{\mathrm{NBco}}\times\tau_s$ as a function of $b_{\theta\mathrm{TAE}}/B_t$. 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 $b_{\theta\mathrm{TAE}}/B_t$ changes at $b_{\theta\mathrm{TAE}}/B_t \sim 7\times10^{-5}$. 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 $b_{\theta\mathrm{TAE}}/B_t$ 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 $\Delta\Gamma_{\mathrm{fast\ ion}}/(P_{\mathrm{NBco}}\times\tau_s)$ on $b_{\theta\mathrm{TAE}}/B_t$ 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 $b_{\theta\mathrm{TAE}}/B_t$ 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.

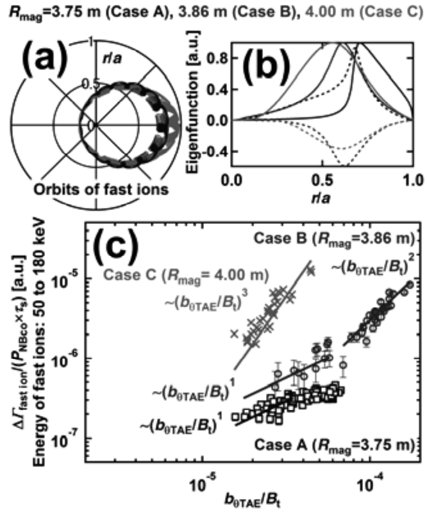

Fig. 1 (a) Co-circulating fast-ion orbits in cases A, B, and C on B_t= 0.6 T. (b) Eigenfunctions of TAE calculated by AE3D for cases A, B, and C. (c) $\Delta\Gamma_{\mathrm{fast\ ion}}/(P_{\mathrm{NBco}}\times\tau_s)$ as a function of $b_{\theta\mathrm{TAE}}/B_t$. Dependence of fast-ion loss flux on $b_{\theta\mathrm{TAE}}/B_t$ changes at $b_{\theta\mathrm{TAE}}/B_t$~$7\times10^{-5}$ in case B.

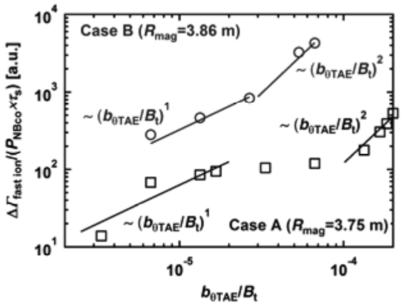

Fig. 2 $\Delta\Gamma_{\mathrm{fast\ ion}}/(P_{\mathrm{NBco}}\times\tau_s)$ as a function of $b_{\theta\mathrm{TAE}}/B_t$ in calculations for cases A and B. The dependence is similar to that obtained in experiments in case A in the low $b_{\theta\mathrm{TAE}}$ regime. The change of the loss process from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

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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.