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


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 \( \beta \), i.e. \( R_{\text{mag}}=3.75 \) m (case A), 3.86 m (case B), and 4.00 m (case C). As \( R_{\text{mag}} \) 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 \( B_r \) represent normalized minor radius and toroidal magnetic field strength, respectively. Note that the TAE gap becomes wider with larger \( R_{\text{mag}} \) since magnetic shear in LHD becomes weaker as \( R_{\text{mag}} \) becomes larger. Figure 1 (c) shows an increment of fast-ion loss flux on \( b_{\text{TAE}}/B_r \) changes at \( b_{\text{TAE}}/B_r \sim 7\times10^{-5} \) in case B.

In case A, the calculated dependence is similar to Fig. 1 (c) in the low \( b_{\text{TAE}} \) regime. The change of the loss process to a diffusive nature appears at \( b_{\text{TAE}}/B_r \sim 0.6 \) T. 

The eigenfunction of TAEs shown in Fig. 1 (b). The eigenfunction is calculated by an ideal MHD code treating shear-Alfvén waves, AE3D\(^5\).

The dependence of \( \Delta f_{\text{fast}} \) on \( b_{\text{TAE}}/B_r \) obtained by simulation is shown in Fig. 2. In case A, the dependence of \( \Delta f_{\text{fast}} \) on \( b_{\text{TAE}}/B_r \) changes at \( b_{\text{TAE}}/B_r \sim 7\times10^{-5} \) in case B.

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 \( b_{\text{TAE}} \). To study fast-ion loss processes in a three-dimensional helical configuration precisely, simulations based on an orbit following model, DELTA5D\(^3\), have been performed. TAE magnetic fluctuation is modeled as \( b = \nabla \times (\alpha \beta B) \), where \( \alpha \) is given based on the eigenfunction of TAEs shown in Fig. 1 (b).

Fig. 1 (a) Co-circulating fast-ion orbits in cases A, B, and C on \( B_r = 0.6 \) T. (b) Eigenfunctions of TAEs calculated by AE3D for cases A, B, and C. (c) \( \Delta f_{\text{fast}} \) on \( b_{\text{TAE}}/B_r \) changes at \( b_{\text{TAE}}/B_r \sim 7\times10^{-5} \) in case B.

Fig. 2 \( \Delta f_{\text{fast}} \) on \( b_{\text{TAE}}/B_r \) in calculations for cases A and B. The dependence is similar to that obtained in experiments in case A in the low \( b_{\text{TAE}} \) regime. The change of the loss process from a convective type to a diffusive type is reproduced by simulation for case B.

References: