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Magnetic Configuration Effects on Fast Ion Losses Induced by Fast Ion Driven Toroidal Alfvén Eigenmodes in the Large Helical Device

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Abstract

Beam-ion losses induced by fast-ion-driven toroidal Alfven eigenmodes (TAE) were measured with a scintillator-based lost fast-ion probe (SLIP) in the large helical device (LHD). The SLIP gave the energy E and pitch angle $\chi=\arccos(v_{//}/v)$ distribution of the lost fast ions simultaneously. The loss fluxes were investigated in three typical magnetic configurations of $R_{\mathrm{ax\_vac}}$=3.60 m, 3.75 m, and 3.90 m, where $R_{\mathrm{ax\_vac}}$ is the magnetic axis position of the vacuum field. Dominant losses induced by TAEs in these three configurations were observed in the following E/χ regions of 50–190 keV/40°, 40–170 keV/25°, and 30–190 keV/30°, respectively. Lost-ion fluxes induced by TAEs clearly depend on the amplitude of TAE magnetic fluctuations, $R_{\mathrm{ax\_vac}}$ and the toroidal field strength B_{t}. The increment of the loss fluxes has the dependence of $(b_{\mathrm{TAE}}/B_{\mathrm{t}})^{\mathrm{s}}$. The power s increases from s=1 to 3 with the increase of the magnetic axis position in finite beta plasmas.

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1. Introduction

One of the crucial issues in realizing self-sustained DT burning plasma is how well fast ions such as alpha particles can be confined. This issue is also important for reactor-relevant plasma such as ITER plasmas [1]. However, significant loss of alpha particles due to fast-ion-driven magnetohydrodynamic (MHD) instabilities such as Alfvén eigenmodes (AEs) [2] excited by alpha particles might induce localized damages of plasma facing components. Hence, better understanding of the process of fast-ion loss due to fast-ion-driven MHD instabilities is required to find a method to control and/or reduce fast-ion losses. Anomalous transport of co-going beam ions due to toroidal Alfvén eigenmodes (TAEs) has been so far recognized in the Large Helical Device (LHD) by an E//B neutral particle analyzer with a tangential line of sight [4]. Recently, TAE-induced beam ion losses were detected by means of a scintillator-based lost-fast ion probe (SLIP) installed at the outboard side of the LHD [5]. This paper is devoted to the study of characteristics of energetic ion losses induced by TAE in various magnetic configurations where neoclassical transport of fast ions would also behave differently, depending on the magnitude of magnetic field ripple.

2. Experimental Setups

There are three negative-ion-based neutral beam (NB) injectors on the LHD, and total power more than ~8 MW having a beam energy of 180–190 keV can be injected. In this experiment, one of them tangentially injected NBs in the counter-direction, whereas the others tangentially inject NBs in the co-direction. Beam-ion losses from the LHD are measured with a SLIP. The SLIP is essentially a magnetic spectrometer that provides information on the energy E and pitch angles $\chi=\arccos(v_{//}/v)$ of escaping fast ions simultaneously. Here, v and $v_{//}$ indicate the velocity of fast ions and the velocity of fast ions parallel to the magnetic field, respectively. The SLIP installed at the outboard side of LHD is designed to detect co-going passing or transitional fast ions with pitch angles and gyroradii in the ranges of 20–70 degrees and 2–24 cm, respectively, at the detector location [6]. Luminous images produced on the scintillator screen are monitored with a 4×4 photomultiplier tube (PMT) array and an image-intensified CMOS camera, simultaneously. The relative sensitivity of PMTs is calibrated with an electro-luminescence sheet emitting a blue-green light, which has uniformity within 10 % error. The energetic ion loss study was carried out at three typical magnetic configurations, i.e. the "inward-shifted configuration" of R_{ax_vac}=3.60 m (R_{ax_vac}: magnetic axis position in the vacuum field), the "standard configuration" of R_{ax_vac}=3.75 m, and the "outward-shifted configuration" of R_{ax_vac}=3.90 m. In this study, the magnetic field strength B_t was varied from 0.60 T to 0.90 T, where the direction of B_t was counter-clockwise from the top view of the torus. In these experiments, the injected power of the NB injectors was adjusted for each configuration. In all shots, TAEs and EPM were excited by beam ions. The dominant energetic ion-driven mode was m~1/n=1 TAE, where m and n are respectively poloidal and toroidal mode numbers determined by toroidal/poloidal magnetic probe arrays. The eigenfunction has a peak at the normalized radial position r/a ~0.6. It consists of mainly two m=1 and m=2 Fourier modes, which have opposite polarity to each other and odd-parity type TAE [5]. In this paper, the TAE amplitude b_{TAE} was evaluated using the value obtained by the magnetic pickup coil placed on the vacuum vessel. The probe is placed at the top of the horizontal elongated section of the vacuum vessel, where the poloidal magnetic field strength is nearly independent of for the magnetic axis position.

3. Beam Ion Losses induced by TAEs in Various Magnetic Configurations

Characteristics of beam ion losses due to TAEs were investigated in the inward shifted configuration (R_{ax_vac}=3.60 m) at B_t=0.60 T and 0.75 T. In these experiments, three tangential NBs were injected into plasmas. The absorbed total NB powers P_{NB}, averaged fast-ion beta $<\beta_{fast}>$, line-averaged electron density $<n_e>$, and magnetic axis position evaluated from the electron temperature profile measured with Thomson scattering R_{mag} were respectively about 7.9 MW, 1.0 %,

$1.3\times10^{19}\mathrm{m}^{-3}$,and 3.86 m at B_t=0.60 T. On the other hand, they were respectively about 6.7 MW, 0.9 %, $1.3\times10^{19}\mathrm{m}^{-3}$ and 3.75m at B_t= 0.75 T. A sharp increase in the loss flux Γ_{SLIP} correlated with TAE bursts was observed in the approximate E/χ region of 50–190 keV/40°. In Fig. 1, the increment of beam-ion loss flux $\Delta\Gamma_{\mathrm{SLIP}}$ normalized by the energetic ion content generated by the co-injected NB injector ($P_{\mathrm{NBco}}\,\tau_{\mathrm{se}}$) is plotted as a function of the amplitude of TAE fluctuation b_{TAE} normalized by B_t, where P_{NBco} and τ_{se} indicate the absorbed power of co-injected NB and the slowing-down time of fast ions by electrons, respectively. Here, the fast-ion loss flux detected with the SLIP is considered to be proportional to the co-going fast-ion density $\propto P_{\mathrm{NBco}}\tau_{\mathrm{se}}$, because the SLIP was designed to detect co-going NBs. Here, $\Delta\Gamma_{\mathrm{SLIP}}$ is evaluated as the increment of Γ_{SLIP} from that just before each TAE burst. The normalized energetic-ion loss flux $\Delta\Gamma_{\mathrm{SLIP}}/P_{\mathrm{NBco}}\tau_{\mathrm{se}}$ increases nearly quadratically with b_{TAE}/B_t at B_t=0.60 T, and nearly proportionally to b_{TAE}/B_t at B_t=0.75 T. In this magnetic configuration, the loss fluxes were scaled as $\Delta\Gamma_{\mathrm{SLIP}}/P_{\mathrm{NBco}}\tau_{\mathrm{se}} \propto (b_{\mathrm{TAE}}/B_t)^2$ at B_t=0.6T, and $\propto (b_{\mathrm{TAE}}/B_t)$ at B_t=0.75T, respectively. That is, the respective loss process indicates a diffusive type at lower B_t (=0.6T) and a convective one at higher B_t (=0.75T), where s=1, 2 and 3 respectively correspond to convective loss, diffusive loss, and loss resulting from stochastic orbit for the form of the loss flux of $\Delta\Gamma_{\mathrm{SLIP}}/P_{\mathrm{NBco}}\tau_{\mathrm{se}}\propto(b_{\mathrm{TAE}}/B_t)^s$[7]. Note that white noise in the loss flux signal Γ_{SLIP} was removed by moving average technique. Accordingly, each loss flux was fitted with the form of $(b_{\mathrm{TAE}}/B_t)^s$ consistently.

Moreover, the magnitude of the loss flux $\Delta\Gamma_{\mathrm{SLIP}}/P_{\mathrm{NBco}}\tau_{\mathrm{se}}$ at B_t=0.75 T is by one order of magnitude lower than that at B_t=0.60 T, as seen from Fig. 1. The character of TAE induced ion losses at lower B_t (=0.60 T) is interpreted as these TAEs would easily push beam ions into the expanded loss-cone region in high-beta plasmas of $<\beta_{\mathrm{dia}}>$~1.7 % with considerable Shafranov shift. On the other hand, the Shafranov shift at B_t=0.75T is appreciably small because of lower toroidal beta (~1.0 %), compared with that at B_t=0.60 T. Thus small Shafranov shift leads to shrinkage of the loss-cone region. This is thought to bring about large diffusive loss in high-beta plasmas with large Shafranov shifts and low convective loss in lower-beta plasmas for the same range of TAE amplitude, as seen from Fig. 1. The Shafranov shift can modify the safety factor profile appreciably [8] and also expand the loss-cone region because of large orbit deviation from the magnetic surfaces [9]. The observed characteristics of beam ion loss fluxes would reflect a combined effect of TAE-induced transport and the size of loss cone region.

A study on TAE-induced loss was also carried out in the configuration of $R_{\mathrm{ax\_vac}}$=3.75 m at B_{t}=0.60 T and 0.75 T. Here, P_{NB}, $<\beta_{\mathrm{fast}}>$, $<n_{\mathrm{e}}>$, and the magnetic axis positions of the finite beta plasma R_{mag} were respectively about 6.3 MW, 0.4 %, $1.7\times10^{19}\mathrm{m}^{-3}$, and 3.85 m for B_{t}=0.60 T, and about 5.5 MW, 0.3 %, $1.8\times10^{19}\mathrm{m}^{-3}$, and 3.90 m for B_{t}=0.75 T. The plasma beta values at both B_{t} values were nearly the same at around 1.3 %. Dominant TAE-induced losses were observed with the SLIP in the approximate E/χ region of 30–190 keV/30°. As shown in Fig.2, the normalized loss flux $\Delta\Gamma_{\mathrm{SLIP}}/P_{\mathrm{NBco}}\tau_{\mathrm{se}}$ decreases with the increase in the magnetic field strength, as same as the above-mentioned experiments. The loss flux $\Delta\Gamma_{\mathrm{SLIP}}/P_{\mathrm{NBco}}\tau_{\mathrm{se}}$ increases nearly quadratically with the relative TAE amplitude $b_{\mathrm{TAE}}/B_{\mathrm{t}}$ at both cases of B_{t}=0.60 T and 0.75 T. This tendency is similar to the characteristics obtained in high-beta plasma at $R_{\mathrm{ax\_vac}}$=3.60 m. Note that the magnetic axis position R_{mag} on relatively low-beta plasma (~1.3 %) in the configuration of $R_{\mathrm{ax\_vac}}$=3.75 m is comparable to that of the high-beta plasma (~1.7 %) in the configuration of $R_{\mathrm{ax\_vac}}$=3.60 m. The loss cone of the relatively low-beta plasma in the $R_{\mathrm{ax\_vac}}$=3.75 m configuration is similar to that of the high-beta plasma at $R_{\mathrm{ax\_vac}}$=3.60 m, because R_{mag} is nearly the same in the two configurations. This experimental result may be explained by modifying the safety factor profile and the loss-cone region.

TAE-induced beam ion losses were also studied in the outward-shifted configuration ($R_{\mathrm{ax\_vac}}$=3.90 m) at B_{t}=0.75 T and 0.90 T. Two NBs were injected into the plasma, and the resulting bulk plasma beta was relatively low (~0.7 %). In this experiment, P_{NB}, $<\beta_{\mathrm{fast}}>$, $<n_{\mathrm{e}}>$, and R_{mag} were about 4.5 MW, 0.3 %, $1.0\times10^{19}\mathrm{m}^{-3}$, and 4.05 m at B_{t}=0.75 T, and about 5.5 MW, 0.2 %, $1.5\times10^{19}\mathrm{m}^{-3}$, and 4.00 m at B_{t}=0.90 T, respectively. Dominant TAE-induced loss fluxes were observed in the approximate E/χ region of 40–170 keV/25°. In this outward-shifted configuration, sizable losses were clearly observed at even higher B_t of 0.90 T, as shown in Fig. 3. This result is related to the fact that the deviation of beam-ion orbits from flux surfaces is considerably large, compared with that in the R_{ax_vac}=3.60 m configuration. In contrast to the results of the above-mentioned configurations shown in Figs. 1 and 2, the normalized loss flux $\Delta\Gamma_{SLIP}/P_{NBco}\tau_{se}$ increases rapidly with the TAE fluctuation amplitude, and is scaled with the higher power of the TAE amplitude, that is, $\propto (b_{TAE}/B_t)^3$ at both cases of B_t=0.75 T and B_t=0.90 T. Although this type of loss was inferred to be due to the destruction of magnetic surfaces in ref. [7], this dependence also may be explained by the loss-cone effect. That is, the loss cone in this configuration is wider than that in the R_{ax_vac}=3.60 m and R_{ax_vac}=3.75 m configurations, and fast ions would easily fall into the loss cone by TAE fluctuations. This situation would lead to a stronger dependence of the loss fluxes on the TAE amplitude.

4. Summary

In LHD, time-resolved energy and pitch-angle measurements of beam-ion losses induced by TAEs were carried out at three typical magnetic configurations R_{ax_vac}=3.60 m, 3.75 m, and 3.90 m, and two different magnitudes of B_t. In all these configurations from B_t=0.60 T to 0.90 T, m~1/n=1 TAE was strongly destabilized and fast-ion losses were induced in the approximate ranges of E=30–190 keV and χ=25°–40°. With the increase of the Shafranov shift (or magnetic axis position shift R_{mag}), the normalized loss fluxes $\Delta\Gamma_{SLIP}/P_{NBco}\tau_{se}$ increase more rapidly with the increase in the relative amplitude of the TAE magnetic fluctuations b_{TAE}/B_t. That is, the normalized loss fluxes increase having the following form $\Delta\Gamma_{SLIP}/P_{NBco}\tau_{se}\propto(b_{TAE}/B_t)^s$. In the plasmas with smaller R_{mag}, the power of the dependence s was s=1, and tended to increase to s=2 with the increase in R_{mag}, and finally to s=3in plasmas with the largest R_{mag}. As mentioned in Section 3, this fact suggests that the convective loss process (s=1) changes to be diffusive (s=2) as TAE amplitude increases, and finally to a stochastic transport of particle orbits in phase space. This tendency may be explained by the expansion of the eigenfunction of TAE and the loss-cone region with the increase in R_{mag}.

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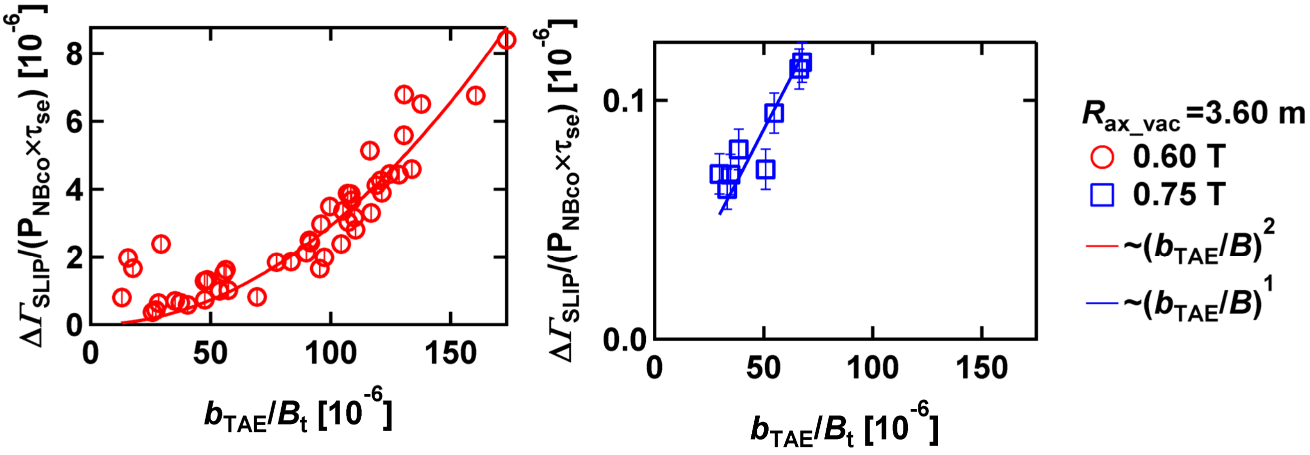

Fig. 1 Dependence of the normalized lost fast-ion fluxes on the magnetic fluctuation amplitude of TAE. The loss fluxes at B_t=0.60 T and 0.75 T are respectively scaled with $(b_{TAE}/B_t)^2$ and $(b_{TAE}/B_t)^1$.

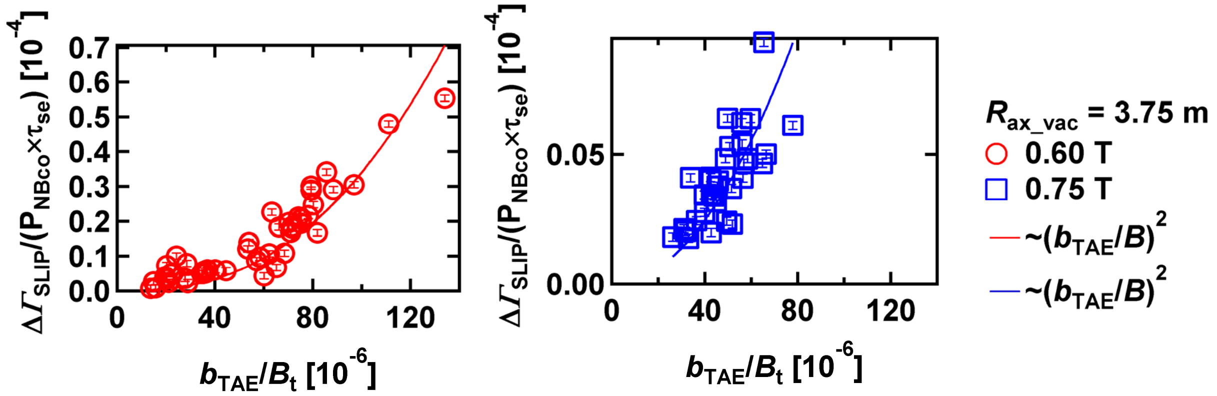

Fig. 2 Dependence of the normalized lost fast-ion flux induced by TAE on the magnetic fluctuation amplitude of TAE. The normalized loss fluxes at B_t=0.60 T and 0.75 T are scaled with $(b_{TAE}/B_t)^2$.

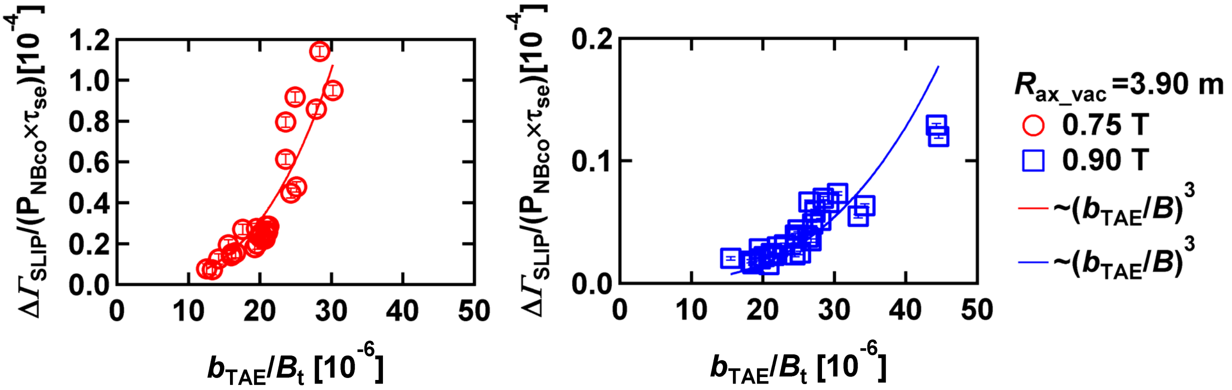

Fig. 3 Dependence of the normalized lost fast-ion flux induced by TAE on the magnetic fluctuation amplitude of TAE. The normalized loss flux on B_t=0.75 T and 0.90 T are scaled with $(b_{TAE}/B_t)^3$.