Fast Ion Losses Induced by Toroidal Alfvén Eigenmode in Various Magnetic Configurations of the Large Helical Device

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One of the important issues in realizing self-sustained DT burning plasma is that how well fast ions such as alpha particles will be confined. This issue is also important in a reactor-relevant plasma such as ITER [1]. However, enhancement of transport of alpha particles due to fast-ion-driven magnetohydrodynamic (MHD) instabilities such as Alfvén eigenmodes (AEs) [2] and energetic-particle-continuum-modes (EPMs) [3] excited by partially slow-downed alpha particle is predicted. Significant loss of fast ions should be avoided because it might damage the plasma facing components. Hence, better understanding of loss process of fast ion 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 loss were detected by means of a scintillator-based lost-fast ion probe (SLIP) installed on LHD [5]. The paper is devoted to the study of characteristics of energetic ion losses induced by TAE in the various magnetic configurations where neoclassical transport of fast ions due to magnetic field ripple are different. In addition to losses due to TAE, we pay attention the combined effects of TAE and low-frequency (f<20 kHz) MHD modes on fast-ion losses.

LHD is equipped with three negative-ion-source based neutral beam (NB) injectors, of which injection energies are up to 190 keV. In this experiment, one of three tangentially injects NBs in the counter-direction, whereas the others tangentially inject NBs in the co-direction. The SLIP works as a magnetic spectrometer, providing information on the energy E and pitch angles $\chi=\arccos(v_{//}/v)$ of escaping fast ions simultaneously as a function of time, where v and $v_{//}$ indicate the velocity and the velocity 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, pitch angle and gyroradius of which are 20–70 degrees and 2–24 cm, respectively, at the detector location [6]. Luminous image produced on the scintillator screen is monitored with a 4×4-photomultiplier tube (PMT) array and a CMOS camera, simultaneously. Relative sensitivity of PMTs is calibrated with an electro-luminescence sheet emitting a blue-green light uniformly within 10 % error. The energetic ion loss study was carried out in three typical magnetic configurations, that is, the "inward-shifted configuration" of R_{ax} =3.6 m (R_{ax}: magnetic axis position in the vacuum field), "standard configuration" of R_{ax}=3.75 m, and "outward-shifted configuration" of R_{ax}=3.9 m. In this study, the magnetic field strength was varied from -0.6 T to -1.0 T, where the minus sign in B_t corresponds to that the toroidal field is directed to be in the counter clockwise from the top view of the torus. In the experimental conditions, the electron temperature at the centre was in the range of ~ 0.8 keV to 1.0 keV, and line-averaged electron density was adjusted in the range of $(1.0\sim2.5)\times10^{19}$ m^{-3}. In all shots of this experiment, TAEs were excited by beam ions. The poloidal/toroidal mode numbers m/n of the observed TAEs were identified to be $m\sim1/n=1$, mode numbers of which were derived from toroidal/poloidal magnetic probe (MP) arrays. This TAE is a type of odd parity mode, and has the peak of the eigenfunction at the normalized radial position r/a ~0.6.

In the inward shifted configuration (R_{ax}=3.6 m), the sharp increase in Γ_{SLIP} correlated with TAE burst was observed in E/χ ~ 50~190 keV/~40° region. In Fig.1, the increment of beam-ion loss flux $\Delta\Gamma_{SLIP}$ normalized by the energetic ion content generated by NBI (P_{NB} τ_s) is plotted as a function of amplitude of TAE fluctuation b_{TAE} normalized by B_t, where P_{NB} and τ_s indicate absorbed power of co-injected NB and slowing down time of fast ion by electron, respectively. In this plot, the amplitude of TAE magnetic fluctuation is evaluated at the MP position. $\Delta\Gamma_{SLIP}$ is evaluated with the difference of Γ_{SLIP} between the pulse peak and that just before each TAE. The error bar corresponds to the level of the white noise. The normalized energetic ion loss $\Delta\Gamma_{SLIP}/P_{NB}\tau_s$ increases nearly quadratically with the increase in b_{TAE} at

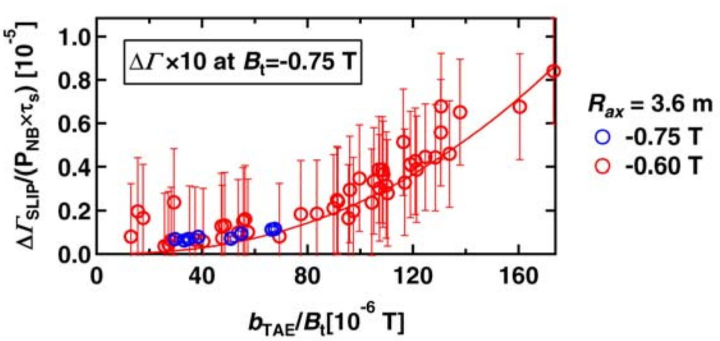

Fig. 1 Dependence of the normalized loss flux induced by TAE on the magnetic fluctuation amplitude of TAE. The solid curve indicates the fitted curve having the dependence on $(b_{TAE})^2$. Note that the loss flux at B_t of -0.75 T is multiplied by a factor of 10.

B_t=-0.6T, but dramatically decreases at increased B_t of -0.75T. Enhanced beam ion loss due to TAEs at lower B_t is thought that TAEs would easily push beam ions with larger orbit deviation from the flux surfaces into loss cone orbits. The relation of $\Delta\Gamma_{SLIP}/P_{NB}\tau_s \propto (b_{TAE})^2$ suggests the loss process is diffusive type, as pointed out in Ref.7. On the other hand, TAE-induced beam ion losses in the outward-shifted configuration (R_{ax}=3.9m) are also clearly observed on E/χ ~40~170 keV/~25°, but even at higher B_t of -1.0 T, as shown in Fig.2. This result will be related to the fact that the deviation of beam ion orbits from flux surfaces is much more significant, compared with that in R_{ax}=3.6 m configuration. Moreover, the loss flux $\Delta\Gamma_{SLIP}/P_{NB}\tau_s$ increases very rapidly with the TAE fluctuation amplitude. At B_t of -0.75T, the loss flux $\Delta\Gamma_{SLIP}/P_{NB}\tau_s$ is scaled with the higher power of the TAE amplitude, that is, $\propto (b_{TAE})^5$. The losses may be caused by destruction of magnetic surfaces [7].

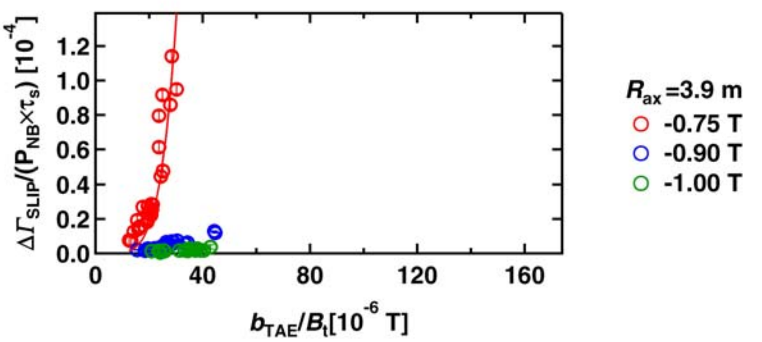

Fig. 2 Dependence of the normalized loss flux induced by TAE on the magnetic fluctuation amplitude of TAE. The solid curve indicates the fitted curve having the dependence on $(b_{TAE})^5$.

In LHD, resistive interchange modes (RICs) are often destabilized, typically in the inward shifted configuration (R_{ax}=3.6m). Actually, energetic ion losses induced by RICs are clearly observed in addition to the losses by TAEs [5]. However, no definitive experimental evidence of combine effect of TAE and low-frequency mode such as RIC had yet been observed. In the standard configuration (R_{ax}=3.75m), a peculiar phenomenon on energetic ion losses induced by TAE burst was observed. As shown in Fig.3, beam-ion loss flux in B_t of -0.60 T is smaller than that of on B_t of -0.75T. This obviously exhibits opposite tendency to the results obtained in configurations with R_{ax}=3.60 m (Fig.1) and 3.90 m (Fig.2). The

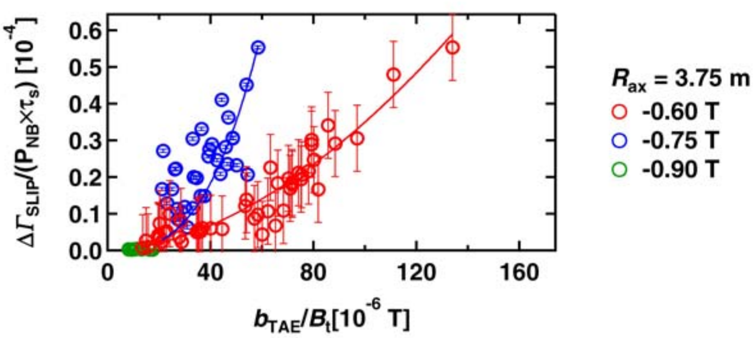

Fig. 3 Dependence of the normalized loss flux induced by TAE on the magnetic fluctuation amplitude of TAE. The red and blue solid curves indicate the fitted curves having the dependence on $(b_{TAE})^2$ and $(b_{TAE})^3$,respectively. The loss flux at B_t of -0.75 T is much higher than that at B_t of -0.6 T.

TAE-induced loss is clearly observed at E/χ ~ 30~110 keV/ ~25° at B_t =-0.6T and -0.75T. In the shot, low frequency magnetic oscillations or perturbations around ~1 kHz are induced by each TAE burst, as shown in Fig.4. The mode structure is m=1 and n=0. This is not the geodesic acoustic mode (GAM), because the GAM frequency is about 13 kHz at the TAE peak location (r/a~0.6). The m=1/n=0 magnetic perturbations maybe related to a sudden horizontal shift caused by sudden drop of beam and bulk plasma pressures. The magnetic perturbations may result in a change of magnetic structure, and hence enhance fast ion loss further. The above-mentioned combined effects of TAEs and other low frequency MHD modes and/or magnetic perturbations will be one of important and interesting subject for further study.

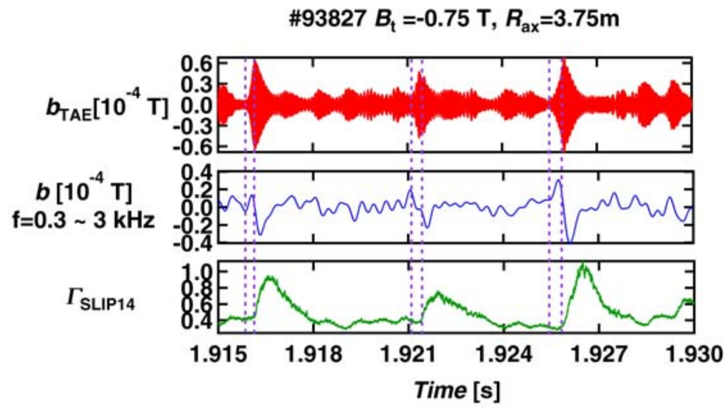

Fig.4 Time evolutions of magnetic fluctuations of TAE, low-frequency fluctuations in the range of 0.3 kHz to 3 kHz, and Γ_{SLIP14}

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