Observation of Fast Ion Losses Induced by Various MHD Modes Driven by Fast Ions and Bulk Plasma Pressure in the Large Helical Device

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Results from a scintillator-based lost-fast ion probe newly installed at the horizontally elongated outboard side of the Large Helical Device are presented. Correlating with bursts of toroidal Alfvén eigenmodes (TAEs) and energetic-particle continuum modes (EPMs), recurrent increases in beam ion losses were observed during co-neutral beam injections. Beam ion loss rate was also enhanced, correlating with low-frequency interchange modes driven by the bulk plasma pressure gradient near the plasma edge.

Keywords: lost-ion probe, fast ion, scintillator, TAE (toroidal Alfvén eigenmode), EPM (energetic-particle continuum mode), interchange mode, LHD (Large Helical Device)

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In existing/future toroidal devices, fast ion-driven magnetohydrodynamic (MHD) instabilities such as toroidal-Alfvén-eigenmodes (TAEs) [1] and energetic-particle continuum modes (EPMs) [2] can potentially enhance the transport of fast ions such as alpha particles. To understand the anomalous transport/loss processes of fast ions induced by those instabilities, scintillator-based lost-fast-ion probes (SLIPs) have been applied to some existing tokamaks/helical systems [3–9]. In the Large Helical Device (LHD), a new type of SLIP has recently been installed on the outboard side of a horizontally elongated poloidal cross section to study the behavior of co-going beam ions, which might interact strongly with these fast ion-driven MHD instabilities [10].

In LHD, the direction of the toroidal field is changed from clockwise (CW) to counter-clockwise (CCW) and vice versa, depending on the physics theme. There are three negative-ion-source-based neutral beam (N-NB) injectors whose acceleration energy is up to 180 keV. Two of the NBs are tangentially injected in the same direction, and another is injected in the opposite direction. In many cases, beam ions are super Alfvénic because of the high beam energy. Strong instabilities are often excited by these ions at relatively low B_t (< 1 T) conditions [11].

The new SLIP on LHD is briefly described here [10]. The SLIP works as a magnetic spectrometer, providing information on the energy and pitch angles ($\chi = \arctan(v_{//}/v)$) of escaping fast ions simultaneously. The SLIP is designed to detect co-going passing or transitional fast ions whose pitch angle and gyroradius are 30-70 degrees and 3-15 cm, respectively, at the detector location. An important feature of this SLIP is that it has two sets of double apertures for use in experiments that involve different directions of the toroidal field line.

First, in order to check whether or not the SLIP signal was contaminated by spurious output due to stray light and short-wavelength light such as soft x-ray and ultraviolet light; the SLIP was applied to an electron cyclotron heated (ECH) plasma without any fast ions. In ECH plasmas, the SLIP was quiet, as we expected, showing no detectable output. Lost fast ions were measured in co-injected N-NB heated plasmas in the CW/CCW direction of the toroidal field. In the CW case, no clear SLIP signal was observed. This may be due to two reasons. One is that fewer fast ions are present in this plasma compared with the CCW case, because only one N-NB injector produces co-going fast ions in the CW case. Fewer fast ions would not strongly destabilize TAEs. Accordingly, this would induce only a small number of fast-ion losses. Another reason for the lack of a clear signal in the CW case is that the SLIP is located 80 mm from the symmetric position for detecting lost fast ions in the CCW or CW case. Thus, fewer fast ions can be detected with the SLIP in the CW case. Results shown in this letter are obtained from co-injected N-NB heated plasmas with line-averaged densities of (0.5-3) $\times 10^{19}$ m^{-3} at B_t < 1.0 T (CCW) in two different magnetic configurations of R_{ax} = 3.6 m and 3.75 m. Some specific channels of 16-photomultiplier data exhibit clear peaks because of energetic beam ion losses caused by various MHD modes.

Figure 1 shows time evolutions of (a) higher-frequency magnetic fluctuations filtered in the frequency range of 60 to 80 kHz, (b) lower-frequency fluctuations filtered in the frequency range of 1 to 15 kHz, and (c)

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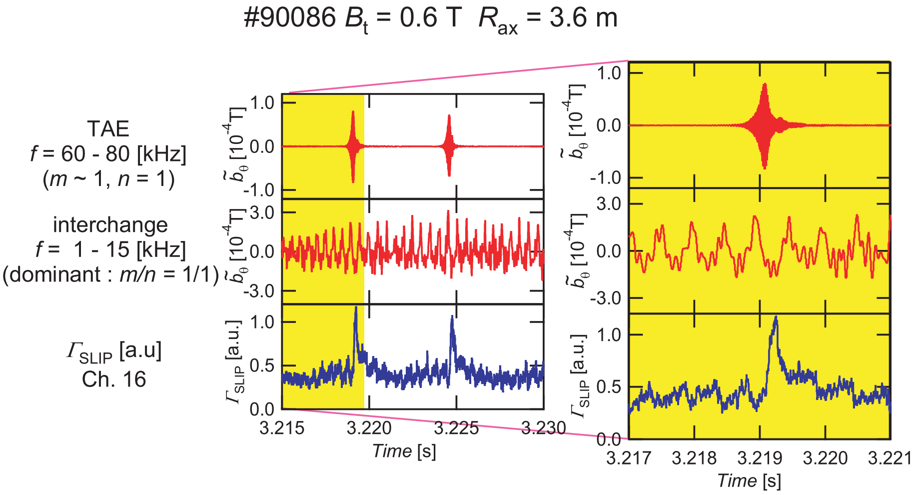

Fig. 1 Typical time traces of magnetic fluctuations of TAE and interchange modes, and SLIP signal in the configuration of R_{ax} = 3.6 m at B_t = 0.6 T (CCW direction). (a) $m \sim 1$, $n = 1$ TAE fluctuation, (b) $m/n = 1/1$ interchange modes, and (c) SLIP signal measured with a PMT.

fast-ion-loss rate detected by SLIP at the outboard side (Larmor radius/pitch angle is about 50 mm / 35 degrees, as confirmed by measurements using a C-MOS camera). These measurements were carried out in the configuration of R_{ax} = 3.6 m at B_t = 0.6 T (CCW). The higher-frequency mode shown in Fig. 1 (a) is recognized as TAE. Its poloidal mode number m and toroidal mode number n, derived with a poloidal/toroidal magnetic probe array, are $m \sim 1$ and $n = 1$, respectively. Conversely, lower-frequency fluctuations are generated by a group of interchange modes with m/n = 1/1, 2/3, and 1/2, respectively. These modes of which rational surfaces reside in the plasma edge region are driven by the bulk plasma pressure gradient there in relatively low-B_t conditions [12]. In SLIP signals, two types of sharp increases are identified: large and small. A large increase corresponds to a TAE burst ($m \sim 1$, $n = 1$). Small increases are generated by interchange modes dominated by an $m = 1/n = 1$ mode structure, which will extend radially from the edge to the core region.

An existing theory of energetic ion loss induced by MHD modes suggests that a radially extended MHD mode destabilized by background plasmas would enhance the radial transport of energetic beam ions [13]. A low-frequency mode with large amplitude could lead to a stochastic orbit of fast ions due to the stochastic magnetic field, causing the confinement degradation of fast ions, even though the level of the stochastic field does not affect bulk plasma confinement [13, 14]. More simply, energetic ion orbits extended toward the plasma edge at low B_t conditions might easily fall into loss orbit due to the large amplitude MHD mode excited near the edge. In fact, a significant decrease in the neutron emission rate was observed in DIII-D when tearing mode instabilities were present [14], suggesting that beam ions are anomalously lost. A similar result was also observed in ASDEX-U: lost fast ions correlate with neoclassical tearing modes [8]. The above-mentioned increase, observed with the SLIP, in the fast-ion loss rate associated with interchange modes in LHD, is understood to be due to a similar loss mechanism observed in DIII-D and ASDEX-U. The mechanism of the observed loss process is currently under investigation.

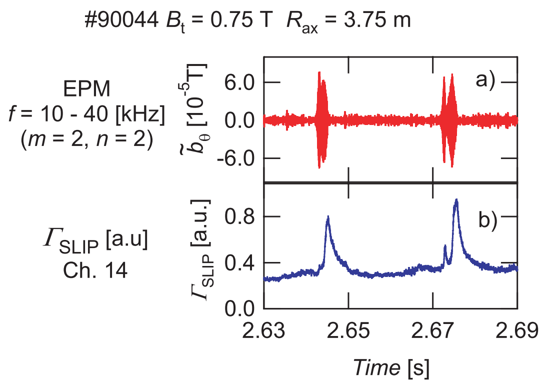

Fig. 2 Typical time traces of EPM fluctuation and SLIP signal in the configuration of R_{ax} = 3.75 m at B_t = 0.75 T (CCW). (a) $m/n = 2/2$ EPM, and (b) SLIP signal measured with a PMT (Larmor radius/pitch angle is about 100 mm / 35 degrees).

Figure 2 shows time evolutions of the magnetic fluctuation, of which frequency chirps down noticeably in a short time (typically ~2 ms), and the fast ion-loss rate detected by the SLIP. These measurements were carried out in the configuration of R_{ax} = 3.75 m at B_t = 0.75 T. In Fig. 2 (a), the range of filtered frequency in the magnetic fluctuation is from 10 kHz to 40 kHz. Its mode number is $m/n = 2/2$. The mode may be EPM, because the mode frequency is substantially lower than the TAE gap frequency (~70 kHz) and is chirped down from ~40 kHz to ~10 kHz rapidly (in ~2 ms). The fast-ion loss rate is sharply increased by these EPM bursts.

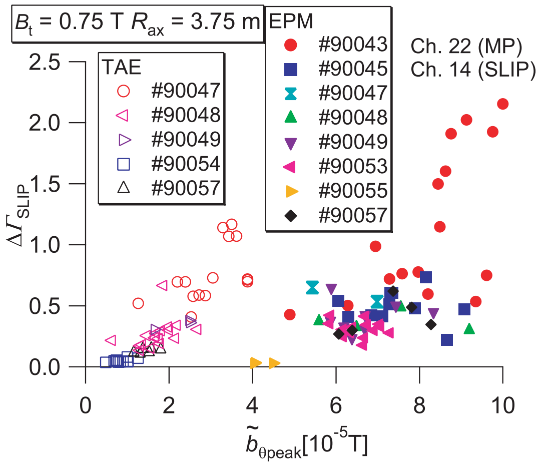

Fig. 3 Increment of SLIP signal as a function of the amplitude of TAE/EPM fluctuations at the probe position. Data points obtained in multi-shots of #90043, #90045, #90047, #90048, #90049, #90053, #90054, #90055, and #90057 are plotted.

In the series of experiments, the dependence of fast-ion losses induced by EPM and TAEs on magnetic fluctuation amplitude were studied. In Fig. 3, the increments in fast-ion loss rates detected by SLIP (Larmor radius/pitch angle is about 100 mm / 35 degrees), $\Delta\Gamma_{\mathrm{SLIP}}$, are shown as a function of the magnetic fluctuation amplitude for each TAE/EPM burst $\tilde{b}_\theta$, where the increment is evaluated as the increase in the ion-loss rate for the level just before the TAE/EPM burst, and the magnetic fluctuation amplitude is evaluated at the magnetic probe position. Although data points scatter appreciably, this figure indicates that $\Delta\Gamma_{\mathrm{SLIP}}$ increases with $|\tilde{b}_\theta|^a$, where $a \sim 2$ to 4. Note that $a = 1$ expresses convective loss, $a = 2$ diffusive loss, and $a \geq 3$ loss due to destructed magnetic surfaces [15].

In summary, a newly developed lost-fast-ion probe was installed at the outboard side in a horizontally elongated section of LHD, and loss rates of co-going beam ions were detected. Enhanced fast-ion losses associated with fast-ion-driven TAE and EPM are clearly observed when N-NB is co-injected into relatively low n_e and B_t plasmas. Furthermore, an interesting observation is that interchange modes enhance the anomalous loss of beam ions in the case of low B_t of less than 0.75 T. The increment of fast-ion losses by TAE/EPM is approximately scaled as $\Delta\Gamma \propto |\tilde{b}_\theta|^a$, with $a \sim$ 2-4, suggesting that these fast-ion losses induced by TAE and EPM are diffusive and/or losses in destructed magnetic surfaces. More detailed loss mechanisms of fast ions by these MHD instabilities are left for future important work.

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