Energetic ion losses caused by magnetohydrodynamic activity resonant and non-resonant with energetic ions in Large Helical Device

Kunihiro Ogawa¹, Mitsutaka Isobe¹,², Kazuo Toi¹, Akihiro Shimizu¹, Donald A Spong³, Masaki Osakabe¹, Satoshi Yamamoto⁴ and the LHD Experiment Group¹

¹ National Institute for Fusion Science, Toki, 509–5292, Japan
² School of Physical Sciences, The Graduate University for Advanced Studies, Toki, 509–5292, Japan
³ Oak Ridge National Laboratory, Oak Ridge, TN, 37831, USA
⁴ Institute of Advanced Energy, Kyoto University, Uji, 611-0011, Japan
E-mail: ogawa.kunihiro@lhd.nifs.ac.jp

Received 3 January 2014, revised 15 May 2014
Accepted for publication 17 June 2014
Published 13 August 2014

Abstract
Experiments to reveal energetic ion dynamics associated with magnetohydrodynamic activity are ongoing in the Large Helical Device (LHD). Interactions between beam-driven toroidal Alfvén eigenmodes (TAEs) and energetic ions have been investigated. Energetic ion losses induced by beam-driven burst TAEs have been observed using a scintillator-based lost fast-ion probe (SLIP) in neutral beam-heated high $\beta$ plasmas. The loss flux of co-going beam ions increases as the TAE amplitude increases. In addition to this, the expulsion of beam ions associated with edge-localized modes (ELMs) has been also recognized in LHD. The SLIP has indicated that beam ions having co-going and barely co-going orbits are affected by ELMs. The relation between ELM amplitude and ELM-induced loss has a dispersed structure. To understand the energetic ion loss process, a numerical simulation based on an orbit-following model, DELTA5D, that incorporates magnetic fluctuations is performed. The calculation result shows that energetic ions confined in the interior region are lost due to TAE instability, with a diffusive process characterizing their loss. For the ELM, energetic ions existing near the confinement/loss boundary are lost through a convective process. We found that the ELM-induced loss flux measured by SLIP changes with the ELM phase. This relation between the ELM amplitude and measured ELM-induced loss results in a more dispersed loss structure.

Keywords: energetic ion, toroidal Alfvén eigenmode, edge-localized mode, lost fast-ion diagnostics, orbit simulation

(Some figures may appear in colour only in the online journal)

1. Introduction
To realize a self-sustained D–T burning plasma, fusion-born energetic alpha particles ($\alpha$’s) should be confined long enough to heat the bulk plasma [1]. In addition to this, loss of $\alpha$’s should be controlled since the localized loss might damage plasma facing components. A better understanding of the transport and loss of these energetic ions is therefore essentially required to realize a nuclear fusion reactor. The principal concern is that D–T-produced $\alpha$’s and super-Alfvénic ions such as beam ions destabilize energetic ion-driven magnetohydrodynamic (MHD) instabilities such as Alfvén eigenmodes (AEs) [2] because those instabilities can potentially cause losses of energetic ions through wave–particle resonance. Recently, the effect of MHD mode non-resonant interactions with energetic ions such as the
edge-localized mode (ELM) [3] is also of great concern since the transport of energetic ions may be affected not only through wave–particle resonance but also stochasticization of energetic ion orbits [4].

Energetic ion losses due to MHD instabilities have been studied intensively in mid- to large-sized tokamaks [1]. Previously, detailed loss processes of energetic ions due to AEs were studied in TFTR [5]. In those experiments, due to global AE, decreases in the neutron emission rate as well as increases in beam-ion losses were observed [6]. On the other hand, energetic ion loss induced by MHD activity that is non-resonant with the energetic ions, such as the sawteeth or tearing mode, were studied [7, 8]. Recently, ELM-induced beam-ion losses have been measured in ASDEX-U, DIII-D and KSTAR [9, 10]. From these experiments it was found that the amplitude of energetic ion loss increases toward the ELM crash while the density fluctuation amplitude due to the ELM does not. The loss process of energetic ions due to the ELM is still not clear.

It is also important when dealing with helical/stellarator plasmas to understand the loss process of energetic ions caused by MHD activities, not only to find a way to realize a helical/stellarator reactor but also to obtain a deeper understanding of the energetic ion loss due to MHD activity in toroidal devices. AE-induced energetic ion loss has been studied in the compact helical system (CHS) [11], Wendelstein 7-AS [12] and the Large Helical Device (LHD) [13]. Previously, in the CHS, it was reported that the energetic ion flux was dependent on the mode structure and mode amplitude levels [11]. The observation of energetic ion losses induced by the resistive interchange mode, which was non-resonant with the energetic ions, was reported in the LHD [13]. It was shown that the energetic ions would be lost through a convective process. Recently, measurement of the ELM structure and study of the characteristics of ELMs has been performed in LHD [14, 15]. However, the effect of ELMs on energetic ion loss in a three-dimensional magnetic field is not clear yet. In tokamaks, externally applied three-dimensional magnetic fields are intensively used to mitigate ELMs [16–19]. Understanding the fast-ion loss process due to ELM in the LHD will contribute to our understanding of ELM-induced fast-ion loss in tokamak plasmas with externally applied three-dimensional magnetic fields. In this paper, we present the results of the characteristics of energetic ion losses due to both toroidal Alfvén eigenmode (TAE) and ELM instabilities. A comparison between the TAE and ELM-induced losses gives us a deeper understanding of the energetic ion loss process.

2. Experimental setups

The LHD is classified as a heliotron device. It is the world’s largest heliotron device, with a major radius and an average minor radius \((a)\) of 3.90 m and 0.6 m, respectively. The direction of the toroidal magnetic field is changeable due to change in external helical coil current. In the experiments described in this paper, the toroidal magnetic field \((B_t)\) is in the counterclockwise direction, looking down from the top. The LHD is equipped with three negative source-based neutral beam injectors (NB1 to NB3) and two diagnostic neutral beam injectors (PNBs) (figure 1). In this experiment, NB1 produces super-Alfvénic beams injected in the co-direction. NB1 injects hydrogen beams with an injection energy of 180 keV. We use a scintillator-based lost fast-ion probe (SLIP) to measure the lost fast ions in this experiment. Figure 2(a) shows a model of the head section of the SLIP. This instrument is essentially a magnetic spectrometer based on the LHD magnetic field, and consists of a pair of apertures and a scintillator plate. We use 4 × 4 photomultipliers to measure the time evolution of scintillation light due to the bombardment of energetic ions with fine time resolution (up to 5 μs). The detailed structure and function of the SLIP are described in [20, 21]. Figure 2 shows the sight lines of fast-time-response Hα detector array (FHA). We used channel 1 of the FHA to measure the ELM. The poloidal magnetic fluctuation amplitude of the TAE \((b_{TAE})\) or ELM \((b_{ELM})\) is measured by a Mirnov coil magnetic probe (MP) placed on the vacuum vessel. The toroidal mode number \((n)\) and poloidal mode number \((m)\) of the MHD modes are identified using signals from the Mirnov coil arrays. The electron temperature \((T_e)\) and the electron density \((n_e)\) profiles are provided by Thomson scattering diagnostics [22]. The line-averaged density \((\langle n_e \rangle)\) is measured with a multi-channel far-infrared laser interferometer [23].

3. Experimental results

The study of TAE and ELM-induced loss was performed in NB-heated LHD plasmas. Figure 3 shows the time evolution of the absorbed power of NB \((P_{NBabs})\), the electron temperature at the center \((T_e0)\), \((\langle n_e \rangle)\), the volume-averaged beta value \((\beta)\) and the frequency spectrogram of the MP signal of a typical discharge in which TAe and ELMs co-exist. The magnetic configuration is \(B_t = 0.9 T\), \(R_{ax} = 3.90 m\) and \(\gamma = 1.2\).
Figure 2. (a) Model of head section of the SLIP. It can discriminate the energy of fast ions entering through the double aperture. (b) Sight lines of fast-time-response Hα detector array (FHA). We use channel 1 in this paper.

Figure 3. Time trace of absorbed power of neutral beam injection (P_{NBabs}) of NB1 and diagnostic beams, line-averaged density, volume-averaged beta and power spectrogram of Mirnov signal on typical discharge with TAEs and ELMs.

In this discharge, plasma is started up and sustained by NB1. The beams injected by NB1 are super-Alfvénic (the ratio of the initial energetic ion velocity to the Alfvén speed is \( \sim 1.5 \)). Note that the PNB having an injection energy of 40 keV is perpendicularly injected for diagnostics. In this experiment, the typical values of \( T_{0i} \), \( n_z \) and \( \beta \) are 0.6 keV, \( \sim 2.0 \times 10^{19} \) m\(^{-3} \) and \( \sim 0.5\% \), respectively. The MP signal analysis shows that strongly excited TAE with 20–40 kHz exists at \( t \sim 4.0 \) s to 4.7 s (figure 3). The toroidal and poloidal mode numbers are \( n = 1 \) and \( m = 1 + 2 \), respectively. The amplitude of the mode at the MP position is \( \sim 2.0 \times 10^{-5} \) T at \( t = 4.2 \) s. Figure 4(a) shows the time evolution of the magnetic fluctuations in the TAE range of frequency measured by the MP and the signal of lost fast ions (\( \Gamma_{\text{fast ion}} \)) with energies \( E \) in the range of 40–160 keV and \( \chi \) in the range of 20°–30°. Note that increases in loss flux due to TAE bursts are clearly observed only in these \( E \) and \( \chi \) ranges. The increment of loss flux (\( \Delta \Gamma_{\text{fast ion}} \)) as a function of \( b_{\text{TAE}}/B_t \) is shown in figure 4(b). It shows that \( \Delta \Gamma_{\text{fast ion}} \) increases with TAE amplitude as expected.

Low-frequency fluctuations of less than 20 kHz are also seen in figure 3. The Mirnov array reveals that this mode has a structure of \( m/n = 1/1 \). The lower frequency mode is identified as an ELM. Such instabilities are observed in LHD plasma having a steep pressure gradient [14]. Unlike tokamaks, the ELMs are the result of non-linear growth of the resistive interchange mode [15]. The fluctuation amplitude of the ELM at the MP position is \( 2 \times 10^{-4} \) T. The time evolution of magnetic fluctuations in the ELM frequency range measured by the MP, Hα signal and \( \Gamma_{\text{fast ion}} \) having an \( E \) value of 160–180 keV and \( \chi \) of 40°–50° are shown in figure 5(a). Due to the ELM burst, increases of Hα and lost fast-ion signal are seen. We choose this \( \Gamma_{\text{fast ion}} \) because large increases in fast-ion loss are seen in this range of \( E \) and \( \chi \). Note that the increases of loss due to ELM seen in all \( E \) and \( \chi \) ranges measured by SLIP. The \( \Delta \Gamma_{\text{fast ion}} \) as a function of \( b_{\text{ELM}}/B_t \) is shown in figure 5(b). Plots of energetic ion loss as a function of ELM amplitude indicate a dispersed structure.

4. Setups for orbit-following models

To understand the TAE or ELM-induced loss, orbit-following simulation including TAE or ELM fluctuation is performed. The DELTA5D code [24] is used to follow the fast-ion orbit inside the LCFS based on equilibrium reconstructed by the VMEC2000 code [25], including time and frequency varying magnetic fluctuation (detail of the fluctuations is described in the next paragraph). The birth profile of beam ions is calculated by the HFREYA code [26] (figure 6(a)). We use the Lorentz orbit code to follow the fast-ion orbit outside the LCFS because DELTA5D calculates the orbit by means of equilibrium reconstructed by the VMEC2000 code, which reconstructs the equilibrium inside the LCFS.
Figure 4. (a) Typical time traces of magnetic fluctuation of a TAE range of frequency and signal of lost fast ions ($b_{\text{TAE}}$). (b) Increment of fast-ion loss as a function of TAE amplitude measured at the magnetic probe position normalized by toroidal magnetic field strength. The increment of fast-ion loss increases with TAE amplitude.

Figure 5. (a) Typical time traces of the magnetic fluctuation of ELM range of frequency, Hα signal and signal of lost fast ions. (b) Increment of Hα signal as a function of ELM amplitude measured at magnetic probe position ($b_{\text{ELM}}$) normalized by toroidal magnetic field strength. There is no clear dependence. (c) Increment of fast-ion loss as a function of $b_{\text{ELM}}/B_t$; it has a dispersed structure.

In DELTA5D, the magnetic fluctuation is modeled as $b = \nabla \times (\alpha B)$. Here, $\alpha$ represents a general function of the position, frequency and amplitude of the magnetic fluctuation. According to the magnetic fluctuation amplitude measured by an MP, the amplitude of $\alpha$ is obtained [27, 28]. In the TAE case, the shear Alfvén continuum is calculated by the STELGAP code [29] (figure 6(b)). The radial structure of $\alpha$ is obtained from the eigenfunction of a stable TAE mode calculated by the AE3D [30], as shown in figure 6(c). The TAEs have a mode structure of $m/n = 1 + 2/1$ and have a peak at $r/a \approx 0.6$. Note that the profile of $n_e$ fluctuations due to the TAE (evaluated from AE3D) eigenfunction agrees well with that measured in previous experiments [13]. The frequency of $\alpha$ and the frequency down-chirping rate are set to be 20 kHz and 20 kHz ms$^{-1}$, respectively, as seen in the experimentally observed TAE burst. Figure 6(d) shows the radial structure of $\alpha$ for an ELM. It is given based on the effective region of ELM measured by TSD (figures 6(e) and (f)). The ELM has a mode structure of $m = 1$ and $n = 1$, and is characterized by a relatively narrow radial profile.
Figure 6. (a) Birth profile of beam ions calculated by HFREY code. (b) Shear Alfvén spectra calculated by the STELGAP code at $t = 4.0$ s. (c) Eigenfunction of TAE as a function of normalized minor radius. The profile is calculated using AE3D code. (d) Eigenfunction of ELM as a function of normalized minor radius. The profile is given according to experimental observation. (e) Electron density profile measured by TSD before ($t = 4.533$ s) and after the ELM ($t = 4.566$ s). Here, negative $r/a$ means the inboard side of a plasma whereas positive $r/a$ means the outboard side of the plasma. (f) Radial profile of decrement of electron density due to an ELM burst. We refer to this profile as a radial ELM profile in calculation.

5. Result of orbit calculation

Figure 7 shows the increment of energy ion loss as a function of TAE amplitude from the calculation. It shows that $\Delta \Gamma_{\text{fast}}$ increases quadratically with $b_{\text{TAE}}/B_i$; the tendency agrees with experimental results. The quadratic dependence shows that energetic ions in the interior region are lost from the plasma with a diffusive process [28, 31]. The increment of energetic ion loss as a function of ELM amplitude is shown in figure 8. Energetic ion loss increases almost linearly with $b_{\text{ELM}}/B_i$ when we fix an initial phase of ELM. This tendency shows that energetic ions near the confinement/loss boundary are mainly lost through a convective process [28, 31]. We found that ELM-induced energetic-ion loss depends on the mode phase of the ELM. In experiments, the ELM could take on any initial phases; therefore, this is roughly consistent with the dispersed structure observed experimentally. However, the phase effect shown in figure 9 seems to be small compared...
Let us discuss the reason why an ELM phase affects the energetic ion loss. Figure 9 shows the exit point of energetic ion on the LCFS due to the TAE and ELM as a function of the poloidal angle. It shows that in the ELM case, the poloidal distribution of energetic ions is largely changed due to the initial phase of the mode compared with the TAE case. In this experiment, the frequency of the ELM is much lower than the orbital frequency of the energetic ions. Then loss points of energetic ions can be largely changed toroidally or poloidally due to ELM phases because the shape of the fluctuation does not change during the toroidal or poloidal transit time of the fast ions. In figure 9, the detectable region of the SLIP on the LCFS is overlaid. Because of the choice $\gamma = 1.20$, the SLIP only can cover from $-180^\circ$ to $-60^\circ$, and $60^\circ$ to $180^\circ$ in the poloidal angle on the LCFS. Due to this fact, the energetic ion loss depends on the phase of the ELM fluctuations.

6. Summary

To understand the loss processes of energetic ions caused by MHD activities that are both resonant and non-resonant with energetic ion orbits, energetic ion losses are measured with a SLIP on a discharge in which TAEs and ELMs co-exist. The $E$ and $\chi$ resolved measurements of energetic ion losses indicate that TAE induces co-going energetic ion losses whereas the ELM induces a loss of energetic ions having co-going and barely co-going orbits. In the TAE case, the energetic ion loss flux increases with an increase of the magnetic fluctuation amplitude. On the other hand, in the ELM case, the plot of the loss flux of energetic ions as a function of magnetic fluctuation amplitude has a more dispersed structure. To understand the difference between TAE-induced energetic ion loss and ELM-induced energetic
ion loss, orbit-following simulations including magnetic fluctuations are performed. In this calculation, a radial profile of a TAE mode is given based on the linear eigenfunction, whereas a radial profile of an ELM is constructed based on experimental observation. The result shows that the TAE-induced loss increases quadratically with the magnetic fluctuation amplitude of the TAE. This qualitatively agrees with experimental results. The dependence of ELM-induced energetic ion losses as a function of the ELM amplitude used in the calculation shows that it has a linear dependence. We found that the effect of the ELM phase on the energetic ion loss gives the dependence of the loss versus the amplitude a more dispersed structure because the initial phase of an ELM changes the poloidal distribution of fast-ion loss.

Acknowledgments

This work was supported in part by the Grant-in-Aid for Scientific Research from JSPS Nos 21360457 and 21340175, and from the LHD project budget (NIFS13ULHH003). The authors are grateful to the LHD operation group for their excellent technical support.

References

[1] Fasoli A et al 2007 Nucl. Fusion 47 S264
[2] Chen C Z and Chance M S 1986 Phys. Fluids 29 3695
[3] Zohm H 1996 Plasma Phys. Control. Fusion 38 105
[4] Mynick H E 1993 Phys. Fluids B 5 1471
[5] Zwebel S J 1989 Nucl. Fusion 29 5 825
[6] Darrow D S et al 1997 Nucl. Fusion 37 7 939
[7] Stratton B C et al 1996 Nucl. Fusion 36 11 1586
[8] García-Muñoz M et al 2007 Nucl. Fusion 47 L10
[9] García-Muñoz M et al 2013 Nucl. Fusion 53 123008
[10] Chen X et al 2013 Phys. Rev. Lett. 110 065004
[11] Isobe M et al 2006 Nucl. Fusion 46 S918
[12] Weller A et al 2001 Phys. Plasmas 8 931
[13] Ogawa K et al 2010 Nucl. Fusion 50 084005
[14] Watanabe F et al 2006 Plasma Phys. Control. Fusion 48 A201
[15] Toi K et al 2014 Nucl. Fusion 54 033001
[16] Hender T et al 1992 Nucl. Fusion 32 2091
[17] Evans T et al 2004 Phys. Rev. Lett. 92 235003
[18] Liang Y et al 2007 Phys. Rev. Lett. 98 265004
[19] Suttrop W et al 2011 Phys. Rev. Lett. 106 225004
[20] Ogawa K, Isobe M and Toi K 2009 J. Plasma Fusion Res. 8 655
[21] Ogawa K, Isobe M and Toi K 2008 Plasma Fusion Res. 3 S1082
[22] Yamada I et al 2010 Fusion Sci. Technol. 58 345
[23] Akiyama T et al 2010 Fusion Sci. Technol. 58 352
[24] Spong D A 2011 Phys. Plasmas 18 056109
[25] Hirshman S P and Betancourt O 1991 J. Comput. Phys. 96 99
[26] Murakami S et al 1995 Trans. Fusion Technol. 27 256
[27] Ogawa K et al 2012 Nucl. Fusion 52 094013
[28] Ogawa K et al 2013 Nucl. Fusion 53 053012
[29] Spong D A, Sanchez R and Weller A 2003 Phys. Plasmas 10 3217
[30] Spong D A, D’azevedo E and Todo Y 2010 Phys. Plasmas 17 022106
[31] Sigmar D J et al 1992 Phys. Fluids B 4 6