Beam Ion Losses Caused by Magnetic Field Ripples in Various Plasma Parameter Ranges in the Large Helical Device*)

Kunihiro OGAWA, Mitsutaka ISOBE[1)], Kazuo TOI[1)] and LHD Experiment Group[1)]

Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan

[1)]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*

(Received 27 December 2011 / Accepted 2 February 2012)

Beam ion losses from Large Helical Device (LHD) plasmas caused by magnetic field ripples or Coulomb collisions are measured using a scintillator-based lost fast-ion probe (SLIP). The gyroradius and pitch angle distribution of beam-ion losses as well as to the total-beam losses arriving at the SLIP are measured in various plasma parameter ranges. The SLIP reveals that most lost beam ions consist of a pitch angle of 50°–60° at relatively high toroidal magnetic field strength (B_t). These ions consist of a transition orbit with a large deviation from the flux surface. The beam ion losses arriving at the SLIP (Γ_{SLIP_SUM}) depend on the changes in the line-averaged electron density in a manner analogous to the behavior of beam ion components created by co-going neutral beam injectors. Γ_{SLIP_SUM} normalized by the beam ion components decreases as the magnetic axis position in a vacuum (R_{ax}) shifts inward at B_t of 0.90 T. Not only beam ions having transition orbit but also those having co-going orbit are measured at the relatively low B_t experiments at R_{ax} = 3.60 m. The loss domain corresponding to the co-going orbit disappeared at B_t = 0.75 T. Beam ions having transition orbit as well as those having passing orbits normalized by the beam ion components are suppressed with increasing B_t.

Keywords: beam ion loss, lost fast ion probe, the large helical device

DOI: 10.1585/pfr.7.2402014

1. Introduction

DT fusion plasmas such as International Thermonuclear Experimental Reactor (ITER) plasmas are heated by quantities of 3.5-MeV alpha particles. Ideally, the particles are substantially confined in the plasma. If they are not well confined, their energy is lost from the plasma, which lowers the heating efficiency; concentrated losses may also damage plasma-facing components. Fast ion confinement and loss in toroidal plasmas are studied not only so these problems may be avoided, but also to achieve high plasma performance in existing devices. High-performance plasmas are heated by fast ions created by neutral beam (NB) injectors or ion cyclotron heating devices [1]. Scintillator-based lost fast-ion probes (SLIPs) have been used extensively to investigate fast ion losses induced by magnetic field ripples in large, fusion-relevant tokamak plasmas [2, 3]. The SLIP not only measures fast-ion loss fluxes but also provides the energy E and pitch angle $\chi = \cos(v_{//}/v)$ of those ions at the SLIP position. Here, $v_{//}$ and v represent the velocity of ions parallel to the magnetic field and the velocity of ions, respectively. Plasmas in helical devices and stellarators have not approached the conditions required for fusion reaction as tokamak plasmas have. Understanding the loss of fast ions in a helical plasma is necessary in order to realize high performance plasmas.

author's e-mail: ogawa.kunihiro@lhd.nifs.ac.jp

*) This article is based on the presentation at the 21st International Toki Conference (ITC21).

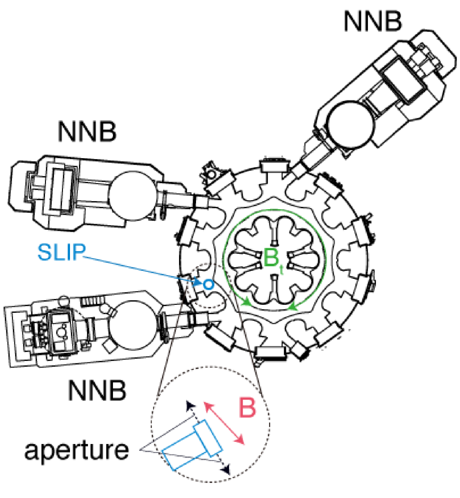

Fig. 1 Bird's-eye view of LHD, NNBIs, and the SLIP. LHD plasmas are heated primarily by three NNBIs.

A bird's eye view of the Large Helical Device (LHD) and negative-ion-based neutral beam injectors (NNBIs) is shown in Fig. 1. LHD plasmas are heated primarily by these NNBIs. One injects hydrogen atoms to the plasma in a clockwise direction, and the others inject them counter-clockwise. The one that injects hydrogen atoms clockwise creates co-going beam ions clockwise with respect to B_t

as seen from the top view, whereas the other two create counter-going beam ions counter clockwise with respect to B_t, and vice versa. The ion acceleration energy is as high as 190 keV. In this study, the beam ion loss measurement described was conducted in the direction of the toroidal field (counter clockwise as seen from the top). This study aims to describe the beam ion loss at various parameter ranges in the LHD.

2. Beam Ion Orbit and Beam Ion Loss Diagnostic in LHD

There are three types of orbits in the LHD [4,5]: passing, transition, and helical-ripple trapped. The toroidal velocity of particles having a passing orbit is always oriented in the same sense. Helically trapped ions consist of a large fraction of their velocity perpendicular to the magnetic field and the trapped valley of the helical coils; they are trapped between adjacent helical coils. Transition ions lie in the pitch angle between the passing and helical ripple-trapped orbits, and they consist of toroidal reflection points at irregular intervals. Their orbits are stochastic and exhibit large deviations from the flux surface. Beam ion losses from LHD plasmas are measured by a SLIP installed on the outboard side of the LHD (Fig. 1). Essentially, the SLIP is essentially a magnetic spectrometer that uses the confining magnetic field of the LHD and a pair of apertures to record the gyro radius centroid $\rho = (2m_h E)^{1/2}/q_h B_{\mathrm{SLIP}}$ and the pitch angle χ on a scintillator plate. Here m_h, q_h and B_{SLIP} represent the mass of a fast ion, electronic charge of a fast ion and magnetic field strength at the SLIP position, respectively. The detectable ranges of ρ and χ are ~2–23 cm and ~25°–75°, respectively. The luminosity versus time measured with a 4 × 4-photomultiplier tube (PMT) array, having high-time resolutions of up to 5 µs, yields the total loss fluxes arriving at the SLIP. The relative sensitivity of each PMT is calibrated with an electroluminescence sheet that emits blue–green light uniformly within a 10% error. Illumination images captured with an image-intensified CMOS camera record the lost ion distribution function versus time with a high ρ/χ resolution of up to 2000 frames/s and 353 × 353 pixels on the scintillator screen. The SLIP is described in detail in Ref. [6]. The SLIP has a pair of apertures that measure the co-going beam ions escaping from the plasma in both B_t directions. The SLIP can be moved horizontally from the outboard side of the LHD to measure the loss at different positions and to allow it to remain in a standby position. Beam ion losses are measured at a SLIP position having a major radius $R = 4.62$ m and $z = 0.215$ m, where z represents the height from the midline of the plasma. This work focuses on the measurement of beam ion losses using the SLIP during discharges, in which the magnetohydrodynamic (MHD)-instability-induced beam ion loss is not sufficient.

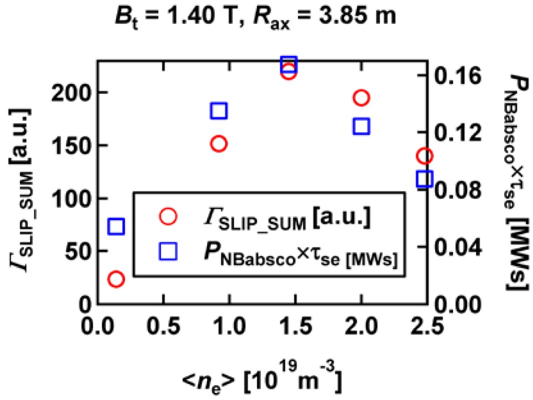

Fig. 2 Dependence of the beam ion loss flux arriving at the SLIP on the line-averaged electron density. The beam ion loss is evaluated by all PMTs, and the electron density is measured with a far-infrared laser. The dependence of the losses has the same tendency as that of co-going beam ion components created by the NNBIs.

3. Beam Ion Losses Measured by the SLIP in Various Configurations

3.1 Beam ion loss induced by Coulomb collisions in relatively high-B_t regime

The dependence of the beam ion loss fluxes on the electron density is obtained at a B_t/R_{ax} value of 1.375 T / 3.85 m. In these experiments, the line-averaged electron density $<n_e>$, electron temperature at the center T_{e0}, and deposition power of the NB injectors P_{NBabs} are 0.2–2.5 × 10^{19} m^{-3}, 1.5–2.0 keV, and 3–10 MW, respectively. In these cases, the SLIP mainly detects beam ions having a χ value of ~60°. These ions consist of transition orbits that are lost because of magnetic field ripples and Coulomb collisions. Transition ions lie in the pitch angle between the passing and the helical ripple-trapped orbit, and they have toroidal reflection points at irregular intervals. Their orbits are stochastic and have large deviation from the flux surface. The beam ions undergoing pitch angle scattering can be transition ions and can immediately reach the SLIP. The variation in $\Gamma_{\mathrm{SLIP\_SUM}}$ with $<n_e>$ is shown in Fig. 2. Here, $\Gamma_{\mathrm{SLIP\_SUM}}$ indicates the total flux loss at the SLIP measured by the PMTs: that is, $\Gamma_{\mathrm{SLIP\_SUM}} = \sum_{i=1}^{16} C_i \Gamma_{\mathrm{SLIP}}$, where C and i represent coefficients corresponding to the relative sensitivity and channel number, respectively. $\Gamma_{\mathrm{SLIP\_SUM}}$ increases with increasing $<n_e>$, reaching a maximum at $<n_e> = 1.5 \times 10^{19}$ m^{-3} and decreasing at higher $<n_e>$. The beam ion contents generated by co-injection NB injectors ($P_{\mathrm{NBabsco}}\ \tau_{se}$) are evaluated using an electron temperature of T_{e0} divided by 2 and an electron density of $<n_e>$, where P_{NBabsco} and τ_{se} represent the deposition power of the NBs and the slowing down time of beam ions by electrons, respectively. The dependence of $\Gamma_{\mathrm{SLIP\_SUM}}$ on $<n_e>$ changes in a manner analogous to the behavior of $P_{\mathrm{NBabsco}}\ \tau_{se}$. A peak appears be-

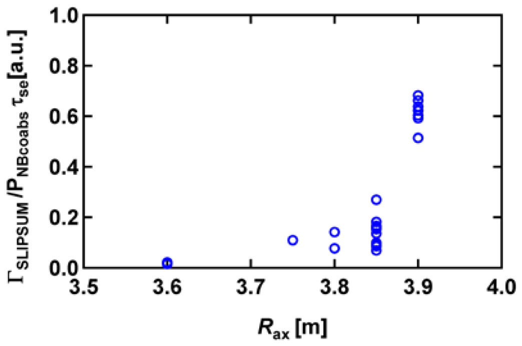

Fig. 3 Normalized beam ion loss flux dependence on R_{ax}. The loss flux decreases as R_{ax} shifts inward because of the decrease in orbit deviation from the flux surface.

cause the increase in the plasma density causes an increase in $P_{NBabsco}$ and a decrease in τ_{se}. The beam ion losses induced by magnetic field ripple and Coulomb collisions are related to $P_{Nbabsco}\,\tau_{se}$, which is thought to be proportional to the beam ion density, because a part of beam ions remaining near the loss region are sent there by Coulomb collision.

$\Gamma_{SLIP\_SUM}/P_{NBabsco}\,\tau_{se}$ on R_{ax} is obtained at a B_t value of 0.90 T. In these experiments, $<n_e>$, T_{e0}, and P_{NBabs} were 1.0–4.0 × $10^{19}\,m^{-3}$, 0.6–1.7 keV, and 3–9 MW, respectively. In these configurations, mainly beam ions having transition orbits are lost from the plasma. Figure 3 shows Γ_{SLIP_SUM} normalized by $P_{NBabsco}\,\tau_{se}$ as a function of R_{ax}. $\Gamma_{SLIP\_SUM}/P_{NBabsco}\,\tau_{se}$ rises continuously, increasing sharply after R_{ax} = 3.80 m. The R_{ax} value at the minimum loss is consistent with the orbit confinement behavior predicted by orbit calculations. Such a configuration would consist of the smallest orbit loss, because the orbits consist of the minimum deviation from the flux surface.

3.2 Beam ion loss dependence in B_t on inward-shifted configuration

Beam ions having the transition orbits are lost from the plasma caused by the Coulomb collision are observed in relatively high-B_t experiments. However, beam ions having passing orbits as well as those having transition orbits can be lost in the relatively low-B_t regime owing to large deviations of the orbits from the flux surface. Figure 4 shows the ρ/χ distribution at the SLIP for R_{ax} = 3.60 m as B_t is varied. The ρ values of the injected beam at the SLIP position for B_t values of 0.60 T, 0.70 T, 0.75 T and 1.50 T were 17 cm, 13 cm, 11 cm, and 6 cm, respectively. The important point is that the gain of the image-intensifier on the CMOS camera was set at a different value in each experiment. There are three loss domains at B_t = 0.60 T. The largest fraction of the beam ion losses, which has a χ range of 45°–60°, corresponds to the transition orbit region. These losses are caused by magnetic field ripples or Coulomb collisions, as mentioned in this section. The second loss domain, which has a χ range of 35°–45°,

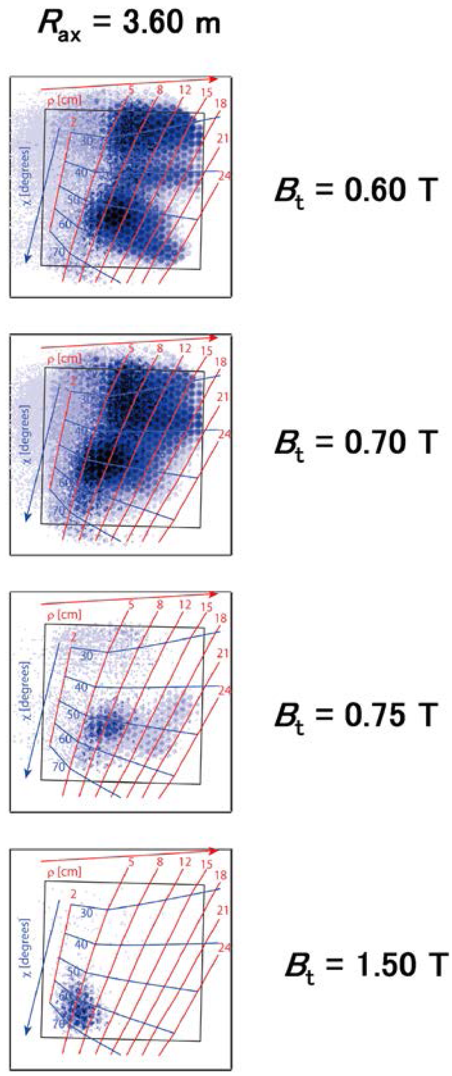

Fig. 4 Beam ion loss patterns captured by CMOS camera (frame rate was 500–2000 frame/s). The ρ values of the lost ions, which had χ values of about 45°–60°, decreased as B_t increased, as expected.

corresponds to the passing orbit region. Here, beam ions are lost because of the toroidal Alfvén eigenmode [7], but the details are outside the focus of this paper. The last loss domain, which has a χ range of 25°–35°, also corresponds to the passing orbit region. These beam ions are the prompt loss ions that ionized the inboard side of the plasma. The resistive interchange mode excited by the bulk plasma pressure at the edge region of the plasma also induces such ion loss. However, it is small compared with the loss of beam ions having transition orbit [7]. Loss of beam ions having transition and passing orbits are also observed at B_t = 0.70 T. Beam ions having transition orbits are only observed in the relatively high B_t case: that is, B_t = 0.75 T and 1.50 T. The loss of beam ions having transition orbits or passing orbits normalized by the dependence of $P_{NBabsco}\,\tau_{se}$ on B_t is shown in Fig. 5. The loss of beam ions having passing orbits or transition orbits is suppressed

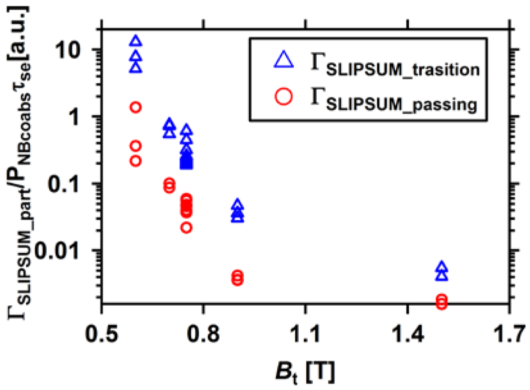

Fig. 5 Beam ion loss dependence on B_t. Beam ion loss decreased dramatically with increasing B_t. $\Gamma_{\mathrm{SLIPSUM\_transition}}$ and $\Gamma_{\mathrm{SLIPSUM_{passing}}}$ represent the loss of beam ions having χ values of 45°–70° and 25°–45°, respectively.

by increasing B_t because the deviation of the orbit from the flux surface decrease. Passing ions can reach the SLIP when $d \approx \rho q + \rho \sin\chi$, where d represents the distance between a flux surface and the SLIP, and q represents the safety factor. The first term corresponds to the orbit deviation from the flux surface [8], and the second corresponds to the Larmor radius. The decrease in ρ because of the increase in B_t strongly affects the flux losses. The deviation in the transition orbits as a function of B_t is not as simple, but the deviation is thought to be decrease as ρ decreases. Significantly slowed beam ions were observed at $B_t = 1.50$ T; the χ values of beam ions lost because of magnetic field ripples or Coulomb collisions increased as shown in Fig. 5. The phenomenon was also observed in the Compact Helical System (CHS) [9]. Although the reason for this is not yet apparent, the observation implies the possibility of changing the loss cone caused by B_t. This possibility requires further investigation via numerical simulation.

4. Summary

Beam ion losses arriving at the SLIP ($\Gamma_{\mathrm{SLIP\_SUM}}$) in the LHD in various plasma parameter ranges were studied. The SLIP provides the energy and pitch angle as well as the beam ion fluxes. The loss of beam ions having transition orbits was observed in relatively high-B_t experiments. These beam ions are lost because of magnetic field ripples and Coulomb collisions. The dependence of $\Gamma_{\mathrm{SLIP\_SUM}}$ on $\langle n_e \rangle$ shows that the loss flux is proportional to the beam ion components created by NB injectors. The beam ion loss flux normalized by the beam ion components created by co-injection NB injectors ($\Gamma_{\mathrm{SLIP\_SUM}}/P_{\mathrm{NBabsco}}\ \tau_{\mathrm{se}}$) decreased as R_{ax} shifted inward at $B_t = 0.90$ T. This result is explained by the orbital characteristics in terms of the deviation of the orbit from the flux surface. Not only beam ions having transition orbits but also those having passing orbits were lost at relatively-low B_t. The dependence of $\Gamma_{\mathrm{SLIP\_SUM}}/P_{\mathrm{NBabsco}}\ \tau_{\mathrm{se}}$ on B_t at $R_{\mathrm{ax}} = 3.60$ m shows that the loss of both beam ions having transition orbits and those having passing orbits are suppressed with increasing B_t as a result of a decrease in the orbit from the flux surface. There is room for further investigation of the observation of higher χ values for beam ions at relatively high B_t, via numerical simulation.

Acknowledgment

This work was supported in part by the Grant-in-Aid for Scientific Research from MEXT, No. 16082209 and from JSPS No. 21360457, No. 21340175, and No. 22-7912, and the LHD project budget (NIFS10ULHH011).

[1] A. Fasoli *et al*., Nucl. Fusion **47**, S264 (2007).
[2] S.J. Zweben, Nucl. Fusion **29**, 825 (1989).
[3] S. Baeumel *et al.*, Rev. Sci. Instrum. **75**, 3563 (2004).
[4] H. Sanuki *et al.*, Phys. Fluids B **2**, 2155 (1990).
[5] H.E. Minick, Phys. Plasmas **13**, 058102 (2006).
[6] K. Ogawa *et al.*, J. Plasma Fusion Res. SERIES **8**, 655 (2009).
[7] K. Ogawa *et al*., Nucl. Fusion **50**, 084005 (2010).
[8] M. Yokoyama, J. Plasma Fusion Res. **76**, 1176 (2000).
[9] D.S. Darrow *et al*., Nucl. Fusion **50**, 105009 (2010).