Characteristics of co- and counter-going beam ion loss from CHS plasmas

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1. Introduction

One of important research issues of Compact Helical System (CHS) experiment is to study confinement property of energetic ions. In CHS, loss cone region of ripple-trapped particle is thought to be considerably large because of the non-axisymmetric magnetic field configuration and the enhanced toroidicity due to its low aspect ratio(R/a=5). Therefore, low collisional or collisionless energetic ion transport related to magnetic field ripple is our major concern. Losses of neutral beam(NB)-injected fast ions have been continuously measured with a scintillator-based escaping fast ion probe in CHS[1,2]. In addition to beam ion loss via classical process, enhanced beam ion losses due to MHD activity and pellet injection were observed. In this article, an escaping fast ion probe on CHS is briefly described and characteristics of co- and counter(ctr.)-going beam ion loss from CHS plasmas are reported.

2. Experimental set-up

Compact Helical System(CHS) is a heliotron/torsatron device with a toroidal period m of 8 and a pole number l of 2[3]. It has major radius R of 1 m and averaged minor radius a of 0.2 m. In standard operation of CHS, toroidal magnetic field B_t is directed to be counterclockwise as seen from the top, so, the averaged ion ∇B drift direction is upwards. There are co- and ctr.-NB injectors on CHS. Both NBs are hydrogen beams and the injection energy is typically 36 - 38 keV. Here, we focus on behavior of coinjected-NB fast ions.

Next, hardware of a scintillator-based escaping fast ion probe on CHS is described. The detector end is a light-tight stainless steel box and a scintillator(ZnS(Ag)) smeared on a quartz substrate is mounted on the bottom of the box. There are two apertures, one behind the other, on one side of detector box to restrict orbits of fast ion which can enter the detector box and reach the scintillator surface. Fast ions with larger gyroradii hit the scintillator surface farther from aperture than those with smaller gyroradii. The strike points of fast ions are dispersed across the line passing through the center of the two apertures according to their pitch angles. The 2-D image of scintillation light is guided via a lens to the outside of vacuum vessel. The image is intensified and measured with a conventional CCD camera. Multi-channel fibers of 4×4 also view the scintillation image and each light carried by each fiber is measured with photomultipliers. This makes it possible to observe fast phenomena. The probe shaft is vertically inserted from an upper diagnostics port at the horizontally elongated cross section. The probe tip is located at R of 1.2 m and typically ~3 cm away from the plasma boundary. The detailed description of the probe is seen in Ref. 1.

3. Beam ion loss from CHS
3.1 Loss via classical process

In the beginning of this experiment, a line passing through the center of two apertures had an angle of +45˚ from *R* direction(see Fig. 1). In this case, lost co-going beam ions are measured in the pitch angle range of ~100˚ to 140˚. In magnetic configuration of CHS, coinjected NB has counterdirection to B_t. As an example, a fast ion orbit reaching the probe is shown in Fig. 2(a). A co-going fast ion which deviates substantially from magnetic surface is detected. This is a barely passing orbit. In August of 1998, the aperture angle was changed to -45˚ to check whether ctr.-going beam ions exist or not in coNB-heated plasmas. In this case, ctr.-going escaping fast ions whose pitch angle ranges from 35˚ to 90˚ are detected. Orbit calculation shows that ctr.-going ions we can detect have magnetically trapped orbits in 1/8 toroidal section and move upwards due to ion ∇*B* drift. As seen in Fig. 2(b), they finally go over the outermost flux surface and reach the probe. This orbit is similar to that of ripple-trapped ions between two toroidal coils in a tokamak. In the aperture angle of -45˚, ctr.-passing fast ions can not reach the probe. Only trapped fast ions can be detected.
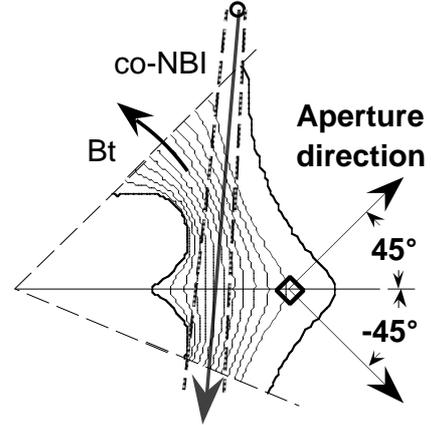

Fig. 1 *Aperture direction of an escaping fast ion probe on CHS. NB is coinjected.*
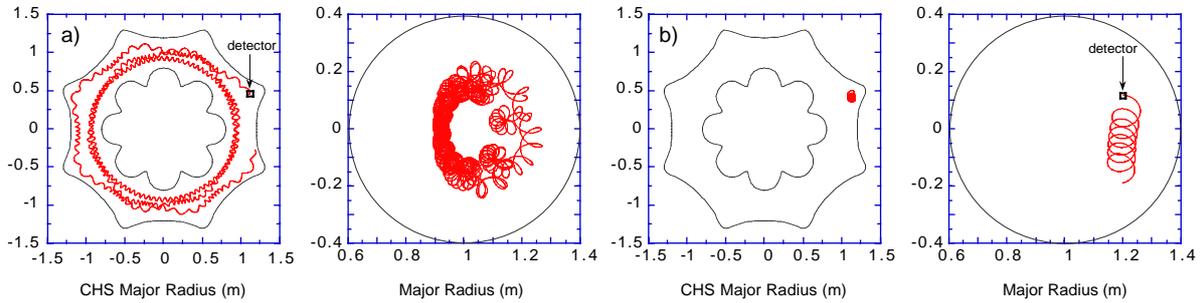

Fig. 2 *Toroidal and poloidal projection of fast ion(proton) orbit reaching the probe in B_t of 0.9 T and R_{ax} of 97.4 cm. The energy and pitch angle at probe position are ; (a) 36 keV, 132˚, (b) 36 keV, 81˚.*

The signal of co-going beam ion loss immediately increases just after NB injection. This seems to be due to prompt orbit loss, and is confirmed by a fast ion orbit loss model that incorporates the beam deposition profile[2,4]. Time evolution of ctr.-going, trapped fast ion loss rate is quite different from that of co-going beam loss rate. The loss signal of ctr.-going ions gradually increases with time. The loss rate of ctr.-going beam ions to probe is much lower, at least 10 times lower than that of co-going ions. This suggests that the loss of ctr.-going ions probably arises due to pitch angle scattering.

3.2 Enhanced loss in unusual events
3.2.1 MHD-induced loss

In CHS, periodic recurrence of the fishbone type bursting mode(*m/n*=3/2) has been observed in low density, coNB-heated plasmas in B_t of 0.9 T[5]. Beam ion loss strongly correlated with

bursting mode is clearly observed in both measurement of co- and ctr.-going fast ions. Fig. 3 shows time traces of fast ion loss rate to probe for co-going barely passing fast ion while MHD activity occurs. The energy of expelled fast ions is about 38 keV and the pitch angle of those ions is about 43°. For trapped ions, expulsions of fast ions having the energy of ~20 keV and the pitch angle of 80° - 90° are observed. Fast ions whose energy is around 10 keV are also expelled. It seems that somewhat slowed down ions are expelled. What has to be noticed is that the enhancement ratio of peak loss rate to base level loss rate for ctr.-going trapped fast ion is much higher, 5 - 10 times higher, than that of co-going beam ion. In general, MHD activity and following expulsion of beam ions become weak as density increases. Analysis shows that there is threshold in amplitude of magnetic fluctuation for expelling beam ions and the ion loss rate increased as the fluctuation becomes large[6]. Usually, beam ion loss signal does not begin until Mirnov coil reaches a maximum. This suggests that mode stabilization occurs after expulsion of fast ions. The repetitive nature of the instabilities and resulting expulsion of beam ions suggest that the beam beta may play an important role in destabilizing of the instabilities. To check this, the beam pressure W_{beam} and thermal plasma pressure W_{thml} are calculated separately by a transport code PROCTR-MOD. The PROCTR-MOD is applicable for steady state condition, so, the analysis is done at the timing that beam driven current reaches the steady state. Fig. 4 shows that the ratio of total W_{beam} to W_{thml} and the enhancement ratio for ctr.-going ion loss as a function of n_e. It is seen that the ratio W_{beam}/W_{thml} in low density plasma is higher than that in high density plasma because of the long slowing down time. MHD-induced fast ion loss is more enhanced in low density plasma, so, it seems that there exists causal relationship between W_{beam}/W_{thml} and MHD-induced fast ion loss.
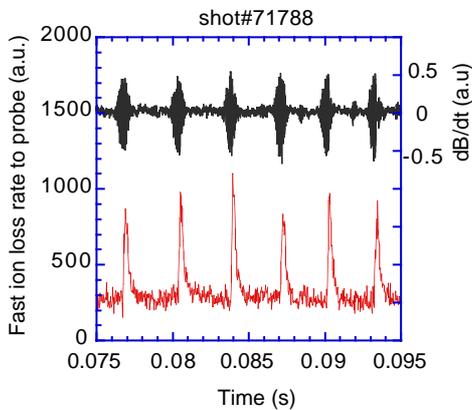

Fig. 3 Time traces of fast ion loss rate to probe and magnetic fluctuation. Expelled ions have co-going barely passing orbit with the pitch angle of ~43 degrees. The energy is near injection energy.
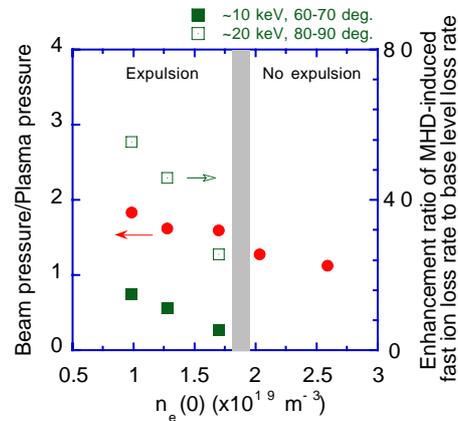
Fig. 4 Ratio of total beam pressure to plasma pressure and enhancement ratio of MHD-induced fast ion loss rate to base level loss rate. This is for ctr.-going, trapped fast ions.

3.2.2 Pellet-induced loss

Enhanced beam ion loss due to tracer impurity pellet injection[7] is also observed. Fig. 5 shows time traces of n_e, charge exchange(CX) neutral particle flux of 36.5 keV measured with a neutral particle analyzer(NPA) and beam ion loss rate measured with the escaping fast ion probe in R_{ax} of 94.9 cm and B_t of 0.9 T. NPA has tangential view on the midplane and it

focused on the energy range from 20 to 40 keV. The pellet injection angle is nearly perpendicular and the trajectory of pellet crosses the view line of NPA. Abrupt increase of CX neutral flux seen in Fig. 5 indicates that CX loss of beam ions surely occurs due to interaction between beam ions and neutral cloud of pellet. It is noted that escaping fast ion signal also increases abruptly and the loss rate in higher pitch angle region is more enhanced compared with that in lower pitch angle region. The same phenomenon also occurs in high magnetic field plasmas. Judging from this, redistribution of beam ions and resulting orbit loss may occur due to pellet cloud. Passing fast ions having relatively low pitch angle, which are dominant among existing beam ions in a plasma, encounter dense neutrals. Once the fast ions become fast neutrals, they start to move straight toward the plasma boundary. The characteristic penetration length of 38 keV neutral particle ranges from 0.3 to 0.7 m in this discharge(n_e ~ 1.0×10^{19} - 2.0×10^{19} m^{-3}, Z_{eff} ~ 3). Therefore, some of them go out of plasma and some of them have a chance to reionize in the peripheral region. Fast ions reionized in the periphery are able to have relatively high pitch angle and they are thought to be easy to escape from the confinement domain. Orbit calculation with taking account of neutralization and following reionization was done to verify the hypothesis mentioned above and the presence of fast ion orbits supporting the hypothesis was confirmed.
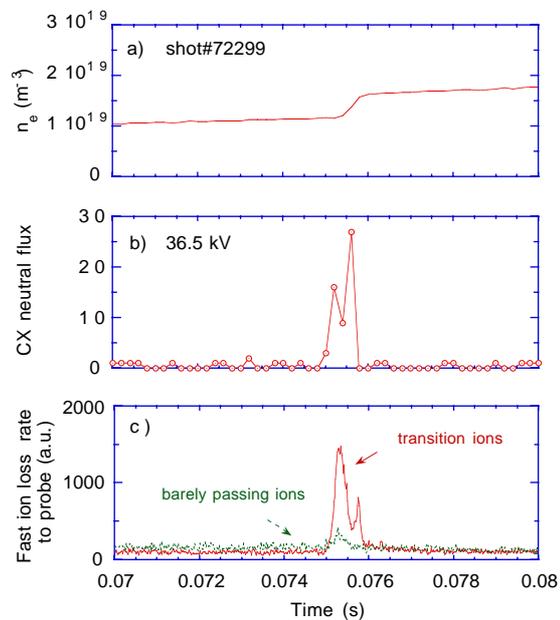

Fig. 5 Time traces of a) ne, b) CX neutral flux of 36.5 keV and c) fast ion loss rate of barely passing and transition ions. Barely passing and transition ions have the pitch angle of 132, 125 degrees, respectively.

4. Summary

In CHS, beam ion losses have been measured with a scintillator-based escaping fast ion probe. Barely passing ions, transition ions and trapped ions in magnetic well of outer region can be detected. In addition to first orbit loss, expulsions of beam ion which coincide with MHD-activity and pellet injection are clearly observed. For pellet-induced fast ion loss, the phenomenon is qualitatively explained by model calculation. Initial analysis for MHD-induced fast ion loss suggests that there is causal relationship between beam pressure and MHD-induced loss but is not well understood yet. To understand beam ion loss in CHS more comprehensively, one more fast ion probe is going to be installed in a different position.

Reference

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