Design Study of Lost Fast-Ion Probe on the Large Helical Device

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A lost fast-ion probe (LIP) with a scintillator screen was designed for measurements of energetic ion loss flux caused by energetic-ion-driven MHD instabilities as well as magnetic field ripple in the Large Helical Device (LHD). The optimum position for the installation of the probe was determined by searching for energetic ion trajectories along which energetic ions launched from the probe can reach the region inside the last closed flux surface, without intersecting with any in-vessel components of the LHD vacuum chamber. The LIP is installed at the outboard side of a horizontally elongated poloidal cross section. It can be moved in the horizontal direction by 750 mm per 1.5 minutes with a pneumatic motor. The aperture of LIP was arranged to measure losses of co-going energetic ions, whose detectable ranges of the pitch angle and gyroradius are 35-50 degrees and 1.5-15 cm, respectively. The scintillator P46 was adopted, being taken into account its high sensitivity and short decay time even at high temperature. The light emitted from the scintillator by energetic ion bombardment is detected by a photomultiplier array with high-time-resolution (up to 200 kHz) and an image intensified CCD camera (up to 2 kHz). Accordingly, thus designed LIP is expected to detect fast loss events of energetic ions induced by MHD instabilities such as Alfvén eigenmodes.

Keywords: lost-ion probe, energetic ion, scintillator, orbit calclation, Alfven eigenmodes

1. Introduction

Good confinement of energetic particles such as alpha particles is crucial for realization of a nuclear fusion reactor. Large amount of loss of energetic ions caused by energetic-ion-driven magneto hydrodynamic (MHD) instabilities should be avoided, because it would quench fusion burn, leading to localized serious damages of the first wall. In the Large Helical Device (LHD), energetic-ion-driven MHD instabilities such as toroidicity-induced Alfvén eigenmodes (TAE) and energetic-particle mode (EPM) are excited in neutral beam (NB)-heated plasmas [1, 2], and induce anomalous transport of energetic ions [3]. We should measure distribution of pitch angle (χ=arccos($v_{//}/v$)) and energy of lost-fast ions due to energetic-ion-driven MHD instabilities, in order to understand detailed loss mechanisms and minimize it. A most powerful diagnostic tool to detect fast-ion loss flux is a lost fast-ion probe (LIP) with scintillator screen [4]. The LIP has been successfully applied to helical/stellarator plasmas [5, 6] as well as tokamaks [7-9]. For this reason, we have designed the LIP which will be installed at the outboard side of a horizontally elongated poloidal cross section in LHD.

The LHD is a helical device with toroidal field periods of 10 and poloidal periods of 2. It has a plasma major radius R is ~3.6 m and an average minor radius $<a>$ is ~0.6m. The toroidal magnetic field strength B_t can be increased up to 2.9 T.

Figure 1 shows a top view of the LHD, NBI injectors, and location of the head part of LIP. The LHD has four NB injectors, three of which (BL-1~3) inject hydrogen neutral beams tangentially (co- or counter-direction) into the plasma, having energies up to 180 keV, and another one (BL-4) injects beam perpendicularly at energy of 40 keV.

2. Positioning Study

In order to detect lost energetic ions effectively, the probe should be placed close to the plasma. On the other hand, the damages of the probe such as melting by lost energetic ion flux should be avoided. From this point of view, a scanning range of the probe in the horizontal direction was carefully determined as explained below.

The procedure of positioning study is as follows : 1) An energetic ion is launched from the possible candidate position of LIP head, having various initial velocities and pitch angles expected in LHD plasma

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conditions, 2) The Lorentz force equation for charged particle's motion ($m\frac{dv}{dt} = q(v\times b)$) is solved backwardly in time in the LHD magnetic field in the Cartesian coordinates, 3) If the fast ion launched from the LIP head enters inside the last closed flux surface of an LHD plasma, we judge that a trajectory of lost ion is found.

Figure 2 show typical orbits of energetic ions reaching the LIP. One has initial energy E_i of 150 keV and pitch angle χ of 108.7 degrees (Fig.2a) and the other has E_i of 150 keV and χ of 41.8 degrees (Fig.2b). B_t and the magnetic axis position of the vacuum field R_{ax} are 0.75 T and 3.6 m, respectively in this case. In this calculation, the trajectories of energetic ions are followed in the static magnetic field without any field perturbations and the radial electric field is assumed to be zero ($\boldsymbol{E}$=0). In the case shown in Fig.2(a), a launched ion doesn't go back into the plasma region and hits the first wall surface immediately. It means that such ion does not reach the probe from the plasma confinement region, that is, will not be detected by the probe actually. On the other hand, in the case shown in Fig. 2 (b), the ion goes back into the plasma and it means that it is detectable by the probe. As can be seen, this is co-going transit energetic ion whose orbit deviates substantially from magnetic flux surfaces.

We have tried to find energetic ions which have small χ, because such ions would easily interact with Alfvén eigenmodes (AE). We have evaluated the numbers of such lost trajectories, by changing the radial position of the probe head in the horizontal direction. Figure 3 shows the counts of lost ions as a function of the radial position in the horizontal direction, where 750 particles are launched from the LIP head, having various energies and pitch angles. We evaluated the counts of lost ions found using above calculation, retracting the position of the LIP head outward in the accessible range of LIP (from R=4.46 m to R=4.6 m) by every 20 mm step. This calculation was carried out for the reference configuration of R_{ax}=3.6 m in two different B_t of 0.75 T and 1 T.

3. Diagnostic Setup

Figure 4 shows a schematic view of the designed LIP installed in the horizontally elongated poloidal cross section of LHD. The probe head is attached to a stainless steel shaft of 3 m long. The LIP head can be inserted in the horizontal plane shifted upward by 80 mm for the equatorial plane of the LHD device, to the inner most position (R=4.46 m) by a pneumatic motor, as shown in Fig. 4a. The LIP passes through a diverter leg to the innermost position. A stainless steel shaft is partially covered with a graphite sleeve of 380 mm long and 5 mm thick, to protect the LIP against high heat flux flowing from a main plasma along divertor leg. The scintillator box of LIP is made of stainless steel and covered with molybdenum plates. Lost energetic ions pass thorough a front- and rear- aperture, and then hit a scintillator surface of which strike point gives information of both gyroradius and pitch angle of the lost ion. (Fig.5) Once a size of aperture, scintillator position and magnetic field strength at the scintillator position are specified, a pattern of scintillator light is uniquely decided.

Two dimensional image of scintillation light due to impact of lost-fast ions has to be transferred outside of the vacuum vessel. In our probe, because the plane of scintillator surface is parallel to the axis of the probe shaft, the scintillation pattern appeared on the screen is first reflected 90 degrees by means of a polished stainless steel mirror mounted inside the probe head box. After this reflection, two dimensional light image is transferred by a series of relay lens mounted inside the probe shaft and is measured with an image-intensified CCD camera and/or photomultiplier tubes. (Fig4b) Form the analysis of light pattern appeared on the scintillator surface, gyroradius and pitch angle of lost-ion flux can be derived.

4. Details of the LIP Head

The position that the LIP is installed to LHD is shown in Fig.1. When the direction of B_t is clock wise (CW) as seen from the top, the ion grad-B and curvature drifts are upward and ions tend to drift toward the probe. The LIP designed in this study can work only in this operation. The LIP will not be able to detect any lost-ion flux when B_t is directed to be counter-clock-wise because of following primary two reasons. One is that ions tend to go away from the LIP because the ion grad-B drift is downward. Another is that gyromotion of energetic ions becomes opposite compared with the CW-B_t case. Even if lost-energetic ions reach the LIP and enter the detector box, they can not hit the scintillator surface. Detail of the LIP head is shown in Fig.6. The size of LIP head is 58 mm (width) × 52 mm (length) × 66 (height), but has defective part near the aperture. The angle between the side surface of the LIP and the aperture is selected to be 21 degrees, so that lost ions having wide range of gyroradius and pitch angle would pass through the aperture effectively. The front aperture has 3 mm wide and 1 mm high whereas the rear aperture has 24.1 mm wide and 1 mm high. The size of aperture was determined so as to obtain optimum energy and pitch angle resolution and signal intensity from calculation. The distance between the two apertures is 10 mm. The normal vector of the aperture is 113 degrees with respect to the local magnetic field direction, to guide energetic ions with 35 to 50 degrees (co-going particle).

Also, in Fig. 5, calculated hit point area of lost ions having the range of 1.5 to 15 cm in gyroradius and 35 to 50 degrees in pitch angle is shown on the scintillator screen. It should be noted that the gyroradius is defined with $\rho=|v|/\omega_c$ where ρ, v, and ω_c indicate gyroradius, velocity of ion, and cyclotron frequency of ion at the position of probe. That is, the gyroradius and pitch angle are not equal to those in a plasma. As a scintillator material, YAG:Ce (P46) is used, because it has high sensitivity and short decay time even at high temperature. P46 is deposited on a quartz plate coated with aluminum, and emits green light. The light emitted from the scintillator is detected by an array of photomultiplier with high-time-resolution (up to 200 kHz).

5 Conclusion

A lost fast ion probe with scintillator (LIP) installed on LHD was designed by finding trajectories of energetic ions which connect from the probe to the plasma confinement region. It is concluded that when the LIP is placed in the range of R=4.46 m to 4.6 m in a planned port position of LHD, energetic lost ion flux due to AEs would be detected. This LIP will be a powerful tool to study interaction between energetic ions and energetic ion driven instabilities.

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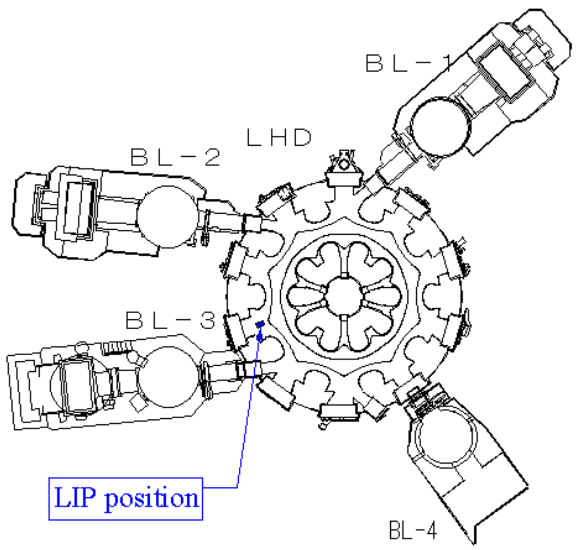
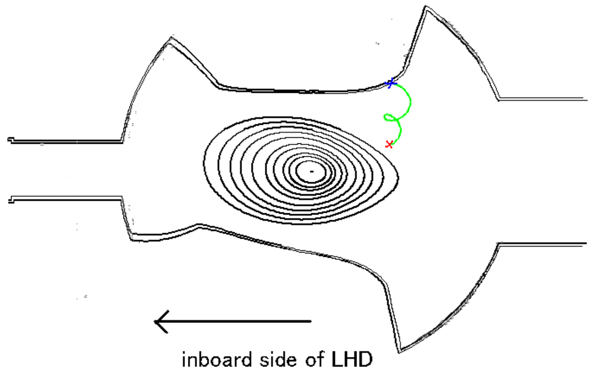
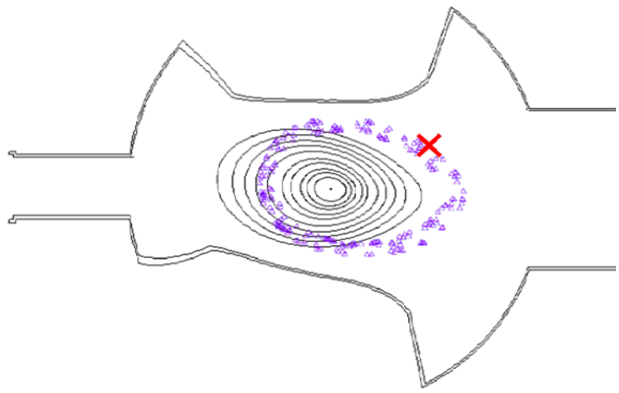


Fig.1 Top view of LHD where NB injectors and a newly designed LIP are arranged. Both BL-1(180keV) and BL-3(180keV) are in operation to be co or counter injection simultaneously. On the other hand, BL-2 (180keV) is in operation to the opposite direction against BL-1 and BL-3. BL-4 is used for perpendicular NBI. The position of LIP is marked near BL-3.



(a)



(b)

Fig.2 Examples of calculated trajectory. Red X mark indicates the initial position of orbit (equal to position of probe head). Blue X mark indicates the hit poison of the ion at the vessel surface. The condition is Bt=0.75 T, Rax = 3.6 m, E=0, B=0. (a) Poloidal projection of a calculated orbit trajectory in LHD, where the initial condition is Ei=150 keV, χ=108.7 degrees. In this case, the probe can't detect this lost energetic ion. (b) Poincare plot of a calculated orbit trajectory in LHD. Initial condition is Ei=150 keV, χ=41.8 degrees. In this case, the probe can detect them.

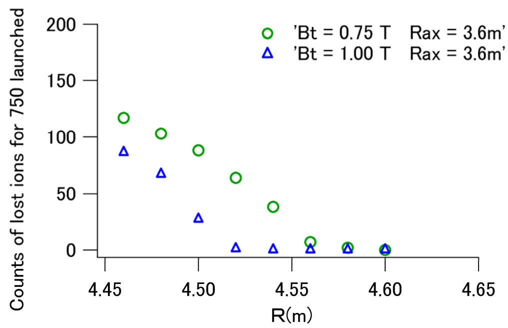
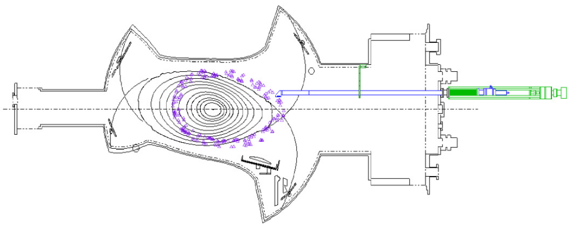


Fig.3 Counts of energetic ions that are lost from the plasma core region and reach to the LIP, where 750 particles are launched from the probe, having various energies and pitch angles. In the configuration of Rax=3.6m. The results at *Bt* = 0.75 T and 1 T are shown by circles and triangles, respectively.

a)



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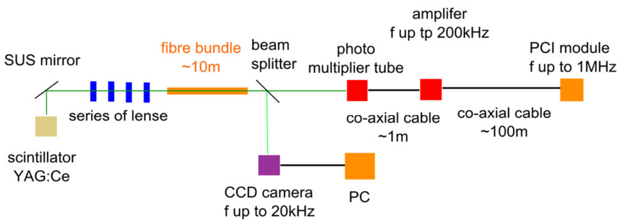

Fig.4 a) Schematic view of LIP placed at the innermost position in the horizontally elongated section of LHD. An example of Poincare plots of the trajectorie of lost ion with 150keV energy and 35.0 degrees pitch angle. It can be moved in the horizontal direction by 750 mm per 1.5 min with a pneumatic motor. A stainless pipe supports probe head is covered by a graphite sleeve of 380 mm length and 5 mm thickness, to protect from high heat flux along divertor leg
b) The route of signal transfer system and data acquisition system of LIP.

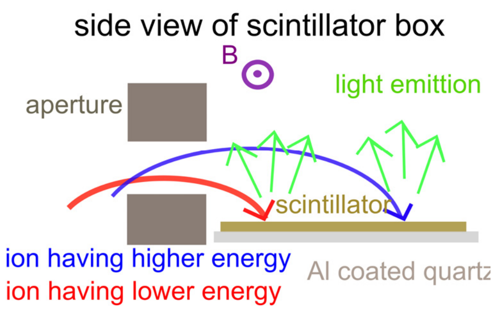

Fig.5 The side view of scintillator box. Lost energetic ions pass through apertures, and then hit a scintillator surface. Strike point gives information of both gyroradius and pitch angle of the lost ion.

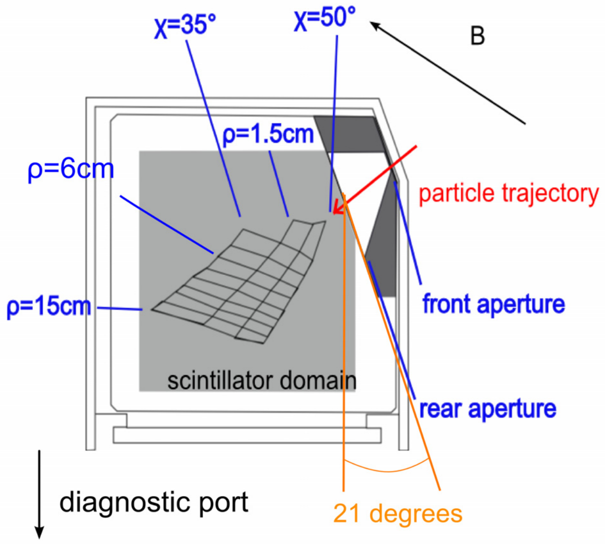

Fig.6 Schematic view of the probe head and expected arrival area of energetic ion. Expected hit point area of lost ions having the range of 1.5 to 15 cm for gyroradius and 35 to 50 degrees. The normal vector of the aperture is 113 degrees with respect to the local magnetic field direction. The size of a front aperture is 3 mm (width) × 1 mm (height) and the size of a rear aperture is 24 mm (width) × 1 mm (height). The distance between two apertures is 10 mm.