# Design Study of a Lost Fast-Ion Probe in Large Helical Device

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A scintillator-based lost fast-ion probe (LIP) was designed and constructed to measure energetic-ion-losses caused by energetic-ion-driven MHD instabilities such as Alfvén eigenmodes in the Large Helical Device (LHD). It provides information about the pitch angle and gyroradius of the lost energetic ions simultaneously. It is installed at the outboard side of a horizontally elongated poloidal cross section to detect co-going energetic ions. Two apertures of the LIP were designed to detect energetic ions, whose pitch angle and gyroradius are 35-50 degrees and 1.5-15 cm at the detector position, respectively. The scintillator P46 was adopted because it has high luminosity even in a high temperature environment. The scintillation light emitted from the scintillator surface by the impact of lost energetic ions is detected using an array of photomultiplier tubes with high time-resolution (up to 200 kHz) and an image-intensified C-MOS camera (up to 2 kHz).



Keywords: lost-ion probe, energetic ion, scintillator, orbit calculation, Alfvén eigenmode

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## 1. Introduction

Good confinement of energetic particles such as alpha particles is crucial for the realization of a nuclear fusion reactor. Loss of large amounts of energetic ions caused by energetic-ion-driven magnetohydrodynamic (MHD) instabilities should be avoided, because it would quench fusion burn, leading to serious localized damages of the first wall. In Large Helical Device (LHD), energetic-ion-driven MHD instabilities such as toroidicity-induced Alfvén eigenmodes (TAE) [1] and energetic-particle continuum mode (EPM) [2] have been observed in neutral beam (NB)-heated plasmas [3, 4], inducing anomalous transport of energetic ions [5]. In order to clarify loss processes of energetic ions by energetic-ion-driven MHD instabilities, a scintillator-based lost fast-ion probe (LIP) is employed in various toroidal devices. The LIP developed for this purpose consists of a scintillator screen and an aperture set, working as a magnetic spectrometer. It can measure distributions of pitch angle ($\chi = \arccos(v_{\parallel}/v)$) and energy of lost energetic ions, simultaneously. The LIP has been applied successfully to helical/stellarator plasmas [6, 7] as well as tokamaks [8–12] and has thus far provided valuable information on anomalous losses of energetic ions induced by energetic-ion-driven MHD instabilities. In this paper, we report the procedure for the design of the LIP constructed for LHD and hardware details of the LIP.

## 2. Study of Probe Positioning

### 2.1 Boundary condition in a calculation

LHD is a large helical device with toroidal field periods of 10 and poloidal periods of 2. It has a plasma major radius $R$ of ~3.6 m and an average minor radius <$a$> of ~0.6 m. The toroidal magnetic field strength $B_t$ can be increased up to 2.9 T. Figure 1 shows the top view of LHD, neutral beam (NB) injectors, and the location of the head part of the LIP. LHD is equipped with four NB injectors, three of which (BL-1~3) inject hydrogen NBs tangentially (co- or counter-direction) into the plasma, having energy $E_b$ up to 180 keV. Another one (BL-4) injects a NB having

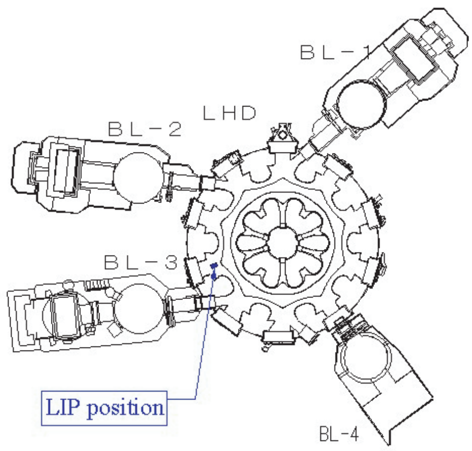


Fig. 1 Top view of LHD where NB injectors and a newly designed LIP are installed. The direction of both BL-1 (180 keV) and BL-3 (180 keV) are in operation to be co- or counter-, depending on the direction of $B_t$. On the other hand, BL-2 (180 keV) is in operation to the direction opposite to BL-1 and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

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$E_b$ of 40 keV perpendicularly. The energy of energetic ions produced by these NBs is in the range of super Alfvénic and can potentially destabilize TAE.

Here, the primary target of measurement using this LIP is co-going beam ions having small-$\chi$ that may escape from the confinement region and be lost at the outboard side of the torus, because co-going NB ions would be anomalously transported toward the outboard by TAE [5]. Therefore, as an initial trial, we consider that the probe is placed at the outboard side of the torus. In CHS, correlated with EPM and TAE activities, anomalous losses of co-going NB ions have been measured successfully by elevating the LIP from the midplane at the outboard side [7]. Referring to this result in CHS, the outboard side of LHD is supposed to be suitable for effectively detecting the loss of energetic ions by AEs.

## 2.2 Calculation method

In order to detect lost energetic NB ions effectively, the LIP should be placed close to the plasma. On the other hand, the probe position should be carefully surveyed, because damage to the LIP due to the heat load should be avoided.

The calculation procedure for the study of LIP positioning is as follows: 1) An energetic ion is launched from a possible candidate position of the LIP head, having various initial velocities and pitch angles expected in LHD plasma conditions, 2) The Lorentz force equation for a charged particle's motion ($m \cdot dv/dt = q(v \times B)$) is solved backward in time in the LHD magnetic field in Cartesian coordinates, 3) If the energetic ion launched from the LIP head enters inside the last closed flux surface of the LHD plasma, it means that the orbit of the lost ion is found.

It should be noted that, in this calculation, the orbits of energetic ions are followed in the static vacuum magnetic field without any field perturbations and the radial electric field is assumed to be zero. This assumption will be acceptable for evaluation of energetic ion losses by energetic-ion driven MHD modes, because lost energetic-ion orbit from outside the plasma confinement region to the probe is predicted to remain nearly unchanged independent of the presence of the MHD instabilities.

Figure 2 shows typical orbits of energetic ions reaching the LIP. One has initial energy $E_i$ of 150 keV and pitch angle $\chi$ of 108.7 degrees (Fig. 2 (a)), and another has $E_i$ of 150 keV and $\chi$ of 41.8 degrees (Fig. 2 (b)). In this case, the toroidal field strength $B_t$ and the magnetic axis position $R_{ax}$ of the vacuum field are 0.75 T and 3.6 m, respectively. In the case shown in Fig. 2 (a), a launched ion does not go back into the plasma region and hits the first wall surface immediately. It means that such an ion does not reach the LIP from the plasma confinement region; i.e., it will not be detected by the LIP. On the other hand, in the case shown in Fig. 2 (b), the ion goes back into the plasma; i.e., it is detectable by the LIP. As can be seen, this is a co-going

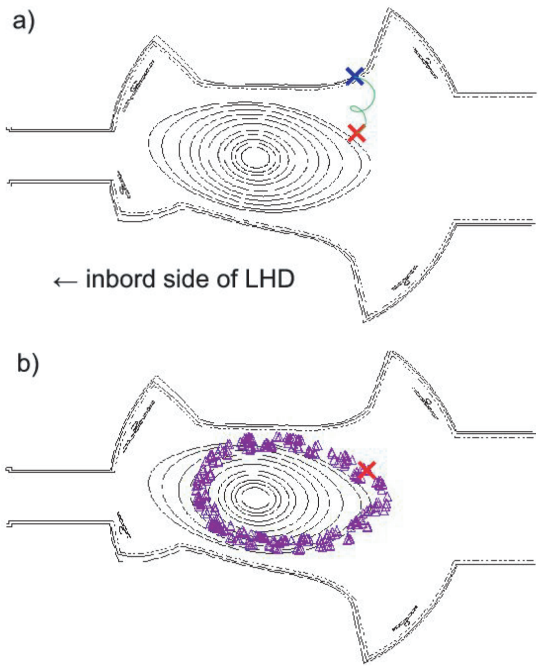


Fig. 2 Examples of calculated orbits in LHD. The red cross indicates the position of a probe head where energetic ions are launched in calculation. The blue cross points the hit position of the lost ion at the vessel surface. The calculation is performed in the vacuum equilibrium of $R_{ax}$ = 3.6 m at $B_t$ = 0.75 T. (a) Poloidal projection of a calculated orbit, where the initial condition is $E_i$ = 150 keV, $\chi$ = 108.7 degrees. In this case, the probe cannot detect this energetic ion. (b) Triangles show a Poincare plot of a calculated orbit. Initial condition is $E_i$ = 150 keV, $\chi$ = 41.8 degrees. In this case, the probe can detect it.

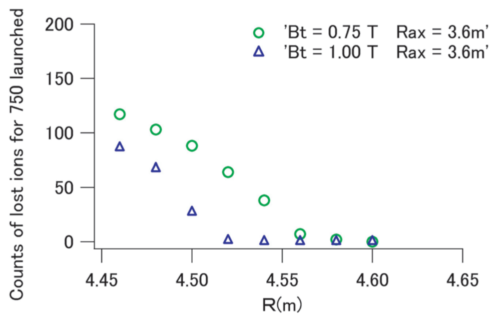


Fig. 3 Counts of energetic ions that are lost from the plasma core region and reach to the LIP, where 750 particles are launched from the probe, having various energies and pitch angles. The configuration is $R_{ax}$ = 3.6 m. The results at $B_t$ = 0.75 and 1 T are shown by circles and triangles, respectively.

transient energetic ion whose outside orbit deviates substantially from magnetic flux surfaces.

The calculation was carried out for the reference configuration of $R_{ax}$ = 3.6 m at two different $B_t$ values of 0.75 and 1 T. The numbers of such lost orbits were evaluated by changing the radial position of the LIP head along the probe shaft parallel to the horizontal plane. 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 in each position. The counts of lost ions are evaluated using the above calculation with retracting the position of the LIP head outward in the accessible range of LIP (from $R = 4.46$ to 4.6 m) in steps of 20 mm.

# 3. Diagnostic Setup

## 3.1 Design of the LIP

The basis of a scintillator-based LIP is that if the aperture of the scintillator box of the LIP is located on the energetic ion orbit, the ion passes through a front and a rear aperture, and then hits the scintillator surface. The strike point provides information about both gyroradius and pitch angle of lost ions (see Fig. 4), because the strike point is determined by them. Once the size of aperture, scintillator position, and magnetic field strength at the scintillator position are specified, the pattern of scintillator light is uniquely decided.

Figure 5 shows a schematic view of the designed LIP installed in the horizontally elongated poloidal cross section of LHD to detect energetic ions ($H^+$). The LIP designed in this study can work in the case that the direction of $B_t$ is clock-wise (CW) as seen from the top. The LIP will not be able to detect any lost-ion flux when $B_t$ is directed to be counterclockwise (CCW) because the gyromotion of energetic ions becomes opposite for the CW-$B_t$ case; they are blocked by the apertures of the LIP box and cannot reach the scintillator surface.

The LIP head is attached to a long stainless steel shaft of 3 m length. It is horizontally inserted at a place 210 mm above the equatorial plane of LHD through a diverter leg, to the inner-most position ($R = 4.46$ m) by a pneumatic motor, as shown in Fig. 5. A stainless steel shaft is partially covered with a graphite sleeve of 380 mm length and 5 mm thickness, to protect the LIP against high heat flux flowing from the main plasma along the divertor leg. The scintillator box of LIP is made of stainless steel and covered with molybdenum plates to protect from the heat load.

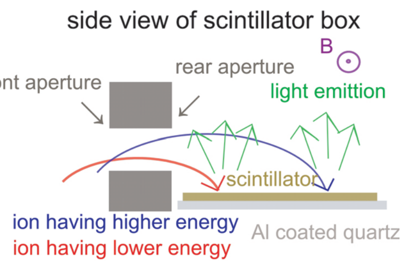


Fig. 4 The side view of the scintillator box. Lost energetic ions pass through two apertures, and then hit the scintillator surface. The strike point provides information about both gyroradius and pitch angle of the lost ion.

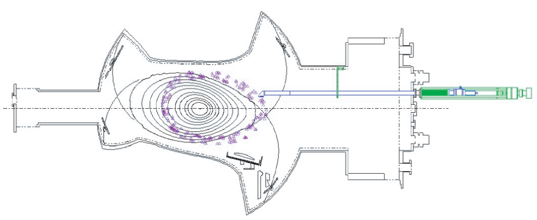

Fig. 5 Schematic view of the LIP placed at the innermost position. The distance between the outermost surface of ergodic layer and the probe head is 120 mm. Triangles designate an example of Poincare plots of the orbits of lost ion with 150 keV energy and 35.0 degrees pitch angle. It can be moved in the horizontal direction by 750 mm per 1.5 min with a pneumatic motor.

## 3.2 Function and details

Details of the LIP head are shown in Fig. 6. The size of the LIP head is 58 mm (width) × 52 mm (length) × 66 mm (height), but has a defective part near the aperture. The angle between the side surface of the LIP and the aperture is selected to be 21 degrees. It was decided on the basis of the magnetic vector of the probe head position so as to be able to evaluate the scintillation pattern easily and to catch energetic ions effectively. Hence, the normal vector of the aperture is 113 degrees with respect to the local magnetic field direction at the innermost position. The front aperture has 3 mm width and 1 mm height whereas the rear aperture has 24.1 mm width and 1 mm height. The size of the aperture was determined so as to obtain an aimed particle whose energy is 100-180 keV and pitch angle is 35-50 degrees (co-going particle) with high resolution. The separation between the two apertures is 10 mm.

In Fig. 6, calculated hit point area of lost ions having the range of 1.5 to 15 cm in gyroradius and 35 to 50 degrees

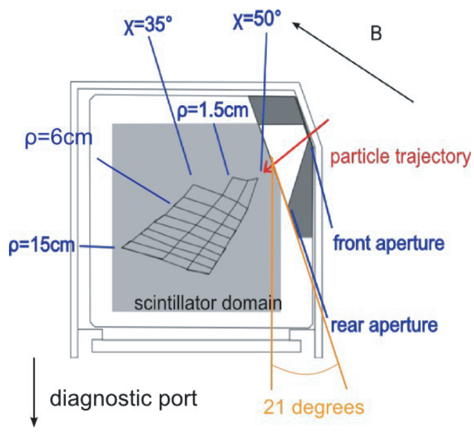


Fig. 6 Schematic view of the probe head and expected arrival area of energetic ions. Expected hit point area of lost ions having the range of 1.5 to 15 cm for gyroradius and 35 to 50 degrees.

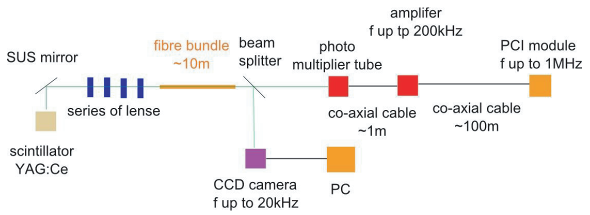


Fig. 7 The block diagram of the signal transfer system and the data acquisition system of the LIP.

in pitch angle is shown on the scintillator screen. It should be noted that the gyroradius is defined as $\rho = |v|/\omega_c$ where $\rho$, $v$, and $\omega_c$ indicate the gyroradius, velocity, and cyclotron frequency of an ion at the position of the probe head. That is, the gyroradius and the pitch angle are not equal to those in a plasma where the lost ions are confined. As a scintillator material, YAG:Ce (P46) is used because it has high luminosity and short decay time even at high temperatures. Scintillator-plate is composed of P46 deposited on a quartz plate coated with aluminum, and emits green light.

A two-dimensional image of scintillation light due to impact of lost-energetic ions is transferred outside the vacuum vessel. In our probe, the scintillation pattern that appears on the screen is first reflected 90 degrees by means of a polished stainless steel mirror mounted inside the probe head box, because the plane of scintillator surface is parallel to the axis of the probe shaft. After this reflection, the two-dimensional light image is transferred by a series of relay lens mounted inside the probe shaft and is measured with an image-intensified C-MOS camera. The light emitted from the scintillator is also detected by an array of photomultiplier tubes with high time-resolution (up to 200 kHz) (Fig. 7). Gyro-radius and pitch angle of lost energetic ion reaching the LIP can be derived by the analysis of light pattern appearing on the scintillator surface.

In applying LIP to a reactor-relevant burning plasma such as ITER, it is required to distinguish energetic-ion species because there exist not only beam deuterons and/or tritons but also fusion products such as alphas and tritons. In such a plasma, it will be possible to distinguish fusion products in MeV range from beam ions to some extent by installing a thin metal foil at the entrance aperture with appropriate thickness according to fast ions' energy of interest. In TFTR deuterium and deuterium-tritium plasmas, this technique was employed for lost-fast ion diagnostics and only lost fusion products were measured successfully [12].

## 4. Summary

A lost fast-ion probe with scintillator (LIP) installed in LHD was designed by finding orbits 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 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 MHD instabilities.


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