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Installation of Bidirectional Lost Fast-Ion Probe in the Large Helical Device

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A bidirectional scintillator-based lost fast-ion probe is installed to measure fast-ion losses induced by energetic-ion-driven magnetohydrodynamic (MHD) instabilities in the Large Helical Device (LHD). It has two set of an aperture assembly so as to measure losses of co-going fast-ions in both clockwise and counter-clockwise directions of the toroidal field. Each aperture assembly was designed to detect escaping energetic ions, whose pitch angle and gyroradius are respectively 30-70 degrees and 3-15 cm, and to block plasma stray light. The scintillator P11 (ZnS:Ag) was adopted because of its high luminosity toward high-energy particles.

Keywords: lost-ion probe, energetic ion, scintillator, Alfvèn eigenmode, LHD

1. Introduction

Anomalous transport of energetic ions caused by energetic-ion-driven magnetohydrodynamic (MHD) instabilities such as Alfvèn eigenmodes (AEs) [1] and energetic-particle continuum mode (EPM) [2] would lead to localized damage of the first wall, quench of DT burn, and/or degradation of heating efficiency. Accordingly, this anomalous transport of energetic ions must be avoided in not only existing tokamaks/helical devices but also in a fusion reactor. In the Large Helical Device (LHD), these energetic-ion-driven MHD instabilities [3, 4] and induced anomalous transport of energetic ions [5] are often observed in neutral beam (NB) heated plasmas. In order to understand loss mechanism of energetic ions induced by these MHD instabilities, information of energy (E) and pitch angle ($\chi = \arccos(v_{/\!/}/v)$) of lost energetic ions is crucially important. An appropriate arrangement of a scintillator and an aperture assembly in a scintillator-based lost fast-ion probe (LIP) acts as a magnetic spectrometer and can derive the information of E and χ of the lost-fast-ions. So far, LIP has been successfully applied to several tokamak and helical devices, and has given us important information of lost energetic ions [6-12].

In this paper, we report the details of a bidirectional scintillator LIP developed newly toward 2008 experimental campaign, aiming at detecting lost energetic ion flux regardless of the direction of the toroidal magnetic field Bt.

2. Concept of Bidirectional Lost Fast-Ion Probe

The bidirectional LIP has been installed in LHD. LHD is a large helical device with toroidal field periods of 10 and poloidal periods of 2. Its plasma major radius R is ~3.6 m and an average minor radius $\langle a \rangle$ is ~ 0.6 m. The toroidal magnetic field strength at the magnetic axis position of R~3.6 m can be increased up to 3 T. In LHD, three negative ion-source based neutral beam injectors (NBI) of which acceleration energy is up to 180 keV are employed to produce and heat up plasma, providing tangential injection of hydrogen NBs. Two NBIs are oriented to the same direction and one NBI is directed oppositely. In the case of the clockwise (CW) direction of the toroidal field as seen from the top, one of three beam lines is directed to the counter-direction and the other two the co-direction. The generated energetic ions are super Alfvènic and will easily destabilize toroidicity-induced AEs and other classes of AEs

In a scintillator probe, if energetic ion has a relevant orbit passing through an aperture assembly which consists of front and rear apertures arranged with an adjusted separation, it can strike a certain position of the scintillator plate, as shown in Fig. 1. The strike position is uniquely determined with local magnetic field and velocity vector of the ion at the probe position. The strike position gives information of the pitch angle and energy of the energetic ion which would be detected by the probe.

In the experimental campaign of LHD in 2007, a proto-type of LIP having only one aperture assembly on one side of the scintillator

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head was installed at the outboard side of the horizontally elongated poloidal cross section [13]. This uni-directional LIP was capable of detecting co-going energetic ions whose orbits deviate from magnetic flux surfaces toward the outboard side only in the case of CW direction of the toroidal field. In the case of CCW direction of the toroidal field, the uni-directional LIP was not capable of detecting any energetic ions. This is because even if co-going fast ions reach the probe head, they can not enter the detector box because of no aperture on the side where fast ions reach. In addition, even if counter-going fast ions enter the detector box, because of the reversal of gyromotion of those ions, they can not hit the scintillator surface (reversed magnetic field case in Fig.1). In LHD experiments, the direction of the toroidal field is often changed from CW to CCW directions and vice versa, depending of research topics. In order to detect lost energetic ions caused by energetic-ion-driven MHD instabilities and to investigate loss mechanisms on various conditions, we have designed and constructed a new LIP having two sets of the aperture assembly which allows us to detect lost-ion flux regardless of the direction of the toroidal field.

The structure of each aperture assembly was carefully designed to avoid contamination of stray light coming from the plasma. The front aperture locates higher height and rear one locates lower height to avoid the stray light effect. The structure of the aperture assembly is schematically shown in Fig. 1.

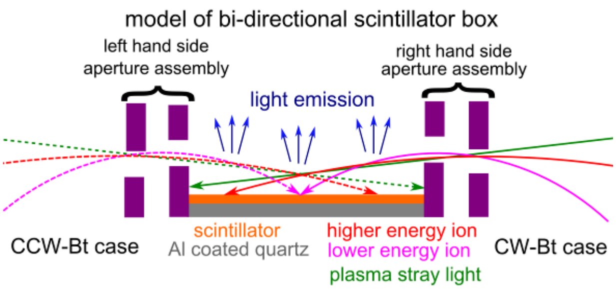

Fig.1 Schematic drawing of a scintillator box of the bidirectional LIP. The height of the rear aperture is higher than that of the front one to avoid scintillation with plasma stray light. Lost energetic ion goes through the front/rear aperture and hit the scintillator plate in the case of both directions of toroidal field (CW, CCW). The location of scintillation is determined, being taken into account expected velocity vector of lost-ion and magnetic field structure.

3. Details of the scintillator probe structure

This LIP consists of three main parts: scintillator head, image-conversion tube, and probe shaft having a function of image transfer tube. They all are made of stainless steel, and whole parts of the scintillator head, image-conversion tube, and the image transfer tube is covered with graphite to protect the probe itself from heat flux from plasma in diverter leg and scrape-off layer. They have a cylindrical shape and each part has 134 mm, 100 mm, and 58 mm in diameter, and 45 mm, 280 mm, and 380 mm in length, respectively. The scintillator head has two sets of an aperture assembly, of which sets are placed on the both left- and right-hand sides of the scintillator head. Accordingly, we call this LIP "bidirectional LIP" because it can detect lost energetic ions travel ling along the magnetic field line from both right- and left-hand sides. The image conversion tube has a function to reduce a scintillation image of ϕ70 mm diameter down to ϕ 45 mm one. The image transfer tube of 3 m length transfers the scintillation image to photon detectors outside the vacuum vessel of LHD with 10 relay lens arranged inside the tube. The LIP is installed at the position 210 mm above the equatorial plane of LHD (Fig. 2), and can be inserted up to 750 mm from the stand-by position along the probe shaft with a pneumatic motor, where the driving speed of the shaft is about 2 m/min

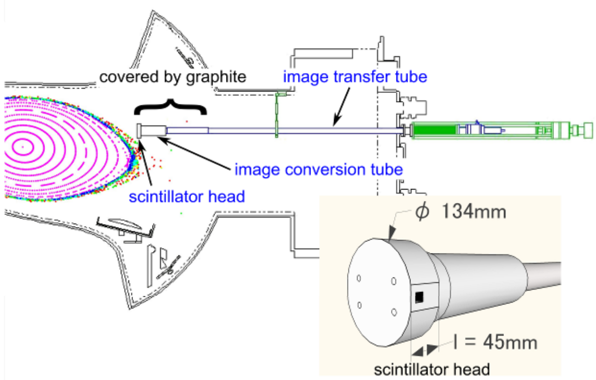

Fig.2 Schematic view of LIP installed LHD with an LHD plasma. The LIP is most inner position. An inset in the lower right side of the figure is the head of LIP, where lost-ions can enter LIP head through the aperture.

The position of LIP head is determined, based on full gyromotion following orbit calculation by solving Lorentz force equation for charged particle motion in the vacuum magnetic field of LHD. This is because our interest is in gyromotion phase of fast ions, as well as position where fast ions are lost. Currently, radial electric field is not considered. The equation is solved backward in time. The calculation is started at the LIP position having certain velocity vector. If fast ions goes back into the plasma confinement region (inside the last closed flux surface), it means that the fast ions can be detected with this probe at that position. It should be noted that the energy and pitch angle of ion in this calculation do not correspond to those in a plasma but to those at the LIP position. This calculation method of an energetic ion orbit is suitable for investigating particle orbit in a plasma with energetic-ion-driven MHD instability, because lost energetic ions are detected by LIP placed outside the plasma, where the magnetic field structure of the region is almost unaffected by the presence of MHD instabilities having small amplitude. Figure 3 shows the number of detectable ions as a function of the expected radial position of LIP (R) along

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the probe shaft. Fast ions of 180 are launched with energies of 150 keV or 180 keV at the position *R* by distributing the pitch angle from 0 to 180 degrees. In Fig.3, *R* indicates the radial position from the centre of the torus along the horizontal plane of LHD. This calculation was carried out in the configurations of R_{ax}=3.6 m and *Bt* =0.425 T, 0.5 T, and 0.75 T. It should be noted that the pitch angles larger than 90 degrees are of counter-going. Lost fast-ions which exist at the outside region of the plasma can be detected with this LIP in expectation. The count decreases rapidly with the increase in *R* from ~4.5m to *R*=4.6m

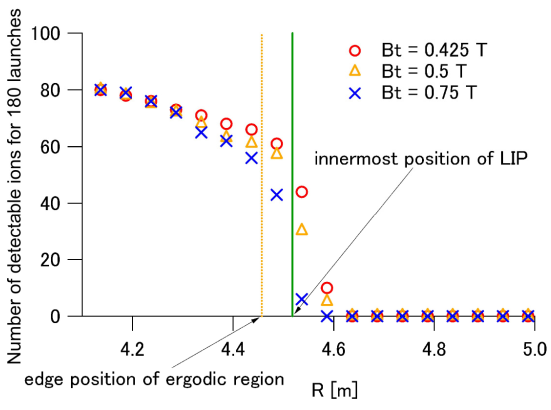

Fig.3 Calculated count of energetic ions can be detected at various radial positions along *R* (=the distance from the centre of LHD), in which calculation 180 ions having various pitch angles are launched from various positions of *R* for energetic ions of *E*=150 keV and 180keV. The magnetic configuration is R_{ax}=3.6 m, and *Bt* =0.425 T, 0.5T and 0.75 T. The count of detectable ions rapidly increases with approaching the boundary of ergodic layer of a plasma. The count in the region of *R*>4.5m corresponds to ions that will be detected by the LIP, because the LIP head can be inserted up to *R*~4.5 m position from the stand-by position (*R*~5.2m).

4. Design of the scintillator head

Figure 4 shows schematic drawing of the scintillator head, i.e. section of scintillator screen and apertures. The size of the front aperture is 3 mm height and 5 mm width whereas the rear one is 3 mm height and 50 mm width. These apertures are overlapped by 1.5 mm height each other having 35mm separation, to avoid the effects of plasma stray light on LIP signal. The geometrical structure of the aperture assembly placed on both sides of the LIP head is designed to detect lost energetic ions whose energy is 100-180 keV and pitch angle is 30-70 degrees (co-going fast ions) with good resolutions of *E* and χ. As a scintillation material, P11 (ZnS:Ag) is adopted because of high luminosity for expected energy range of lost energetic ions. The center wavelength of scintillation light is 450 nm, and the size of scintillator is 50 mm × 50 mm which is slightly larger than that of the uni-directional LIP installed in the 2007 campaign of LHD. Figure 4 also shows two expected scintillation patterns calculated on the plausible assumption of uniform magnetic field on the scintillator plate, for both directions of the toroidal field, i.e., CW and counter-CW (CCW). This assumption is acceptable for this case, because the size of the scintillator head is much smaller than the characteristic scale length of magnetic field of LHD. As shown in Fig.4, the scintillator plate in the LIP head is placed by 5 degrees tilted toward the counter-clock wise direction for the horizontal plane to improve collecting rate of energetic ions and scintillation pattern. This tilting angle is determined by the orbit calculation. As seen from Fig.4, co-going energetic ions in both directions of toroidal field cases are expected to be detected by this newly developed bidirectional LIP, having good resolutions of the energy and pitch angle of lost-ions.

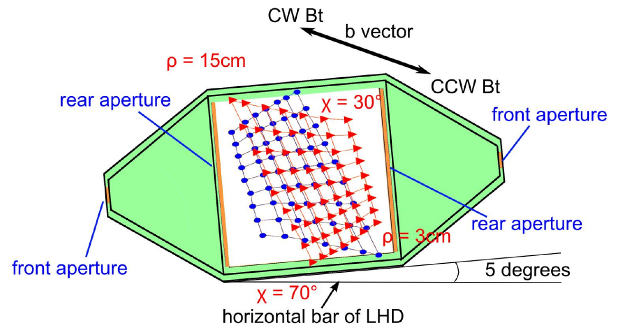

Fig.4 Schematic drawing of the scintillator head viewed from the outside of the horizontal port where the LIP was installed. The hit points calculated for lost-ions having various gyroradii ρ and pitch angles χ at both CW and CCW cases of toroidal magnetic field, where red triangles show the co-going particle in the CW case, and blue circles show the co-going particle in the CCW case. Expected ranges of gyroradius and pitch angle of lost-ions are respectively 3-15 cm (correspond to 7 keV to 173 keV at magnetic field is 0.4 T) and 30-70 degrees.

5. Measurement section

The main scheme of measurement section is not much changed compared with LIP in 2007 [13], therefore the important/modified parts are written here. A two dimensional image of scintillation light is transferred to outside the vacuum vessel with a set of relay lenses. The light is transferred to split-box by imaging quartz fiber bundle, and is split in two with a half mirror. One side of the light is detected by an array of photomultiplier tubes (it consist of 16 photomultipliers) with high time-response (up to 200 kHz), it is for detecting fast-time-response of lost ions induced by energetic-ion-driven MHD instabilities. Another side of the light is detecting by image intensified C-MOS camera (flame rate is up to 2 kHz, and resolution is up to 512×512 pixels) so as to measure the information of pitch angle and energy of fast ions.

6. Summary

A bidirectional scintillator-based lost fast-ion probe is designed

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and constructed to study anomalous losses of fast ions induced by fast-ion-driven MHD modes in LHD. The structure of two assemblies of entrance apertures has been determined through a large number of orbit calculations on fast protons for energies of 150 keV and 180 keV and various pitch angles. The aperture design was performed with attention to avoiding contamination of unfavourable stray light coming from a plasma. The LIP developed in this work can detect co-going energetic ions which will reach the LIP in both cases of CW and CCW directions of the toroidal magnetic field. This LIP will be applied to LHD plasmas for investigation of energetic ion losses induced by energetic-ion-driven MHD instabilities on various experimental conditions.

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