Design of Lost Fast-Ion Probe Based on Thin Faraday Films in Heliotron J*)

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A lost fast-ion probe based on thin Faraday films (FLIP) is designed to measure fast-ion losses caused by fast-ion-driven MHD modes as well as magnetic field ripples in Heliotron J. The FLIP works as a magnetic spectrometer providing the energy and pitch angle of lost fast-ions. The installation location of FLIP is studied using Lorentz orbit code. Upper port of Heliotron J at the corner section is a primary target to install the FLIP, because not only co-going fast ions but also counter-going fast ions will be detected at this position. The FLIP will give the decisive information to study fast-ion losses in Heliotron J.

Keywords: lost fast-ion probe, fast ion, faraday film, orbit calculation

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1. Introduction

In a fusion device, fast ions such as fusion born alpha particles might excite Alfvén eigenmodes (AEs). These instabilities are predicted to cause enhanced fast-ion transport leading to a localized damage on plasma facing components [1]. Understanding the interaction of AEs and fast ions through experimental observation in existing device is necessary to find a way to reduce the fast-ion loss in future devices. In previous experiments performed in Heliotron J, characteristics of AEs excited by neutral beam (NB) injected fast ions have been studied [2]. In these experiments, increases of fast-ion loss due to these AEs were measured with a Langmuir probe placed on the outside of the last closed flux surface [3]. To clarify causality between AEs and consequent fast-ion losses, velocity-space information of lost ions i.e. energy E and pitch angles χ is critical. A lost fast-ion probe based on thin Faraday films (FLIP) has been designed to measure E and χ of fast ions escaping from the plasma in Heliotron J. An FLIP has been used in CHS [4, 5], NSTX [6], JET [7, 8] and DIII-D [9]. There are three advantages to use an FLIP. The first is that the absolute flux of lost fast-ions can be estimated. The second is the capability of operation in relatively hostile thermal and radiation environments. The third is cost-effective relatively in construction compared with a scintillator-based lost fast-ion probe [10]. This paper describes the procedure for the design of the FLIP and details of the FLIP hardware.

2. Study of Probe Positioning

Heliotron J is a medium-sized helical axis heliotron device with major radius of 1.2 m and averaged minor radius of ~0.2 m. Two tangential neutral beam injectors (NBIs) are equipped with Heliotron J. One of the NBIs injects neutral beams in the co-direction while the other injects beams in the counter direction. The injection energy and the injection power of NBIs are up to 30 keV and up to 0.7 MW, respectively.

The procedure for the study of FLIP positioning is described as follows. At first, fast ions are launched from a candidate position of the FLIP head, having various energies and pitch angles. Second, trajectory of each ion is followed backward in time using the Lorentz orbit code. The code solves the equation of motion of a charged particle $m\mathrm{d}\boldsymbol{v}/\mathrm{d}t = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$ with Runge-Kutta solver on the condition of $\boldsymbol{E} = 0$. Here, m, v, t, q, E and B represent mass of the particle, velocity of the particle, time, charge of the particle, electric field and magnetic field, respectively. In this calculation, variation of energy of a fast ion is less than 0.2% in 10^5 steps. Finally, we judge whether the ion can enter the plasma domain without hitting the vacuum vessel. If the ion reaches the plasma region, it means that the lost fast-ion is measured by the FLIP. Other obstacles e.g. ICRF antenna or Langmuir probes are not included in this calculation. The blocking effect due to them will be evaluated on each experiment. Beam ions are launched from

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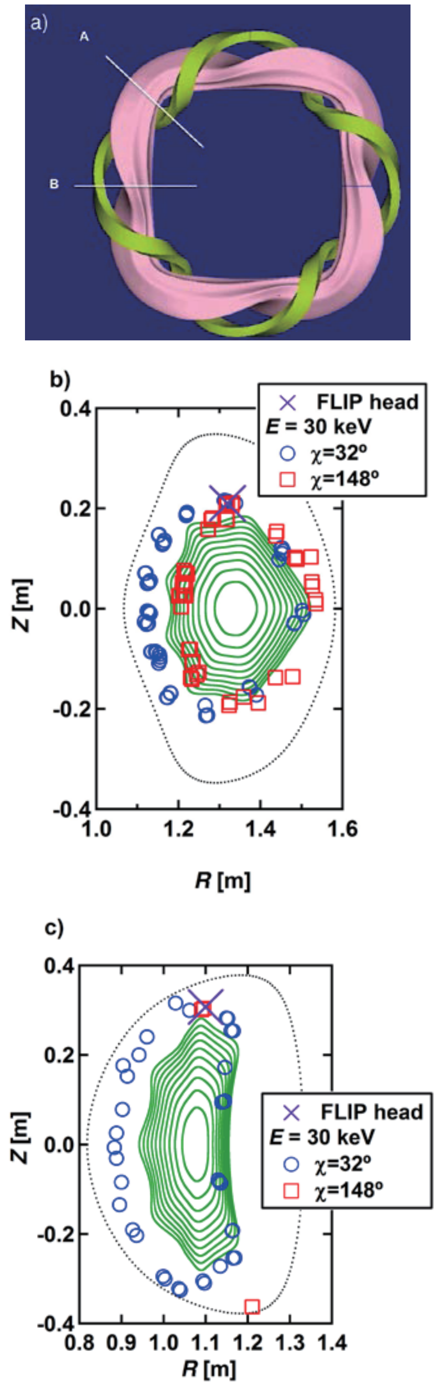

Fig. 1 a) Top view of Heliotron J plasma. b) Poincare orbit of co- and counter-going fast ions launched from candidate position of the FLIP head at cross section A. Black dots indicate the shape of the vacuum vessel and green lines represent the flux surfaces of Heliotron J plasma. c) Poincare orbit of co- and counter-going fast ions launched from candidate position of the FLIP head at cross section B. Only two Poincare plots exist for co-going ion because the ion hit the vacuum vessel. The distance between the FLIP head and LCFS in Figs. a) and b) is 30 mm.

candidate positions of the FLIP head. Figures 1 b) and c) show Poincaré plots of typical orbits of fast ions having the energy of 30 keV on the condition of toroidal magnetic field strength of 1.25 T. The start position of fast ions i.e. FLIP head position is represented as a purple cross. The pitch angles of fast ions are set 148 degrees and 32 degrees, respectively. They are typical pitch angle of co- and counter-beam ions injected by NB. We found that we can get beam ions at upper side of toroidal angle A and B on Fig. 1 a) at a distance of about 30 mm from the LCFS. In the other candidate positions, FLIP head should be placed at a distance of about 10 mm from LCFS to get beam ions. Unwanted heat load from a plasma is thought to be smaller at upper side of toroidal angle A and B due to larger distance from the LCFS. As shown in Fig. 1 b), co-going fast ion as well as counter-going fast ion reaches the plasma domain at cross section A (corner section), whereas at cross section B (straight section), only a counter-going fast ion reaches the plasma domain. We decide that an upper diagnostic port of Heliotron J at the corner section will be a primary target to install the FLIP because this position is suitable for detection of both co- and counter-going fast ions.

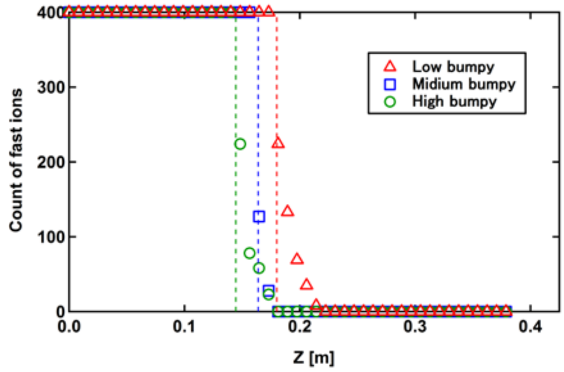

Fig. 2 Number of fast ions can reach the FLIP as a function of vertical position at the corner section on three configurations having different bumpy field components. In this calculation 400 particles are launched from the probe, having various pitch angles. Broken lines show the position of LCFS in three conditions.

The distance between FLIP and LCFS should be carefully surveyed because damage to the FLIP due to heat load should be avoided. To make reference of the accessible region of FLIP without heat load problem, the counts of fast ions are evaluated with retracing the position of the FLIP head upward (Fig. 2). The calculation was carried out for three configurations having different bumpy field components. In this figure, 400 particles are launched from the FLIP head, having energy of 30 keV and pitch angles of 0 degrees to 180 degrees in each position. In this calculation, injection energy of fast ion is chosen because deviation of fast ion orbit from the flux surface increases as energy of fast ions. The number of count grows rapidly near the LCFS position. On the low bumpy case, FLIP head should be placed at $Z < 0.21$ m to measure lost fast-ions whereas FLIP head should be placed at $Z < 0.17$ m on medium and high bumpy cases. On middle bumpy case, we should pay more attention to the heat load issue to FILP compared with the others because gradient of count of fast ions is steeper.

3. Lost Fast-Ion Probe based on Thin Faraday Films

The FLIP is essentially a magnetic spectrometer using Heliotron J magnetic field, consisting of a pair of apertures and a thin Faraday films. The strike point of fast ions on the films provides information of energy and pitch angle of lost fast ions (see Fig. 3). The schematically drawing of the probe is shown in Fig. 4. The probe shaft made from a stainless steel is mounted on a linear bellows driving system to be moved in the vertical direction by 600 mm. The port on which the probe is mounted is equipped with a gate valve so that the probe can be mounted and dismounted without need to vent the main vessel. We employ a rotary stage to revolve the probe head section. The stage alters the direction of the aperture so as to change the region of detectable pitch angle of fast ions because the grid of pitch angle map on Faraday films are decided by the direction of the aperture and the direction of the magnetic field.

The head of FLIP is made from a pure molybdenum. The size of the box is 44 mm × 38 mm. There are thin Faraday films on the bottom of the box. Faraday film is aluminum vapor deposited onto one face of the quartz substrate. The thickness of the films is about 0.2 μm. There is a set of aperture on the side of the FLIP head. The front aperture and second aperture have 1.5 mm width and 0.5 mm height and 9 mm width and 0.5 mm height, respectively. The separation of two apertures is 5.5 mm. The size of the aperture is determined using the grid calculation program [3] so as to obtain an aimed particle whose energy is up to 30 keV. Figure 5 shows the typical energy and pitch angle map of FLIP. It can cover the energy and pitch angle ranges from 1.8 keV to 45 keV and 10 degrees to 80 degrees, respectively. Green squares shown in Fig. 5 represent the region of each Faraday film. Two of them cover the low-energy range whereas high-energy range is covered by five films. Note that the one film located on the right-top is for evaluation of noise level because no fast ion will be

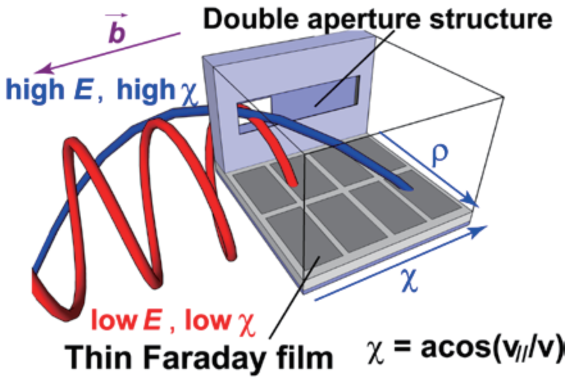

Fig. 3 A schematic drawing of probe operation, including fast ion orbits.

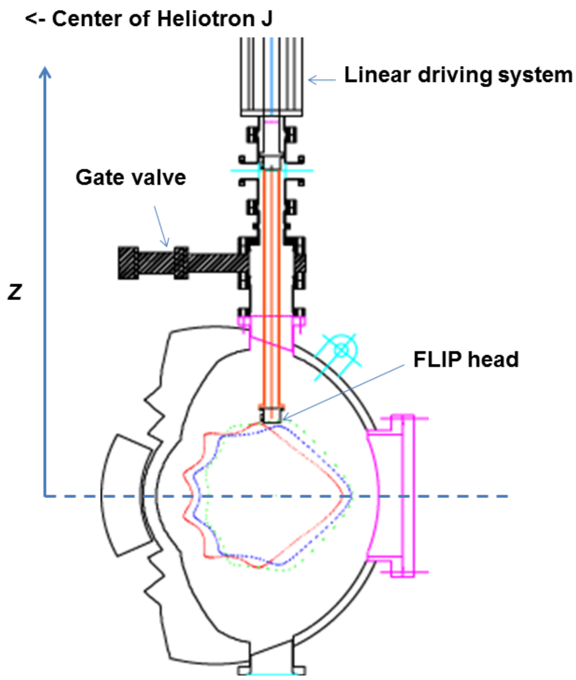

Fig. 4 A schematic drawing of the FLIP placed at the innermost position with last closed flux surfaces of Heliotron J.

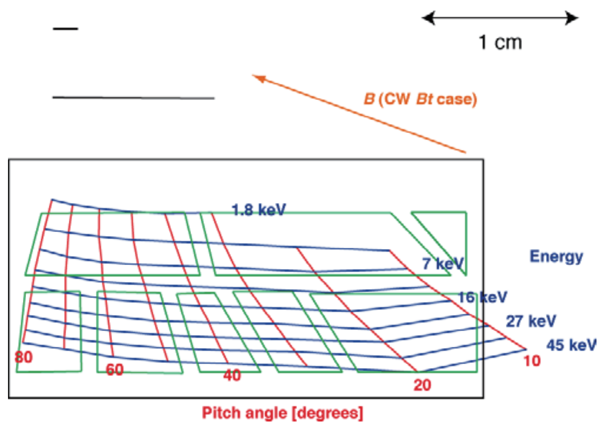

Fig. 5 Typical energy and pitch angle map of FLIP. Expected energy and pitch angle range of lost fast ions are 1.8 keV to 45 keV and 10 to 80 degrees, respectively.

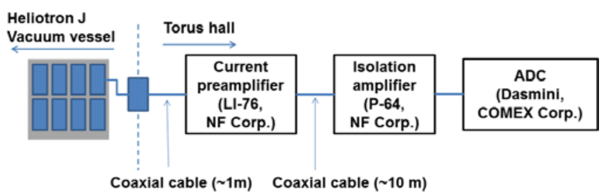

Fig. 6 The block diagram of the signal transfer and data acquisition systems of the FLIP.

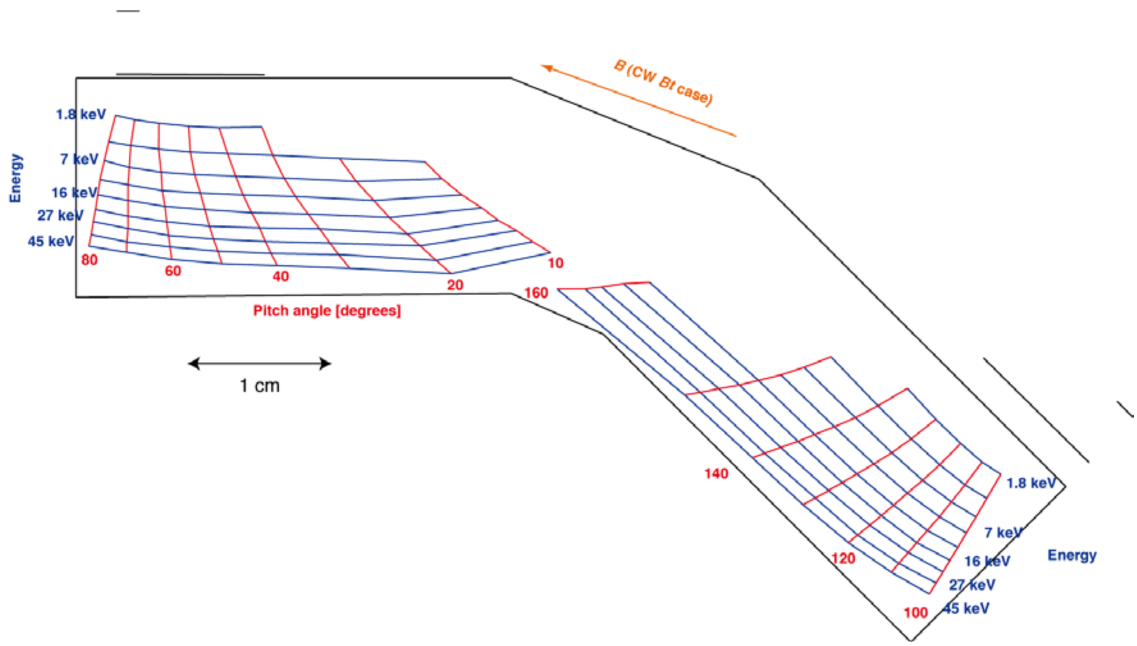

Fig. 7 Energy and pitch angle map of double aperture FLIP. Detectable energy range of lost fast ions is 1.8 keV to 45 keV. Detectable pitch angle ranges of co- and counter-going fast ions are 10 to 80 degrees and 100 to 160 degrees, respectively.

detected by this film. The foil is connected by a short cable to a current amplifier (NF Corp. LI-76). The signals are transmitted to the isolation amplifier (NF Corp. P64) and are digitized using analog to digital converter having sampling rate of 1 MHz, (COMEX Corp./Dasmini, 16 bit resolution) as shown in Fig. 6. We are going to install the FLIP system in summer of 2013 and expect to get the signal at 2013 campaign.

To enhance the study of fast ion loss, we plan to upgrade the FLIP head to get the co- and counter-going fast ion simultaneously at the same position. Figure 7 shows the modified FLIP head design. The head have two sets of aperture; one is for detecting co-going fast ions whereas the other is for detecting counter-going fast ions. The blocking effect of fast ion by FLIP head may not be critical, because co-going fast ions come from the left upper side whereas counter-going fast ions come from right lower side.

4. Summary

A lost fast ion probe based on thin Faraday films is designed. The position of the FLIP is searched by finding the orbit from the plasma region to the FLIP position. The FLIP will be mounted on the top of the device at a corner section because not only co-going fast ions but also counter-going ones can be detected by the FLIP. This FLIP will be applied to Heliotron J for investigation of fast-ion losses induced by fast ion driven MHD modes as well as magnetic ripple.

Acknowledgments

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