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Design and initial operation of lost fast-ion probe based on thin Faraday films in CHS

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The purpose of this work is to measure lost fast ions as an ion current so as to make quantitative argument on flux of fast-ion loss possible. We have designed and constructed a lost fast-ion probe based on combination of thin Faraday films and small rectangular apertures, called FLIP, for the Compact Helical System. The current generated by escaping fast ions has been successfully measured with the FLIP in neutral-beam-heated plasmas. The FLIP detected increased flux of escaping fast ions while fast-ion-driven magnetohydrodynamics instabilities appear. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2221681]

I. INTRODUCTION

A scintillator-based lost fast-ion probe[1,2] (SLIP) has been employed in the Compact Helical System[3] (CHS) to study anomalous transport and/or resulting losses of fast ions caused by fast-ion-driven magnetohydrodynamics (MHD) instabilities in neutral-beam (NB)-heated plasmas.[4,5] Although the SLIP can provide the relative intensity of lost fast-ion flux at the probe position and information on their gyroradius centroid and pitch angle, an issue on their absolute flux still remains because of difficulty of absolute calibration of the SLIP. In order to enhance further fast-ion physics experiment in CHS, we have designed and constructed a new lost fast-ion probe based on thin Faraday films (FLIP), providing the electric current generated by lost fast ions. The probes based on the same technique have been so far developed and tested in tokamaks.[6–10] Compared with the SLIP, primary advantages of the FLIP are lower system cost and capability for quantitative evaluation of absolute flux of lost fast ions. Also, the FLIP is supposed to be promising for lost alpha diagnostic in a future reactor plasma because it can be operated in hostile thermal and radiation environments, whereas the SLIP may not be because the luminosity of scintillator depends on temperature and largely falls when temperature goes over about 150°–200°.[11] Moreover, there exists an issue in long-distance transmission of two-dimensional image of scintillation light due to impact of lost alpha particles in neutron and γ-ray hard environments. A possible major disadvantage of the FLIP is that it may easily suffer from electromagnetic noise because a weak current has to be measured. Poorer energy and pitch-angle resolution may be also drawbacks in detailed understanding of fast-ion behaviors. In this article, the design concept of the FLIP and initial results of lost fast-ion diagnostic in NB-heated plasmas of CHS are described.

II. LOST FAST-ION PROBE BASED ON THIN FARADAY FILM

The probe position relative to the magnetic flux surfaces of CHS plasma and the function of FLIP are schematically illustrated in Fig. 1. The FLIP is installed on an upper diagnostic port at the outboard sides of CHS where the cross section of plasmas is horizontally elongated and the probe shaft made from a stainless steel is mounted on a linear translation stage that allows it to be moved vertically. A photograph of the FLIP in the vicinity of probe tip is shown in Fig. 2. The essential part of the FLIP is a molybdenum steel box with thin films of aluminum (Al) vapor deposited onto one face of the quartz substrate (34×34 mm^2, 1 mm thick) on the bottom of the box. The thickness of thin Al films is about 0.2 μm. Two apertures, one behind the other, are on one side and restrict the orbits of fast ion that can enter the probe. The first aperture is 2.0 mm wide and 0.8 mm high and the second is 14.25 mm wide and 0.8 mm high, and they are separated by 8.6 mm. The probe driving system and the aperture structure are basically the same as those of the existing SLIP. As seen in Fig. 1, the Al film (10×15.5 mm^2 for each) is divided into six zones to provide gyroradius centroid and pitch angle of lost fast ions simultaneously. Fast ions with larger gyroradii strike the Al films farther from the apertures than those with smaller gyroradii and their strike points are dispersed along a line passing through the center of the two apertures according to their pitch angles. Currently, the Al films, i.e., ion collectors, are operated without biasing voltage.

The electric circuit employed here is shown in Fig. 3. The current from each Al film flows through a multipin vacuum feedthrough connector on a Conflat flange to current-input preamplifiers (NF Co., model: LI-76). Inside the vacuum vessel, the heat-resistant polytetrafluoroethylene (PTFE)-insulated wires are used from the Al films to the feedthrough connector. From the connector to the current amplifiers, we make use of coaxial cables of 1 m/50 Ω. A

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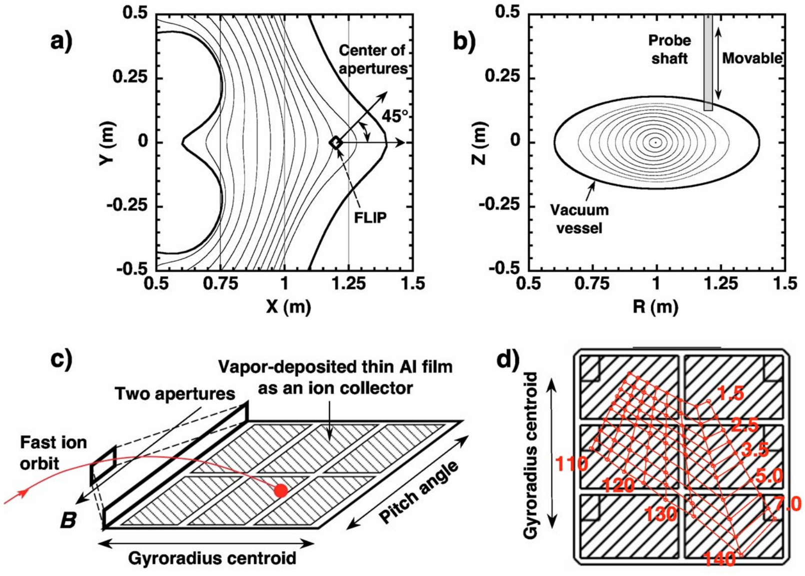

FIG. 1. (a) Schematic drawing on position of lost fast-ion probe based on thin Faraday film (FLIP) relative to the magnetic flux surfaces of MHD equilibrium having $R_{ax}=0.974$ m as seen from above. (b) Position at poloidal cross section, (c) function of FLIP, and (d) map of gyroradius centroid and pitch angle on thin Faraday film when the probe tip is placed at $Z\sim0.11$ m. The FLIP can be moved vertically. B_t is directed to be counterclockwise. Tangentially coinjected beam ions circulate clockwise in CHS.

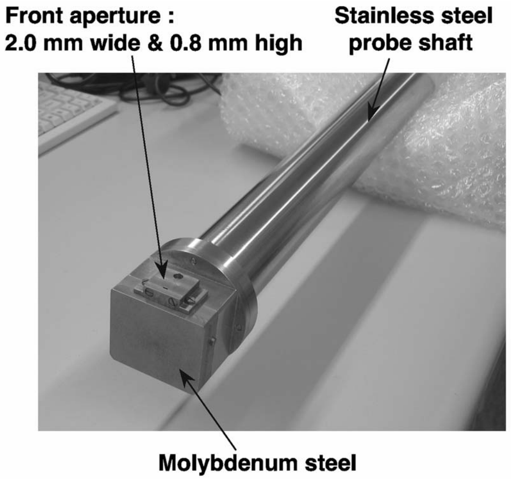

FIG. 2. Photograph of essential part of the FLIP prepared for CHS experiment.

cylindrical conducting sheath of the coaxial cable is grounded to the CHS vacuum chamber. The frequency response and gain of the current preamplifiers used here are variable. In the present experiment, they are chosen to be from dc to 20 kHz and 10^6 V/A, respectively. After the current preamplifiers, signals in voltage are transmitted to isolation amplifiers (NF Co., model: P-64) by coaxial cables of 10 m/50 Ω and are then digitized in a computer automated measurement and control (CAMAC) wave form recorder (Jorway Co., model: Aurora-14) with the sampling frequency of 500 kHz.

III. INITIAL EXPERIMENTAL RESULTS

The electric currents generated by escaping fast ions have been successfully observed in NB-heated plasmas of CHS. Figure 4 shows wave forms of line-averaged electron density, magnetic spectrogram measured with a Mirnov coil, Hα light emissivity, and the FLIP currents originating in lost fast ions obtained from the ion collector of channels 3 and 5 in $R_{ax}/B_t=0.974$ m/0.91 T. In this shot, two NBs ($E_b=40$ and 32 keV) are tangentially coinjected into a relatively low density target plasma [$n_e=(0.3-0.6)\times10^{19}$ m^{-3}]. The probe tip is placed at $Z\sim0.11$ m where the local magnetic field

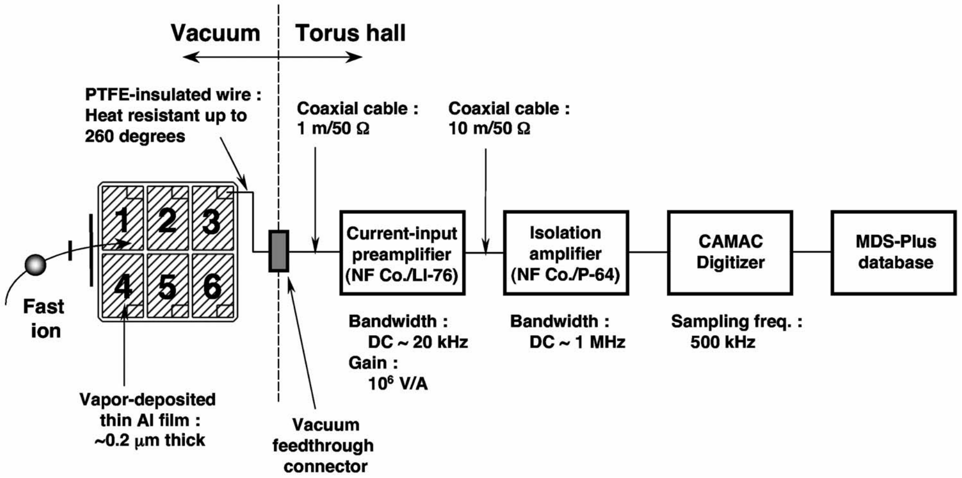

FIG. 3. Electric circuit used for FLIP in CHS. The total bandwidth of the system is from dc to 20 kHz, limited by the current-input preamplifier.

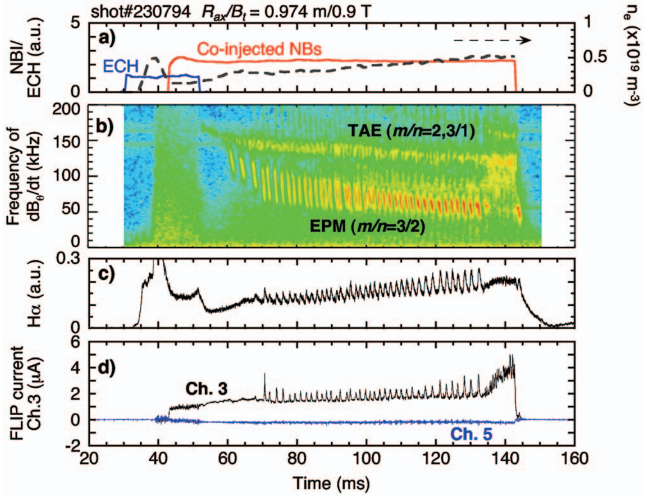

FIG. 4. (Color) Electric current generated by escaping fast ions in a neutral-beam-heated plasma of CHS ($R_{\rm ax}/B_t$=0.974 m/0.91 T). (a) Timing of NBs and electron cyclotron heating (ECH), time evolution of line-integrated electron density, (b) magnetic spectrogram measured with a Mirnov coil, (c) emissivity of Hα light, and (d) current of escaping fast ions evaluated from the FLIP signal (channels 3 and 5). Here, the plus sign in the current signal represents the ion current whereas the minus sign stands for the electron current.

strength is about 0.6 T. Judging from the result of SLIP, i.e., the two-dimensional distribution of scintillation light appeared on the scintillator surface due to the impact of lost fast ions,[1,2] the current measured in channel 3 is expected to be the largest among all ion collectors. Here, the films of channels 3 and 5 can collect beam ions having energy close to E_b. The orbit calculation shows that the collector of channel 3 can detect cogoing transit beam ions having relatively low pitch angle (χ[=arccos($v_\parallel/v$)]$>133°$). Their orbits deviate substantially from the magnetic flux surfaces toward the large major radius side. On the other hand, the collector of channel 5 can detect trapped beam ions having relatively high pitch angle ($\chi<132°$). As seen in Fig. 4, the FLIP current appears just after NB injection and evolves gradually in time. In this discharge, the energetic particle mode (EPM) ($m/n=3/2$) and the toroidicity-induced Alfvén eigenmode (TAE) ($m/n=2,3/1$) are excited due to tangentially coinjected beam ions. Here, m and n represent poloidal and toroidal mode numbers, respectively. Correlated with the bursting EPMs [b_θ=(5–10)$\times10^{-5}$ T], the FLIP current is periodically enhanced, indicating beam ion losses due to the EPM activities. This observation is consistent with that of the SLIP.[4,5] Hα light emissivity from the edge chord at the outboard side of horizontally elongated cross section also increases periodically. This is due to enhanced transport of beam ions toward the outboard side of the torus. When the intense TAE [b_θ=(2–3)$\times10^{-5}$ T] appears in the latter part of discharge, the FLIP indicates that the TAE activities enhance beam ion transport more than EPM. This is also consistent with the observation with the SLIP.[12] The value of electric current measured in channel 3 is roughly estimated to be a couple of microamperes, whereas the total current of NBs is about 48 A as a port-through current. Although we expected that the strong magnetic field of CHS causes most secondary electrons emitted from ion impact on the ion collectors to orbit back to the collector surface, the current having opposite sign appeared in channels 1, 5, and 6 where fast ions do not strike. This is supposed to be due to the effect of secondary electrons emitted from the ion collector of channel 3.

IV. SUMMARY

The lost fast-ion probe based on thin Faraday films (FLIP) has been developed for the fast-ion physics experiment in CHS. The electric current originating in lost fast ions has been successfully measured in NB-heated plasmas. The FLIP indicates that correlated with EPM and TAE activities, fast-ion losses are significantly increased. This observation is consistent with that observed with the existing scintillator-based lost fast-ion probe (SLIP). The effect of secondary electrons has been seen in the channels where fast ions do not strike. As a next step, the ion collectors will be positively biased so as to suppress emission of secondary electrons and make quantitative argument on beam ion losses possible.

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