Recent progress of fast-ion loss detector project in Asian fusion experiments

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Abstract: The A3 foresight program is accelerating close collaboration for fast-ion diagnostics development between Asian three countries. A recent big step in our activities is that the operation of fast-ion loss detector (FILD) on HL-2A has begun lately. The localized bright spot appeared on the scintillator screen while a high-energy neutral beam was tangentially co-injected. The design of FILD system on EAST is steadily ongoing. The diagnostics port available for our purpose was decided in March, 2013. For KSTAR, the FILD is working successfully. In order to understand observed beam-ion loss signals while the RMP coils are turned on, the LORBIT code has been improved recently to treat non-axisymmetric perturbed field due to RMP coils and discreteness of TF coils.

Keywords: Fast ions, NBI, scintillator, RMP, TF ripple

1. Introduction

Issues related to fast particles are of great concern in nuclear fusion research. For example, in ITER, D-T produced 3.5 MeV alpha particles are super-Alfvénic and can potentially destabilize fast-ion-driven MHD instabilities, e.g. fishbone mode and Alfvén eigenmode. As a result of excitation of those modes, the anomalous loss of alphas may occur, leading to a reduction of fusion power output and damage to the first wall. The A3 foresight program on critical physics issues specific to steady state sustainment of high-performance plasmas was lunched in 2012. For the reason mention above, a physics study on fast ions is one of main subjects in this program. Our immediate goal in the early stage of the A3 program is to set up scintillator-based fast-ion loss detectors onto four major fusion devices in Asia, i.e., KSTAR, EAST, HL-2A, and LHD. In the latter stage of this program, joint experiments will be proposed to reveal physics issues associated with fast ions in toroidal fusion plasmas. In this paper, recent progress on fast-ion detector project in Asia in the first half of 2013 is overviewed.

2. Scintillator-based fast-ion loss detectors in fusion

Scintillator-based fast-ion loss detectors (FILDs) have been widely employed to investigate orbit issues and/or anomalous loss of fast ions due to fast-ion-driven MHD instabilities in toroidal fusion plasmas, e.g. TFTR [1], JFT-2M [2], NSTX [3], JET [4], ASDEX-U [5], DIII-D [6], KSTAR [7], Alcator C-Mod [8], and HL-2A [9] in tokamaks, and CHS [10], W7-AS [11], LHD [12], and TJ-II [13] in helical/stellarator devices. The typical head section of FILD is schematically depicted in Fig. 1. The detector is classified into a magnetic spectrometer, providing gyroradius centroid and pitch angle of escaping fast ion simultaneously as a function of time. Further detailed information for FILD is available in Ref. 1-13.

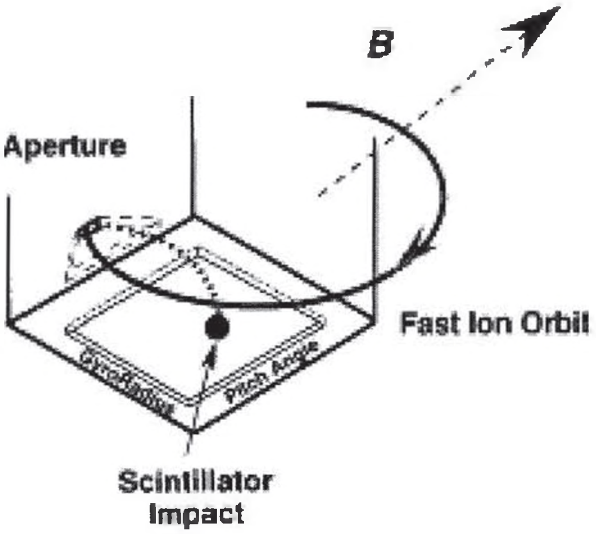

Fig. 1 Schematic drawing of the head section of FILD. [10]

3. Results from collaborative works

3.1. Progress of HL-2A FILD

Institute of Nuclear Science and Technology, Sichuan University, SWIP and NIFS have formed a trinity to design and develop the FILD for HL-2A. The detector was fabricated in Sichuan University and was installed onto HL-2A in March, 2013 [14]. The detector was designed so as to realize wide coverage in gyroradius centroid and pitch angle, detecting escaping fast ions having co-going transit and/or banana orbits. The ZnS:Ag (25 mm x 25 mm) was chosen as a phosphor because of high luminosity and fast decay time which is less than 10 μs. The detector is placed at the equatorial plane and is horizontally movable. The detector tip is typically ~3 cm away from LCFS.

Fast-ion loss signals were successfully obtained by the FILD in beam-heated discharges. Localized bright spot appeared on the scintillator screen when NB was tangentially co-injected. Fig. 2 shows time evolutions of scintillation light patterns on the screen. Main discharge parameters in this shot were as follows, i.e., B_t=1.3 T, I_p=160 kA, n_e=1.2x10^{19} m^{-3}, and P_{NBI}=0.8 MW. The frame rate of camera was set to be ~3 fps with exposure time of 1/30 s. As can be seen in Fig. 2, the localized scintillation light spot appears on the screen right after NB turn-on. The light spot becomes brighter during beam injection. After NB turn-off, the scintillation light disappears as expected. It can be therefore reasonably concluded that measured scintillation light spot is due to impact of escaping beam ions.

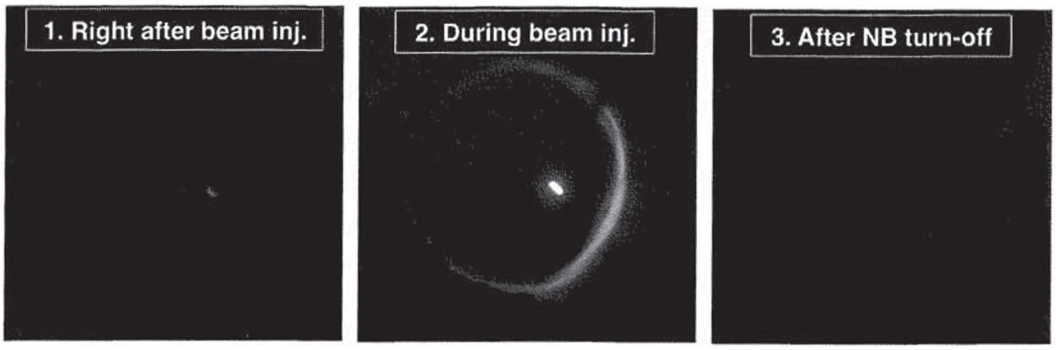

Fig. 2. Time evolutions of scintillation light distribution on the screen in a beam-heated discharge of HL-2A. B_t and I_p were 1.3 T and 160 kA, respectively.

Analysis considering the scintillator size and aperture structure indicated that the measured scintillation light spot center is consistent with the beam injection energy (E_b~40 keV). It also indicated that the measured pitch angle ranges from 65 degrees to 70 degrees. To understand orbit of escaping beam ions reaching the FILD of HL-2A, beam ions were launched from the FILD head position, i.e., (R, Z)=(2.13 m, 0 m) with energy/pitch angle of ~35 keV (D+)/68 degrees and calculated orbits backward in time by using the LORBIT code [15]. Fig. 3 shows a typical example of escaping fast-ion orbit reaching the FILD. Because B_t and I_p are relatively low in this particular shot, the orbit becomes fairly fat banana.

Measurement section of HL-2A FILD is going to be upgraded. In next campaign, PMT array (8x8) having fast-time response will be available. In HL-2A, fast-ion driven fishbone mode [16] and high-frequency mode, most likely toroidal-Alfvén eigenmode have been observed while NB is injected. Effect of those instabilities on fast-ion transport and/or loss is going to be investigated in next campaign.

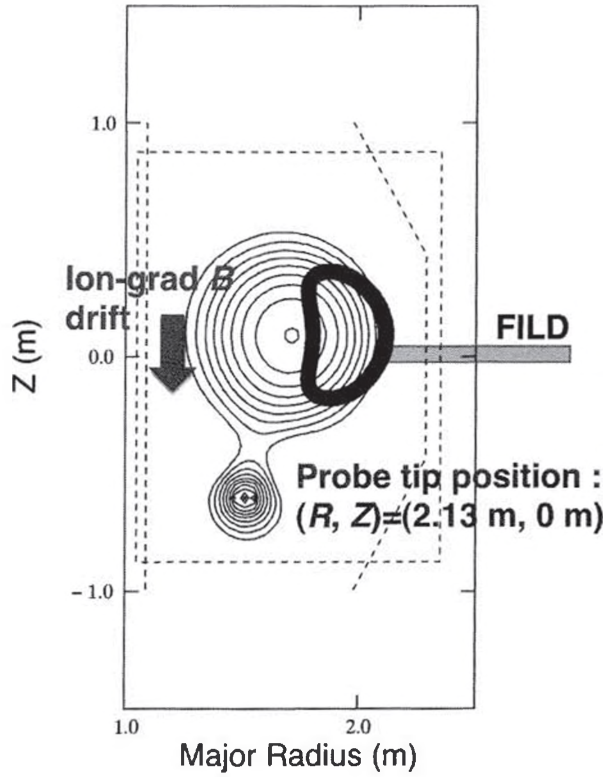

Fig. 3. Typical orbit of escaping beam ions reaching the FILD.

3.2. EAST

The design of FILD for EAST is steadily ongoing in the collaboration between ASIPP and NIFS. The diagnostics port available for our purpose was decided in March, 2013 with the help of the LORBIT code. The structure of the detector head section is being designed carefully by using the NLSDETSIM3 code to realize wide coverage in detectable energy and pitch angle. In EAST, the FILD will be installed on the upper half plane of the J port because ion-grad *B* drift direction is upward in the standard operation of EAST. The detector is designed to be horizontally movable. The diagnostics port for FILD and preliminary drawing of the FILD on EAST are shown in Fig. 4.

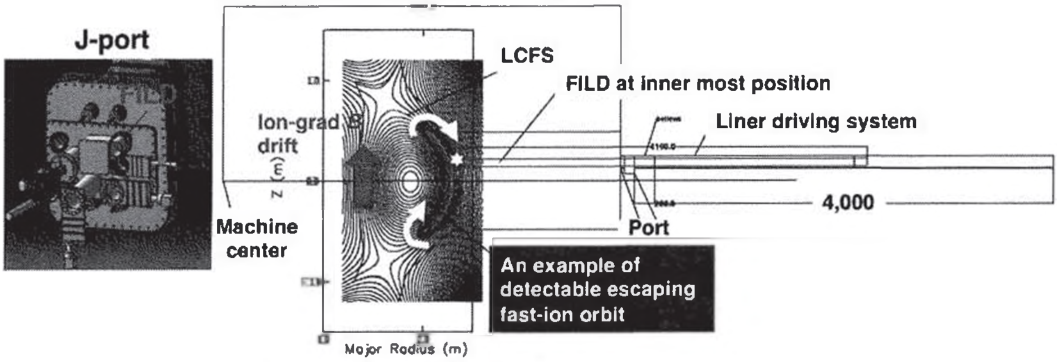

Fig. 4. External appearance of J-port of EAST (left figure) and preliminary design of bellows driving system for the probe shaft (right figure).

3.3. KSTAR

For KSTAR, the FILD is working successfully. LORBIT code of 2-D version has been used to check a class of escaping fast-ion orbit reaching FILD on KSTAR. In 2012 KSTAR campaign, effect of perturbed field produced by RMP coil on fast-ion loss detector signal was observed. In this case, existing 2-D LORBIT is no longer available for understanding of fast-ion transport caused by 3D effect. In order to understand observed beam-ion loss signals while the resonant magnetic perturbation (RMP) coils are turned on, the LORBIT code has been improved lately in the collaboration between NFRI and NIFS to treat non-axisymmetric perturbed field due to RMP coils. Toroidal field (TF) ripple caused by discreteness of TF coils can be also considered in the revised code. At first, we made a comparison of flux surfaces between contours of poloidal flux □□calculated by EFIT and field line reconstructed by □□without RMP field. Fig. 5 shows the comparison between the two. Black solid lines and red fine dots represent contours of □ and flux surfaces calculated by the field line, respectively. As can be seen, we got good agreement between the two. Next, we calculated magnetic flux surfaces for two patterns of RMP coil currents, i.e. n=1, +90 phase with 4 kAt and n=2, even parity with 4 kAt. Magnetic islands appear when RMP coils are turned on. In addition, magnetic flux surfaces become stochastic due to perturbed field due to RMP coil. Magnetic islands and stochasticity of field line can potentially cause a visible effect on fast-ion orbit and transport. Effect of non-axisymmetric RMP coil field on fast-ion behavior is being intensively carried out [17].

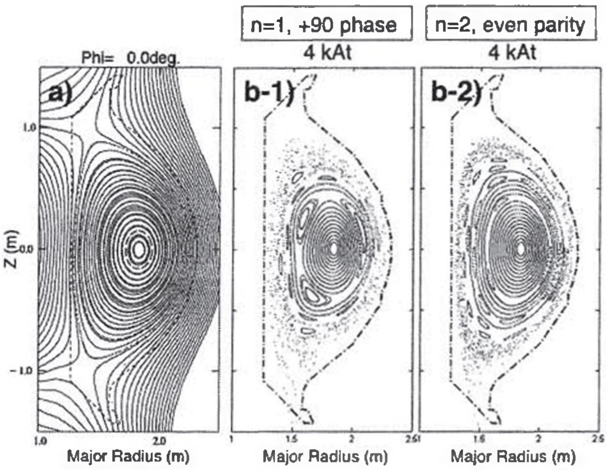

Fig. 5. a) Comparison of flux surfaces between contours of poloidal flux calculated by EFIT and field line reconstructed by without RMP field. b) Flux surfaces for two patterns of RMP coil currents, i.e. n=1, +90 phase with 4 kAt and n=2, even parity with 4 kAt.

4. Conclusion

Scintillator-based FILDs have been steadily enhanced in Asian fusion experiments to investigate physics associated with fast ions. A recent big step is that the operation of FILD on HL-2A has begun lately. The localized bright spot appeared on the screen while NB was tangentially co-injected. It disappeared after NB was turned off as expected. The analysis indicated that the measured energy of escaping beam ions matches the beam injection energy. The measured scintillation light in HL-2A is therefore due to impact of escaping beam ions. The design of FILD system on EAST is steadily ongoing. The diagnostics port available for our purpose was decided in March, 2013 with the help of the LORBIT code. The structure of the detector head section is being designed carefully to realize wide coverage in detectable energy and pitch angle. For KSTAR, the FILD is working successfully. In order to understand observed beam-ion loss signals while the RMP coils are turned on, the LORBIT code has been improved recently to treat non-axisymmetric perturbed field due to RMP coils. TF ripple caused by discreteness of TF coils can be also considered in the modified code. The preliminary orbit calculation suggested that the effect of non-axisymmetric RMP field on collisionless beam-ion orbit is visible.

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