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Scintillator-based fast ion loss measurements in the EAST

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A new scintillator-based fast ion loss detector (FILD) has been installed on Experimental Advanced Superconducting Tokamak (EAST) to investigate the fast ion loss behavior in high performance plasma with neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH). A two dimensional 40 mm × 40 mm scintillator-coated (ZnS:Ag) stainless plate is mounted in the front of the detector, capturing the escaping fast ions. Photons from the scintillator plate are imaged with a Phantom V2010 CCD camera. The lost fast ions can be measured with the pitch angle from 60° to 120° and the gyroradius from 10 mm to 180 mm. This paper will describe the details of FILD diagnostic on EAST and describe preliminary measurements during NBI and ICRH heating. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4962245]

I. INTRODUCTION

Fast ions generated by auxiliary heating systems such as neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH) can heat plasma and drive current. So, it is preferred to keep the fast ion in good confinement. It is the same for fusion born particles in the next-step devices. Well-confined particles are desirable for transferring energy to the fuel particles. However, fast ions can be redistributed and lost due to toroidal magnetic field ripples, induced by test blanket modules (TBMs), resonant magnetic perturbations (RMPs), etc., and by magnetohydrodynamic (MHD) fluctuations, as well as prompt losses. Significant losses of fast ions can reduce auxiliary heating efficiency and current drive.[1] Fast ion losses also lead to localized heat loads that could drastically damage plasma facing components. The fast ion loss detector (FILD) was first deployed on the TFTR tokamak[2] and now has been applied in several devices such as JET,[3] ASDEX-Upgrade,[4] LHD,[5] DIII-D,[6] KSTAR,[7] and HL-2A.[8] The Experimental Advanced Superconducting Tokamak (EAST) employs two beam lines of NBI systems.[9] Each beam line consists of two ion sources with beam energy in the range of 50-80 keV and total beam power up to 8 MW. The ICRF system was upgraded recently to a frequency range of 25-70 MHz with power up to 12 MW.[10] To investigate the fast ions loss behavior on EAST, a scintillator based FILD diagnostic was developed.

The paper is organized as follows. The detailed description of the recently developed FILD system is presented in Sec. II. Initial results for EAST NBI and ICRH heated plasmas are described in Sec. III. Future improvements of the FILD diagnostic are presented in Sec. IV. The summary is given in Sec. V.

II. DESCRIPTION OF FILD DIAGNOSTIC

The FILD diagnostic is composed of a detector head, a long shaft for moving the detector, vacuum systems, and the data acquisition system. Figure 1 shows the long shaft with supporting and driving systems. To replace the scintillator in the detector head without venting the vacuum vessel, there is a vacuum isolation valve between the port flange and an exchange box followed by the shaft chamber. The detector head attached at the end of the movable shaft can travel a long distance (>2 m) from the exchange box to the plasma boundary. Spindle axes and assorted servo motors from Festo, Inc. are used to move the shaft and detector head into the vacuum vessel. A similar driving system is also used in the fast reciprocating probe system (FRPS) on EAST.[11] So the detector head can move like fast reciprocating probe during long pulse discharges to protect it from over heating. The differential pumping rotation platform allows the shaft to be rotated by a servo motor to align the detector aperture with the magnetic field. It is suitable for the case of reversal of the toroidal magnetic field in EAST. The vacuum leakage rate of this system meets the requirements of EAST. The layout of auxiliary heating systems is shown in Figure 2. The FILD system was installed just above the midplane at the J-Port location.

The 3D model of detector head is shown in Figure 3. The main parts of detector head are the ion collimator (the front aperture and the rear aperture shown in Figure 3) and the scintillator screening, sealed in a light-tight stainless steel (SS) box. The key parameters of FILD are determined by the geometric designs of detector head: the diameter of the front aperture, the dimension of scintillator screen, and the

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[b)]See Appendix of B. N. Wan *et al.*, Nucl. Fusion **55**, 104015 (2015).

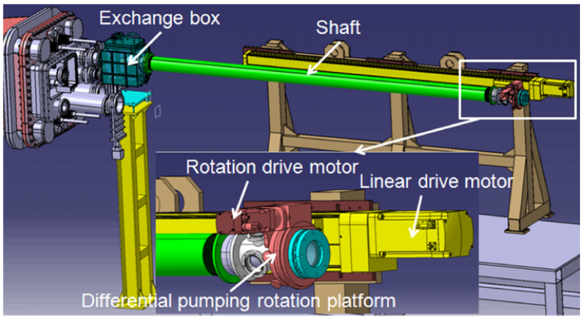

FIG. 1. Drawing of the FILD system installed on EAST shows the exchange box, shaft, driving system, and supporting system.

distance between the aperture and the scintillator. Blackening treatment of the detector head has been done to alleviate light reflected from the SS box inner surface. The (SS) box allows a 50 mm × 50 mm scintillator screen at maximum in it, but at present, the size of scintillator screen is 40 mm × 40 mm. The detector can capture the fast ions with pitch angles between 60° and 120° and gyro-radii from 10 mm to 180 mm, as shown in Figure 4. The aperture is located at the center of collimator, so the current detector head can measure both co- and counter-rotation fast ion loss simultaneously. The ZnS:Ag scintillator phosphor (decay time: 70 ns, emission peak: 450 nm) was deposited just behind a 1 mm thick SS plate which can prevent the x-ray radiation from the plasma.

The main function of this system is to collect light emitted from scintillator screen by impinging collimated fast ions. To improve the light collection efficiency, a relay optics system (ROS) is adopted. The ROS is composed of seven lens groups including three field lens groups. The equivalent focal length of the ROS is 358.4 mm, the object space NA is 0.035, the maximum field of view at object distance is 52 mm × 52 mm, and the distance between the scintillator screen and first lens of the ROS is 680 mm. Altogether, the ROS has a geometric length over 4 m. The ROS collected light from the scintillator is divided into two parts by an optical splitter with one part transferred to a fast CCD camera and another part focused on a fiber bundle just in front of photomultiplier tube (PMT). The CCD is a fast C-MOS type Phantom V2010-96GB camera

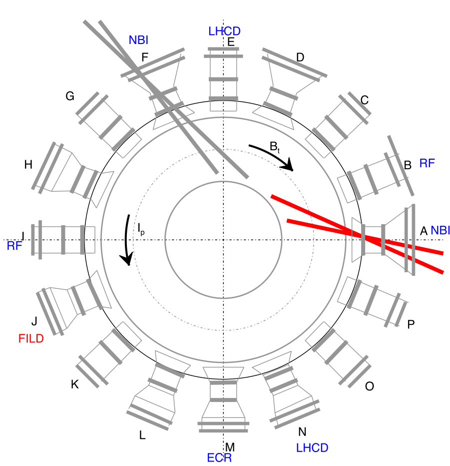

FIG. 2. Distribution of the auxiliary heating systems and location of FILD (top view).

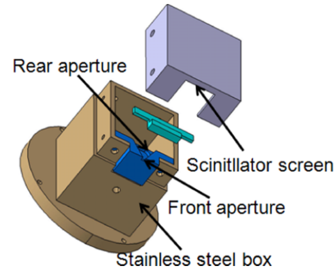

FIG. 3. 3D model of detector head. The detector head is composed of ion collimator, scintillator screen, and light-tight stainless box.

(1280 × 800 pixels) from Vision Research, Inc. The focal length of the lens placed between the optical splitter and camera is 144 mm, the image space NA is 0.0826, and the image space is 22.4 mm × 22.4 mm.

III. PRELIMINARY RESULTS

During the 2015 campaign, both co- and counter-NBI systems (NBI1 and NBI2 at ports A and E in Figure 2) were employed. Figure 4 shows a scintillator image captured by CCD camera during a NBI shot, which revealed the ions loss during a major disruption. The temporal evolution of the main parameters in the discharge is also displayed in Figure 4. Usually the plasma became unstable and the internal energy/neutron yield decreased when counter-NBI (NBI2R (L for left source, R for right source; NBI1R and NBI2L are tangential beam lines)) was injected. When the plasma is unstable, especially during a major disruption like in Figure 4, the scintillator twinkle significantly increases and bright spots caused by counter-rotating fast ions were also detected. There are four bright spots in Figure 4, caused by four NBI beams (shown in Figure 2), respectively. The fast

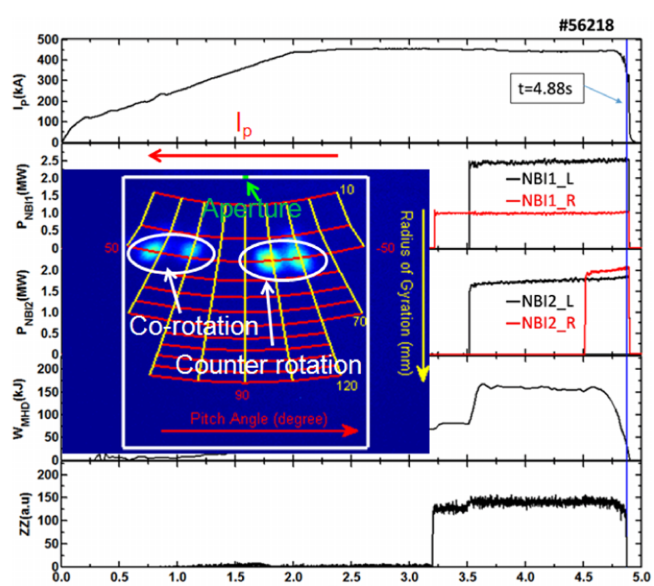

FIG. 4. Co- and counter-rotation NBI fast ion losses during the disruption ($I_P = 450$ kA, $I_T = -10\,000$ A, $P_{NBI1L} = 2.5$ MW, $E_{NBI1L} = 60$ keV, $P_{NBI1R} = 1.0$ MW, $E_{NBI1R} = 45$ keV, $P_{NBI2L} = 1.7$ MW, $E_{NBI2L} = 55$ keV, $P_{NBI2R} = 2.0$ MW, $E_{NBI2R} = 60$ keV).

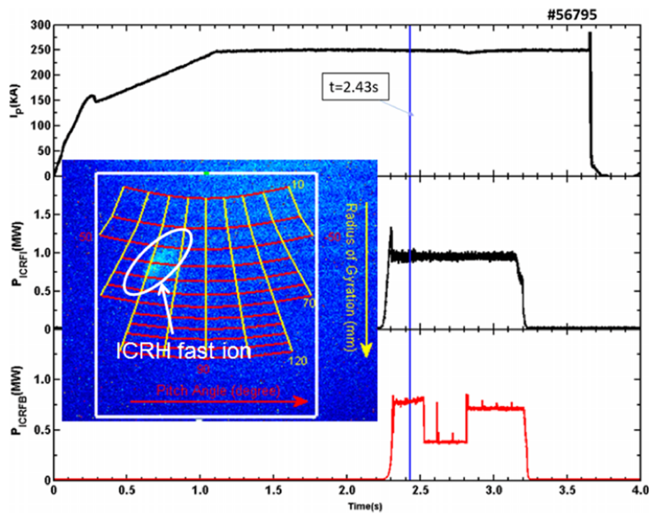

FIG. 5. Fast ion losses of ICRH ($I_P = 250$ kA, $I_T = -7500$ A).

ions losses from the tangential beams of both the NBI1 and NBI2 beam lines have smaller pitch angles and are the two bright spots near the center shown in Figure 4.

Figure 5 shows the fast ion loss during an ICRH heated discharge with H/D ratio less than 3%. In Figure 5, co-rotation ICRH fast ion loss is very obvious, and counter-rotating fast ion loss was also detected. These FILD data show the most direct evidence of fast ions produced by ICRH minority ion heating on EAST.

IV. IMPROVEMENT OF THE FILD DIAGNOSTIC

Besides the CCD camera, a 25-channel (5×5) PMT (Hamamatsu Photonics, H10492-003) array with 2 MHz sampling rate per channel data for measuring fast MHD phenomena is planned to be utilized for better temporal resolution. Light from the optical splitter will sent to the PMTs by an optical fiber bundle.

Some modifications will be made to the detector head design to alleviate the melt caused by plasma sputtering. A melted corner of the detector head is shown in Figure 6. As shown on the right, the aperture is on top when the direction of toroidal magnetic field is clockwise (view from top). As the FILD system is installed above the midplane, the lower edge of the detector head is closer to plasma and displays bear more severe sputtering. In addition to mechanical modifications, it is also planned to retract the head when the FILD diagnostic is not actively required, like FRPS on EAST,[11] to avoid excessive heat loading during long-pulse discharges.

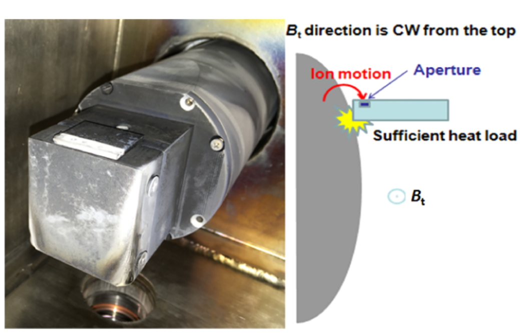

FIG. 6. Melted corner of detector head closet to the plasma in the exchange box.

V. SUMMARY

A new scintillator-based fast ion loss detector (FILD) has been installed on EAST for measuring the loss of NBI and ICRH produced fast ions. The detector head can be replaced in an exchange box and reinserted into the EAST vacuum vessel without breaking vessel vacuum, and the aperture can be aligned with the magnetic field by the differential pumping rotation platform. FILD has successfully imaged fast ion loss in NBI and ICRH discharges in EAST utilizing a CCD camera. It can be measured with a pitch angle from 60° to 120° and a gyroradius from 10 mm to 180 mm. In the upcoming campaign, the FILD system will be upgraded with a PMT detector and faster data acquisition system for better temporal resolution. In addition, some mechanical modifications will be done to the detector head and shaft structure to alleviate plasma induced sputtering.

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