Cover page

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Recent Advances of Scintillator-based Escaping Fast Ion Diagnostics in Toroidal Fusion Plasmas in Japan, Korea, and China

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Abstract The scintillator-based fast-ion loss detector (FILD) project in Japan, Korea, and China has been accelerated in an international collaboration framework to enhance comprehensive understanding fast-ion behaviors in toroidal fusion plasmas. The FILDs in LHD heliotron, KSTAR, HL-2A, and EAST tokamaks are successfully working as a result of joint work. Physics experiments on fast ions, such as effects of Alfvénic mode, tearing mode, resonant magnetic perturbation field, and disruption on fast-ion behaviors are ongoing. This paper describes the FILD developed for each device and those effects on fast ions in LHD, KSTAR, HL-2A, and EAST.

Keywords: fast ion, scintillator, fast-ion loss detector, NBI, fast-ion-driven MHD instability

1. Introduction

Good confinement of fast ions in fusion plasmas is crucial to the success of the fusion reactor since fusion-born α particles play an essential role in steady state sustainment of a future burning plasma as a primary heating source. Although unfavorable effects on fast-ion orbit caused by axisymmetry breaking of the system is one of the oldest issues in fusion, attention is now being focused on it again because the non-axisymmetric three-dimensional (3-D) perturbed field produced by resonant magnetic perturbation (RMP) is often superposed to mitigate edge localized mode (ELM) in recent experiments. Fast-ion-driven magnetohydrodynamics (MHD) instabilities such as toroidal-Alfvén eigenmode (TAE) [1] and energetic-particle continuum mode (EPM) [2] are also of great concern since those instabilities can potentially lead to redistribution and/or loss of fast ion. For the reasons above mentioned, tight collaboration on fast-ion physics in fusion were initiated in 2012 in three Asian countries of Japan, Korea, and China in the support of the A3 foresight program on critical physics issues specific to steady state sustainment of high-performance plasmas [3]. A primary purpose of our joint work is to obtain comprehensive understanding of fast-ion transport and/or loss caused by 3-D field and/or fast-ion-driven MHD instabilities in toroidal fusion plasmas. Our immediate goal in the early stage of this program is to set up scintillator-based fast-ion loss detectors (FILDs) onto four major fusion devices in East Asia, i.e., the LHD heliotron [4,5], the KSTAR [6], the HL-2A [7], and the EAST [8] tokamaks. The FILD is a type of magnetic spectrometer for charged particles, providing energy and pitch-angle (velocity component) of escaping fast ions as a function of time simultaneously. Note that the FILD was developed originally at the Princeton Plasma Physics Laboratory for escaping charged fusion products in the TFTR tokamak [8-11]. After the shutdown of TFTR, the technology of FILD was transferred to CHS at the National Institute for Fusion Science (NIFS) for escaping beam-ion diagnostics [12,13]. At present, the FILD has become a fundamental diagnostic tool for escaping fast-ion diagnostics and has been widely used in many magnetic confinement fusion devices [14-19].

As a result of intensive joint collaboration in the framework of the A3 foresight program, installation of the FILD onto four major devices in East Asia was completed in 2014. In LHD, TAE and/or EPM-induced fast-ion losses have been intensively studied by using the FILD [20-22]. Effects of resonant magnetic perturbation (RMP) field on fast-ion behavior have been also investigated [23]. The KSTAR FILD is successfully working. A study on behavior of fast ions due to RMP field is in the center of attention in KSTAR [24, 25]. In HL-2A, fast-ion losses induced by tearing modes, long-lived modes, sawtooth crash, and disruption have been observed [26]. A recent important step in our work is that the operation of the FILD on EAST has begun. The localized bright spot appears on the screen while neutral beam (NB) is tangentially injected and disappears after NB is turned off as expected. In this paper, current status on the FILD projects in Japan, Korea and China, and representative results obtained from ongoing activities are shown.

2. Experimental setup and representative results

2.1 FILD on LHD

The LHD FILD project was initiated in 2001 after the successful operation of the FILD in CHS [27]. As a result of continuous efforts to improve the detector performance, the LHD FILD has reached the existing system schematically depicted in Fig. 1. Because significant radial transport of co-going transit beam ions due to TAE bursts was recognized by a charge-exchange neutral particle analyzer having a tangential line of sight [28], the FILD was designed to detect escaping co-circulating transit beam ions whose trajectories deviate substantially from magnetic flux surfaces. The scintillation light image on the ZnS(Ag) screen due to impact of escaping beam ions is transferred by using a long image bundle fiber of 35 m and is focused on to the image intensifier connected to the CMOS camera placed in the basement. This design issued from a great concern about irradiation effects of neutron and γ-ray onto highly integrated electronics of the FILD in a deuterium discharge planned in LHD. Because the CMOS camera employed in LHD is not fast enough to follow rapid events such as beam ion transport due to TAE bursts, fast-photomultiplier tube (PMT) array consisting of 16 tubes is employed at the same time.

The LHD is equipped with intense NB injection heating system, i.e., three negative-ion source based NB injectors, here called N-NBIs, with E_b/P_{NB}=180 keV/~5 MW for each in the tangential direction and two positive-ion source based NB injectors with E_b/P_{NB}=40 keV/~6 MW for each in the perpendicular direction. In addition to high NB heating power, beam ions provided by N-NBIs can be super Alfvénic if the toroidal magnetic field strength is lower than 1 T. For this reason, fast-ion-driven MHD instabilities have been often observed while high-energy tangential NBs are injected into low-B_t (< ~1 T) plasmas [29].

Figure 2 shows typical time evolutions of the FILD signals in the N-NB heated discharge of LHD in B_t of 0.9 T. Recurrent magnetic fluctuation bursts of which frequency ranges from ~20 kHz to ~35 kHz are observed. Because beam ions are super Alfvénic and the mode frequency is in the TAE gap on the shear Alfvén continua, the observed mode is recognized as TAEs. Correlated with the TAE bursts, periodic increases of fast-ion loss flux reaching the FILD are recognized. The FILD indicated that energy and pitch-angle of escaping beam ions are 100~180 keV and 30~40 degrees, respectively. It is interesting to note that two bright spots appear on the scintillator screen while TAEs are destabilized whereas a single weal spot is seen while TAEs are not present. The observation tells us that TAEs induced beam ions having particular pitch-angles.

2.2 FILD on the KSTAR

Experimental studies on the energetic-particle physics of KSTAR plasmas have been conducted since the 2011 campaign by starting development of the FILD. The KSTAR FILD [6] is based on the TG-Green ($SrGa_2S_4:Eu^{2+}$) scintillator plate exhibiting the energy and the pitch-angle of the escaping fast ions. The FILD-1 head which is controlled by the linear manipulator system (Fig. 3 (a)) has the shaped front surface of the graphite protector in order to avoid the excessive heat load that can cause unexpected emission from the scintillator due to thermal stimulation. In particular, scintillator material was coated on the thick stainless steel plate to block the hard X-ray whose energy is below 1 MeV. The FILD-2 system depicted in Fig. 3(b) is located at a different toroidal location (I-port) which is equipped 135°apart from the FILD-1 position (C-port). Since availability of the port at the I-port is very poor, flexible in-vessel wound fiber guide (made by Schott) has been inserted into the special housing. Imaging test with the in-vessel halogen lamp (Fig. 3(b)) shows the clear picture of the scintillator plate through the narrow viewport. All the optical systems are made of the commercial lens sets to expedite development except the optical-fiber components to be connected to the PMT array (FILD-1) and the APDCAM (FILD-2). The focus of all the channels connected to the PMT array via a 16 channel fiber bundle are checked by means of backward lighting from the end of the fiber bundle to the scintillator plate inside the FILD head (Fig. 3(a)). It has been found that the period of the optical alignment to guarantee the clear focus on the PMT array can be longer than one week during the experimental campaign. This means that the optical systems of the KSTAR FILDs are more or less free from vibration or displacement of tokamak body.

The KSTAR FILD system has shown various physical phenomena such as fast-ion loss behaviors related to the edge magnetic perturbations [24, 25, 30], tearing modes (TMs) [25], and others. In particular, RMP intending ELM mitigation and/or suppression could change local fast-ion loss intensity significantly [30]. Figure 4 shows the example of the fast-ion loss intensity changes depending on the directions of the radial magnetic perturbations (B_r). B_t and I_p are 1.8 T and 0.5 MA, respectively in the two discharges. Outward B_r at the FILD head location increases the fast-ion loss signal, however, inward B_r decreases fast-ion loss signal intensity significantly. By changing the "phasing" of the RMP coil current polarity with the fixed helicity (e.g. n=1 or 2), toroidal localization of the fast-ion loss depending on the RMP helicity have been identified [24, 25]. Further analyses based on full 3-D orbit simulations with Lorentz-Orbit (LORBIT) code [31] have been performed to confirm the toroidal variation of the loss patterns. As described in Fig. 4, LORBIT simulations show the outward B_r makes clear intersections between the fast-ion orbits (blue dots) and the FILD-head, and vice versa.

Moreover, fast-ion orbits become stochastic at the edge region as shown in Fig. 4. Flexibility of RMP configuration on KSTAR and diagnostic capability of KSTAR enable extending the physics studies on the interactions between the fast-ion orbits and the RMP-stimulated edge stochasticity as well as radial perturbations. Besides the RMP-associated fast-ion loss, fast-ion loss correlated with the core MHD instability such as TM is observed on the spectrogram of the PMT signal sensitive to the low pitch-angle side implying the resonant interaction with the core magnetic perturbations (Fig. 5) [25].

2.3 FILD on the HL-2A

A new scintillator-based FILD has been developed and operated in the HL-2A tokamak to measure the losses of beam ions, as shown in Fig. 6. The FILD can travel across an equatorial plane port and the aperture angle can be varied rotationally with respect to the axis of the probe shaft by two-step motors in order to optimize the radial position and the collimator angle. The light pattern on the scintillator screen is measured with a PMT array and a high-speed camera. The PMT array measures the total loss rate of beam ions with a high-time resolution up to 1 MHz. On the other hand, the camera provides fast-ion-loss pattern on the screen with a high energy and pitch-angle resolution although the flame rate is much slower than the frequency response of the PMT array.

Characteristics of fast-ion losses caused by various MHD instabilities, such as tearing mode, long-lived mode (LLM), sawtooth crash, and disruption, have been studied experimentally in the HL-2A tokamak. Figure 7 shows the time behavior of two-dimensional images of scintillation light pattern due to impact of escaping fast ion caused by the TM. From Fig. 7 (t_2) and (t_3), it can be recognized that another bright light spot appears on the scintillator screen during the TM. Along with the disappearance of the TM, the spot becomes week and then vanishes, as seen in the image of t4. Therefore, it is reasonably mentioned that the second light spot is associated with the TM, in other words, the fast-ion loss event is induced by the TM. Also, it should be noted the light spot becomes brighter as the TM amplitude becomes higher, suggesting increase of fast-ion losses increase with increase of TM amplitude. The energy and pitch-angle of the escaping beam ions caused by the TM are identified to be 30 keV and 60 degrees, respectively. It is interesting to note that fast-ion losses caused by sawtooth crash are broad in energy and pitch-angle ranges compared with the TM and the LLM. This observation tells us some interaction between fast ions and magnetic disturbance, which cause the losses with the wide range of energy and pitch-angle. During disruptions, the total neutron emission rate largely drops by ~90 %, suggesting the significant loss of fast ions due to the strong magnetic perturbations. Concerning about this phenomenon, the FILD of HL-2A shows the clear experimental evidence of drastic losses of fast ions during disruptions.

2.4 FILD on the EAST

The FILD in EAST is the newest in our activities. The EAST FILD project was initiated in 2011 in the collaboration between NIFS and the Institute of Plasma Physics, Chinese Academy of Science. In 2012, the FILD position suitable for escaping beam-ion detection was carefully investigated for EAST by using the LORBIT code [31]. Subsequently, the detailed design of the probe head section was carried out. As a result of efforts mentioned above, the specific FILD design was performed in

2013 and then the FILD was installed onto EAST in 2014.

A photograph of the FILD on EAST is shown in Fig. 8. The FILD is placed ~15 cm above from the equatorial plane of the tokamak. It can be inserted almost vertically into the vacuum chamber. It is also designed so as to rotate the probe head section. In EAST, the ZnS(Ag) scintillation phosphor was chosen. The EAST FILD is now equipped with only a fast camera. To follow rapid events such as beam-ion loss due to TAE and/or EPM, the measurement section has been upgraded lately by using PMT array consisting of 25 channels. In EAST, the tangential NB injection heating began in 2014. Localized bright spot on the scintillator screen due to impact of escaping beam ions appeared while NB was injected as shown in Fig. 9. The measured pitch-angle of escaping fast ions ranges from 110 degrees to 125 degrees. The FILD indicates that energy of measured escaping beam ion matches that of beam injection energy (E_b~40 keV). Bright spot appears when NB is turned on and disappears when NB is turned off. Also, measured pitch-angle is reasonable in terms of orbit topology of beam ions in EAST. Therefore, it can be reasonably concluded that measured bright spot is due to impact of escaping beam ions having a prompt loss orbit.

3. Summary

Close collaborative works for fast-ion diagnostics development in Japan, Korea, and China have been carried out. The FILDs have been setup onto LHD, KSTAR, HL-2A, and EAST as a result of joint work. Our efforts have been made to reveal 3-D magnetic field effects on confinement property of fast ions and fast-ion losses caused by MHD instabilities resonant and non-resonant with fast ions. The FILDs developed in this project are successfully working in each machine. In LHD, the TAE has been often destabilized by super-Alfvénic beam ions, expelling beam ions in particular range of pitch-angles. In KSTAR, it has been identified that toroidal localization of the fast-ion loss depends on the RMP helicity. In HL-2A, fast-ion losses associated with various MHD instabilities, such as tearing mode, long-lived mode, sawtooth crash, and disruption, have been characterized. As for EAST, the fast-ion losses have been recognized by using the FILD and have been identified as a prompt loss of beam ions. As a next step, joint experiments will be conducted to reveal common physics issues related to fast ions in tokamak and stellarator.

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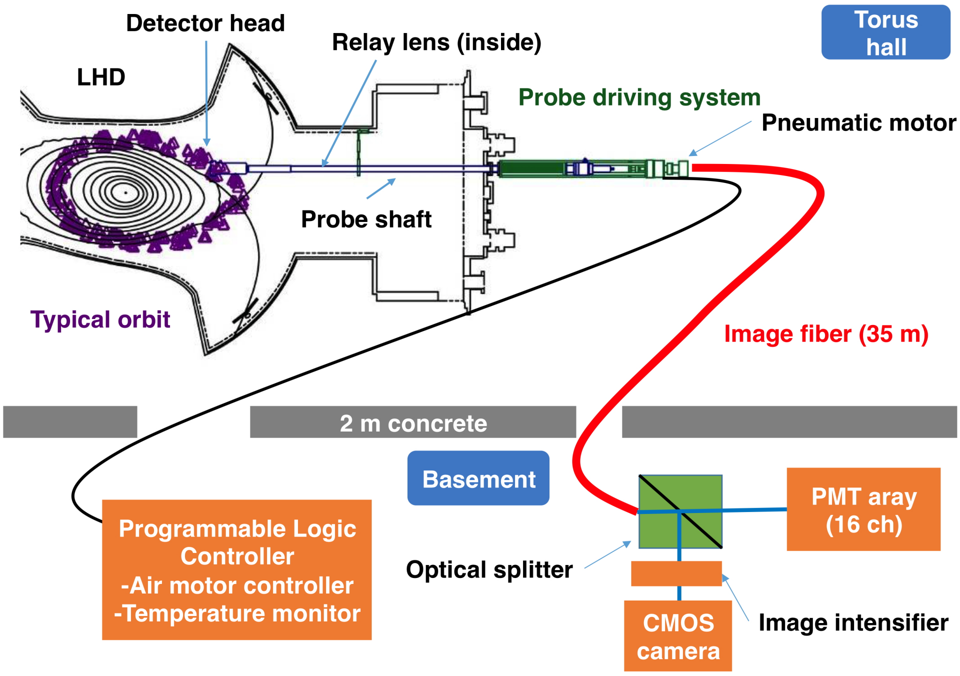

Figure 1 : Schematic drawing of scintillator-based FILD system on the LHD heliotron. The FILD can be remotely controlled from the LHD control room.

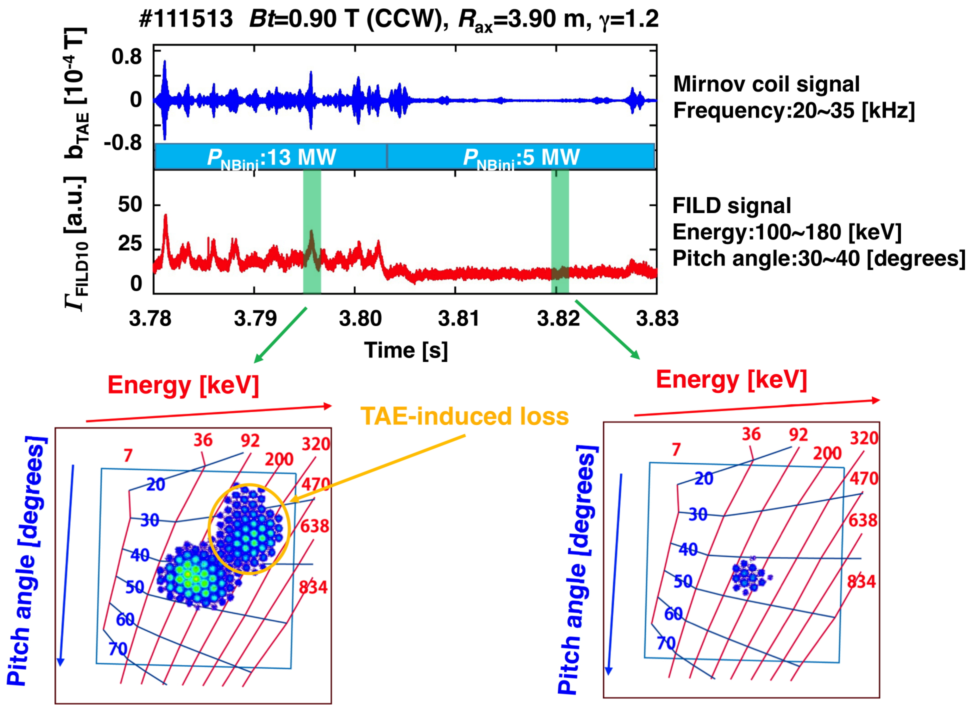

Figure 2 : Typical time evolutions of magnetic fluctuation and escaping beam ion flux measured with the PMT in a TAE discharge of LHD. Energy and pitch-angle of escaping beam ions measured with the FILD are also shown.

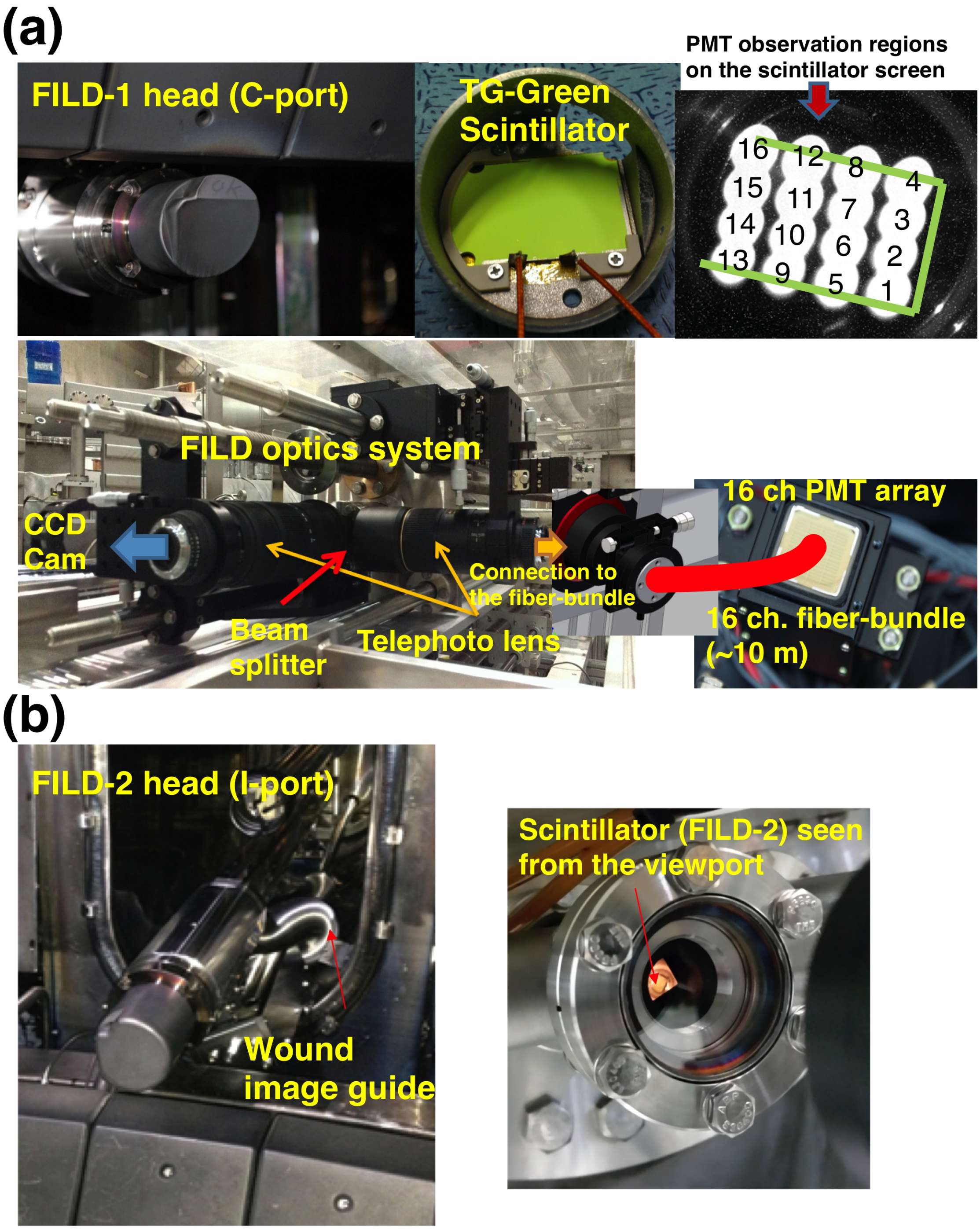

Figure 3 : Scintillator-based FILD systems are installed on KSTAR tokamak. (a) FILD-1 system controlled by the manipulator at C-port consists of the CCD camera part and the fast-measurement system (PMT array). A 16-channel multi-anode PMT (Hamamatsu Photonics K.K., model : H8711) is employed. (b) FILD-2 system at I-port will be used for the study on fast-ion loss interplaying with non-axisymmetric fields.

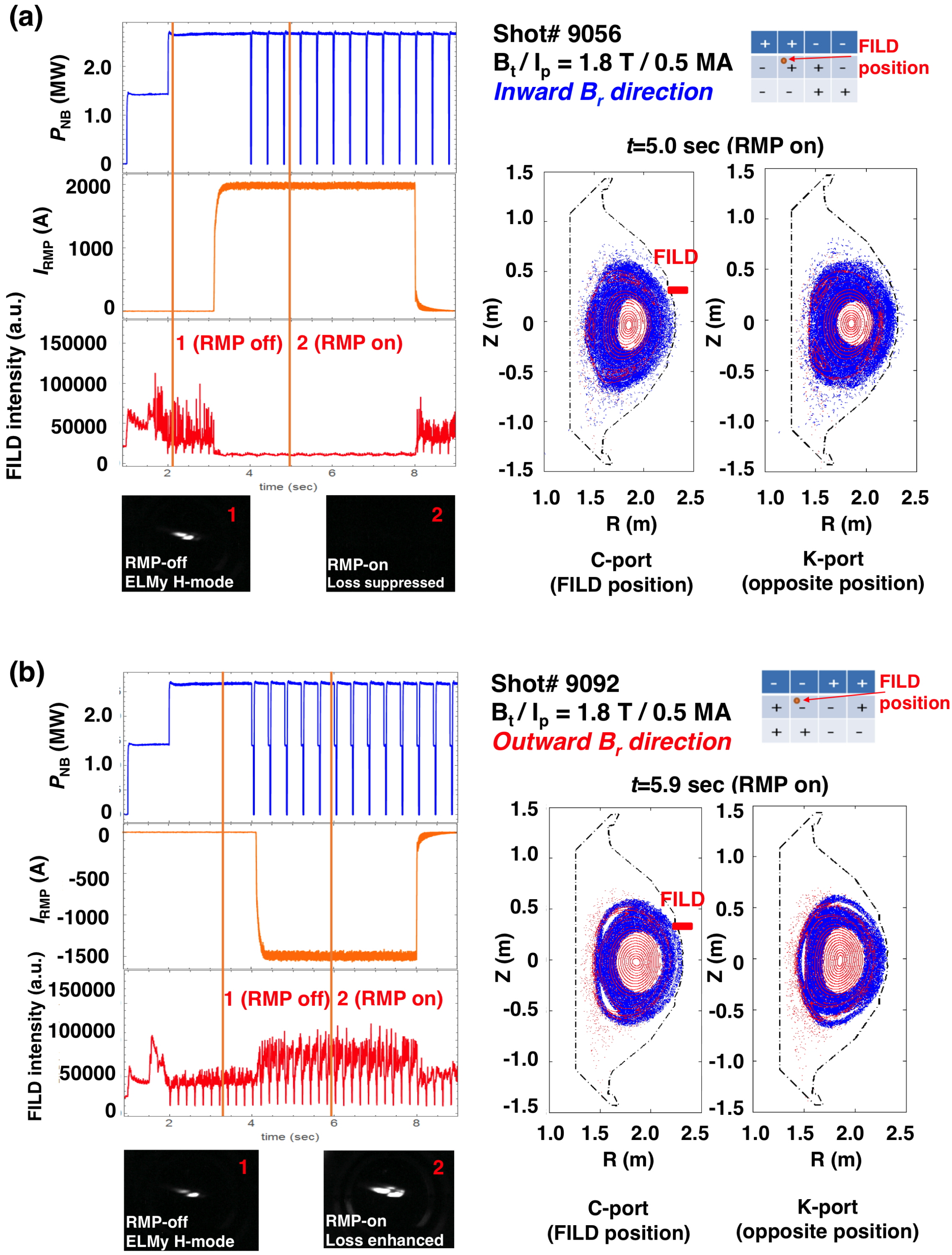

Figure 4 : (a) Fast-ion loss behaviors associated with the inward magnetic perturbation direction are captured on the FILD CCD images in the KSTAR tokamak. LORBIT simulations confirm toroidal localization of the fast-ion losses. (b) Fast-ion loss behaviors associated with the outward magnetic perturbation direction are captured on the FILD CCD images. LORBIT simulations confirm toroidal localization of the fast-ion losses.

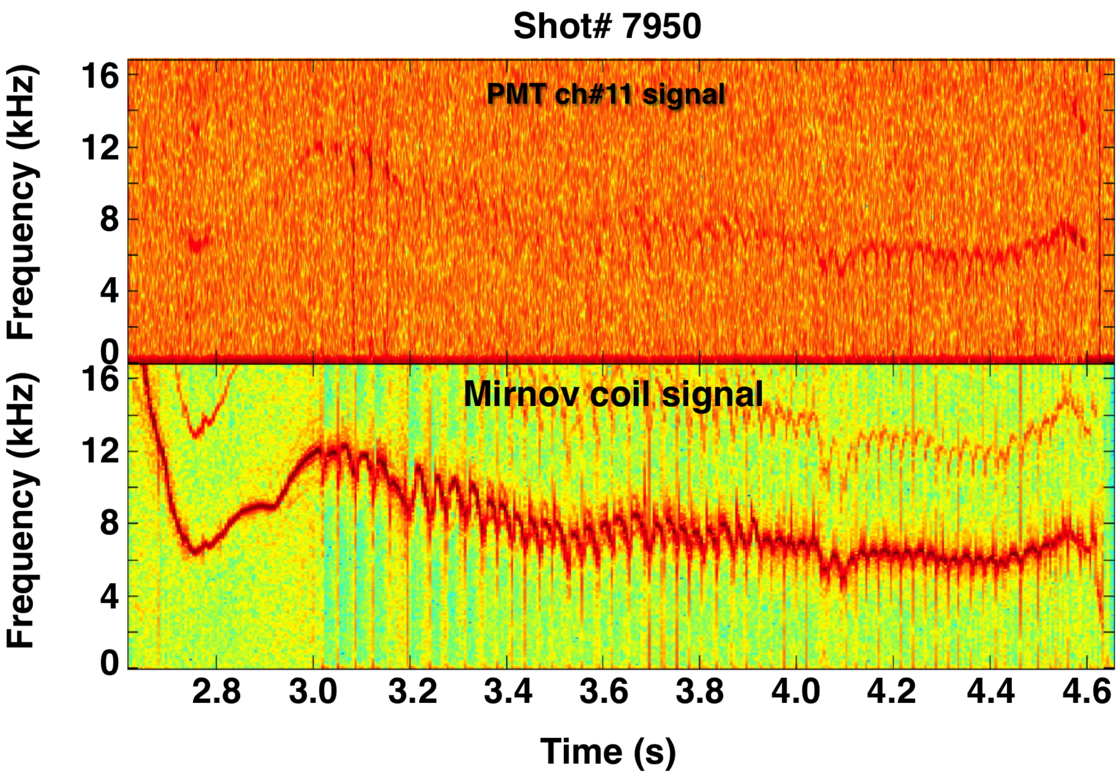

Figure 5 : Spectrogram of PMT#11 signal shows clear correlation with the tearing mode in the KSTAR tokamak.

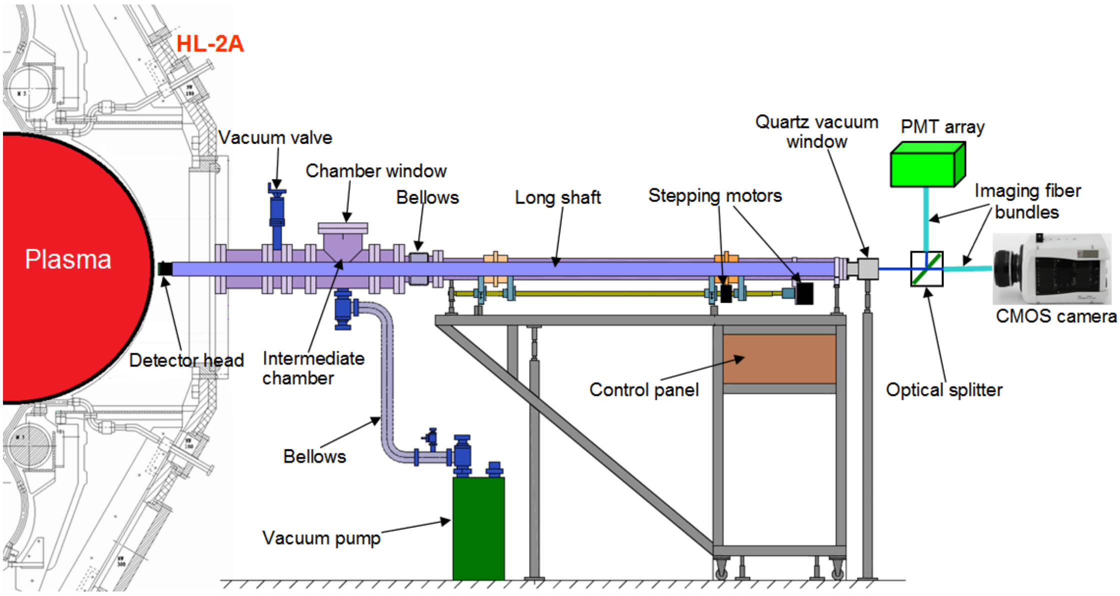

Figure 6 : Schematic overview of the FILD in the HL-2A tokamak.

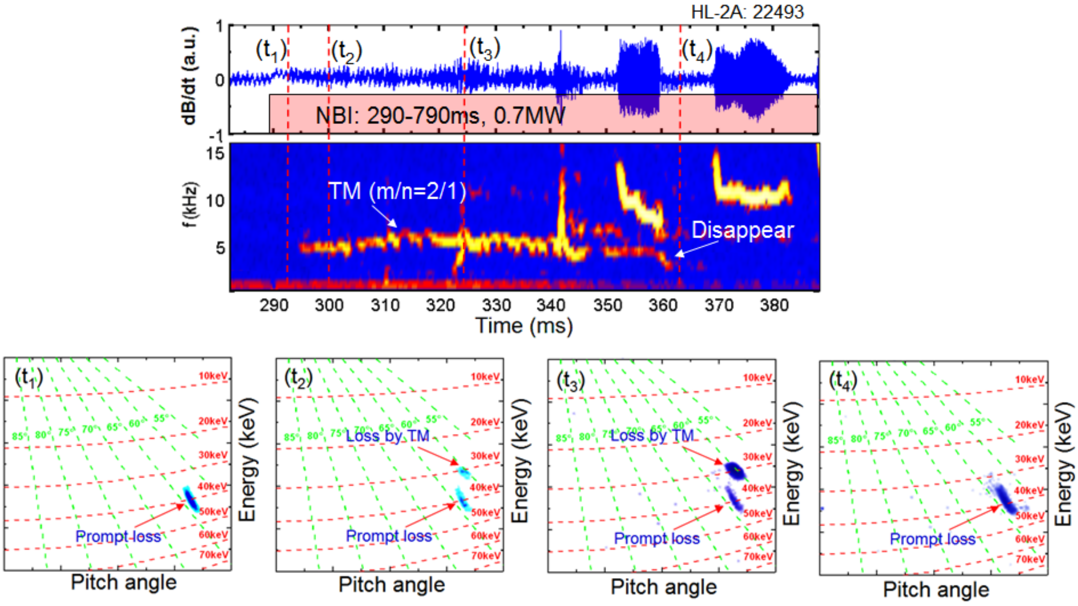

Figure 7 : Typical fast-ion losses induced by tearing mode in the HL-2A tokamak.

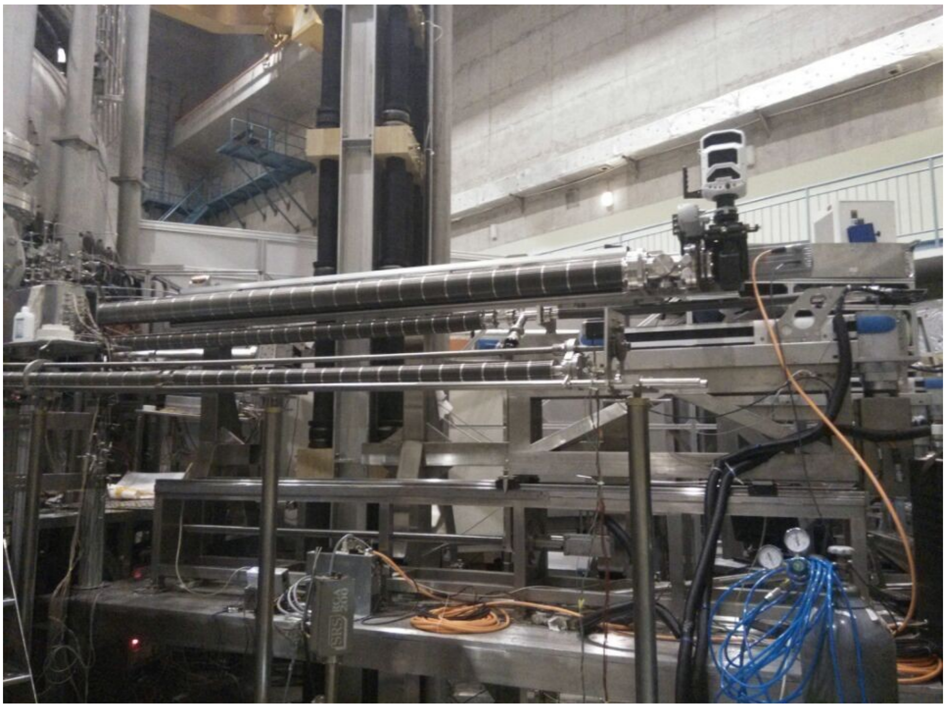

Figure 8 : External appearance of FILD on the EAST tokamak.

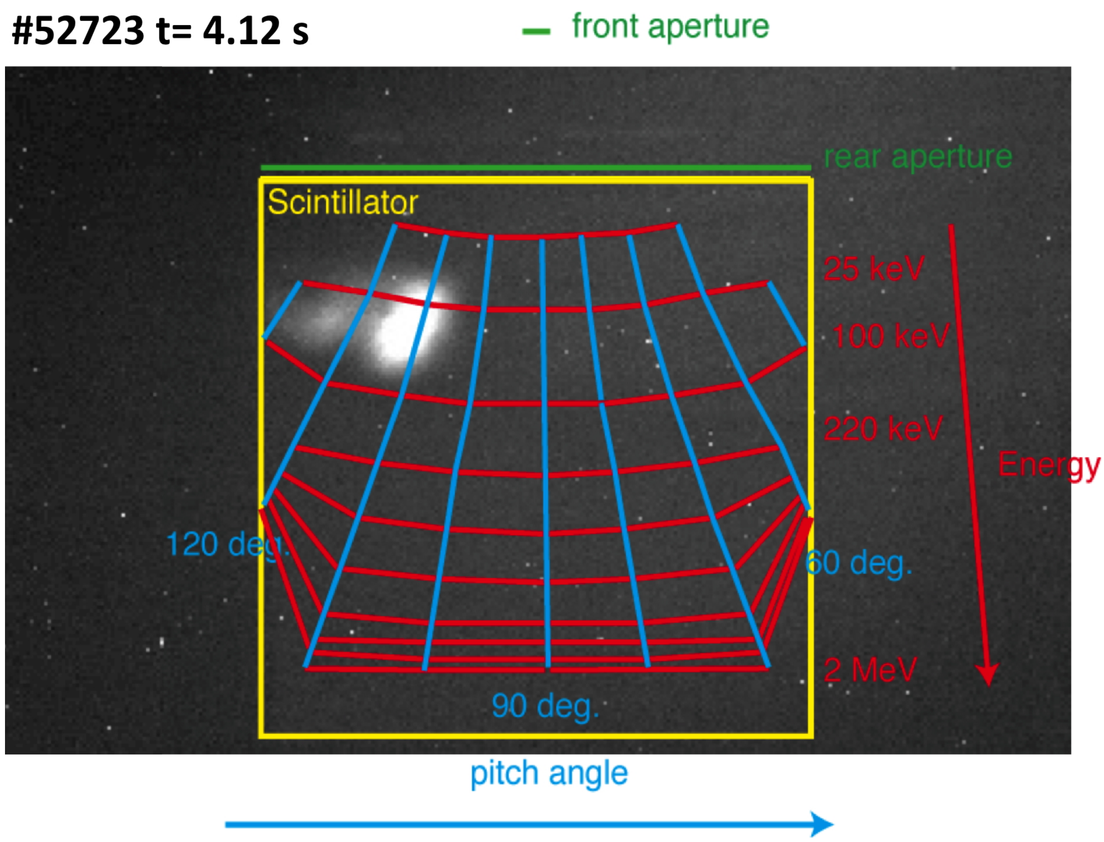

Figure 9 : Localized bright spot on the scintillator screen due to impact of escaping beam ions in the EAST tokamak. B_t and I_p are 1.8 T and 400 kA, respectively. The direction of toroidal magnetic field is directed to be clockwise as seen from the top whereas I_p is in the counterclockwise direction.