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ABSTRACT

A poloidal array of scintillator-based Fast-Ion Loss Detectors (FILDs) has been installed in the ASDEX Upgrade (AUG) tokamak. While all AUG FILD systems are mounted on reciprocating arms driven externally by servomotors, the reciprocating system of the FILD probe located just below the midplane is based on a magnetic coil that is energized in real-time by the AUG discharge control system. This novel reciprocating system allows, for the first time, real-time control of the FILD position including infrared measurements of its probe head temperature to avoid overheating. This considerably expands the diagnostic operational window, enabling unprecedented radial measurements of fast-ion losses. Fast collimator-slit sweeping (up to 0.2 mm/ms) is used to obtain radially resolved velocity-space measurements along 8 cm within the scrape-off layer. This provides a direct evaluation of the neutral beam deposition profiles via first-orbit losses. Moreover, the light-ion beam probe (LIBP) technique is used to infer radial profiles of fast-ion orbit deflection. This radial-LIBP technique is applied to trapped orbits (exploring both the plasma core and the FILD stroke near the wall), enabling radial localization of internal plasma fluctuations (neoclassical tearing modes). This is quantitatively compared against electron cyclotron emission measurements, showing excellent agreement. For the first time, radial profiles of fast-ion losses in MHD quiescent plasmas as well as in the presence of magnetic islands and edge localized modes are presented.

I. INTRODUCTION

To ignite a magnetically confined plasma, fast-ions created by auxiliary heating systems [neutral beam injectors (NBIs) and ion-cyclotron resonance heating (ICRH)] must be confined for a sufficient time so that they thermalize, thus transferring their energy to the bulk plasma via Coulomb collisions. Moreover, a burning plasma can only be self-sustained if the resulting large population of fusion-born α particles is retained within the plasma so that it can be used as the primary heating source.[1] On the contrary, if these fast/energetic particles escape the plasma and hit the wall, they might cause serious damage, jeopardizing the integrity of the whole device, especially if these losses are strongly localized.

In this context, aiming at characterizing the mechanisms responsible for classical and non-classical fast-ion transport and losses, the scintillator-based fast-ion loss detector (FILD)[2] provides accurate velocity-space measurements of escaping ions at MHz temporal resolution. In contrast to its many applications, one of the main limitations of this diagnostic consists in the fact that the interrogated phase-space volume is localized as a point in real-space, being impossible to withdraw any conclusion about the spatial dependence of the velocity-space of escaping ions.

On the contrary, the magnetically driven FILD[3] recently installed in the ASDEX Upgrade (AUG) tokamak is able to adapt its insertion in real-time, enabling access to unexplored physics, such as radially resolved velocity-space measurements, and radially resolving the internal perturbations by means of the light-ion beam probe (LIBP) technique.

This manuscript is organized as follows: Section II introduces the FILD working principle along with the FILD poloidal array installed in the AUG tokamak and its phase-space coverage. In Sec. III, the magnetically driven manipulator used to insert the FILD in real-time is assessed. Section IV describes the first radially resolved velocity-space measurements, and Sec. V discusses the radial dependence of MHD-induced fast-ion losses. Future applications of this diagnostic are proposed in Sec. VI together with the conclusions of this work.

II. FILD ARRAY IN ASDEX UPGRADE

FILDs work as magnetic spectrometers using incoming ions, which, on their gyro-orbits, enter the probe head though a collimator pinhole and impinge onto a scintillator plate. The striking point on the scintillator plate depends on the particle pitch-angle and gyroradius (i.e., energy if the ion charge–mass ratio is known). Therefore, FILD provides the time-resolved energy and pitch-angle measurement of the escaping ions. The very short decay time (below 1 μs) and high quantum efficiency of the scintillating material allow us to obtain MHz temporal resolution if the appropriate light acquisition systems are employed. The high temporal resolution can be used to identify intra-ELM mechanisms responsible for the losses.

There are five FILDs installed on the AUG tokamak (Fig. 1). FILD1, FILD2, FILD3, and (the more recently installed) FILD5[4] have their own permanent manipulators[5] to modify their insertion in a shot-to-shot basis. On the other hand, the magnetically driven manipulator employed on FILD4 enables the adaptation of its insertion (up to a maximum of 8 cm) during the plasma discharge.

Each FILD covers a bi-dimensional phase-space surface at the edge of the fast-ion distribution. The simultaneous measurements of different phase-space surfaces provided by the FILD array improve the phase-space coverage and help in diagnosing the spatial dependence of the losses on the wall (e.g., ripple, externally applied magnetic perturbations, and MHD instabilities). Moreover, the radial scan produced by FILD4 enables the measurement of a 3D volume in phase-space.

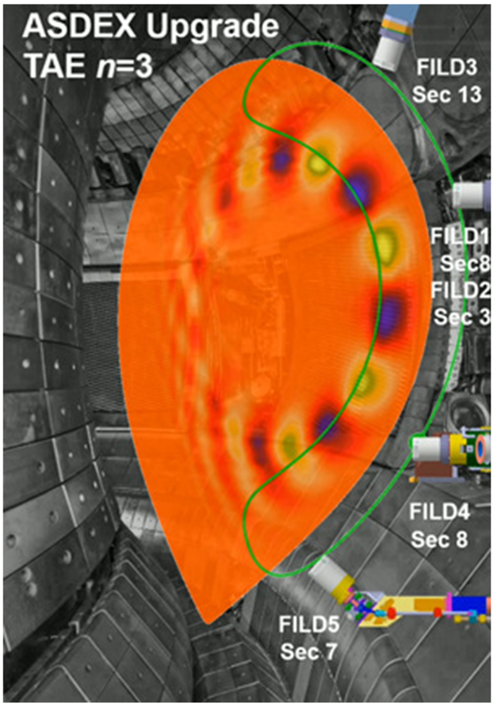

FIG. 1. Poloidal view of the AUG vessel and CAD of the installed FILD systems. A poloidal projection of a trapped particle is included, which is interacting with a toroidicity-induced Alfvén eigenmode on its inner banana leg and captured by FILDs on its outer leg.

III. MAGNETICALLY DRIVEN FILD

Before producing radial measurements, the dynamics of the new FILD, the heat loads on the probe head, and its light acquisition systems need to be assessed. A more detailed description of the system can be found in Refs. 3 and 6.

A. Dynamical assessment

The probe head of this *in situ* system is constantly being pulled back by a retaining spring. An in-vessel coil is externally energized, creating a magnetic moment along its longitudinal axis that tries to align with the existing toroidal magnetic field of the AUG tokamak, thereby producing the torque needed to overcome the retaining spring force. The voltage applied to the coil is regulated by a programmable power supply (CAENels FASTPS058400)[7] directly controlled by the discharge control system (DCS) in real-time using a TELNET communication protocol. This power supply has the capability of delivering a maximum voltage and current of 80 V and 5 A, respectively, which are regulated within 1 ms. The resulting torque applied on the coil is

$$\tau_{coil} = \frac{NAB\cos(\theta)}{R}\left(V - NAB\cos(\theta)\dot{\theta} - L_{self}\dot{I}\right), \tag{1}$$

with N being the number of coil windings, A being the coil transversal area, B being the toroidal magnetic field at the coil location, R being the coil resistance, θ being the coil rotation, L_{self} being the self-inductance, I being the electrical current circulating through the coil, and V being the voltage supplied by the power supply. The second term of Eq. (1) corresponds to the back-electromotive force, damping the system and restricting its velocity but also providing stability. In the last term, the coil self-inductance ($L_{self} = \mu_0 N^2 A/h$) is minimized by maximizing the coil height (h) within the design constraints.

The equations governing magnetically driven manipulators can be found in Refs. 8–10. Those equations are particularized to the design of this new FILD and linearized around the equilibrium point of $\theta = 0$. That linear model is integrated in time using a fourth order Runge–Kutta algorithm that converges in time with 1 ms time steps. The actual value of the toroidal magnetic field at the coil location is included in the model for each analyzed discharge. As shown in Fig. 2, these simple simulations are already in good agreement with the measured FILD trajectory. This linear model is used to validate insertion measurements (inferred from the induced back-electromotive force coil current[8–10]) and to optimize the scanning cycles used to obtain FILD radial measurements.

B. Thermal assessment

The thermal behavior of the FILD probe head is simulated for different purposes.[11] The simulated heat load can be subtracted to the IR measurements of the probe head to estimate the absolute fast-ion flux on the head.[12] On the other hand, these simulations provide an estimation of the characteristic time of the heating process, helping us to set upper boundary limits on the FILD real-time control.

The applied parallel heat load is extrapolated from divertor target measurements (Fig. 3) using two different exponential decays[13] to account for the near and far scrape-off layers. The applied heat load on each FILD depends on its poloidal location and the incident angle of the magnetic field and probe head surface. Field-line 3D tracing is used to calculate the wet (receiving heat flux) surfaces and field-line length, which is compared against the collection length.[14] The obtained heat fluxes are applied in a finite element analysis using ANSYS.[15] The obtained spatial temperature distributions agree well with IR measurements for different FILDs. The predicted temperatures are below the measurements because fast-ion heat flux is not included in the model. Figure 4 shows the simulated evolution of the maximum temperature of the FILD probe head for different duty cycles. One can observe that the heating process is much slower than the typical times (~100 ms) required to retract FILD a couple of centimeters to reduce the incident heat flux. One should also note that a duty cycle of 50% (similar case when scanning the FILD insertion) significantly reduces the maximum temperature of the probe head.

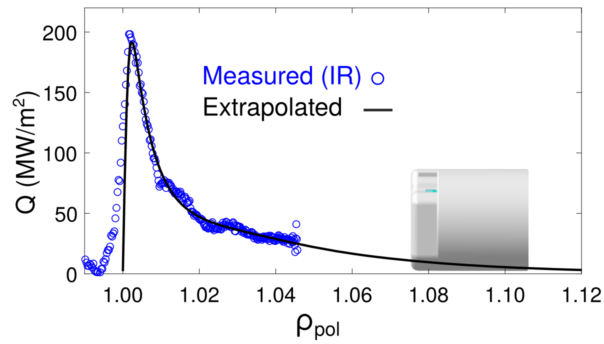

FIG. 3. Measured IR heat flux on the divertor and its extrapolation toward the FILD probe head.

C. Light acquisition systems

The light pattern emitted by the scintillator plate is simultaneously recorded by two different light acquisition systems. A Charge Coupled Device (CCD) camera[16] provides high velocity-space resolution (480 × 640 pixels) measurements every 20 ms. On the other hand, the high temporal resolution measurements are provided by an Avalanche Photo Diode (APD) camera[17] of 32 pixels recording at a sampling rate up to 2 MHz. Both cameras are installed outside the reactor vessel, and the light emitted by the scintillator is transported to an anti-reflection coated vacuum window by using a 3.5 m quartz-made image guide. The thickness of the fibers composing the image guide limits the velocity-space resolution, inducing the artifacts observed in Figs. 6 and 7. This limitation on the velocity-space resolution of the CCD camera does not affect the radial dependence of the measurements.

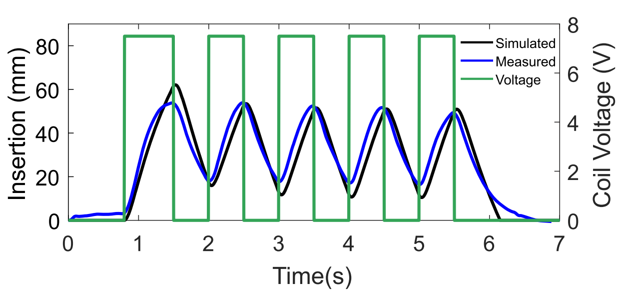

FIG. 2. Predicted and measured FILD trajectories showing insertion/retraction cycles during plasma pulse #36498 with a toroidal magnetic field on the axis of $B_t = -2.5$ T and at the FILD coil location of B = −1.9 T.

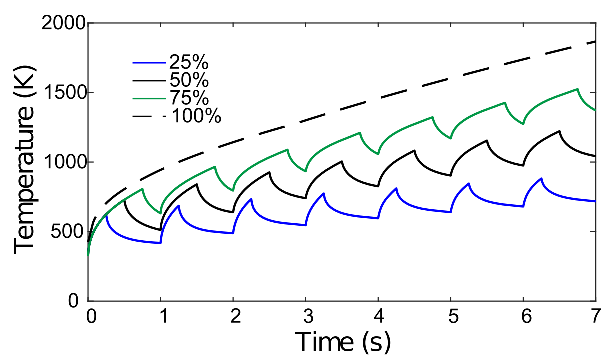

FIG. 4. Predicted evolution of the maximum temperature on the FILD head for different duty cycles.

IV. RADIALLY RESOLVED VELOCITY-SPACE MEASUREMENTS

When FILD is inserted at a fixed location, it is able to produce time-resolved velocity-space measurements at the edge of the fast-ion distribution function. For instance, the new FILD was able to identify passing (trapped) orbits produced by a sequence of applied tangential (radial) beams.[3]

While FILD can be moved in a shot-to-shot basis to infer fast-ion profiles,[18] the new diagnostic technique reported in this paper consists in performing consecutive scans on the FILD insertion. If the plasma parameters are constant throughout the scanning cycles, the time-resolved fast-ion measurements can be translated into radially resolved velocity-space measurements.

A. 3D measurements of fast-ion losses

The FILD insertion/retraction cycles are applied to discharges with a plasma current $I_p = 0.8$MA and magnetic field $B_t = -1.8$ T, producing critical damping on the FILD manipulator and thus enabling the fast movement of the FILD head needed for performing insertion/retraction cycles.

Figure 5 shows the time traces of a discharge in which 2.5 MW beam sources [# 3 (60 keV) and # 8 (93 keV)] are consecutively applied combined with eventual 2.9 MW of ICRH power at 30 MHz. Despite the temporal changes in the applied heating systems, the electron density remains practically constant at the core ($n_e = 5.4 \cdot 10^{-19}$ m^{-3}) and edge ($n_e = 3.2 \cdot 10^{-19}$ m^{-3}). The field-line helicity at the edge $q_{95} = 3.8$ is also unperturbed during the whole shot, while the electron temperature T_e is slightly modified by the applied heating scheme, remaining relatively constant through each phase.

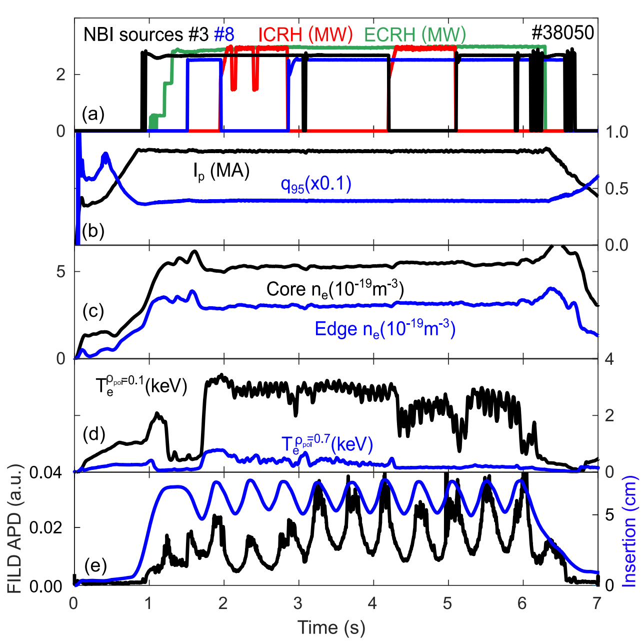

FIG. 5. Time traces of plasma discharge # 38050 showing (a) evolution of the applied NBI and ICRH, (b) evolution of the plasma current I_p and edge field-line helicity q_{95}, (c) core and edge electron densities n_e, (d) electron temperatures T_e at the core and at $\rho_{pol} = 0.7$, (e) the insertion of FILD and the fast-ion loss level measured by channel # 19 of the FILD APD camera.

The inferred evolution of FILD insertion is depicted in Fig. 5(e). One can observe that FILD is fully inserted once the first NBI beam has been applied. Then, after FILD reaches a steady inserted position, the voltage on the magnetic coil is sequentially reversed, forcing the system to oscillate by 25 mm for each 400 ms, modulating the measured FILD signal produced by the APD camera. This translates into 25 mm radial profiles of fast-ion losses for each 200 ms. The critical damping on the FILD manipulator produced by the magnetic field on this scenario was crucial to obtain the large number of cycles/second. This ratio could be further increased by optimizing the voltage curve applied on the coil; however, the CCD sampling rate is limited to 20 ms, limiting the radial resolution of the velocity-space measurements in case FILD moves faster.

For each insertion cycle, one can combine the time-resolved velocity-space measurement with the inferred time-resolved FILD insertion,

$$FILD = FILD(Energy, Pitch, Time), \tag{2a}$$

$$R_{FILD} = R_{FILD}(Time), \tag{2b}$$

to produce 3D measurements of the escaping fast-ion population,

$$FILD = FILD(Energy, Pitch, R_{FILD}). \tag{3}$$

Figure 6 illustrates the resulting 3D fast-ion distribution as a 3D contour plot, showing fast-ion losses produced by both NBI and ICRH. To reconstruct the energy of these measurements, deuterium ions are assumed for both NBI and ICRH signals.

B. Radial measurements of NBI and ICRH ions

Figure 7 shows the measured velocity-space pattern at the innermost insertion. The pattern of Fig. 6 is observed more clearly.

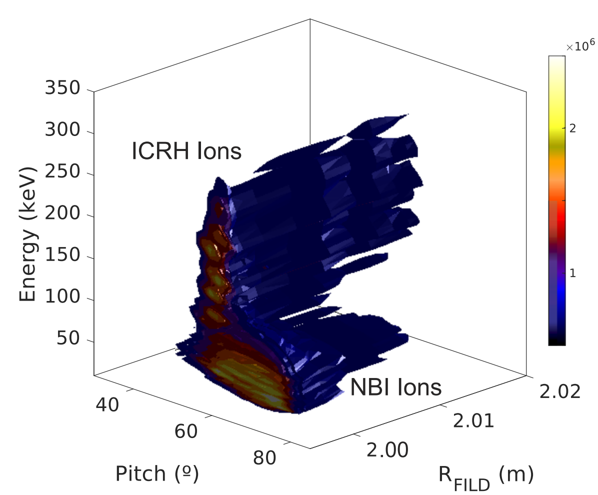

FIG. 6. 3D contour plot of the measured fast-ion distribution in shot # 38050 between 4.86 and 5.1 s as a function of the particle energy (keV), pitch-angle (°), and radial location of the FILD collimator slit (m).

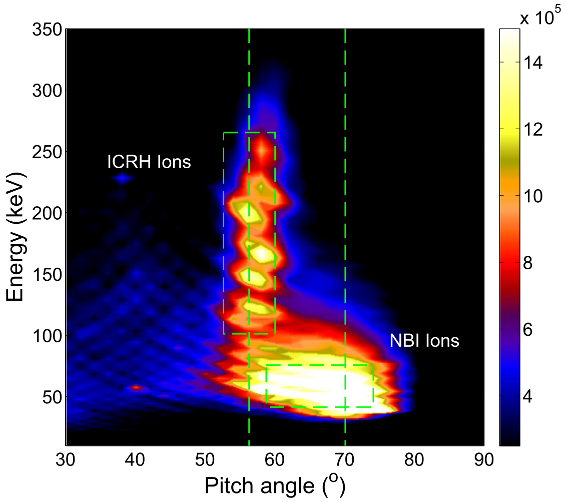

FIG. 7. Measured velocity-space pattern at the innermost insertion for shot # 38050 and 5.1 s. Deuterium is assumed for reconstructing the measured energy. The artifacts produced by the image guide can be identified as localized spots on the ICRH region. Regions of interest used to produce Fig. 8 and pitch-angles interrogated in Fig. 9 are over-plotted.

This 2D image, normally employed for FILD at a fixed location, helps in defining the regions of interest (ROIs) corresponding to both NBI and ICRH ions (green dashed rectangles).

The ROI values are radially plotted over consecutive reciprocating cycles (in which the heating scheme is not modified) in Fig. 8.

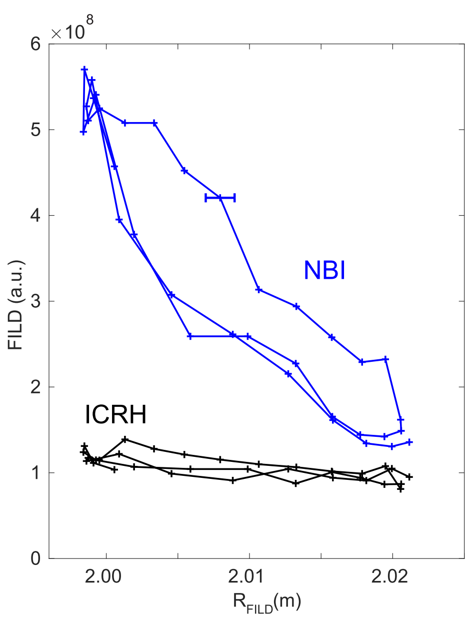

FIG. 8. Radially resolved ROI values defined for NBI (E ⊂ [45, 95] keV, pitch ⊂ [58, 74]°) and ICRH (E ⊂ [100, 270] keV, pitch ⊂ [52, 60]°) ions over consecutive reciprocating cycles. The NBI ions are observed to have a larger radial gradient than the ICRH population.

The uncertainty in the ROI signal induced by the CCD camera readout noise is smaller than 1%, being negligible when compared to the uncertainty in R_{FILD} (1 mm) induced by the coil resistivity (0.01 Ω) readout. For the sake of clarity, Fig. 8 includes the error bar associated with a single measurement point. Both NBI and ICRH profiles are obtained from the same CCD frames; hence, any systematic error in R_{FILD} displaces both profiles jointly. Despite both heating systems producing similar levels of signal in FILD, the radial gradient of the measured fast-ion distribution is much larger for NBI ions than for ICRH ions. This can be qualitatively explained by the fact that NBI ions are deposited at the plasma edge, while ICRH ions are generated at the absorption layer at the core.

Besides the radial evolution of the integrated NBI and ICRH distribution, one can also use the 3D measurements to investigate the radial dependence of the fast-ion energy at each measured pitch-angle. In Fig. 9, the radial profiles at a given pitch-angle (°) are plotted for NBI and ICRH ions. For the sake of clarity, these interrogated pitch-angles are identified as vertical dashed green lines in Fig. 7. One can again identify the different radial gradients for ICRH and NBI ions. Furthermore, these measurements help us to notice that the radial profile of ICRH ions is different for each energy, having a larger gradient with smaller energy. These novel observations can help validate models that reproduce the fast-ion accelerated ICRH distribution.

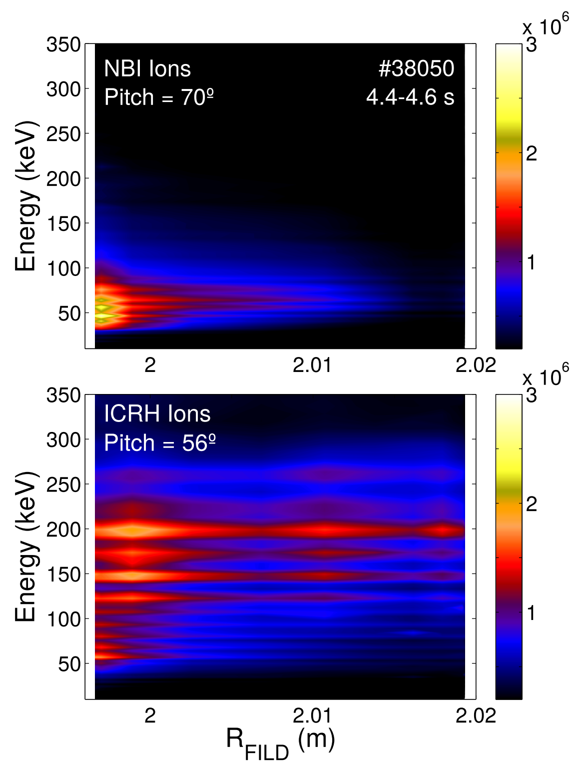

FIG. 9. Radially and energy resolved fast-ion loss measurements for the pitch-angles corresponding to NBI ions (70°) and ICRH ions (56°). One can observe that ICRH ions with larger energy have smaller radial gradients than those with lower energy.

C. Radial profiles from different NBI sources

Figure 10(a) depicts the measured velocity-space pattern at the FILD innermost insertion of a phase where NBI source # 6 and # 8 (93 keV) are simultaneously applied. Source No. 6 is tangential, while source # 8 injects ions more radially. The measured pitch-angle profile at the injected energy is plotted in Fig. 10(b) together with the predicted losses using the ASCOT[19] code. ASCOT reproduces the measured pitch-angle profile and enables the identification of the birth location of the ions heating the FILD probe. All the simulated ions injected by NBI source # 8 that reach FILD come from the high-field side (HFS) of the plasma, while the simulated ions injected by source # 6 and hitting FILD are ionized at both the low-field side (LFS) and HFS. ASCOT simulations help us to conclude that the measured spot corresponds to the particles ionized at the LFS, whereas the particles ionized at the HFS are not captured by FILD in the experiment. This can be explained by the fact that these ions hit FILD with a small pitch-angle and cannot reach the scintillator plate.

Figure 11 shows the radial profile for the ROIs defined on the measured velocity-space pattern (Fig. 10) for each beam. One can observe that particles ionized at the LFS are captured ≈1 cm earlier by FILD. This can be partially explained by the fact that FILD moves across the passing/lost boundary for particles ionized at the HFS. Another explanation is that particles injected by beam # 6 explore the plasma core and interact with internal instabilities that cause orbit deflection, as explained in more detail in Sec. V. The radial profile measured for beam source # 8, which is not perturbed by internal fluctuations, has been reproduced by the ASCOT code, showing excellent agreement.

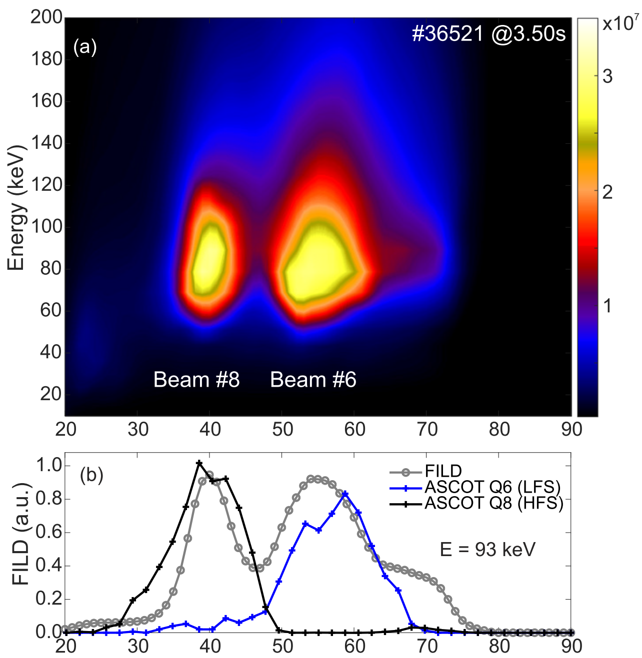

FIG. 10. (a) Measured velocity-space pattern produced by NBI source Nos. 6 and 8. (b) Comparison of the measured pitch-angle profile at the injection energy (93 keV) of the measured FILD signal and ASCOT predictions.

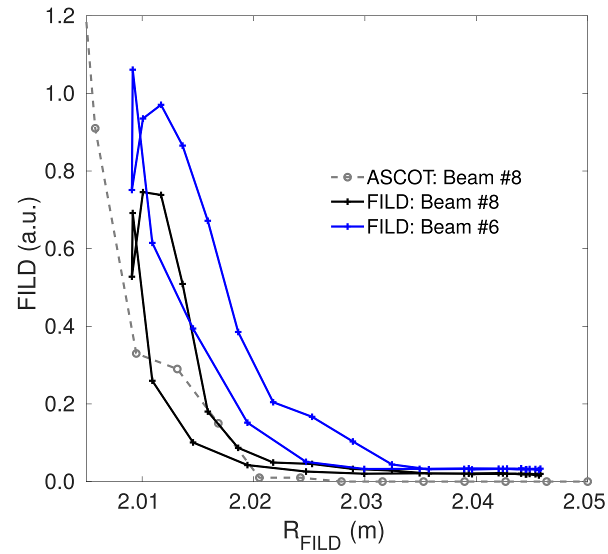

FIG. 11. Measured radial profiles for beam # 8 (ionized at the HFS) and No. 6 (ionized at the LFS). ASCOT simulations reproduce the measured beam deposition profile of source # 8.

V. RADIALLY RESOLVED PERTURBATIONS

Besides radially resolving the quiescent velocity-space distribution of fast-ions at the edge, the high temporal resolution of the FILD systems enables us to radially resolve fast-ion losses induced by core and edge perturbations.

A. Radial profile of ELM-induced fast-ion losses

Measurements of fast-ion losses induced by Edge Localized Modes (ELMs) have been reported by Garcia-Munoz *et al.*[20] and Galdon-Quiroga *et al.*[21] among many other works. The high sampling frequency of the APD camera (up to 2 MHz) enables resolving these losses. Figure 12(a) shows the temporal evolution of the ELM monitor during a FILD insertion/retraction cycle. In Fig. 12(b), the FILD signal is modulated by its insertion and the spikes induced by the ELMs are clearly visible and isolated using a simple spike detection algorithm.

The radially resolved ELM spikes induced in FILD can be collected for all cycles produced during a whole plasma discharge, producing the measurements shown in Fig. 13. This technique can be employed to study the radial dependence of ELM-induced fast-ion losses under different heating schemes, field-line helicity, and, as shown in the example, different applied magnetic fields. The statistics shown in Fig. 13 are, however, limited and thus need to be improved before any physical interpretation of these measurements.

B. Radially resolved orbit deflection induced by magnetic islands

In scenarios with existing magnetic islands, the position of the FILD probe was scanned, producing the first radially resolved

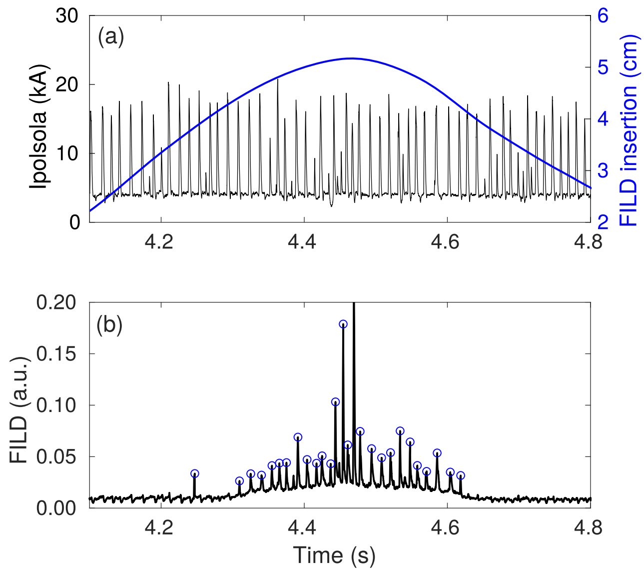

FIG. 12. (a) Temporal evolution of the divertor target current, used as an ELM monitor along with the FILD inferred insertion. (b) Measured FILD signal including spikes induced by ELMs.

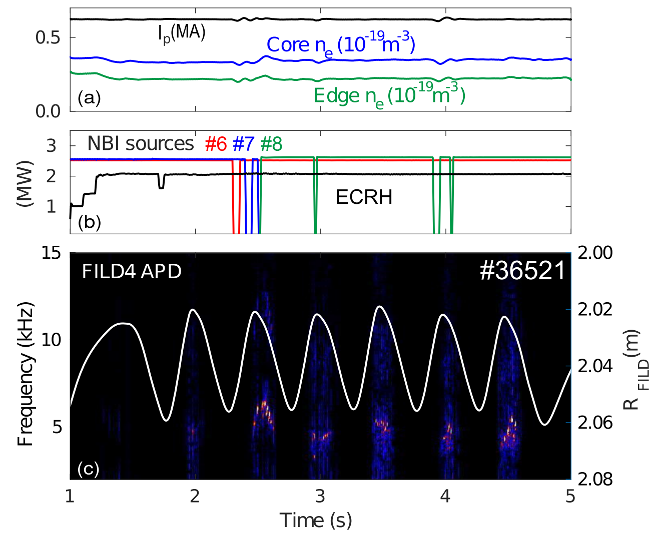

FIG. 14. Overview of discharge # 36521 showing (a) the temporal evolution of the plasma current, core and edge electron densities, and (b) applied NBI and ECRH heating and (c) the spectrogram of the FILD signal showing MHD-induced coherent losses modulated by the FILD insertion.

measurements of coherent fast-ion losses induced by internal perturbations. Figure 14 depicts the time traces of an example discharge where the electron density and plasma current are constant through the entire pulse. 2 MW of ECRH power are applied together with a total of 5 MW of NBI using source Nos. 6 and 7. At 2.5 s, source # 7 is replaced by # 8. This discharge has a plasma current of I_p = 0.8MA and a magnetic field of $B_t = -2.5$ T, overdamping the FILD movement and thus restricting the achievable number of cycles/second. The FILD trajectory is depicted in Fig. 14(c) together with the spectrogram of the APD recorded signal, in which the coherent MHD-induced fast-ion losses are visible. The intensity of the measured coherent losses is clearly amplified when the FILD probe is inserted. The Light-Ion Beam Probe (LIBP)[22,23] technique is applied to these radial measurements. This technique provides an experimental estimation of the fast-ion orbit radial displacement (ξ) by means of analyzing the modulated FILD signal (ΔF) induced by ions that are lost in their first poloidal transit after a single pass through the internal perturbation,

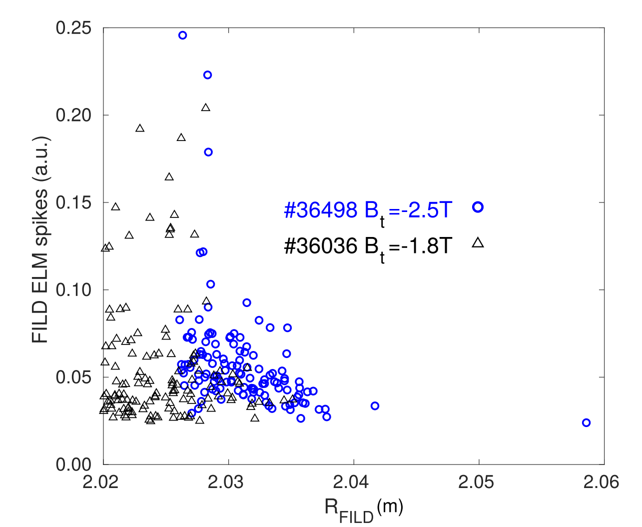

FIG. 13. Measured spikes on the FILD signal induced by ELMs during two different discharges at different magnetic fields on the axis.

$$\xi \approx (\Delta F/\bar{F})L_i. \tag{4}$$

$\bar{F}$ is the unperturbed (mean) fast-ion flux and L_i is the ionization scale length at the orbit birth location, which can be substituted by the density scale length near the edge due to the strong linear dependence of the ionization profile on edge electron density n_e.

The LIBP technique is applied to the time window from 3.3 to 3.7 s, when, as shown in Fig. 14, the electron density, applied heating, and frequency of the MHD instability are constant. A spectrogram of a magnetic pickup coil is illustrated in Fig. 15(a), showing the evolution of the perturbation that has been identified as a Double Tearing Mode (DTM), radially expanding from ρ_{pol} = 0.35 to 0.65 and having toroidal and poloidal periodicities of $(n, m) = (1, 3)$. Figure 15(b) shows the spectrogram of the coherent FILD signal from the APD camera during the time window of interest. Coherent losses observed at the spectrogram are not only modulated by the FILD insertion but also by the DTM amplitude. To disentangle this effect, the mode amplitude is tracked as shown in Fig. 15(a) and smaller time windows on the FILD signal are selected at each local maximum, resulting in samples of FILD measurements at almost constant DTM amplitude and frequency.

The samples of the raw FILD signal, plotted as scattered points in Fig. 15(c), can be averaged to obtain $\bar{F}$ and Fourier-transformed

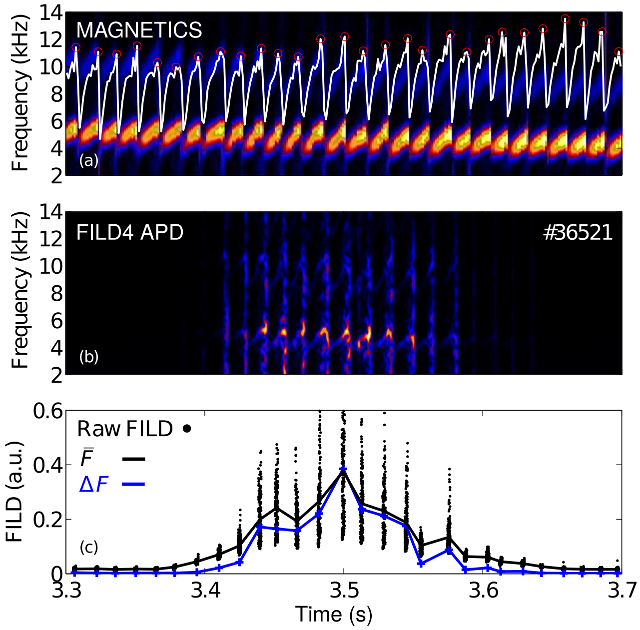

FIG. 15. (a) Magnetic spectrogram of the DTM with overlaid tracked amplitude. (b) Spectrogram of the FILD signal showing coherent losses at the same frequency as the DTM. (c) Samples of the raw FILD signal together with its mean values and oscillating component at the mode frequency.

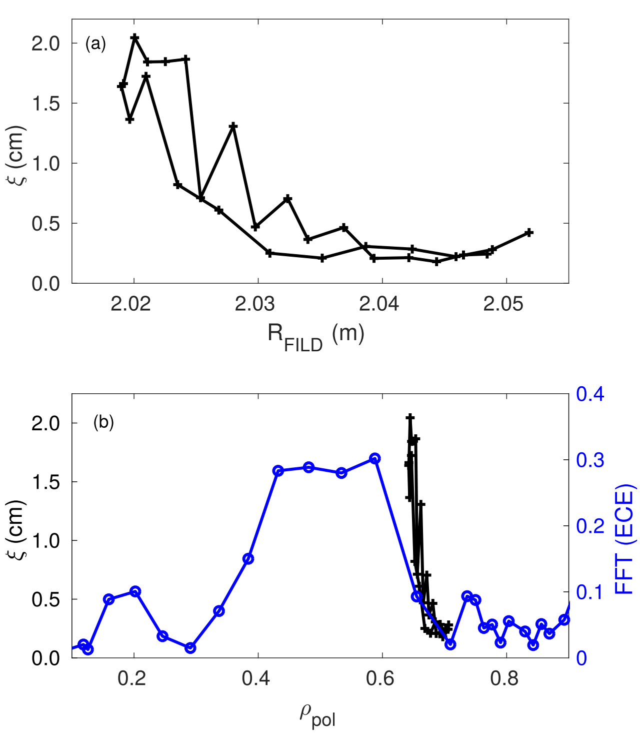

FIG. 16. Radial profile of orbit deflection at the FILD location (a) and at the innermost ρ_{pol} of the measured orbit (b) together with the DTM radial structure measured by ECE.

to obtain the fluctuating component at the DTM frequency (ΔF). The resulting values of ($\bar{F}, \Delta F$) are analyzed by applying Eq. (4) to produce time-resolved estimations of the orbit deflection.

Since FILD performs an insertion/retraction cycle, the radial profile of the orbit deflection is obtained as shown in Fig. 16(a). This radial profile corresponds to the outer banana leg of the measured trapped orbits. Velocity-space measurements reveal that these ions are captured with an energy of $E = 93$ keV and a pitch-angle of 65°. This information is used to track the measured orbits backward in time to connect FILD location (R_{FILD}) with the innermost flux surface explored by each orbit, which helps to remap the radial profile against the minimum ρ_{pol} of the internal banana leg. This internal profile is compared against the reconstructed mode structure obtained by electron cyclotron emission (ECE) [Fig. 16(b)]. Despite the limited radial range covered by FILD, the measured dependence of the orbit deflection seems to agree with the reconstructed ECE profile, with FILD measuring a larger number of radial points along the covered range when compared to ECE. The FILD internal radial range could be expanded by combining orbits measured by different APD pixels.

VI. OUTLOOK AND SUMMARY

A new FILD system installed in the AUG tokamak is able to adapt its position during the discharge. Thermal and dynamical simulations are performed to test the feasibility of the scanning cycles, which are used to obtain radially resolved velocity-space measurements of escaping ions. Since the position of the FILD system is regulated in real-time by the DCS, future control strategies based on any signal or event can be easily implemented. The most natural strategy will be to adapt the FILD insertion based on its probe head temperature measured with the safety camera, expanding the operational window to any plasma discharge and optimizing the measurements. However, FILD could also react to changes in the position of the last closed flux surface. In addition to this, if the magnetic field of the device is modified, the voltage on the coil could be adapted in real-time, so FILD is fixed at constant insertion.

On the other hand, the first radially resolved FILD measurements of NBI and ICRH ions are described and compared against simulations. Furthermore, radial profiles of losses induced by edge (ELM) and internal (DTM) perturbations are described. The LIBP technique is applied to these measurements to resolve the internal radial structure of the DTM. In the future, this radially resolved LIBP technique can also be applied to a large variety of internal fluctuations, such as Alfvén eigenmodes, magnetic islands, and externally applied 3D magnetic perturbations.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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