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Summary of the Fast-Ion D_α Measurements in Various Plasma Conditions in DIII-D

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Fast-ion populations are created by fusion reactions, neutral beam injection, and radio frequency heating (rf) in tokamaks. They are a major source of energy, momentum, and particles for the plasma. Understanding the behaviour of fast ions is of great importance in fusion research. The fast-ion D_α (FIDA) diagnostic is aimed at providing a reliable fast-ion measurement.

The fast-ion D_α (FIDA) diagnostic measures the Balmer-α light emitted by neutralized fast ions. In MHD-quiescent plasmas, the FIDA radial profile agrees with the simulated profile based on the fast-ion distribution function from TRANSP. During ion cyclotron heating (ICH), the FIDA diagnostic observes that fast ions with high perpendicular energy are accelerated. The elevated FIDA radial profile is consistent with the fast-ion pressure profile inferred from equilibrium reconstruction. In discharges with instabilities, the FIDA measurements show that fast ions can be redistributed.

An initial test of the FIDA concept [1] was performed utilizing the existing charge exchange recombination (CER) diagnostic starting in 2003. At the same time, a Monte Carlo simulation code was developed to predict the FIDA spectra based on an existing fast-ion distribution function. After the initial success, a paper [2] describing the design of a dedicated two-channel system was published. A rich set of data was obtained from the dedicated system in 2005, and the data in various plasma conditions were analyzed and compared to simulations in 2006. This led to several papers being published or written in 2007, including an instruments paper that discusses the instrument and data analysis in detail [3], a paper that focuses on measurements in quiet plasmas [4], a paper on measurements during ICH [5], and a paper on measurements in discharges with instabilities [6]. This paper briefly summarizes these most recent results.

Conceptually, the FIDA diagnostic is very similar to the CER diagnostic [7]. As fast ions orbit around the device and pass through a neutral beam, some of them will charge exchange with injected or halo neutrals and become neutralized. If the neutralized fast ions are in excited states, they may radiatively decay after traveling a distance. The FIDA diagnostic detects the D_α light, which is the n=3 to n=2 transition. Based on the Doppler shift of the detected photons, the velocity component of the fast ions along the viewing line can be derived. The FIDA diagnostic is spatially localized since it is an active charge exchange diagnostic.

Figure 1 shows a schematic view of the dedicated FIDA system. A lens located at a port under the midplane collects and focuses light onto several optical fibers. The light travels along the optical fibers to a Czerny-Turner spectrometer. At the exit focal plane of the spectrometer, the light is dispersed into a two dimensional pattern: vertically, the light is separated into two chords; horizontally, the light from each fiber is dispersed in wavelength. A vertical bar sitting on two horizontal translation stages on the exit focal plane blocks the portion of the spectrum with bright interfering signals that would otherwise satuate the detector. The image on the exit focal plane is reduced by two camera lenses coupled together by a macrocoupler and a step ring. A CCD camera with its CCD chip on the focal plane of the second lens detects the light.

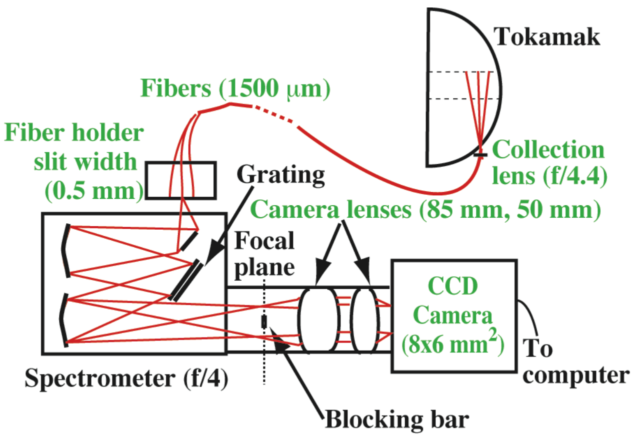

FIG. 1. Top view of the dedicated FIDA system.

Before utilizing the FIDA instrument to study fast-ion acceleration during ICH and fast-ion transport by instabilities, a thorough benchmark is required to validate this novel diagnostic technique. MHD-quiescent plasmas with dilute fast-ion populations provide an ideal testbed since fast ions decelerate classically and diffuse negligibly. In such plasma conditions, TRANSP [8] provides a reliable fast-ion distribution function. One of the most critical benchmarks is to compare the measured FIDA profile with the simulated profile based on the fast-ion distribution function from TRANSP. Because each chord differs in many aspects such as observational volume, viewing angle, light path, etc., a relative profile is usually used to remove the chord specifics. Figure 2 shows the comparison in a discharge that starts in H-mode (high density) and ends in L-mode (low density). When the electron density decreases, the FIDA signal increases because the slowing down time increases, the beam neutral density increases (beam penetrates further into the plasma), and the fast-ion birth density increases. This is confirmed by the simulated profile, which jumps up substantially when the plasma undergoes the transition from H-mode to L-mode. To obtain the relative profile from measurements, the FIDA measurements for

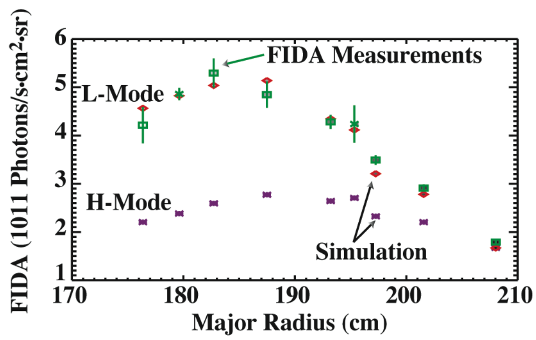

FIG. 2. Comparison of simulated profiles [H-mode (violet), L-mode (red)] and measured relative FIDA profile [L-mode (green)]. The FIDA signal is averaged over E_λ (energy component along the viewing line) between 20 keV and 40 keV.

each chord in H-mode are scaled to match the corresponding simulated FIDA signal. Using the same relative calibration for the L-mode signals, excellent agreement is obtained between the measured FIDA profile and the simulated profile. The discrepancies for most chords are within error bars. The agreement shows that relative profiles can provide precise information on how fast-ion profiles evolve.

High harmonic ICH can accelerate fast ions in the perpendicular direction. The FIDA diagnostic is well suited to measure this acceleration because the vertical views measure the vertical velocity, which is a component of the perpendicular velocity. Figure 3 shows a discharge with low plasma density and 1 MW of 60 MHz fast wave heating corresponding to the 4th harmonic. Spectral comparison between before rf and during rf for chords around the resonance layer clearly indicates that fast ions with high perpendicular energy are strongly accelerated, while those with low perpendicular energy are barely affected. This is consistent with the finite Larmor radius effect of ICH heating. In Fig. 3, the beam ion pressure profile from equilibrium reconstruction constrained by motional Stark effect (MSE) jumps up when rf is turned on. The FIDA measurements before rf are scaled to match the fast-ion pressure profile to obtain a relative calibration. During rf, the FIDA profile using this relative calibration and the fast-ion pressure profile agree very well, both indicating that fast ions are accelerated by ICH.

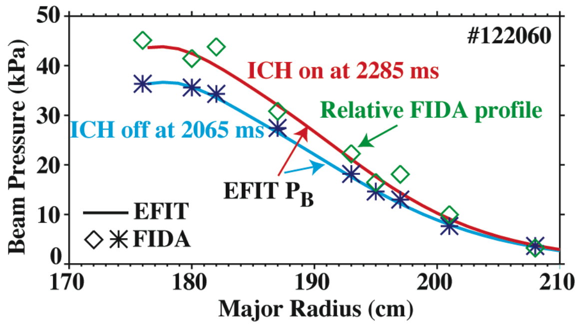

FIG. 3. Comparison of beam-ion pressure profiles and relative FIDA profile. The FIDA signal is averaged over E_λ between 40 keV and 80 keV.

The primary objective of the FIDA diagnostic is to study fast-ion transport by collective instabilities. In one of the recent submitted papers, we have seen central flattening of the fast-ion profile by Alfvén eigenmodes, and the extent of flattening is correlated with the magnitude of the Alfvén activity [6]. Since the FIDA diagnostic takes data every 1 ms, it is capable of detecting fast-ion transport by sawtooth crashes. A rapid sawtooth crash occurs in less than 1 ms and redistributes fast ions from the core of the plasma to outside the q=1 surface [9]; after the crash,

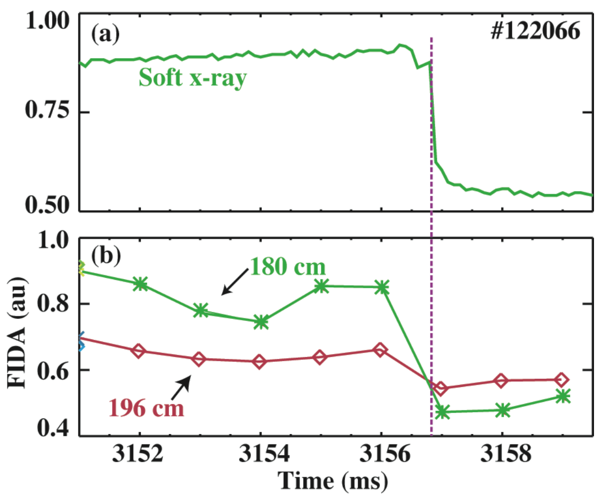

FIG. 4. Time evolution of (a) soft x-ray signal and (b) FIDA signals from two chords averaged over E_λ between 30 keV and 80 keV.

the fast-ion density recovers on a relatively slow time scale (≥10 ms). In Fig. 4(a), the quick drop of the soft x-ray signal at 3167 ms indicates a sawtooth crash. In Fig. 4(b), the central FIDA channel (R = 180 cm) drops by a factor of 2, while the FIDA channel that is just inside of the q=1 surface (R = 196 cm) drops around 20%, which is consistent with the expected redistribution of fast ions.

In summary, the FIDA diagnostic is benchmarked in MHD-quiescent plasmas. The FIDA simulation code can reliably predict the FIDA profile based on an existing fast-ion distribution function. It is very suitable for observing fast-ion acceleration via ICH. It is established as a powerful diagnostic of fast-ion transport by instabilities.

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