Influence of ion cyclotron heating and MHD instabilities on the fast-ion distribution in ASDEX Upgrade

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Introduction

Fast ions are generated in present-day tokamaks by neutral beam injection and ion cyclotron resonance heating, and are used for plasma heating and current drive. In future fusion devices, energetic α-particles from fusion reactions will be the main heating mechanism. Hence, it is crucial to understand the transport behavior and creation mechanisms of fast ions.

A way to measure the fast-ion distribution is the FIDA (fast-ion D-alpha) diagnostic, which analyzes the Doppler-shifted D-alpha radiation of neutralized fast-ions spectroscopically. With lines of sight at different radial positions, radial fast-ion density profiles can be measured. At the same time, the shape of the Doppler spectrum contains information about the 2D velocity space distribution $f(E, v_{\parallel}/v)$. Observation from different viewing angles allows consequently a tomographic reconstruction of $f(E, v_{\parallel}/v)$. For this purpose, the FIDA diagnostic at AUG has been upgraded from two to five views for the 2014 campaign, and the spectrometer has been upgraded to measure blue and red Doppler shifts simultaneously.

These recently developed diagnostic capabilities are used to study the effect of sawtooth crashes on the fast-ion velocity distribution and the further acceleration of fast D ions by 2nd harmonic ion cyclotron heating.

Diagnostic setup

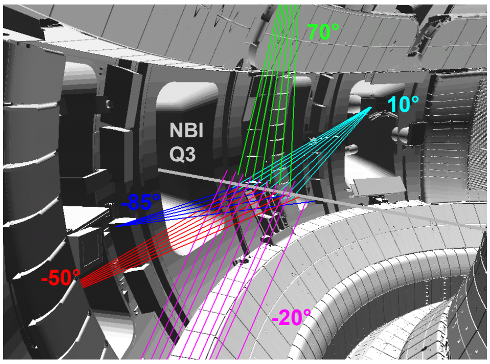

Figure 1: *3D visualization of the five FIDA line of sight arrays.*

The FIDA diagnostic at ASDEX Upgrade consists now of five viewing arrays (see fig. 1). Each view consists of several radially distributed lines of sight, and has a different angle towards the magnetic field Φ. The latter determines the observed region in velocity space, and hence an equal distribution of angles (in the plasma center) has been chosen: $\Phi \approx 10^\circ, -20^\circ, -50^\circ, 70^\circ$ and 85°. The FIDA spectrometers are capable of measuring the blue- and red-shifted part of the D-alpha spectrum simultaneously, and have a capacity of up to 37 viewing channels. Each wavelength λ in the FIDA spectrum can be interpreted as a weighted integral of the fast-ion velocity distribution $f(E,\xi)$:

$$FIDA(\lambda) = \int_0^\infty \int_{-1}^{+1} W(\lambda,E,\xi) f(E,\xi)\,\mathrm{d}E\mathrm{d}\xi \tag{1}$$

Hereby, the pitch is denoted with $\xi = v_\parallel/v$. The so called weight functions W can be calculated with the FIDASIM code [1, 2]. In fig. 2, weight functions are shown for five FIDA views in the plasma center and two wavelengths corresponding to Doppler-shifts $\Delta\lambda = \pm 3.9$ nm. Weight functions at different Doppler-shifts have typically similar shapes, but are shifted with respect to the energy. It can be seen that the velocity space is well covered. This allows a tomographic reconstruction of $f(E,\xi)$. Therefore, eq. 1 is discretized to a matrix equation $\vec{s} = W\vec{f}$. The tomography can then be calculated from the FIDA signals $\vec{s}$ by $\vec{f} = W^+\vec{s}$, where we calculate W^+ by first order Tikhonov regularization as described in [3]. This is equivalent to calculating a least-squares fit, with the additional condition, that the solution f should have small gradients.

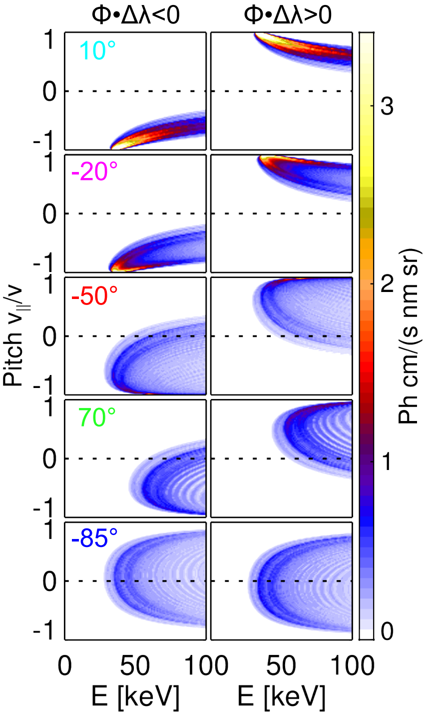

Figure 2: *Weight functions of the five FIDA views and two Doppler-shifts* $\Delta\lambda = \pm 3.9$ nm.

Influence of RF heating on the beam ion distribution

The coupling of radio frequency (RF) waves to ions is an important physics aspect for future fusion devices. In ITER, 2^{nd} harmonic ion cyclotron resonance heating of tritium is one of the foreseen ICRF schemes, along with He-3 minority heating. The 2^{nd} harmonic heating has the benefit, that it can accelerate the main ion species directly, however it is only efficient for ions with large Larmor radii (with respect to the RF wave length). At ASDEX Upgrade, the Larmor radii of D beam ions (i.e. from 60 keV NBI) are large enough for effective 2^{nd} harmonic absorption.

We have analyzed discharge #30809, which has $B_\text{t} = -2.4$ T and $I_\text{p} = 1.0$ MA. The ICRF frequency is 36.5 MHz and the resonance layer is hence located at $R \approx 1.69$ m, i.e. very close to the magnetic axis. We have compared $t = 4.60$ s with 2.4 MW NBI + 1.8 MW ICRF and $t = 4.48$ s with 2.4 MW NBI only. FIDA data from four views are available for this discharge. We have calculated tomographies from central lines of sight ($R \approx 1.75 - 1.78$ m), well behind the ICRF resonance layer.

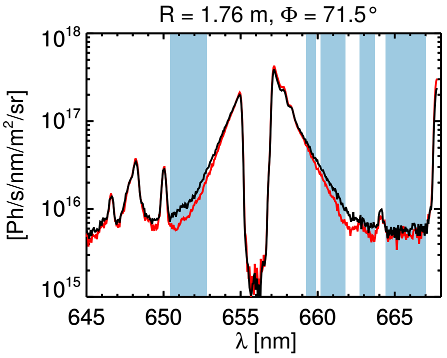

Figure 3: *FIDA spectrum for* 4.48 s *(red) and* 4.60 s *(black). The blue shaded area is used for the tomography.*

The spectra of the $\Phi = 72^\circ$ view are shown in fig. 3. It can be seen directly, that the FIDA spectrum is broader for $t = 4.60$ s, which indicates the presence of more energetic fast ions. The tomography is shown in fig. 4. It has to be noted, that in the presence of ICRF also fast H (minority) ions are expected to contribute to the Balmer-Alpha spectrum. The weight functions for hydrogen are almost identical with respect to the velocity (or E/m). Therefore, we have plotted the tomography as function of E/m and interpret it as the sum of fast D and fast H.

The NBI injection energy (30 keV/u) is indicated with a dotted line. At $t = 4.48$ s, the tomography yields mainly fast ions with energies below the injection energy, as expected. In the presence of ICRF ($t = 4.60$ s), two high energy tails are clearly seen. The stronger tail appears at pitches ≈ 0.7, and can be identified as beam ions, which are further accelerated. A second, weaker high energy tail is seen at pitches -0.3 to 0.0. It could originate from trapped ICRF-accelerated deuterium ions, which have the inside of their banana orbit at our measurement position with negative pitches, and from fast H ions, which are accelerated to high perpendicular velocities by ICRH. The tomography results can be directly compared to theoretical predictions or analytical models of the H fast-ion distribution function [4], and this will remain for future work.

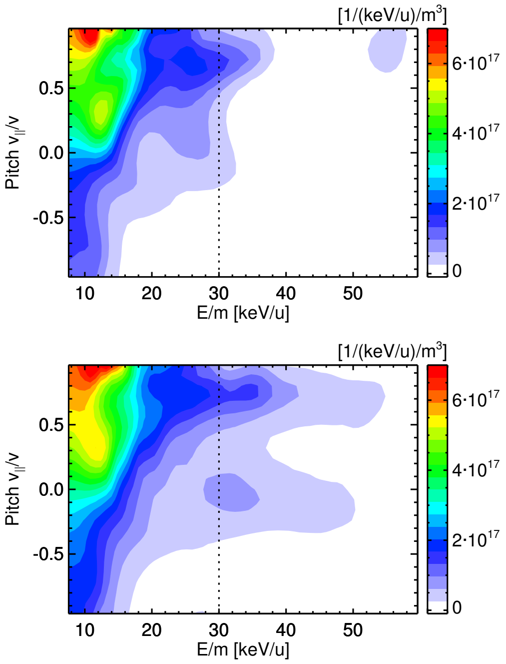

Figure 4: *FIDA tomography in the presence of 30 keV/u NBI and NBI+ICRF (down).*

Fast-ion redistribution by sawtooth crashes

Sawtooth crashes can strongly redistribute fast ions, which has been demonstrated e.g. from FIDA [5] or neutron measurements [6]. The improved FIDA setup and the additional views can be used now to study the velocity dependence of this redistribution in detail.

We have analyzed discharge #31557. The discharge was run with a magnetic field of -2.6 T, a plasma current of 1 MA and 2.5 MW NBI. Sawtooth crashes are directly visible e.g. in time traces of electron temperate and the FIDA raw signals.

We have calculated reconstructions before and after the sawtooth at 2.24s from five FIDA views, which measure all approximately at the same radial position at $\rho_{\mathrm{pol}} \approx 0.10$, and inside the sawtooth inversion radius ($\rho_{\mathrm{pol}} \approx 0.45$). Regions with impurity lines and beam emission are excluded from the input spectra.

The result of the tomography is shown in fig. 5. From the reconstruction, it is possible to determine the total fast-ion density (of fast-ions above 20 keV), and thus quantify the effect of the sawtooth: It causes a 25% drop of fast-ion density in the plasma center. With a cut of the fast-ion distribution function at constant energy, we can estimate, how this total density drop is distributed along different pitches (fig. 6). It can be seen that fast-ions with high pitches are much stronger distributed (-50%), while more strongly gyrating fast ions with pitches close to 0 are much less affected by the sawtooth. This is in accordance with [7], where a FIDA tomography is calculated with singular value decomposition from four FIDA views.

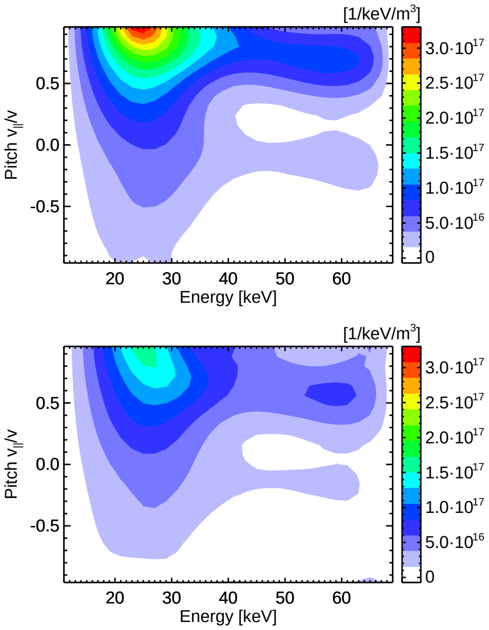

Figure 5: *FIDA tomography before (top) and after a sawtooth crash.*

Summary and conclusion

The recent upgrades of the FIDA diagnostic at ASDEX Upgrade allow a tomographic reconstruction of the 2D fast-ion velocity distribution and hence velocity-space resolved fast-ion studies. In the presence of sawtooth crashes, a 25% overall decrease of central fast-ion density is observed, whereby the decrease is found to be much stronger (up to 50%) for fast ions with large pitches $v_{\|}/v$. The effect of ICRF heating on a beam ion distribution is clearly seen by high energetic tails in the tomography above the NBI injection energy. The pitch distribution of the energetic tails can be resolved, and two contributions at $\frac{v_{\|}}{v} \approx 0.7$ (approx. same as NBI) and at $\frac{v_{\|}}{v} \approx -0.15$ are found.

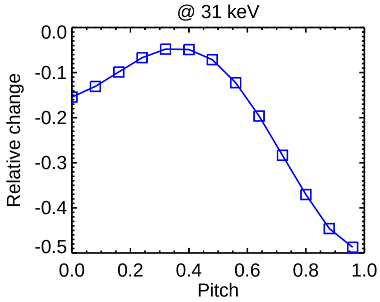

Figure 6: *Pitch distribution of the relative change of $f(E = 31\,\mathrm{keV}, v_{\|}/v)$.*

Acknowledgment

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