

## Fast-ion transport studies by FIDA spectroscopy at ASDEX Upgrade

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Good confinement of fast, supra-thermal ions is essential for the success of future fusion devices because this determines the plasma performance through their heating and current drive efficiencies. While the fast-ion transport in MHD-quiescent plasmas is thought to be dominated by the relatively small, neo-classical diffusion induced by collisions, a strong fast-ion transport is expected when MHD instabilities are present, such as sawtooth crashes. These two aspects are investigated experimentally in the ASDEX Upgrade (AUG) tokamak where fast-ions can be generated by neutral beam injection (NBI).

### Diagnostic setup

The transport properties of fast-ions are analyzed with a fast-ion D-alpha (FIDA) spectroscopy diagnostic, recently installed in AUG. Through charge exchange reactions with neutrals present along an NBI line, fast-ions receive a bound electron and can then emit Balmer alpha radiation with large Doppler shifts, due to their high velocities.

Figure 1 illustrates the geometry setup of the FIDA diagnostic at AUG which uses

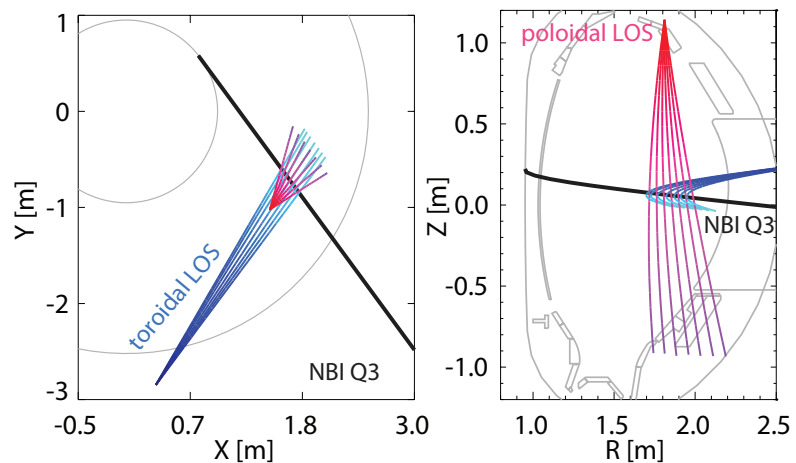


Figure 1: Top-down and poloidal view of the AUG FIDA geometry. The toroidal LOS are plotted in blue, the poloidal ones in purple and NBI Q3 in black.

both poloidal and toroidal lines of sight (LOS) to collect this radiation. The LOS intersect a 2.5 MW heating beam, named Q3, at various locations and thereby permit radially resolved measurements. The spectra obtained from the LOS can only be analyzed at large wavelength shifts (at 660 - 661 nm) because the FIDA radiation for wavelength close to 656.1 nm coincides with strong radiation from beam and thermal neutrals (beam emission and halo radiation) and by D-alpha radiation from the plasma edge [1]. This defines the region of the velocity space accessible by a given LOS as large Doppler shifts are mainly observed from fast-ions propagating parallel to the LOS. The toroidal LOS consequently measure co-rotating fast-ions while the poloidal LOS are sensitive to the fast-ions with large gyro orbits.

The velocity space observed by a central toroidal and poloidal LOS is depicted in figure 2 as a function of energy and pitch ( $pitch = v_{||}/v$  where  $v_{||}$  is the fast-ion velocity parallel to the magnetic field). In addition to the so called weight function, the velocity space distribution of fast-ions from NBI Q3, present in the measurement volume of the two LOS, is plotted in gray shades. The overlap with the weight function shows that both views of the FIDA diagnostic can analyze fast beam-ions in the energy range above 30 keV.

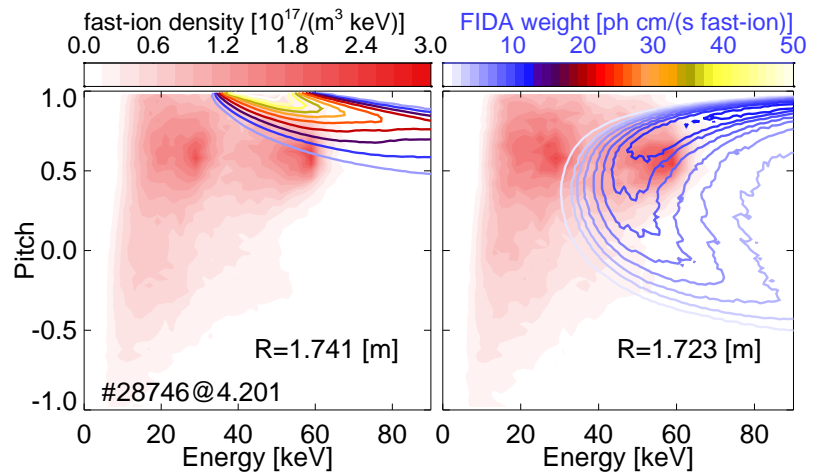


Figure 2: Weight function of a toroidal (left) and a poloidal LOS (right) for wavelengths between 660 and 661 nm. A theoretical distribution of fast-ions from NBI Q3 (60kV) is shown in shades of red.

### Fast-ion transport in the presence of sawtooth crashes

The temporal resolution of the FIDA diagnostic (2 ms) allows the investigation of the fast-ion confinement in the presence of MHD instabilities. In particular after sawtooth crashes, a significant radial fast-ion redistribution can be observed. Figure 3 shows the temporal evolution of radial FIDA intensity profiles from the toroidal and poloidal LOS that are calculated by integrating the measured spectra per LOS in wavelength and by subtracting a constant offset,

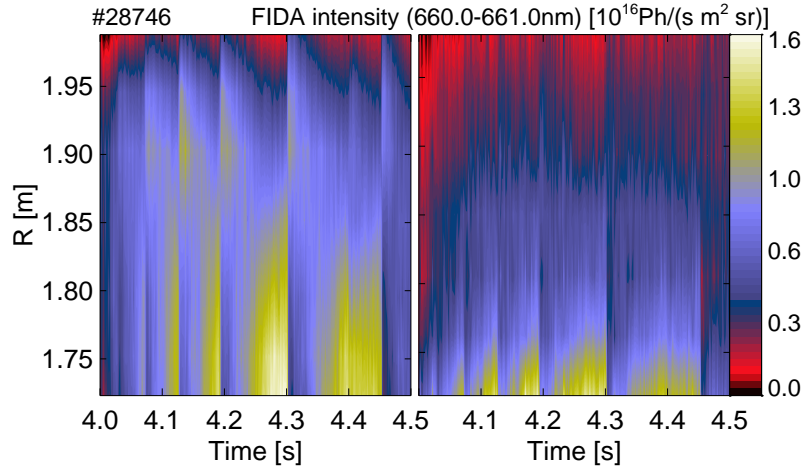


Figure 3: Temporal evolution of radial FIDA intensity profiles from the toroidal LOS (left) and poloidal LOS (right) for wavelengths between 660 and 661 nm.

originating from passive radiation. The data was acquired in discharge #28746, which was performed with a magnetic field of -2.5 T, a plasma current of 1 MA and with 2.5 MW of NBI heating from Q3. Sawtooth crashes appear with a period of roughly 100 ms and cause strong

reduction of the FIDA signal at  $R \sim 1.7$  m<sup>1</sup> and an increase at  $R \sim 1.9$  m (mainly observed by the toroidal LOS).

A quantitative interpretation of this observation is, however, difficult because the data also depends on the density of neutrals present along the NBI path, the charge exchange probability and on the amount of D-alpha radiation emitted by a neutralized fast-ion before it is lost or re-ionized. For this reason, the measurement is compared to predicted fast-ion distribution functions from TRANSP [2] that are translated into spectra and radial profiles by FIDASIM [3].

A comparison between the measurement (symbols) and simulation (lines) is given in figure 4. The fast-ion redistribution due to the sawtooth crash has been calculated with the TRANSP code including the Kadomtsev model [4] to account for the heat and particle transport caused by the magnetic reconnection during the crash. The black solid lines represent the simulation before the sawtooth crash for the

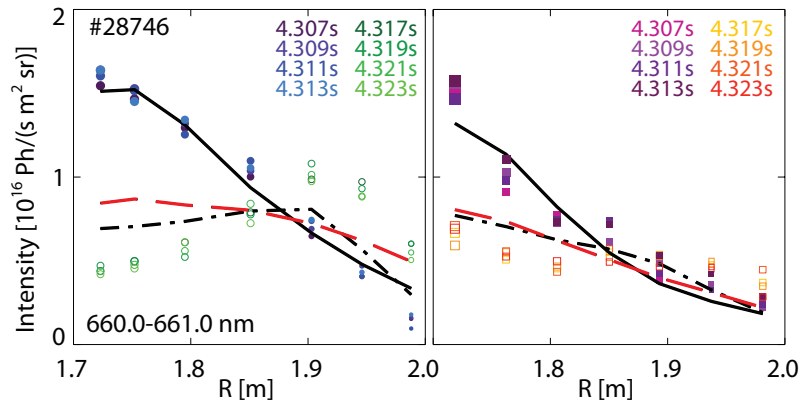


Figure 4: Measured and simulated radial FIDA intensity profiles for the toroidal (left) and poloidal (right) LOS before and after a sawtooth crash.

toroidal (left) and poloidal (right) LOS. Excellent agreement is obtained. The two black dashed lines correspond to the time points after the sawtooth crash. They agree with the observed strong reduction of the FIDA radiation in the plasma center which proves that the TRANSP predicted redistribution of more than 50% of the central fast-ion population is valid. Outside the sawtooth inversion radius, however, the increase of the FIDA radiation, measured by the toroidal LOS, is not very well matched. This can possibly be explained by a fast-ion redistribution in the velocity space that is not correctly described in the Kadomtsev model.

### Fast-ion transport in MHD-quiescent discharges

In addition to the neo-classical predictions from TRANSP (black lines in figure 4), simulated FIDA profiles for the time before the sawtooth crash using an anomalous fast-ion diffusion of  $0.5m^2/s$  are shown in red. This simulation clearly does not agree with the data indicating that the fast-ions are well confined, with the exception of the sawtooth instability. In order to check this result, the decay time of the redistributed fast-ion population after the sawtooth crashes has been analyzed.

<sup>1</sup>The magnetic axis is situated at  $R=1.7$  m and the separatrix is situated  $R=2.15$  m (mid-plane).

Figure 5 shows on the left the evolution of the fast-ion density calculated from the measurement of the toroidal LOS. The charge exchange and photon emission probability of fast-ions has been derived using beam and halo neutral densities from FIDASIM

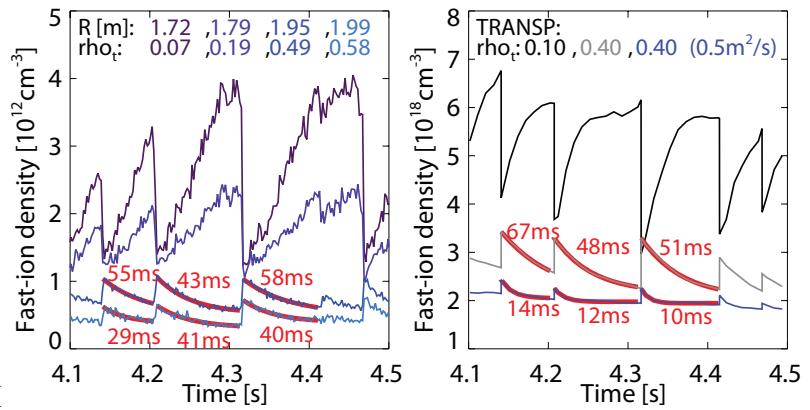


Figure 5: Measured (left) and simulated (right) evolution of the fast-ion density. The channels outside the sawtooth inversion radius are fitted by an exponential function (red). The simulated fast-ion density shown in blue represents an anomalous fast-ion transport of  $0.5 \text{ m}^2/\text{s}$ .

and a TRANSP predicted fast-ion velocity distribution. The density evolution of the two channels outside the sawtooth inversion radius has been fitted by an exponential function (red) which yields decay times

that range from 30 ms to 60 ms. These times can now be compared to the TRANSP predicted evolution of the fast-ion density shown on the right of figure 5. The data outside the sawtooth inversion radius ( $\rho_t = 0.4$ , gray) shows decay times similar to the measurement. In contrast, the simulation shown in blue, representing an anomalous fast-ion diffusion of  $0.5 \text{ m}^2/\text{s}$ , yields significantly smaller decay times in the range of 10 -20 ms. This again suggests that the fast-ion transport in between the sawtooth crashes is, as expected, dominated by collisions only.

## Summary and Outlook

The FIDA diagnostic at AUG permits the analysis of the confinement of NBI generated fast-ions with high temporal and spatial resolution. Strong fast-ion redistribution has been observed in the presence of sawtooth crashes and comparisons to the Kadomtsev model (TRANSP) show reasonably good agreement in the plasma core. In the absence of the sawteeth, two different analysis techniques evidence a neo-classical fast-ion transport. In future investigations, the FIDA measurements will be compared to the data from fast-ion loss detectors (FILD) and neutral particle analyzers (NPA). Furthermore, a tomographie approach using multiple LOS geometries will be applied to obtain a better velocity space resolution of the measurement.

## References

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