

Investigation of the fast-ion transport by FIDA spectroscopy at ASDEX Upgrade

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Introduction

The fast-ion confinement is of special interest for future fusion devices because fast-ions significantly contribute to plasma heating and current drive and can, if poorly confined, even damage the first wall. Produced by fusion reactions and external heating systems such as neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH), fast-ions can be redistributed or ejected from the plasma by processes such as MHD instabilities [1] or micro turbulence. The so called anomalous transport of fast-ions, related to these processes, must consequently be investigated and understood. A relatively new approach to study the fast-ion confinement is fast-ion D-alpha (FIDA) spectroscopy [2] which analyzes strongly Doppler shifted Balmer alpha radiation ($\lambda_0=656.1\text{nm}$) of neutralized fast Deuterium ions. The so called FIDA radiation can be observed localized along NBI lines thanks to the high density of neutrals that provides a significant probability to neutralize fast-ions through charge exchange reactions. The intensity of the FIDA radiation yields information on the fast-ion density. Measured wavelength shifts contain information on the fast-ion velocity distribution.

In this paper we first present the FIDA diagnostic setup at the tokamak ASDEX Upgrade (AUG). Then, a validation of the forward simulation tool F90FIDASIM is presented which is required to interpret the measurements as FIDA spectroscopy only yields convoluted signals. Finally, investigations of the radial fast-ion transport during on- and off-axis NBI heating and observations of the fast-ion redistribution caused by sawtooth crashes are presented.

Experimental setup

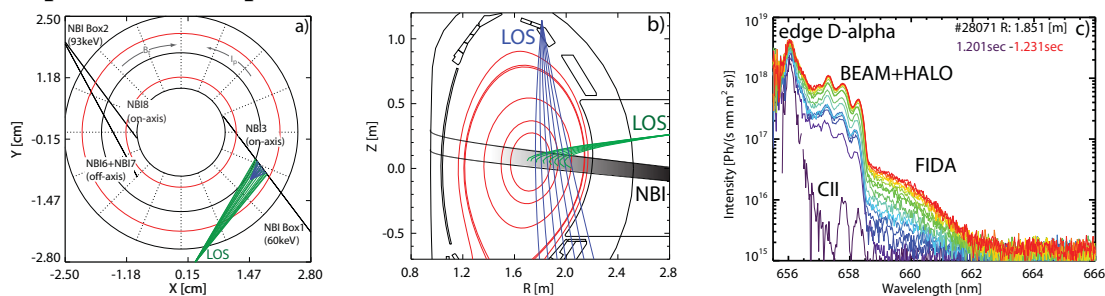


Figure 1a+b) Radial and top-down view on the AUG tokamak with the toroidal (green) and poloidal (blue) LOS of the FIDA diagnostic. c) Spectra observed after turning on NBI3 (60keV) in addition to NBI8 (93keV)

The FIDA diagnostic at AUG consists of 15 toroidal lines of sight (LOS) [3] and has recently been upgraded with 11 additional poloidal LOS. Figures 1a and b show the geometry of the LOS which are focused on a 2.5MW heating beam (NBI3). The system has a time resolution of 2ms and is optimized for wavelengths above 656nm because mainly red-shifted FIDA

radiation is observed due to the geometry of the LOS and the NBI. Figure 1c shows spectra before and after turning on NBI3. Without NBI3, only passive line radiation from the plasma edge and Bremsstrahlung are present. With NBI3, the active radiation becomes visible which consists of the beam, halo and FIDA radiation. Figures 2 a and b show so called weight functions [3] of a toroidal and poloidal LOS that display the part of the velocity space that can be observed by the diagnostic between 660.5nm and 661.5nm. While the toroidal LOS mainly observe co-rotating fast-ions, the poloidal LOS observe fast-ions with smaller pitch angles (pitch= $v_{\parallel}/v_{\text{tot}}$). Additionally, figures 2a and b show a theoretical velocity-space distribution of fast-ions injected by NBI3. The velocity space distribution has a larger overlap with the poloidal weight function than with the toroidal one. Consequently we typically observe between 660.5nm and 661.5nm a larger level of FIDA radiation in the poloidal spectra than in the toroidal spectra (see figure 2c).

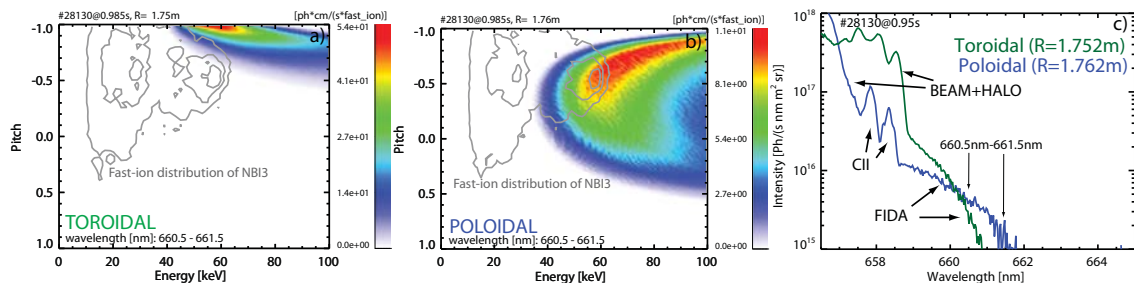


Figure 2a+b) Theoretical velocity distribution of fast-ions from NBI3 (gray) and toroidal and poloidal weight-functions (in color) c) Active spectra (background subtracted) of fast-ions injected by NBI3.

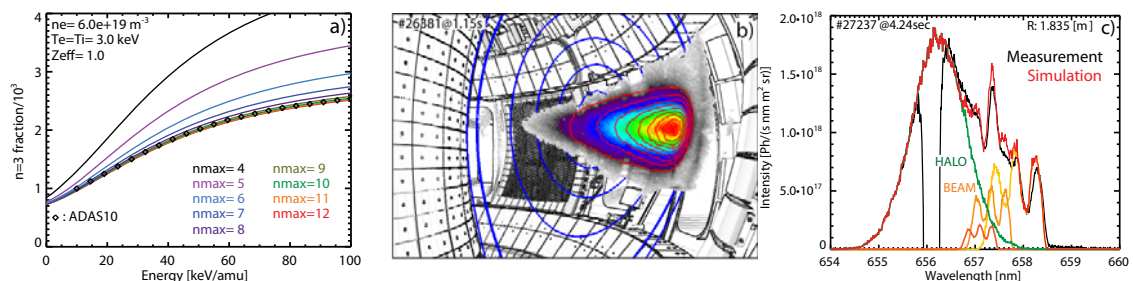


Figure 3a) Population of the n=3 state relative to the n=1 state from F90FIDASIM and ADAS [5] b) Beam-imaging measurement of NBI3 compared to the beam and halo radiation simulated by F90FIDASIM. c) Comparison of a measured active spectrum (BES) to the simulation of the beam and halo radiation.

Validation of F90FIDASIM

The Monte Carlo code F90FIDASIM (originally FIDASIM [4]) is used at AUG to predict synthetic FIDA spectra from a given fast-ion distribution function. Before modeling the FIDA radiation, the code calculates the radiation and density of beam and halo neutrals which are needed to determine the charge exchange probability of fast-ions. The attenuation, excitation, and photon emission of beam, halo and fast (FIDA) neutrals is calculated in F90FIDASIM by a time-dependent collisional radiative model that has been compared to the one provided by ADAS [5]. As can be seen in figure 3a, a good agreement is obtained in the relative population of the n=3 state of beam neutrals when simulating up to 12 excited states. The

geometry of NBI3 has been verified using a beam imaging diagnostic that observes the beam and halo radiation of NBI3. Figure 3b shows, on top of a CAD image of AUG, a measured image of the diagnostic from which the passive radiation has been subtracted. In addition, the beam and halo radiation predicted by F90FIDASIM are displayed with red contour lines which indicate a very good agreement between the measurement and the simulation. Figure 3c compares a spectrum measured by a beam emission spectroscopy diagnostic that uses toroidal LOS situated next to the FIDA diagnostic [6] to F90FIDASIM. Clearly, the shape and the absolute intensity of the measured spectrum agree very well with the simulation. This shows that F90FIDASIM consistently models the spectra and the density of beam and halo neutrals. Furthermore, this result also validates the simulation of the FIDA radiation because the code employs the same geometry, algorithms and cross sections when calculating the radiation emitted by fast neutrals.

Investigation of on- and off-axis NBI profiles

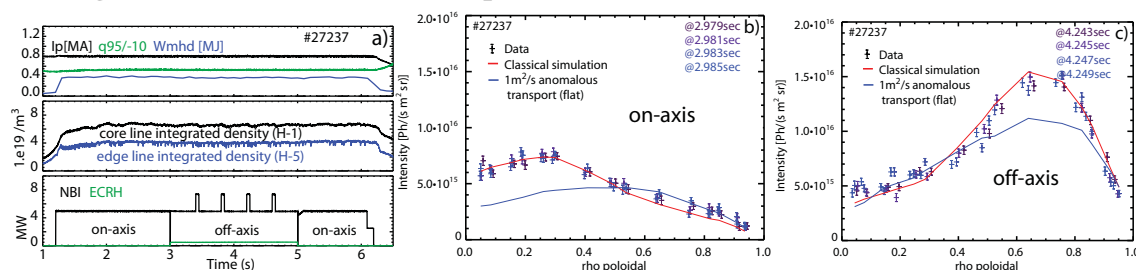


Figure 4a) Time traces of discharge #27237 b+c) Measured and simulated radial FIDA intensity profiles during on- and off-axis NBI assuming classical (red) and anomalous fast-ion transport (blue) of $1\text{m}^2/\text{s}$.

AUG has a powerful and flexible NBI heating system that allows the study of the confinement of fast-ions injected with different energies, pitch angles, and vertical positions. Of special interest is the confinement of fast-ions produced by the off-axis sources NBI6+7 (figure 1a) because previous experiments indicated a weaker off-axis character of current drive from these sources than expected [7]. The FIDA technique now enables us to clarify if this discrepancy is caused by a significant amount of anomalous transport of fast-ions. Discharge #27237 was performed similarly to the previous experiments with a toroidal magnetic field of -2.5T , a plasma current of 800kA and with about 5.5MW of total heating power (figure 4a). Between 3 and 5 seconds, 5MW of on-axis NBI is replaced by 5MW of heating power from the two off-axis NBI sources plus short pulses from NBI3 needed for the FIDA technique. Figure 4b and c show radial FIDA intensity profiles that were measured at 2.982s and 4.246s during weak MHD activity. The profiles, which correspond to fast-ions with energies above 25keV , have been calculated by integrating the FIDA radiation per LOS between 659.5 and 661.0nm . As can be seen, the shape of the profiles clearly illustrates the on- and off-axis character of NBI heating. In addition, figures 4b and c show simulated profiles from F90FIDASIM that correspond to TRANSP predicted fast-ion distribution functions representing a classical (red) and a non-classical behavior (blue) of fast-ions. The good agreement between the measurement and the classical simulation indicates that, in the

presence of only weak MHD activity, the anomalous fast-ion transport is well below $1\text{m}^2/\text{s}$. This now opens new questions regarding the current drive efficiency of off-axis NBI.

Redistribution of fast-ions by sawtooth crashes

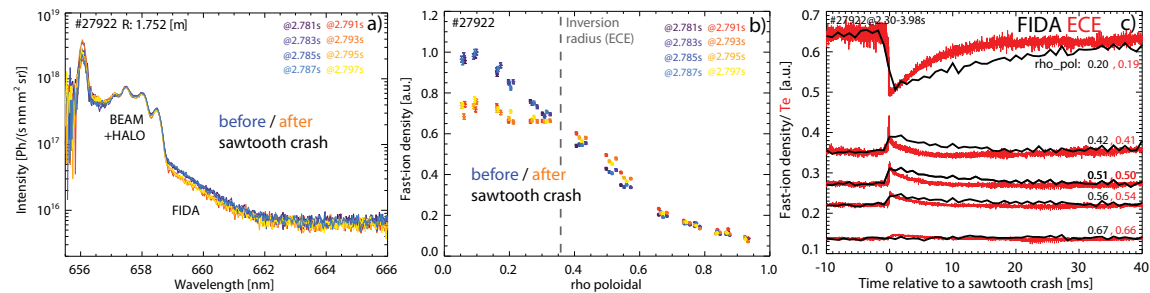


Figure 5a+b) FIDA spectra of a central LOS and fast-ion density profiles before and after a sawtooth crash c) Time averaged temporal evolution of several channels of the FIDA and the ECE diagnostic.

In the presence of sawtooth crashes, a significant redistribution of passing fast-ions can be observed with the FIDA diagnostic. Figure 5a shows spectra of a central LOS before and after a sawtooth crash that were observed in a discharge with 5MW of on-axis NBI heating. After the crash, the FIDA radiation is clearly reduced while the beam and halo radiation remain unaffected. Radial density profiles of fast-ions are shown in figure 5b. The profiles have been calculated by integrating the FIDA radiation per LOS between 659.5nm and 661.0nm and by estimating the density of neutrals that can charge exchange with fast-ions from the beam and halo radiation contained in the spectra. As can be seen, the central fast-ion density is reduced while, at mid radius, an additional off-axis contribution becomes visible. This observation is in agreement with theory because sawtooth crashes are expected to eject passing fast-ions from the plasma center. The coherently time averaged temporal evolution of several channels of the FIDA diagnostic is shown in figure 5c. In addition, the coherently time averaged evolution of the electron temperature (ECE) is shown in red color which has been measured at radial positions similar to the FIDA measurement and which has been normalized to the fast-ion densities before the sawtooth crash. The temporal behavior of the fast-ions is similar to that of the electrons which can be explained by the energy transfer of the fast-ions to the electrons. Furthermore, no significant radial propagation of the additional off-axis contribution is observed which might indicate a classical fast-ion behavior between sawteeth. In future experiments, also changes of the velocity distribution of fast-ions will be studied as the newly installed poloidal LOS have proven to access different regions in the velocity space.

References

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