# Fast-ion transport study in the plasma periphery of ASDEX Upgrade using fast-ion D-alpha spectroscopy

A. Jansen van Vuuren[1], B. Geiger[1], P.A. Schneider[1], A.S. Jacobsen[1], K. Mitosinkova[2],
M. Cavedon[1], and the ASDEX Upgrade and EUROfusion MST1 Teams*
[1] *Max-Planck Institute for Plasma Physics, Garching, Germany*
[2] *Institute of Plasma Physics of the CAS, Prague, Czech Republic*

## Introduction

Good confinement of fast ions is important for fusion devices to ensure efficient plasma heating and current drive. At the edge fast ions can easily be transported to unconfined orbits, become lost and potentially damage first wall components if the losses are localised [1]. Several mechanisms exist that can redistribute fast ions, these are losses due to charge exchange (CX) reactions with background neutrals, stationary perturbations of the magnetic fields (TF-ripple and RMPs) and fluctuations of the magnetic and electric fields e.g. by magneto-hydrodynamic modes. Of these mode-induced transport might be the most critical one.

To investigate the transport effects on edge fast ions, experiments were carried out at the ASDEX Upgrade (AUG) tokamak with on-axis toroidal magnetic field $B_t$ = 2.6 T and plasma current $I_p$ = 0.6 MA. 2 MW of electron cyclotron resonant heating (ECRH) was applied to prevent impurity accumulation with an additional 5 MW of off-axis neutral beam injection (NBI) heating to provide fast ions. The resulting H-mode plasmas had core line averaged densities $n_e$ below $5\times10^{19}$ $\mathrm{m}^{-3}$. Fast-ion $\mathrm{D}_\alpha$ (FIDA) spectroscopy [2] was applied to analyse the fast-ion content. FIDA spectroscopy measures the Doppler shifted Balmer alpha emission resulting from CX reactions between fast ions and donor neutrals. For localised active measurements an NBI beam is used as an active source of donor neutrals. However, line integrated passive FIDA due to CX of fast ions with background neutrals is also present, especially along the edge where the density of background neutrals is highest and decreases inwards as the neutral density rapidly attenuates. During experiments with on-axis NBI heating, the low fast-ion density at the edge generally ensures that passive FIDA does not contribute significantly to the total signal. However, when the edge fast-ion density is increased due to the shallower beam deposition of off-axis heating or expulsions of fast ions from the core, the passive FIDA intensity can become comparable to the active FIDA intensity. This complicates the analysis of local fast-ion densi-

---

*See author list of "H. Meyer et al, Nucl. Fusion **57** 102014 (2017)" ties and needs to be addressed to correctly interpret the measured signal. In addition, passive FIDA contains useful information, not only on edge fast-ion densities but also on the background neutral density. In this paper we report on passive FIDA as a tool to investigate edge fast-ion transport as well as to gain knowledge on the neutral density, with specific emphasis on the effect of edge localised modes (ELMs).

## Experimental Results and Analysis

The standard FIDA system at AUG has a set of lines of sight (LOS) that view NBI beam Q3 out to R=2.005 m. To extend measurements across the edge an existing CX spectroscopic system was made use of, that is otherwise used for edge impurity ion measurements. The system has 19 toroidal and 4 poloidal LOS closely spaced to provide a high radial resolution across the plasma pedestal. The spectral range of the spectrometer was adjusted to measure the blue shifted FIDA spectra from 647 to 656 nm. The spectrometer is a f/4 Czerny-Turner like design with a Princeton Instruments 512ProEM CCD camera with exposure time set to 2.3 ms [3].

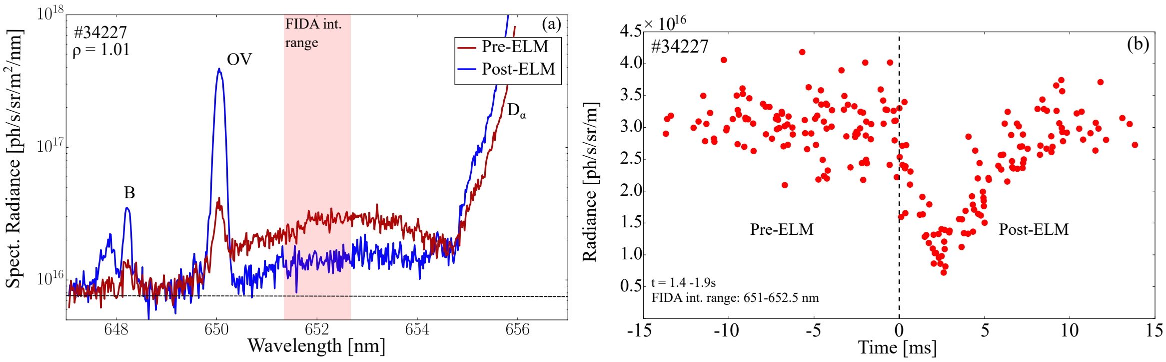

Figure 1: (a) ELM averaged spectra measured by the edge CX system for a single channel, showing pre- and post-ELM averaged spectra. (b) Integrated passive FIDA synchronized with respect to the closest ELM crash. Negative times indicate time before an ELM crash and positive after an ELM crash.

Figure 1(a) shows two conditionally averaged spectra from measurements on a toroidal LOS tangent to $\rho_{pol}$ = 1.01. The red spectrum is the average of frames 4 to 2 ms before an ELM crash, while the blue spectrum is the averaged spectrum of frames measured 2 to 3 ms after an ELM crash. The data shown is from a 0.5 s window of ELM activity with a quasi regular period of around 20 ms. The wing of the $D_\alpha$ emission line is visible on the right, with the bulge shaped feature from 651 to 655 nm due to passive FIDA. Some impurity lines, most noticeably $OV$, are also present. The passive FIDA measured during these discharges was comparable in intensity to the active FIDA (measured during 50 ms beam blibs of Q3) motivating a thorough analysis of the passive FIDA, especially since it was observed that the passive FIDA signal was not static. ELMs were observed to have a clear effect on the passive FIDA as can be seen in the difference

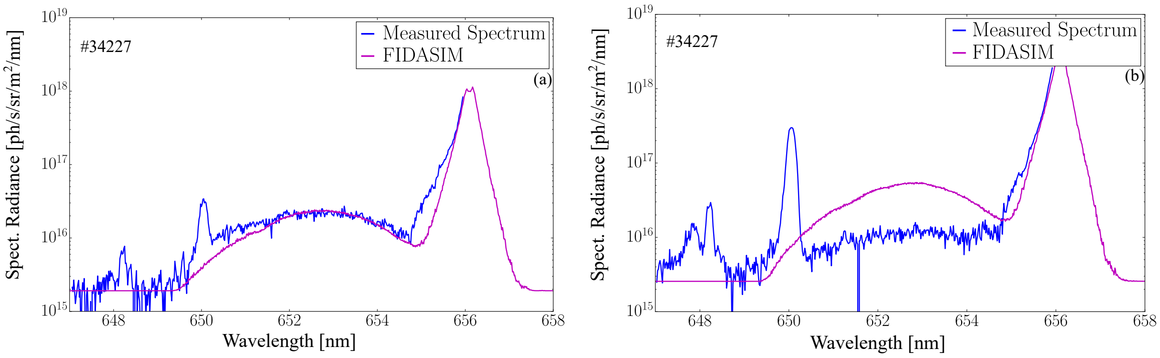

Figure 2: (a) Comparison of synthetic FIDASIM spectrum with ELM averaged pre-ELM spectrum. (b) Comparison of synthetic FIDASIM spectrum with ELM averaged post-ELM spectrum.

between the spectra in figure 1(a). The passive FIDA is lower after the ELM crash while the impurity lines, especially O*V* shows a large increase following the crash. Synchronizing the spectrum integrated passive FIDA (highlighted in red) according to the nearest ELM crash as shown in figure 1(b) demonstrates this behaviour clearly. The passive FIDA reaches a minimum at half the pre-ELM intensity after 2 ms. The signal slowly recovers 3 ms after the crash reaching pre-ELM intensities around 7 ms after the crash. The sharp intensity spikes of impurity lines accompanying the ELM crashes are due to the electron density increasing in the scrape-off layer (O*V* should radiate at about 100 eV). On the other hand, the passive FIDA signal depends on both the background neutral and fast-ion density behaviour during the ELM.

## Neutral and Passive FIDA Modelling

Neutral modelling was carried out with the 1D neutral transport code KN1D [4], that calculates the neutral density profile given the plasma kinetic profiles and the neutral pressure near the wall as measured with a manometer at the outer midplane. With the toroidal LOS from the CX system not deviating poloidally far from the outer midplane, this 1D approach should be reasonable despite the fact that the neutral density varies in the poloidal plane. FIDASIM [5] was expanded to calculate the spectral component produced by CX emission of the bulk plasma with background neutrals. With the bulk ion density (inferred from the electron density) known across the edge, the neutral density profiles could be evaluated through forward modelling, and comparing the calculated thermal spectrum with the measured data. The neutral density profile were then scaled to match the thermal $D_\alpha$ emission.

With the neutral density fixed the passive FIDA can be addressed unambiguously using FIDASIM. Theoretical fast-ion distributions were obtained from the TRANSP code [6]. TRANSP is able to account for fast ion CX losses considering an internally calculated neutral profile from its FRANTIC module. For analysis the TRANSP neutral density was adjusted to match the KN1D neutral profiles in order to have realistic CX losses. FIDASIM was further expanded to extrapolate the TRANSP fast-ion density across the separatrix by applying an exponential decay fitted to the last 2 cm inside the seperatrix across the poloidal cross section. This was necessary since the LOS view mostly the SOL. The extrapolation was in good agreement with fast-ion density calculated by the full orbit fast ion code LOCUST [7]. Figure 2(a) shows the spectrum calculated by FIDASIM for the thermal and passive FIDA emission before the ELM. The calculated spectrum matches the measured spectrum very well. Figure 2(b) shows however the passive FIDA is over estimated for the post-ELM case. The mismatch cannot be contributed to a change in the neutral density which must increase to match the thermal emission hence indicating an overestimation of the fast-ion density by TRANSP. Being a neo-classical code it implies an additional fast-ion transport induced by the ELMs.

## Conclusions and Outlook

Low density experiments were performed at AUG with 5 MW of off-axis NBI heating that show high fast-ion densities at the edge. During those experiments strong CX losses were observed by a FIDA diagnostic that measured intense signals originating from CX reactions between fast ions and background neutrals. The experimental measurements show a clear modulation of the passive FIDA signal during ELMs. This is explained by fast-ion losses from the SOL, as has been observed with fast-ion loss detectors [8]. In the next AUG campaign a new edge FIDA spectrometer will measure simultaneously the FIDA and the cold $D_\alpha$ emission that will allow for the analysis of the fast-ion and neutral density along the same LOS, with acquisition times down to 100 $\mu$s. Fast edge kinetic profiles are also expected to be available with a new high speed helium beam diagnostic. Techniques to analyse the neutral profile from data aquired with neutral particle analysers is also being developed.

## Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

## References

[1] A. Fasoli et al., Nuclear Fusion **47** (2007).
[2] W.W. Heidbrink et al, Plasma Phys. Control. Fusion **46**, 12 (2004)
[3] M. Cavedon, Dissertation, TU München, 2016
[4] B. LaBombard, Plasma Science and Fusion Center Research Report PSFC-RR-01-3, (2001)
[5] W.W. Heidbrink et al, Commun. Comput. Phys. **10**, 3 (2011)
[6] A. Pankin et al., Computer Physics Communications **159**, 157-184 (2004)
[7] R. J. Akers et al., $39^{th}$ EPS Conference & $16^{th}$ Int Congress on Plasma Physics, P5.088, (2012)
[8] M. García-Muñoz et al., Plasma Phys. Control. Fusion **55**, 12 (2013)