Diagnosing fast ion redistribution due to sawtooth instabilities using fast ion deuterium-α spectroscopy in the Mega Amp Spherical Tokamak

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Introduction

In a previous study [1] MAST data were simulated with the code TRANSP/NUBEAM, comparing models of sawtooth crashes to experimental neutron camera data. It was found that the data were insufficient to distinguish between the different models. This paper summarises work done to extend the investigation to include fast-ion deuterium-α (FIDA) spectroscopy in an attempt to resolve this. More information can be found in [2].

Background

FIDA can be used to make local measurements of the fast-ion distribution in tokamak plasmas. Charge exchange occurs between deuterium neutrals, injected into the plasma via the neutral beam injection (NBI) system, and the fast-ion population. The resultant fast neutral can be in an excited state, and de-excitation from quantum state n=3 to n=2 generates a Balmer-α photon. The Doppler shift of this photon is determined by the line-of-sight velocity of the original fast ion, so information about the fast-ion distribution can be inferred. To interpret the data we utilise forward modelling with the codes TRANSP/NUBEAM [3, 4] and FIDASIM [5]. TRANSP is a plasma transport and equilibrium solver that with the Monte-Carlo NUBEAM module allows the simulation of NBI systems and the plasma fast-ion population. FIDASIM takes the plasma parameters and generated fast-ion distribution from TRANSP and produces synthetic spectra that can then be compared to the experimental data.

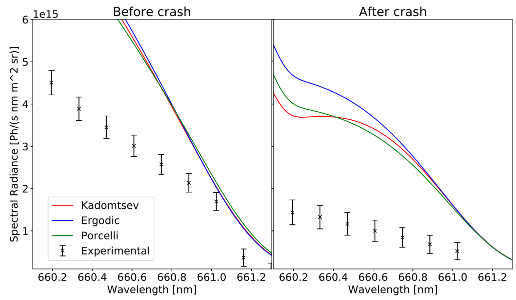

Figure 1: Experimental and synthetic spectra showing the region where FIDA light can be observed at R=1.139 m in plasma midplane. Spectrum contribution from full energy BES peak seen at the lower wavelengths, but discrepancy between the experimental and synthetic spectra persists to higher wavelengths.

Sawtooth instability and modelling

Sawtooth crashes arise from an internal kink instability with toroidal mode number $n = 1$ and dominant poloidal mode number $m = 1$. They are characterised by a sudden flattening of temperature and density profiles in the core of the plasma [6], triggered by the safety factor q dropping below 1 in the plasma core. The sawtooth instability and its interaction with the fast ion population is of interest to the development of ITER plasmas, as crashes can degrade the quality of the fast ion confinement or more generally cause redistribution in both configuration and velocity space, in particular an expulsion of fast ions from the sawtoothing region [7]. TRANSP implements models to account for the effect of sawtooth crashes on the plasma. The three investigated by [1] were the Kadomtsev, Ergodic Kadomtsev, and Porcelli models. The Kadomtsev and Ergodic Kadomtsev (hereafter referred to as 'ergodic') models both feature complete reconnection: $q \geqslant 1$ everywhere in plasma after crash. In the Kadomtsev model plasma is mixed according to helical flux matching, in the ergodic there is a general mixing within the sawtoothing region. The Porcelli model features incomplete reconnection: $q(r = 0) < 1$ after crash. The TRANSP data used in this study were the same as those used in [1].

Analysis

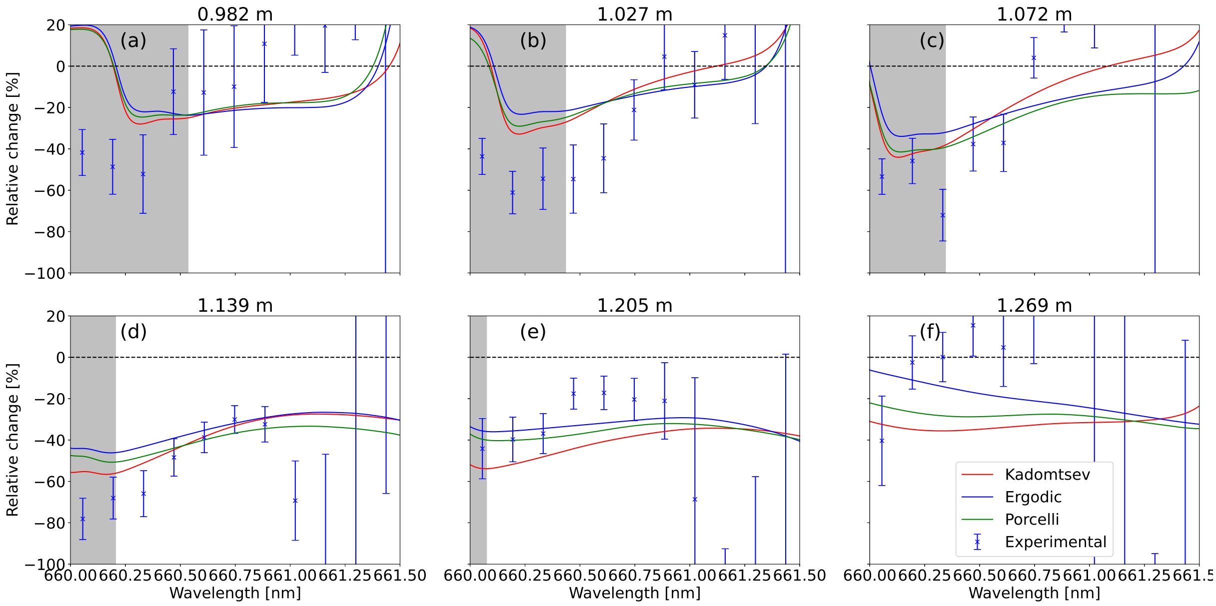

Figure 2: Relative change in spectral radiance across a number of FIDA channels. The grey shaded area in plots (a)-(e) designates where the effect of the BES peak has a significant effect on the synthetic data, so direct comparisons between the observations and the models cannot be made here.

The data from three MAST pulses (#29880-#29882) were averaged together, then further averaged in time. Averaging between the pulses was appropriate as they were designed to be identical, with a small time-shift to align the investigated crash. It was found generally that there was significant mismatch between the experimental and synthetic results. An example is shown in Figure 1. A possible explanation is discussed further below. It was observed that even in instances of reasonable agreement between experimental and modelled spectra all three models produce very similar synthetic spectra, with typical separation being smaller than the error on the experimental data. It was therefore concluded that FIDA data were insufficient to distinguish which of the three analysed models best suited the experimental data.

Relative change

The significant mismatch between experiment and simulation could be due to problems with the absolute calibration of the diagnostic. Examining the relative change of the FIDA signal after a sawtooth crash allow this source of error to be reduced, and is shown in Fig. 2 for a number of channels. Part of the spectrum in each channel contains unavoidable contamination from the beam emission (BES) peaks, and is shaded in grey. Direct comparison between experiment and simulation is not possible in this region. There is generally reasonable agreement between experiment and simulation across the channels, except for $R = 1.139$ m. Thomson scattering data suggests that the location of the outboard midplane inversion region is approximately 1.16 m. It is hypothesised that the guiding centre approximation made in NUBEAM [4] for tracking particle orbits in the local magnetic field may introduce error in the synthetic spectrum near the boundary of the sawtoothing region. Further investigation would be required to confirm this.

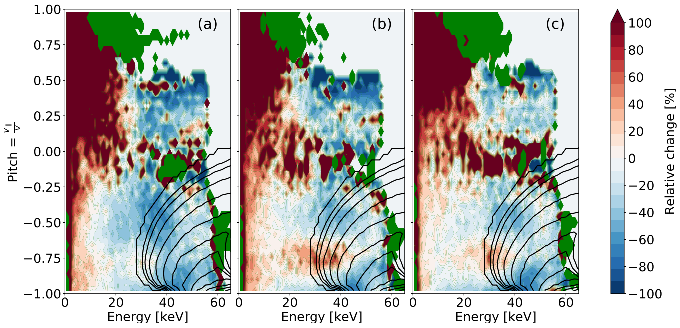

Figure 3: Relative change in modelled fast-ion distribution function for $R = 1.205$m in the midplane. (a) Kadomtsev, (b) ergodic, (c) Porcelli. Green areas represent phase-space regions with a fast-ion presence after the crash that had no presence before. The black contours represent the weight function for the FIDA diagnostic in the fast-ion dominated wavelength range and the spatial location of measurement.

Fast-ion distribution

With reasonably good correspondence between the experimental and synthetic relative change, it is instructive to examine the underlying fast-ion distributions generated by TRANSP. The regions of the distribution that the diagnostic is sensitive to are described by a *weight function*, a measure of the probability that a charge exchange reaction results in the emission of a photon of a specific wavelength or range of wavelengths, given the line-of-sight velocity of the fast ion. The FIDA diagnostic can only examine regions of phase-space with a non-zero value of the weight function. Figure 3 shows the relative change in the fast-ion distribution for the three models for a channel at $R = 1.205$ m, with the contours of the weight function for this spatial location and for the FIDA dominated wavelength range overlaid. Here we can see significant loss of fast-ions (up to 50%) between energies 45 to 55 keV across pitches between -0.25 and -1 in all of the models, with increases in the ergodic and Porcelli models around pitch -0.75 and energies 25 to 40 keV. This is reflected in the synthetic spectra in Figure 2 (e) with the drop in the Kadomtsev model being the largest, and smaller drops in the other models. In the other channels the weight function primarily intersects the population of newly injected fast ions around 55 keV, so in these channels a smaller change in FIDA radiance due to redistribution of the FI population by the sawtooth is observed.

Summary

Comparing forward modelled synthetic spectra generated with FIDASIM to experimental FIDA data was insufficient to distinguish between three models of sawtooth crashes (Kadomtsev, Ergodic Kadomtsev and Porcelli), as the synthetic spectra generated are similar and in general the differences are smaller than the errors on the experimental data. While there is significant mismatch between the experimental and synthetic data, speculated to be due to calibration issues, looking at relative changes instead of absolute data gives reasonable matches and allows for further analysis. Large drops in the measured spectral radiance are observed which is reflected in all of the synthetic spectra, with minor differences. It is hoped that the additional fast ion diagnostics present on MAST-U may allow for a disambiguation of the sawtooth models. This work was funded partly by the RCUK Energy Programme [grant number EP/T012250/1]. It was also carried out partly within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] M. Cecconello *et. al.*, Plasma Phys. Control. Fusion **60**, 5, p. 055008 (2018)

[2] A. R. Jackson *et. al.*, Nucl. Fusion **60**, p. 126035, (2020)

[3] R. J. Hawryluk, Physics of Plasmas Close to Thermonuclear Conditions, pp. 19–46 (1981)

[4] A. Pankin *et. al.*, Comput. Phys. Commun., **159**, 3, pp. 157–184 (2004)

[5] B. Geiger *et. al.*, Plasma Phys. Control., **62**, 10 (2020)

[6] S. von Goeler *et. al.*, Phys. Rev. Lett., **33**, 20, pp. 1201–1203 (1974)

[7] F. Wising *et. al.*, Plasma Phys. Control., **34**, 5, pp. 853–862 (1992)