Fast-Ion Deuterium Alpha observations of the effects of fast-particle-driven MHD in the Mega-Ampere Spherical Tokamak

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Introduction

Magnetohydrodynamic (MHD) modes driven by fast particles cause losses of these particles from tokamak plasmas [1]. The present work focusses on the effects of low-frequency ($20-50\,$kHz) MHD modes driven unstable by the fast-ion population in MAST plasmas. MAST is a spherical tokamak with typical parameters $R = 0.9\,$m, $a = 0.6\,$m, $I_p = 400-900\,$kA and $B_T = 0.4-0.6\,$T. Fast ions are produced by ionization of two neutral beams which each inject up to 2 MW of NBI power at primary energies of $60-70\,$keV. The beams inject tangentially in the co-plasma-current direction during normal operation; their tangency radius is 0.7 m.

In MAST, low-frequency MHD modes driven by fast ions take two forms. The first of these, the *fishbone*, is an energetic particle mode. Fishbones appear $\sim 50\,$ms after beam switch-on in typical MAST discharges, and are seen as bursts of magnetic activity which evolve over $3-5\,$ms, sweeping down in frequency typically from $50-20\,$kHz. The second mode of interest is the long-lived internal kink, or *LLM*. Although this kink mode occurs within ideal MHD, its stability is modified by the fast-ion population [2]. The mode appears concomitant with the disappearance of fishbones, and evolves slowly in frequency, tracking the plasma rotation. Figure 1 shows the MHD activity in a beam-heated MAST shot. Fishbones occur from 0.15 s, chirping down from $\sim 50\,$kHz. The LLM appears at 0.25 s.

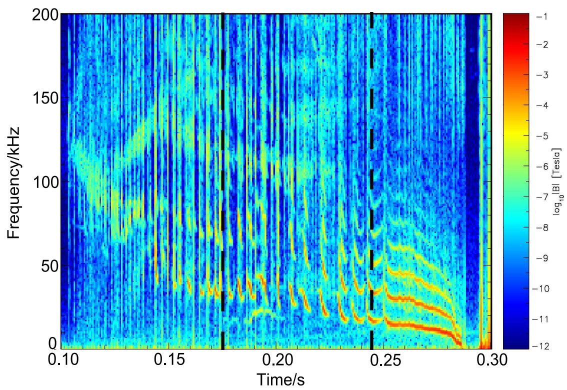

Figure 1: Spectrogram of a beam-heated MAST discharge (#28186) from a Mirnov pick-up coil located on the outboard midplane.

This paper presents the results of a recent Fast-Ion Dα (FIDA) spectroscopic study of the effects of fishbones and the LLM on fast ions in MAST. This is the first systematic study of these instabilities using a FIDA diagnostic. The diagnostic is outlined briefly in the next section.

FIDA diagnostic technique

FIDA spectroscopy was first applied on the tokamak DIII-D in 2004 [3]. Utilising the Balmer alpha light emitted by re-neutralized fast deuterons which undergo charge exchange with beam neutrals, the Doppler shift of the emitted Dα light from $\lambda_0 = 656.1$ nm indicates the fast ion's velocity along the line-of-sight. This line-of-sight velocity is dictated by the ion's energy, pitch and gyro-phase. Each viewing chord samples a bounded region in energy/pitch space determined by the selected wavelength.

The diagnostic on MAST incorporates toroidal and vertical views. Toroidal views observe injected D^0 and co-going fast ions from behind; beam emission and FIDA light are redshifted. These views are nearly parallel to the magnetic field at the point of beam intersection in the plasma core, so are sensitive to passing fast ions. Vertical views, by contrast, are nearly perpendicular to the field in the core and so are sensitive to trapped ions. Observing blueshifted FIDA signal with these chords provides a spectrum free from beam emission and C^+ impurity lines.

We present the results of a study of the effects of MHD modes on the fast-ion population in MAST. Cases were selected in which the magnetic activity was as 'clean' as possible, to isolate the effects of each mode. The spectrogram in Fig. 1 is an example of such a scenario. ELMs, sawteeth and tearing modes are absent from these discharges at the times selected for analysis.

Results and discussion

FIDA spectroscopy on MAST is capable of resolving changes in the fast-ion population with millisecond temporal resolution and spatial resolution ~ 10 cm. Figure 2 shows the signal from core (red) and edge (green) channels. Well-separated fishbones are observed in the Mirnov coil signal (purple) between 0.22 s and 0.26 s. The bursts of magnetic activity cause drops in the core FIDA signal, followed by a period of recovery between events. Such behaviour is consistent with a 'predator-prey' model of the fishbone cycle whereby the fast-ion pressure gradient builds to the point at which the mode is destabilised; the mode redistributes fast ions so that the drive is reduced; the mode is stabilised and decays in amplitude; and the cycle repeats.

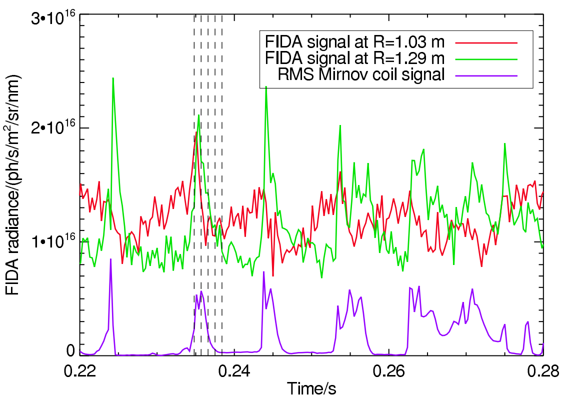

Figure 2: Time trace of FIDA signal at core and edge radii in MAST shot #26863, $\lambda = 660.5$ nm.

The spectral resolution of the FIDA diagnostic provides information about the fast-ion distribution in velocity space. Figure 3 shows the evolution of the FIDA spectrum at $R = 1.03\,\text{m}$ around the time of the second fishbone in Fig. 2. Spectra are plotted at the times marked by dashed vertical lines in Fig. 2. There exists an apparent threshold energy at $\sim 55\,\text{keV}$ above which the fast ions are largely unaffected (the minimum energy contributing to the signal at a given wavelength is shown on the top axis). Below this energy, the signal is depleted on timescales of $1-2\,\text{ms}$. The injection energy of both beams in this discharge is 60 keV.

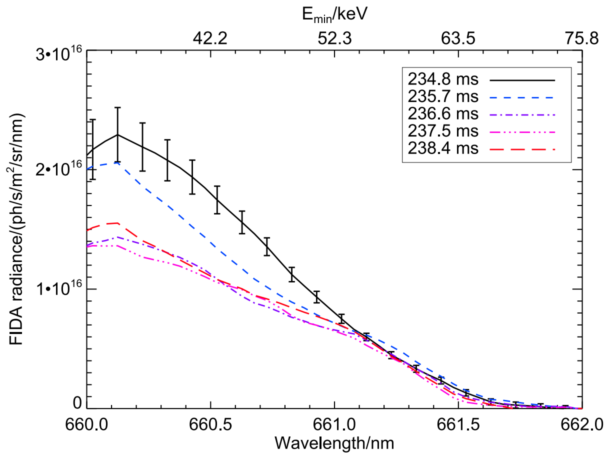

Figure 3: FIDA spectra from a core channel around the time of the fishbone in MAST shot #26863 indicated by dashed lines in Fig. 2.

Since MAST shots are highly repeatable, properties of the ensemble of fishbones may be inferred from repeated shots. Of particular interest is the scaling of the change in FIDA signal with the mode amplitude; studies on JET [4] suggest that the relative change in neutron rate scales with the mode amplitude. A set of fishbones from three nominally identical MAST shots was examined for correlation between FIDA signal and mode amplitude, but none was found ($\rho < 0.1$). The drop in FIDA signal *was* however found to scale with the peak time derivative of the perturbation, $\dot{B}_\theta$. This scaling is unexplained by the model of the interaction between fishbones and fast particles proposed in [5]. Figure 4 illustrates the positive correlation (with one outlier) between drop in FIDA signal and peak amplitude of the Mirnov coil signal.

Further results relevant to the study of fishbones in MAST using FIDA are summarised in a recent publication [6]. We now turn our attention to the effects of the LLM on fast ions.

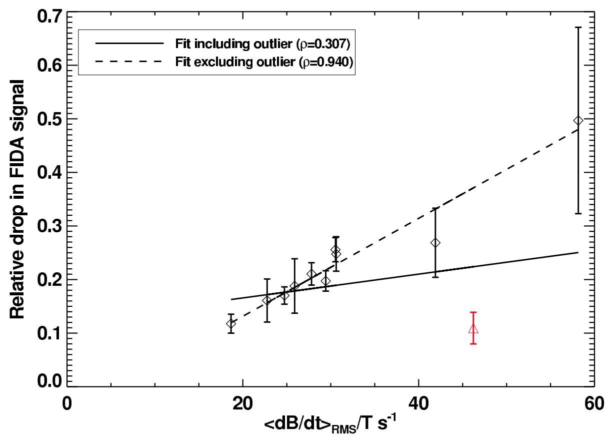

Figure 4: Correlation between relative drop in core FIDA signal and peak RMS Mirnov coil signal for a set of fishbones from nominally identical MAST discharges.

While the kink-ballooning nature of the fishbone [7] implies an extended perturbation spanning much of the minor radius, the onset of the LLM occurs when the minimum value of the safety factor is much closer to unity. This results in an almost purely $n = 1, m = 1$ structure [2] localized in the plasma core. It is expected that the effects on the fast-ion population should be similarly localized. Figure 5 shows radial profiles of the FIDA signal during MAST shot #27527. (a) is the profile before the onset of significant fast-particle-driven MHD. With a fixed factor of

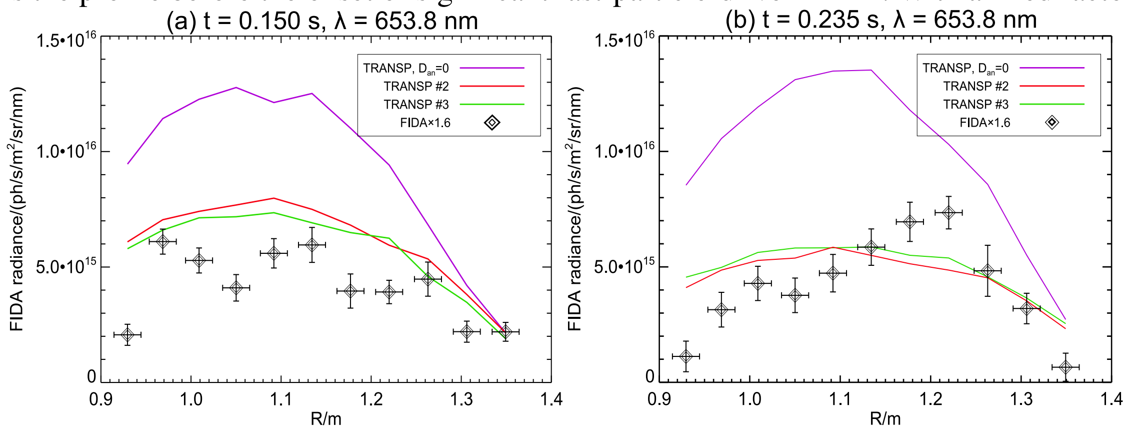

Figure 5: Comparisons of FIDA radial profiles from MAST shot #27527 at the times and wavelength indicated in the subfigure captions. At 0.150 s, only a few, relatively weak, chirping toroidicity-induced Alfvén eigenmodes are present. At 0.235 s however, a LLM is present in the plasma.

1.6 applied to account for systematic calibration errors, the signal magnitude and shape agree approximately with TRANSP predictions including 1.8 $\mathrm{m^2\,s^{-1}}$ anomalous fast-ion diffusion (green curve). In (b), at which time a LLM is present, the profile is suppressed in the core of the plasma compared to the modelled profile with 1.7 $\mathrm{m^2\,s^{-1}}$ anomalous diffusion (green curve).

Conclusions

FIDA spectroscopy has been used to observe redistribution of fast ions by fishbones and the long-lived mode in MAST. The drop in core signal caused by fishbones is correlated with the peak time derivative of the perturbation. The LLM suppresses the FIDA signal in the core of the plasma throughout its duration. TRANSP modelling with spatially flat fast-ion diffusivity is insufficient to account for this behaviour. Work is ongoing to include spatially-varying diffusivity in simulations to attempt to reproduce the measured neutron rate and FIDA signal.

References

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This work was funded by the RCUK Energy Programme under grant EP/I501045 and the European Communities under the contract of association between EURATOM and CCFE. The views and opinions expressed herein do not necessarily reflect those of the European Commission or the ITER Organization.