

Measurements of plasma rotation in the MAST tokamak using high resolution charge-exchange spectroscopy

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Introduction

An attractive feature of the spherical tokamak (ST) is its enhanced stability compared to conventional tokamaks. Indeed, the START tokamak reached a record toroidal beta of 40% [1]. An instability particular to the ST occurs in the form of the internal reconnection event (IRE), which, although causing a significant loss of energy from the plasma, does not usually lead to a disruption. The IRE is one example of an event that may be studied on the MAST tokamak using a high spatial (~ 1 cm) and temporal (5 ms) resolution charge-exchange spectroscopy (CXRS) diagnostic [2]. This system permits the study of the evolution of the ion velocity and temperature profiles in plasmas exhibiting mode locking, sawtooth oscillations and IREs. The sawtooth inversion radius derived from the acceleration profile is in good agreement with the one obtained from the Thomson scattering system. Another phenomenon is the outward propagating fine structure that has been observed on the ion velocity and temperature profiles. The key to studying these phenomena is to overcome various challenges posed to the time-resolved analysis of the charge-exchange data, which will be discussed below.

The MAST CXRS system

The MAST CXRS system has a total of 224 chords, including one set of 64 toroidal chords on each of the two mid-plane heating beams. One of these was an ORNL beam (~ 2 MW) until its recent upgrade to match the other beam, a JET-style PINI, which offers improved focussing characteristics as well as a beam power of 2.5 MW. Each spatial channel is coupled to a single 400 micron hard-clad silica fibre. All chords are coupled to a single, custom-built, high-throughput transmission-grating spectrometer, featuring Canon 200mm/f1.8 and 85mm/f1.2 I/O optics, a large 2600 l/mm grating and a PixelVision BioXight CCD camera with a back-illuminated CCD, 14 bit ADC, 4-tap readout at 2.2 MHz/tap. A narrowband (~ 3 nm) interference filter allows for 7 columns of fibres in the dispersion direction. The system usually measures the CVI $n=8 \rightarrow 7$ line at 5292.05 Å, though it is designed to permit measurement of other lines. Spatial calibrations are performed using a photogrammetry technique, employing an algorithm to match a wire grid model of in-vessel components to a camera picture capturing the images of the backlit optical fibres on the vacuum vessel wall. The instrument functions are obtained by illuminating the collection optics with a frequency-doubled Nd:YAG laser. Previously, a wavelength calibration was obtained by running a xenon glow in the tokamak (Xe II, 5292.22 Å); however, this is soon to be performed using a spectral lamp to illuminate the collection optics.

Time resolved analysis

MAST plasmas typically exhibit an intense, radially extended CVI passive emission shell due to electron-impact excitation and charge-exchange reactions with thermal neutrals. This background component is a severe limitation for time-resolved analysis, as it has to be removed to obtain the net charge-exchange signal. Because of their identical viewing geometry, the only difference in the passive emission measured by the two toroidal collection lenses (in the absence of toroidal asymmetries induced by, e.g., gas fuelling) is due to transmission differences (mainly caused by non-uniform deposits on the vacuum windows) and different instrument functions. When only one beam is operating, or is much brighter than the other, the net charge-exchange spectra may be obtained by subtracting the two sets of spectra. A simple analysis proceeds as follows. First, the spectra are scaled to match up the continuum (bremsstrahlung) emission, which the lenses sample identically. Then, they are convolved with *each other's* instrument functions. Finally they are subtracted and a least-squares Gaussian fit is performed, folding in the convolution of the two sets of instrument functions as the new instrument function. Although this method has proved highly successful, the convolutions performed on the raw data may introduce systematic problems that are difficult to assess quantitatively. A better approach is to reconstruct the passive signal on the active channels by fitting a model to the passive spectra. This has provided more reliable profiles, though the current model of the spectrum is insufficient to adequately reconstruct the passive signals in some cases. The development of a full forward model, which constructs the spectra on all chords given radial profiles of carbon density, temperature, velocity, passive emission from various spectral lines, as well as calibration and beam density information, is well underway. It has already been used to explain unexpected features seen on the intensity distribution of the poloidal channels. Also, it has been used to show that the effect of on-chip smearing is noticeable, though tolerable at present. The model has allowed us to determine the optimal location for a new background lens which is being installed to provide an independent measurement of the passive emission, enhancing the performance in the presence of both heating beams. In addition, it has shown that the results of subtracting the passive from the active data can be severely compromised when using a passive view that is tilted to sample above or below the beam, which has led to this solution not being pursued on MAST. It is intended that this model will be incorporated in a Bayesian analysis platform currently under construction at JET.

Results

The MAST CXRS diagnostic is a very powerful tool for advancing physics studies, through high quality measurements of the evolution of ion temperature and rotation profiles. A number of examples are presented below. Fig. 1 shows false colour plots of the normalised spatial gradients $d/dr(\ln v)$ and $d/dr(\ln T)$ during shot #12533 (L-mode, CDN, 750 kA, 1.6 MW NBI), clearly showing outward propagating structures which appear to follow rational q -surfaces as they evolve in time. The q -surfaces have been obtained from EFIT, so the position of the $q=1$ surface in particular is subject to some uncertainty. The maximum velocity and temperature perturbations are ~ 25 km/s and ~ 100 eV respectively. It is unclear at present what is causing this phenomenon.

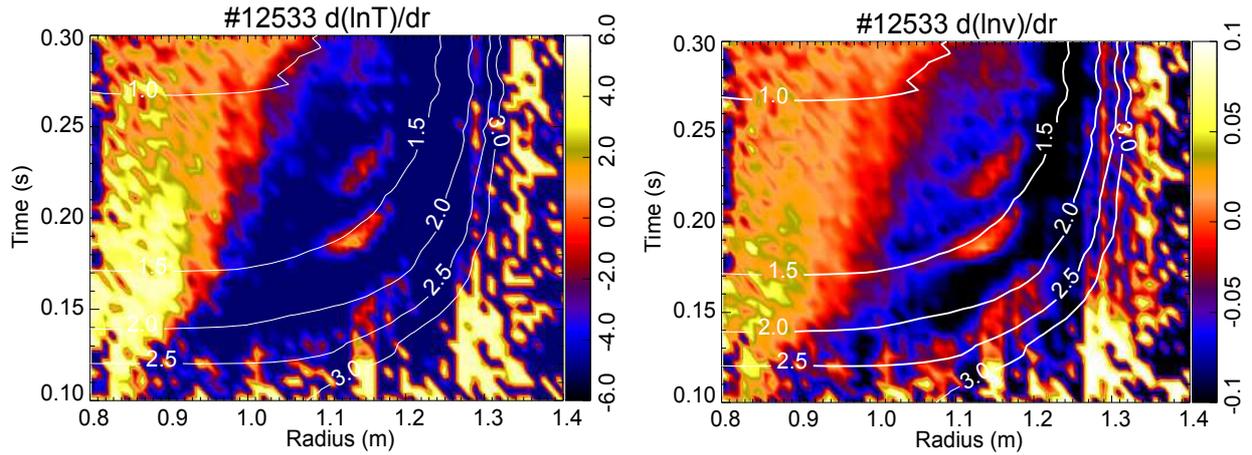


Fig 1: Normalised gradients of ion velocity and temperature, with contours of constant q -value overlaid, clearly showing outward propagating structures. $R/a = 0.82-0.90 / 1.30-1.36$

The plasma rotation velocity has long been known to respond to sawtooth oscillations [3], on a time scale consistent with a magnetic perturbation creating a $\delta\mathbf{E} \times \mathbf{B}$ torque. Following the sawtooth crash, the profile recovers on a diffusive time scale. On MAST, though the time resolution is insufficient to follow the evolution during the crash itself, the high spatial resolution clearly shows the existence of an inversion in the acceleration profile. This is shown in Fig. 2, for shot #13336 (L-mode, SND, 730 kA, 900 kW NBI). The measurement of the temporal evolution during the sawtooth ramp allows transport studies to be made under non-equilibrium conditions. The temperature profile shows similar behaviour, though less pronounced. A deceleration of the plasma inside and an acceleration outside the sawtooth inversion radius are observed during the sawtooth crash, while the opposite occurs during the sawtooth ramp. The inversion radius is found to be 1.16 ± 0.02 m, in good agreement with the Thomson scattering data (1.15 m).

Fig. 3 shows two shots that are very similar initially, but develop differently after the first IRE. In shot #18347, a locked mode and an IRE at 0.331 s reduce the velocity over the entire radial profile, keeping the plasma virtually stationary for 0.14 s without leading to a disruption. Given that the MAST vacuum vessel is so remote from the plasma, it implies that closer conducting structures are almost certainly having an effect on reducing the velocity. Shot #18353 shows mode locking and two IREs. However, in this case, the plasma spins back up repeatedly after each velocity crash. When the ORNL beam switches off

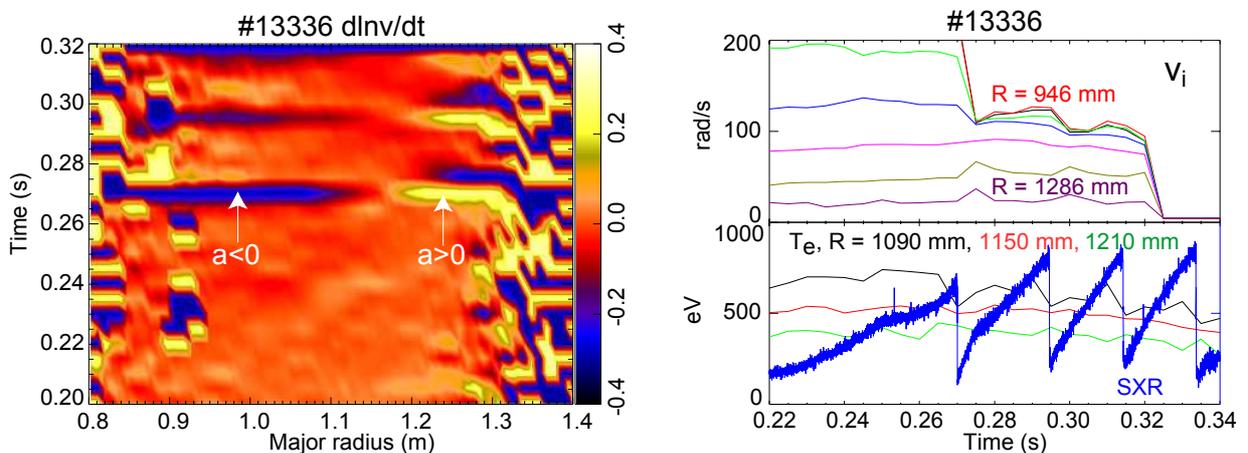


Fig 2: (L) Normalised time-derivative of the rotation velocity, showing a transition from acceleration to deceleration at $R \sim 1.16$ m, at $t = 0.27$ s and $t = 0.29$ s. (R) Time traces of v_i and T_e (top) and SXR (bottom).

at 0.405 s, a sudden drop is observed in the electron and ion temperature as well as the rotation velocity, though the electron density increases and the plasma stored energy shows a much slower decay. The only apparent difference between these two shots is the slightly higher beam power in #18347. Further investigation of these observations is underway to shed more light on the interplay between MHD activity and the transport of heat and angular momentum.

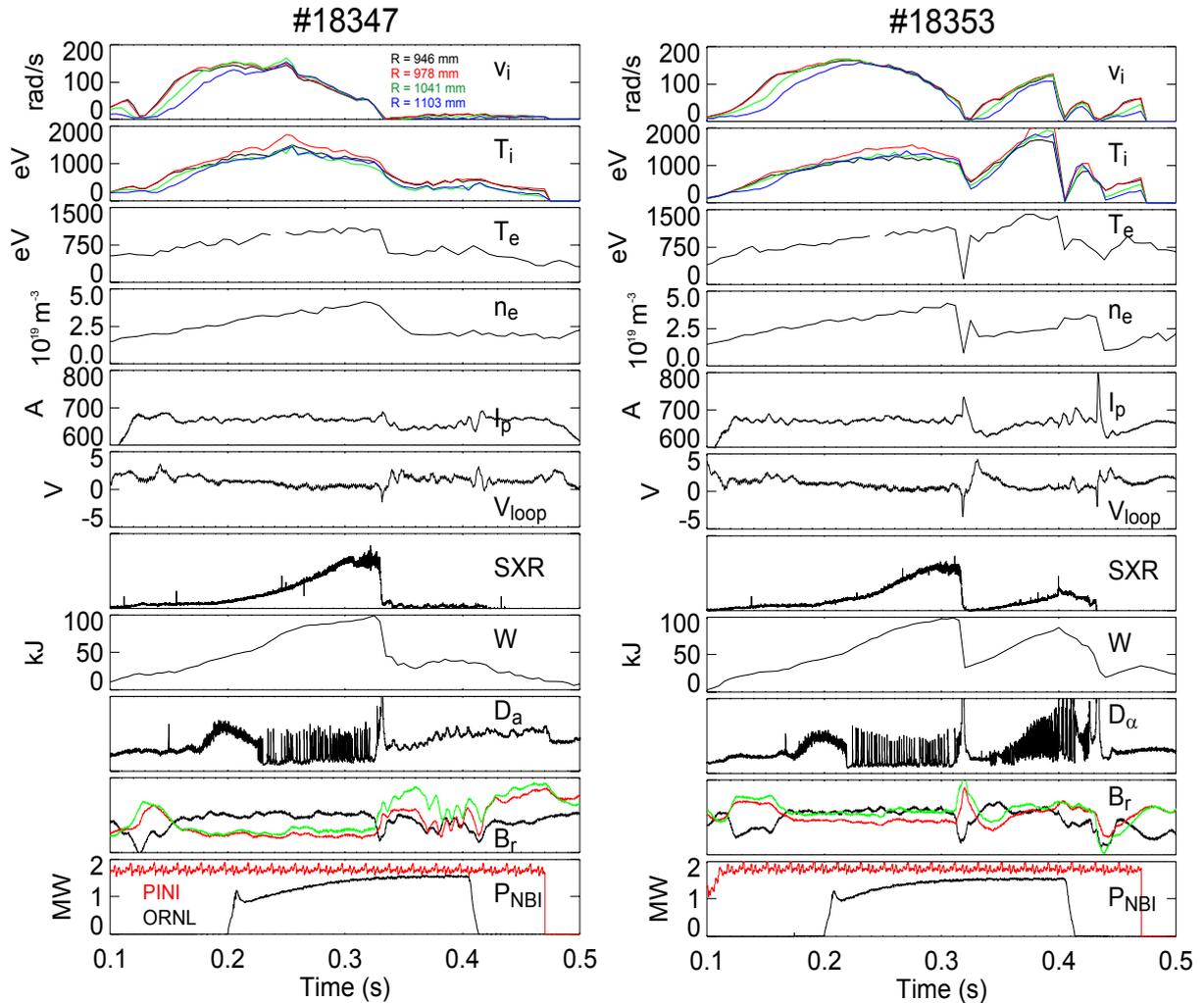


Fig 3: The evolution of v_i and T_i for different spatial channels as well as core T_e and n_e , plasma current (I_p), loop voltage (v_{loop}), soft X-ray (SXR), plasma stored energy (W), D_α , difference in radial magnetic field strength from opposite saddle coil pairs (B_r) and NBI power. Mode locking, followed by an IRE and the loss of H-mode is observed during both shots at around 0.3 s. In shot #18353, however, the mode unlocks whereas in #18347 it does not. Both shots have a CDN configuration.

References

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