On the Neutral Beam Heating of MAST

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Abstract. We present a brief synopsis of the phenomenology associated with Neutral Beam heating (NBI) of the MAST Spherical Tokamak. Results, although at an early stage of analysis, are highly encouraging for the future auxiliary heating capabilities of the device. In particular, only 500-800kW of NBI power (30keV H injection, ~10% of design total) is sufficient to significantly increase T_e and to double the thermal electron pressure. Further, preliminary results indicate that the ion temperature increases by a factor of ~3, qualitatively consistent within systematic errors with that expected, given tolerable fast ion loss and ITER confinement scaling IPB98(y,1). NBI data recorded so far exhibit suprathermal ion tail formation and ohmic discharges a phenomenologically similar tail following Internal Reconnection Events. The injected fast ions, corresponding to 10-50% of the total stored energy, are responsible for driving a wide variety of sporadic, high frequency MHD modes, the low magnetic fields (and hence low Alfvén speeds) inherent to the Spherical Tokamak geometry providing an ideal testing ground for fast-particle MHD theory.

1. Introduction

The Spherical Tokamak (ST) concept, proposed by Peng and Strickler in 1986 [1], is a means by which high β (associated with the RFP and spheromak), can be combined with the confinement properties and magneto-hydrodynamic (MHD) stability of the tokamak. The most successful heating mechanism used to date in the ST is Neutral Beam Injection (NBI) [2]. In this paper, we present a brief report of the experimental data gathered so far using the MAST device, together with a modest ~500-800kW of 30keV H injection [3]. During the first campaign, the South injector alone was operational (at full specification, the two beams are together designed to deliver 5MW of tightly focused 70keV Deuterium). To diagnose the fast ion population resulting from NBI injection, together with changes to the bulk thermal plasma temperature, an E||B Neutral Particle Analyser (NPA) [4], loaned to UKAEA by PPPL, has been installed. The NPA is mounted with a line of sight in the plasma mid-plane at a tangency radius of 0.7m (~1 poloidal Larmor radius inboard of the magnetic axis for 80keV D injection into a typical MAST plasma).

2. Temporal evolution of I_p, T_i, W_e and W_{th}

Figure 1 shows representative H and D spectra for MAST discharge 2932. There is a clear bifurcation in the D spectrum at approximately 6 keV delimiting the formation of a suprathermal tail. This tail is routinely observed in NBI discharges and has an effective temperature and magnitude strongly correlated with sawtooth temporal phase. Also of note is that neutral H flux is routinely observed above the NBI primary injection energy (in this case E_0~32keV). In particular, the tail gradient is often well in excess of that expected due to energy diffusion. A similar phenomenon is also seen following Internal Reconnection Events (IRE) in ohmic plasmas (shown in figure 2 for discharge 2841 containing an IRE at 183ms).

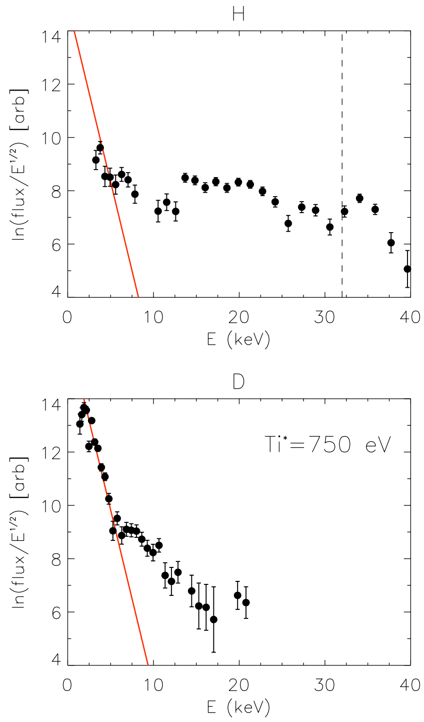

Figure 1 H and D neutral flux spectra recorded using the mid-plane mounted E||B NPA for shot 2932.

Analysis of the relaxation of the tail after the IRE (described in section 3) shows that fast ions subsequently decelerate due to Coulomb collisions. In order to measure the thermal ion temperature in NBI discharges and in the absence of IRE generated tails, it is sufficient to fit D spectra to bins below the bifurcation energy where spectra are routinely linear. For plasmas produced to date, modelling predicts that typically 25-30% of the injected power was channelled directly to the thermal ion population (assuming negligible losses), in this case corresponding to ~194kW of direct ion heating (out of 744kW injected). Figure 3 shows T_i vs. time for discharge 2932. As the beam was turned on, there was a rapid increase in measured temperature; the peak is not yet fully understood, however it may be due to bias from the suprathermal tail at the bifurcation energy or to a hot channel at the upper end of the fit. After approximately 30ms, the measured temperature reached a steady state and in this case exhibited a 3 fold increase compared with that for ohmic discharges. Estimates suggest that ~69kW of electron-ion equipartition heating sustained the ohmic ion temperature of ~250eV, prior to NBI, corresponding approximately to τ_E~19ms (assuming profile similarity and an ion dilution factor of 0.8). This assumes that the electron temperature at the core did not vary significantly between 100ms and 150ms (Thomson Scattering time 120ms). This is clearly an approximation; however, empirically, the core electron temperature does not routinely appear to rise as much during NBI as the core ion temperature recorded by the NPA, the increased electron heating instead manifesting itself as increased electron pressure or an increase in the plasma volume. In the NBI phase of the discharge, the core ion temperature appears consistent with core electron temperature measured from Thomson Scattering (Ti~Te~775eV) and as such corresponds to τ_E ~ 20ms ie. comparable within systematic errors with the ohmic confinement

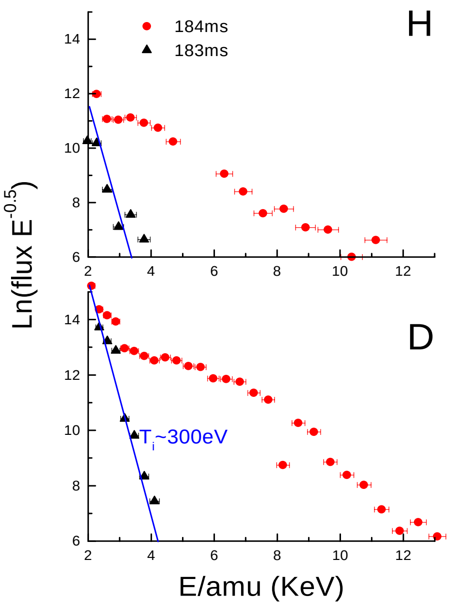

FIG. 2. Ion tail formation following IRE in MAST Ohmic discharge 2841.

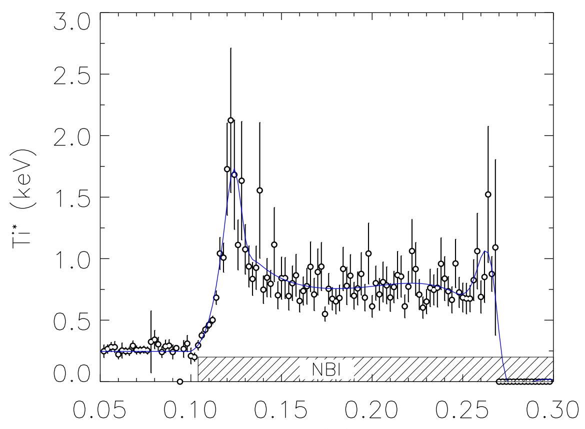

FIG. 3. Ion temperature recorded by the NPA throughout discharge 2932.

time. Confinement times also appear consistent with ITER IPB98 (y,1) predictions for Elmy H-mode plasmas ($\tau_E \sim 17$ms in the NBI phase). The rise in ion temperature due to NBI is thus qualitatively understood (although clearly there are significant systematic errors at this stage in the analysis, particularly due to the transient nature of the discharges, plasma motion etc.). It should be mentioned that a small number of ion temperature measurements determined using Charge Exchange spectroscopy do not appear to register the same rise in T_i as that seen by the NPA. The CX spectrometer on MAST is still being commissioned and does suffer from low levels of core carbon light emission (in part due to the low levels of beam power so far achieved). One should consider the possibility, however, that the thermal ion plasma may not be Maxwellian or isotropic during NBI, especially in the light of large fast ion beta and possible anomalous tail formation.

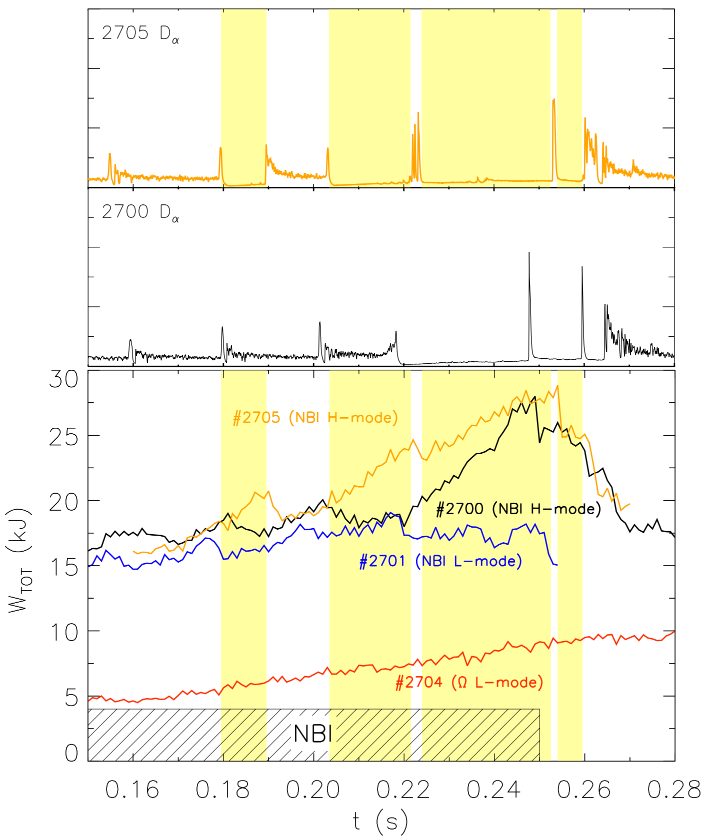

FIG. 4. Evolution of the plasma stored energy in discharge series 2700-2705. The benefit of injecting a modest ~0.5MW of NBI can clearly be seen, in particular for achieving L-H transition.

Where there exist discharges with similarly programmed coil currents, gas-puff and vessel conditioning, one can compare the thermal electron pressures and total plasma stored energies for ohmic and NBI heated plasmas. Work on EFIT calibration is ongoing; even so, the code is capable of providing qualitative information regarding the introduction of NBI. Four such discharges are available – 2700, 2701, 2704 and 2705. Discharge 2700 is NBI heated and undergoes an L-H transition at 219ms, 2701 is NBI heated but fails to enter H-mode, discharge 2704 is ohmically heated and discharge 2705 is quantitatively very similar to discharge 2700, entering H-mode slightly earlier at 204ms and demonstrating that vacuum conditions did not change significantly over the run period. Figure 4 shows the temporal evolution of the stored thermal energy for the four shots; clearly showing that introdution of in this case, ~540kW of NBI power (the ohmic power IV~ 0.7MW using $V \sim \partial\Psi / \partial t$ from EFIT) was effective in doubling the total stored energy. The stored electron energy approximately doubled from ~4.5kJ to 9.0kJ (using n_e and T_e from TS data recorded at 240ms and 250ms for discharges 2704 and 2701, respectively, and using EFIT flux surface geometry). The core electron temperature rose from ~590eV to 880eV, a significant fraction of the rise in electron pressure being expressed as an increase in plasma volume. Lastly, T_i recorded by the NPA approximately doubled from 471eV to 878eV on the introduction of the beam. For a number of discharges, NBI has also been effective in triggering an L-H transition (eg. discharges 2700 and 2705), whereupon rises in plasma density, electron temperature, electron pressure and ion temperature are observed [5]. The total fast ion stored energy predicted by a combination of NBI Monte Carlo modelling and experimental data from TS and NPA data results in a total kinetic energy of

~27kJ for discharge 2700 at 250ms, in the H-mode phase of the discharge. This compares well with that produced by EFIT (27.5kJ) suggesting that, even though EFIT calibration work is at an early stage, provided the plasma shape appears to match well that of the CCD camera image, the stored energy appears to be well modelled. Even though results are currently rather approximate, they are highly promising for the future of NBI heating on MAST as they have been achieved with only ~10% of the design NBI power.

3. Fast ion evolution

In order to test further the validity of fast ion power deposition predictions, a direct check of the fast ion collisional evolution has been carried out. Figure 5 shows a plot of the time taken for fast ion spectra to relax back to thermal spectra against the prediction from electron collisional drag and thermal ion scattering in a uniform and steady state plasma (using TS data for n_e and T_e). Discharges included are such that the measured slowing down time is less than 40ms (ie. less than or of order the energy confinement time) and the TS laser was fired within 10ms of beam termination. Approximate correlation is observed, although with some departure at the largest relaxation times. This is probably due, in part, to orbits traversing colder regions away from the magnetic axis but mostly to thermal electrons cooling as spectra evolve (the majority of points above 30ms with TS point before the beam trip). This is qualitatively supported by the observation that measured and predicted fast ion spectra tend to diverge more rapidly as fast ions approach thermalization. Nevertheless, bearing in mind the significant systematic errors in the analysis, the fast ions appear to evolve predominantly due to Coulomb collisions as expected.

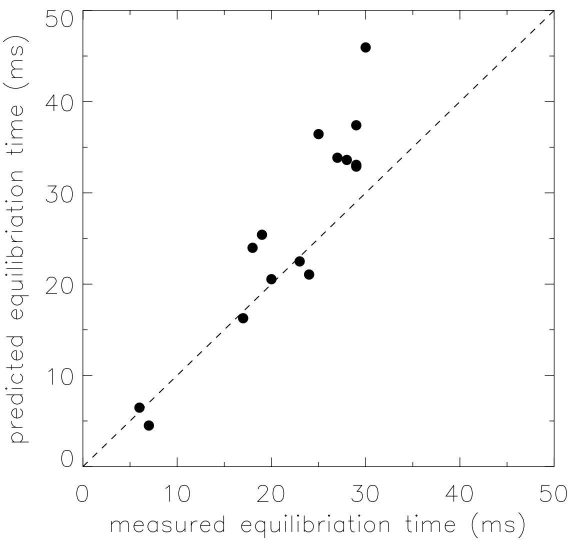

FIG. 5. Measured slowing down time against that for a uniform, steady state plasma.

4. Fast particle driven MHD.

The low magnetic fields characteristic of the spherical tokamak provide an ideal testing ground for studying fast particle driven instabilities, as the injected neutral beam ions are inevitably super-Alfvénic. In the first MAST campaign, 270 discharges had high frequency digitised magnetics data, 111 of which were NBI heated. Analysis is at an early stage, however it is clear that there is a rich variety of mode activity at frequencies below 500kHz. For illustration, figure 6 shows a spectrogram for discharge 2932, the low density shot discussed in section 2, where multiple discrete modes can be seen between 153ms and 173ms. Fishbone-like bursts occur in conjunction with the steady mode activity. The discrete modes do not appear after 173ms, which has been identified as the time of a sawtooth crash with an m=1 precursor and a large resulting heat efflux, observed both on soft X-ray and bolometer signals. Taking account of changes in plasma density, one finds that the frequency decrease through the shot is consistent with TAE gap frequency scaling. Four discrete modes can be identified, spaced equally in frequency with $\delta\nu$=10kHz. The TAE gap frequency at this time was ~200kHz, the peak amplitude $\delta B_Z/B \approx 1.6\times10^{-4}$, and the bandwidth $\delta\nu/\nu \approx 3\%$. This

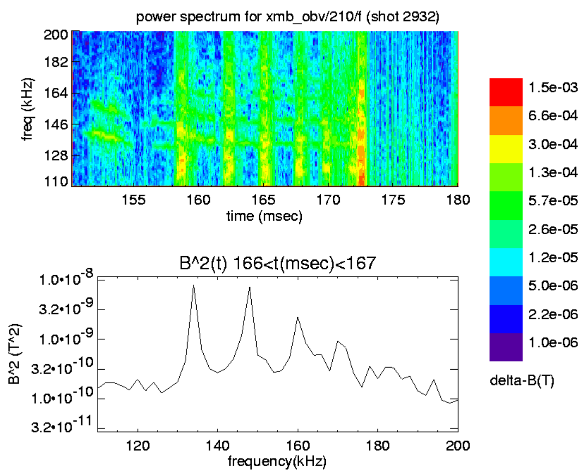

FIG. 6 . Spectrogram for discharge 2932 showing at least 4 discrete modes (indicated by the time averaged plot of $B^2(t)$ vs. frequency spectrum) persisting through a series of fishbone-like broad-band events.

discharge provides the clearest evidence yet seen on MAST for fast particle driven TAEs. To date, with the NPA orientated at R_T=0.7m, no measurable losses have been observed, and indeed, EFIT reconstructions so far carried out suggest that the wide variety of signatures recorded are benign.

5. Summary

We have described briefly some of the phenomenology of NBI heating in the MAST Spherical Tokamak. Results are extremely encouraging, only 500kW of NBI power (~10% of design value) is sufficient to substantially increase the electron temperature and pressure and to raise T_i by roughly a factor ~3, as expected from direct ion heating (assuming good beam absorption and ITER confinement scaling IPB98(y,1)). Beta determined via magnetics is in qualitative agreement with kinetically determined values combined with modelling of the fast particle content. We have observed the unexpected pheonomenon of suprathermal ion tail formation, the magnitude and effective temperature of which correlates with sawtooth temporal phase. In addition, fast ions are seen well in excess of the injection energy in fast Hydrogen spectra and also in ohmically heated plasmas following Internal Reconnection Events. Preliminary studies of the fast ion decelaration mechanism show, within systematic errors, that fast ions evolve predominantly due to Coulomb collisions. H-mode plasmas have been generated using NBI, whereupon significant increases in plasma stored energy, electron temperature, ion temperature and particle confinement have been observed. The prospects for probing the ST beta limit are good, as are those for studying highly bootstrapped, NBCD seeded long pulse plasmas. Lastly, we have shown tentative evidence for fast particle driven TAE activity in NBI driven plasmas; a rich variety of high frequency, sporadic, but seemingly benign signatures having been recorded.

References

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