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Study of fast ion distribution in NBI heated MAST plasmas

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1. Introduction

In spherical tokamaks the low toroidal field is comparable to the poloidal field. As a result, energetic ion orbit topologies differ significantly from similarly sized conventional tokamaks. For example, larger fast ion gyroradii and poloidal orbit width can lead to enhancement in the charge–exchange losses. This is especially important for trapped particles as they predominately located at the plasma outer periphery where there is high neutral density. The MAST[1] tokamak is well equipped for these studies and provides both L- and H-mode plasmas in a wide range of plasma parameters. Two co-injected deuterium Neutral Beam Injectors (NBI) are used to heat the plasma, each capable of delivering up to 2.5MW of 40-70 keV neutral beams. The relatively large MAST vacuum vessel allows the outboard plasma edge and the tokamak vessel to be separated by a neutral gas blanket, facilitating the study of neutral density effects on the fast ion confinement and charge exchange losses. The electron density and temperature are measured by a 200Hz Thomson scattering diagnostic system(reinforced by 300pt system) and the edge neutral density is reconstructed from D_α linear CCD camera measurements. The energy distribution of fast ions, originating from NBI, is monitored using a 78 channel dual mass Neutral Particle Analyser (NPA) diagnostic[2] (0.5< E(keV)/A(amu)<70) with the energy resolution ($\Delta E/E$) of ~3-7% across the energy range of the detector. The NPA spatial scanning system has a tangency range from R_{NPA} ~ 1.3m in co- to R_{NPA} ~ -0.5m in the counter beam direction and can view both NBI lines, which are injected at R_{tan} of 70cm as shown in Figure 1.

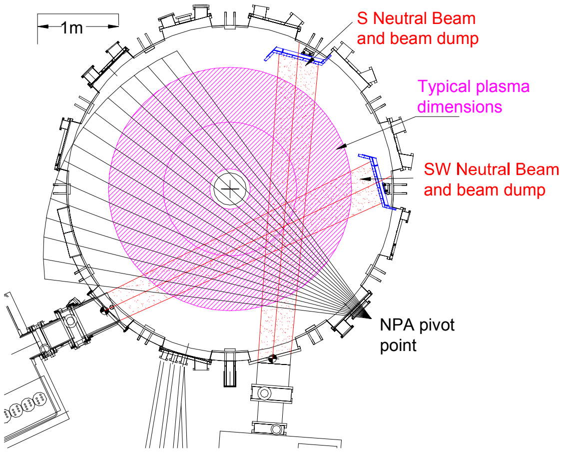

Fig. 1. MAST NBI and NPA layout.

2. Experimental results and TRANSP simulation

The horizontal scanning capability of the NPA has enabled measurements of the anisotropic fast ion distribution in a set of identical MAST discharges. In these 800kA flattop H-mode discharges only the SW NBI has been operational injecting a total of P_{inj}~1.25 MW of

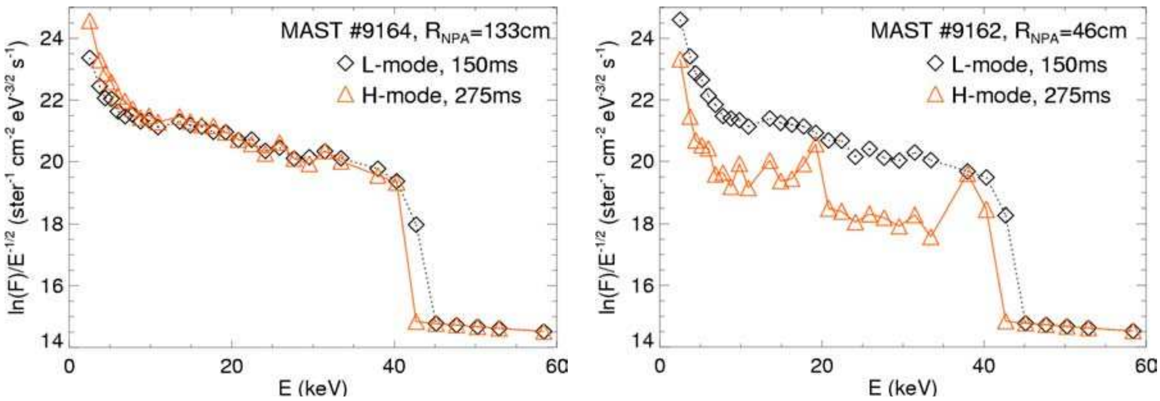

Fig. 2. The NPA spectra obtained during L- and H-mode parts of the discharge

40keV deuterium beam. Clear differences in character of the fast ion distribution in both energy and radius between L- and H-mode have been observed. Examples of NPA spectra are presented in Figure 2. When the NPA is positioned to view the edge of the plasma at R_{NPA}=133cm the observed fast ion distributions are almost identical during L- and H-mode phases of the discharge. In the discharge 9162 the NPA line of sight crossed the core of the MAST plasma at R_{NPA}=46cm showing a significant depletion of the observed fast neutrals in a wide energy range during the high density H-mode. The magnitude of the observed phenomenon decreases rapidly with an increase in NPA tangency radius, R_{NPA}, and is practically undetectable for the edge lines of sight (R_{NPA}=133cm) as seen in Figure 2.

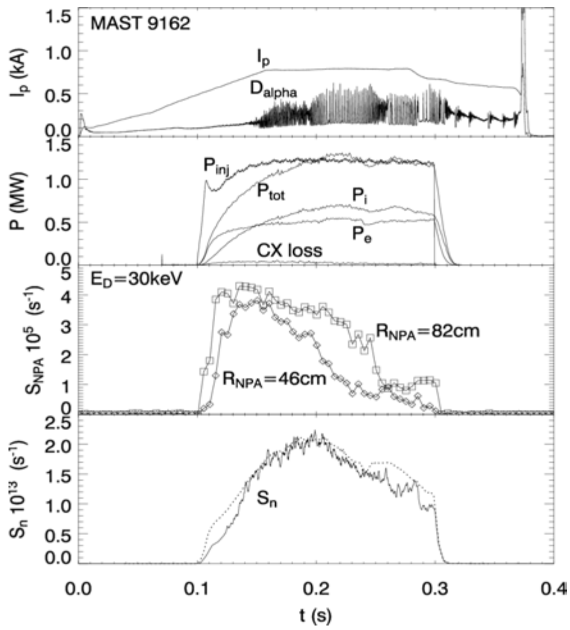

Fig. 3. TRANSP simulations of neutron yield and powers transmitted from fast ions to plasma

The results of a TRANSP analysis for the discharges of interest are shown in Figure 3. The onset of the H-mode at ~0.16s is marked by ELMs in the D_α trace and leads to decrease in the observed neutral flux. This is particularly evident in NPA lines of sight passing through the core of the plasma. An example of E_D=30keV particle flux for R_{NPA}=46cm and R_{NPA}=82cm is shown in Figure 3. The observed decay in NPA flux is not accompanied by any changes of the total power transmitted from fast ions to plasma, P_{tot}, and powers transmitted to each plasma component, P_i and P_e as MAST plasma goes into H-mode. Most importantly the charge exchange losses modelled by the TRANSP code are low (few percent) and even decrease during the H-mode phase of the discharge due to the lower neutral density in the pedestal region. The code-simulated evolution of neutron yield is also presented, plotted as a dashed line in Figure 3, and is in an agreement with experiment (solid line). The TRANSP code is also capable of modelling the neutral flux measured by the NPA including the simulation of horizontal and vertical observation angle. The parameters affecting the neutral density profiles (edge temperature and density, influx velocity, recycling ratio etc.) were varied within realistic upper and lower limits. The resulting spectra have proven to be very robust to those variations with the main modelling sensitivities arising from the value of the edge neutral density. Two simulated spectra together with experimental NPA measurements for representative lines of sight passing through the core (R_{NPA}=46cm) and edge (R_{NPA}=123cm) of the MAST plasma are shown in Figure 4. The solid line shows the simulations performed using the experimentally obtained edge neutral density. A simulation performed at 25% of the experimental value of the neutral density is also presented (dashed line) and shows much lower charge exchange losses at the plasma edge, underlining the importance of neutral density monitoring for the fast ion modelling especially when the emission is predominantly passive.

3. Discussions

The TRANSP simulations are in agreement with experiment for both L- and H- mode parts of the discharge including the observed "loss" features of the NPA spectrum during H-mode. The code modelling incorporated the measured profiles of T_e, n_e and n_0 both inboard of the separatrix, from TS and the linear D_α camera and in the SOL from Langmuir probe measurements. The experimentally obtained Z_{eff} profile was also incorporated. The simulation did not include any MHD driven anomalous losses supporting the classical behaviour of energetic ions. Neither experiment nor modelling shows an increase in the fast ion losses despite observed features in the fast ion spectra during H-mode.

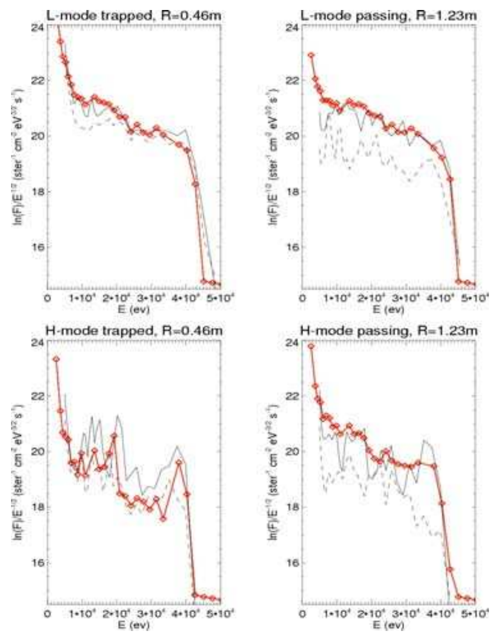

Fig. 4 TRASP simulation of the NPA flux measurements is in agreement with experiment (diamonds).

A possible mechanism causing the apparent enhancement of loss features in NPA spectrum during the steep n_e gradient or H-mode part of the discharge is a re-weighting of the radial particle emissivity profile along the NPA line-of-sight. The NPA measurements are best understood by appreciating the role of the radial emissivity distribution and the pitch angle, v||/v, for each line-of-sight. Each fast ion spectrum is an accumulated measurement along each line of sight weighted by the emissivity function $\sim n_0 n_I < \sigma v >_{cx}$. For the edge NPA lines of sight the observed value of pitch angle varies only marginally along the whole line of sight at around v||/v~0.9 and thus the measurements are dominated by passing fast particles. For lines of sight crossing the core of the MAST plasma the pitch angle varies within a much broader range. It rises from v||/v~0.2 at the edge region where the NPA flux is dominated by trapped ions to v||/v~0.9 as NPA chords cross the central region of MAST plasma where the fast ions are mainly deposited on passing orbits. The analysis of the radial emissivity profile shows that in L-mode, the NPA charge exchange flux is seeded mainly by the direct beam neutral density (i.e. active emission), - the region dominated by passing particles at the pitch angles of v||/v~0.9. As the plasma evolves into H-mode, the broad density profiles with steep n_e gradient shifts a core weighted beam deposition to the plasma edge, region of lower pitch angle of v||/v~0.2, much increasing the observed fraction of ions born on trapped orbits. The observed depletion features of the fast ion spectra are evident only during the H-mode part of the discharge when the viewed fraction of trapped particles is dramatically increased and the magnitude of the effect decreases with increase in NPA tangency radius. This implies that the trapped ion population is primarily affected. The trapped fast ions born in the plasma periphery have much larger banana orbits, especially in the low toroidal field of spherical tokamaks, with frequent radial excursions outside the plasma separatrix, the region of high neutral density. This makes them vulnerable to charge exchange losses resulting in the observed depletion of the NPA fast ion spectra in H-mode. These low but unavoidable edge losses (a few percent) may also be present but hidden from NPA observations in the low density L-mode phase of the discharge when the NPA flux originates from the core of the MAST plasma dominated by much better confined passing particles. It must be emphasised that the observed phenomenon is not a consequence of any H-mode characteristic other than broad, high-density profiles with steep edge gradients, which are prevalent in MAST H-mode plasmas.

References

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