Introduction

An $E \parallel B$ neutral particle analyser (NPA) has been deployed on the MAST experiment at the Culham Science Centre, UK, to facilitate the study of ion behaviour in low aspect ratio plasmas. Under Ohmic operation, ion temperatures are routinely measured and are found to be in accordance with scaling laws and results from impurity spectroscopy. Fast particle populations are observed following internal reconnection events - potentially arising due to the subsequent redistribution of magnetic energy. Fast ion behaviour is further studied through the use of a pair of high energy hydrogen neutral beams. These are found to provide significant plasma heating - as predicted by computer modelling - and injected ions are observed to slow according to classical Coulomb collision theory. Additionally, a suprathermal deuterium tail appears under beam injection - consistent with the large angle Coulomb scattering of thermal ions with beam neutrals.

Ion behaviour during Ohmic operations

A 1-D neutral transport model, DOUBLE, predicts a measurable neutral flux from the core region of Ohmic MAST plasmas under normal operating conditions ($100 \leq T_e \leq 1100\,eV$, $6 \times 10^{18} \leq n_e \leq 6 \times 10^{19} \, m^{-3}$). NPA measured neutral spectra and the resulting ion temperatures are thus taken to be indicative of the plasma core. Typically, $T_{io}$ is found to be in the range $200 – 400\,eV$ - in agreement with the Artsimovich scaling law predictions [1]. A valid cross correlation, with impurity spectroscopy derived ion tempera-
tures (observing \(C^{5+} n = 8 \rightarrow 7, \lambda = 529.1\text{nm}\)), has also been achieved.

During internal reconnection events, large suprathermal ion tails have been observed (figure 1(a)). Preliminary investigations show a direct correlation between the size of these tails and the change in magnetic energy during the reconnections.

**Ion behaviour during neutral beam injection**

MAST is augmented with two tangential neutral hydrogen beams currently injecting at a total power of \(\sim 2\text{MW}\). NPA measured spectra clearly resolve the individual beam energy components and suggest minimal charge exchange losses - in accordance with orbit tracking simulations. Combined with beam attenuation models, which predict centrally weighted deposition of beam neutrals, conditions for beam heating are considered to be good; experimental data, from the NPA and from Thomson scattering, have been able to verify this claim [2], with increases by a factor of \(\sim 2 - 3\) in \(T_i\) and \(\sim 1.5\) in \(T_e\), typically measured.

Using information derived from the NPA results, the following aspects of fast ion behaviour have been investigated.

**Beam slowing**

Appealing to classical Coulomb collision theory, the slowing of a high energy ion population in a plasma can be described using [3]

\[
\frac{dW_b}{dt} = -\frac{2W_b}{\tau_{ei}}(1 + \left(\frac{W_e}{W_b}\right)^{3/2})
\]

where, \(W_b\) is the energy of beam particles, \(W_e\) is the ‘critical’ beam energy - where electrons and ions receive an equal beam energy transfer - and \(\tau_{ei}\) is the electron-ion collision time. This equation can be combined with the NPA measured spectrum at beam turn off, along with interferometer determined plasma density, and \(T_e\) from Thomson scattering, to simulate the temporal evolution of beam ions - as demonstrated in figure 2(a). Experimental data are clearly modelled well, indicating collisional deceleration - i.e. no dominance of anomalous slowing down.

Integrating and solving equation (1) for the case where beam particles slow from their injected energy to the background plasma energy, gives the characteristic beam slowing time, \(\tau_c\)

\[
\tau_c = \frac{\tau_{ei}}{3} \ln \left[\frac{1 + \left(W_e/W_{i0}\right)^{3/2}}{\left(W_e/W_{i0}\right)^{3/2} + \left(W_e/W_{i0}\right)^{3/2}}\right]
\]
where $W_{i0}$ is the initial beam injection energy. Calculating this time for a database of shots which exhibit undisturbed (i.e. by plasma disruption or MHD effects) slowing behaviour, allows a comparison with NPA measured relaxation times. Results are shown in figure 2(b); a clear correlation exists again, indicating that the slowing of beam ions is well described by classical theory. The divergence at large $\tau_s$ is explained by the fact that, in these cases, the slowing time is longer than the energy confinement time (typically $\sim 20 - 40 ms$). Consequently, during the course of the beam slowing, the plasma temperature drops, leading to increased energy loss rate and hence decreased relaxation time.

**Suprathermal ion production through large angle Coulomb scattering**

Similar to the situation following an IRE, a high energy ion tail is observed during neutral beam injection. A possible mechanism for this is through large angle Coulomb scattering of background ions with beam neutrals; in this situation it is possible for ions to gain up to around half of the beam neutral’s energy (considering hydrogen neutrals in a deuterium plasma) [4]. Looking at the simplified case of an isotropic source of fast ions in a radially symmetric plasma, a 0-D analytical expression has been derived to compare the densities of fast scattered background
ions with fast ions from NBI

\[
\frac{n_{fi}}{n_i} = \frac{44\pi \lambda_s^2}{1152\pi^2 m_i^2 c_0} \int_{v_{fi}/6}^{v_{fi}} dv \frac{1}{v_i} = \frac{693 \lambda_s^2}{288\pi m_i^2 c_0^2 v_{fi}^3}
\]

(3)

where the subscript, \(f, i\), refers to beam ions and, \(i\), to background ions.

Despite the simplifications made in this analysis, results are found to be of the same order of magnitude as NPA measurements. As such, a more detailed approach is being undertaken to model this effect, including the large angle scattering process in a full 3-D Fokker Planck code, FPP. Figure 3 demonstrates the application of the analytical expression (3) - using a beam source obtained with the LOCUST orbit tracking code; clearly theoretical predictions for tail size and bifurcation point are in reasonable agreement with experimental data. It is hoped that further agreement will be achieved through a refining of reaction cross sections and pitch angle scattering dependencies in the FPP code.

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References


