ION PHYSICS IN THE ‘START’ SPHERICAL TOKAMAK

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1. Introduction

The tight aspect ratio ($A \sim 1.3$) and low magnetic field (~ 0.3T) of the START plasma ($a \sim$ 0.2m,$B_0 \sim$ 0.1T,$I_P \sim$ 200kA, $\kappa \sim$ 1.8) provide an interesting testing ground for the neoclassical theory of thermal ion (100-300eV) transport and an oportunity to study the performance of high beta (30-40%) spherical discharges as well as fast ion kinetic theory during high power neutral beam co-injection (NBI) ($P_b \sim$1MW, $E_0 \sim$32keV, $R_T = 0.28$m). The majority of fast ions are born close to the mid-plane on passing trajectories which travel close to or cross the last closed flux surface (LCFS). Orbit topologies are significantly different to those of Large Aspect Ratio trajectories and thus require careful treatment. High neutral density in the SOL, due mainly to the plasma occupying only $\sim 7\%$ of the vessel volume, leads to challenging problems in optimization of plasma performance, resulting particularly in a strong scaling of NBI heating efficiency with plasma current.

A model has been developed (LOCUST) to calculate bulk thermal electron and ion heating, NBI current drive, fast ion distribution function and to simulate various diagnostic signals. LOCUST includes a discrete particle tracking algorithm, fast ion deceleration due to Coulomb scattering and thermal electron drag, charge exchange driven cross field transport and all known significant loss mechanisms. This is required together with EFIT, to provide additional confirmation of the record beta values observed in START.

2. Fast ion analysis

In order to measure ambient D_2 density outside the LCFS, a Bayard-Alpert fast ion gauge was mounted at the vessel wall. A series of NBI pulses with gas puff and toroidal field (TF) alone (ie. no breakdown) were generated to check gauge calibration by examining bolometer and instrumented beam stop power scaling with neutral density and TF field. Both diagnostics are modelled well when beam-blocking is taken into account. During a typical START discharge, neutral density outside the LCFS is sufficient to generate prompt loss ($n_{\mathrm{D/D_2}} \sim 10^{18} - 10^{19}\mathrm{m}^{-3}$).

To investigate the validity of β_T measurements from equilibrium reconstruction using magnetics alone, as well as to investigate model predictions of the fast ion distribution, a series of low Troyon beta ($\beta_T \sim 4\%, I_P \sim 170\mathrm{kA}$), identical discharges were generated and the neutral particle analyzer (NPA) sight-line was scanned through the mid-plane. The internal neutral density was unfolded from the equatorial multi-chord D_α array signal, comparing well with HSLAB [2] model predictions. The Thomson scattering (TS) laser was set to trigger prior to the start of sawteeth as well as sufficiently far into the pulse that density and temperature are changing on a time scale longer than the beam slowing down time. Thermal ion temperature was reconstructed via multi-chord charge exchange spectroscopy [3]. The modelled width of the edge neutral density and magnitude of the core value were adjusted to obtain a good fit to experimental NPA and bolometer data. An iterative procedure was used to generate a 'self consistent' equilibrium using EFIT and LOCUST (forcing pressure isotropy in pitch angle). Two or three iterations of the EFIT solution and LOCUST are usually sufficient to achieve reasonable convergence of the pressure profile. Figure 1. shows a typical self consistent pressure profile for the high beta discharge #36544 at $t = 30$ms. Dark and light shaded areas represent experimental thermal pressure and model fast ion pressure respectively and the dashed line is the pressure from EFIT solution. Figure 2. shows experimental and model NPA data at various energies including attenuation due to re-ionization and smearing due to experimental resolution. Experimental data are divided into two sets as one group of discharges was more detached from the centre column (solid points) and comprised lower neutral density. A scaling factor relative to the second data set (open) was applied, the ratio of the two central neutral densities, this procedure being valid as core charge exchange is a perturbative phenomenon. Both sets of experimental data were normalized to fit model predictions (as absolute NPA calibration is uncertain). This does not however cause a problem as the NPA spectral shape and the bolometer signal are strong functions of neutral density magnitude and penetration. The modelled neutral density profile required to match the experimental bolometer flux and to achieve a good fit to the NPA spectral shape, shows good agreement with the experimental profile.

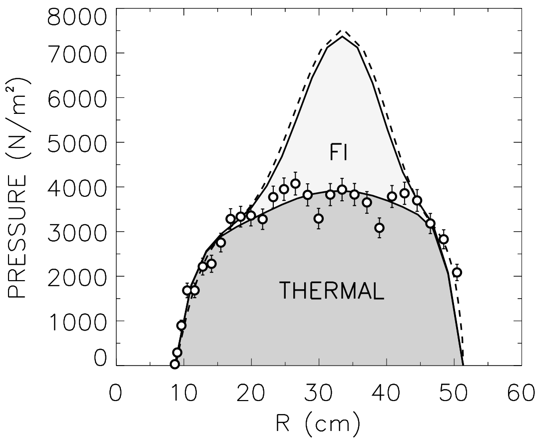

Figure 1. Self consistent pressure profile for high $\beta_T = 27^{+4}_{-4}\%$ discharge #36544 ($I_P = 290$kA). Points represent experimental thermal pressure, light shaded area the fast ion pressure and dashed line the EFIT profile.

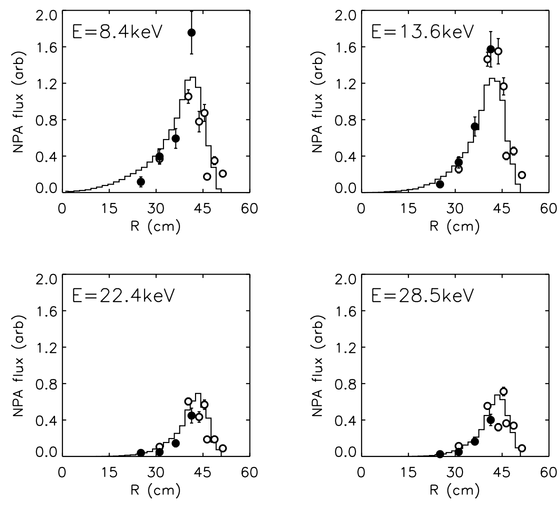

Figure 2. Experimental (points) and model (line) NPA signal against tangency radius R_T for various energies (low beta series #35096).

The resulting β_T for the low beta shot series is $3.7^{+0.6}_{-0.3}\%$ with systematic errors determined by varying fitting constraints to pressure and central q_0. The corresponding fast ion heating efficiency, $\eta_{\rm NBI}$ is $25-33\%$ ($P_b = 810\text{kW}, P_e = 184\text{kW}, P_i = 21\text{kW}$ for $\eta_{\rm NBI} = 25\%$), with the range generated mainly by variation of neutral density within experimental bounds. Earlier, we alluded to the importance of carrying out reconstruction prior to the observation of sawteeth in order to minimise any fast ion redistribution of the fast ions.

Figure 3. shows a typical vertical SXR signal, NPA flux (10.4keV channel at tangency radius R_T of 48cm) and bolometer flux for a pulse from the low beta shot series. Clear ejection of fast

ions is seen at NPA tangency radii in excess of 40cm at all energies, corresponding to the major radius where the neutral density starts to rise. No significant sawtooth correlated increase in D_α light is observed; however some correlation is seen at the bolometer. The model shows that at the TS time (30ms), the finite bolometer view is starting to vignette the flux outside the tangency radius of 40cm. As the plasma evolves and increases in volume, this will be even more the case, so it is not surprising that only a small perturbation to the bolometer signal during sawteeth is observed as the bulk signal will emanate from the plasma core. Data suggest that an insignificant fraction of fast ions are lost due to sawtooth mixing and any resulting modification to the neutral density. This conclusion is drawn from the constancy of the bolometer signal during sawteeth, the fact that the NPA flux rapidly returns to the value before the start of sawteeth after each crash, and from equilibrium reconstruction using magnetics alone through a typical sawtooth period.

Analysis of a typical START high β_T discharge at high $I_P(290\mathrm{kA})$ has been performed, resulting in $\beta_T = 27^{+4}_{-4}\%$, $\beta_n = 3.4^{+0.6}_{-0.4}$ and central beta $\beta_0 = 76^{+5}_{-4}\%$, corresponding to a stored fast ion energy content of ~400J ($\sim 20\%$ of total). Extrapolating the volume average beta of this discharge to the time of maximum β_T, results in a central beta of around 100%. The fast ion heating efficiency at I_P=$290\mathrm{kA}$ for this case is estimated to be of order 54-84%, higher than for the low beta shot series due mainly to the higher value of I_P. Figure 4. shows electron density and temperature profiles together with EFIT flux surface averaged profiles for discharge #36544. n_e rises towards the edge, an observation also reported in DIII-D high beta discharges [4]. Figure 5. shows START beta space with self consistent equilibria included (circled), together with associated systematic errors.

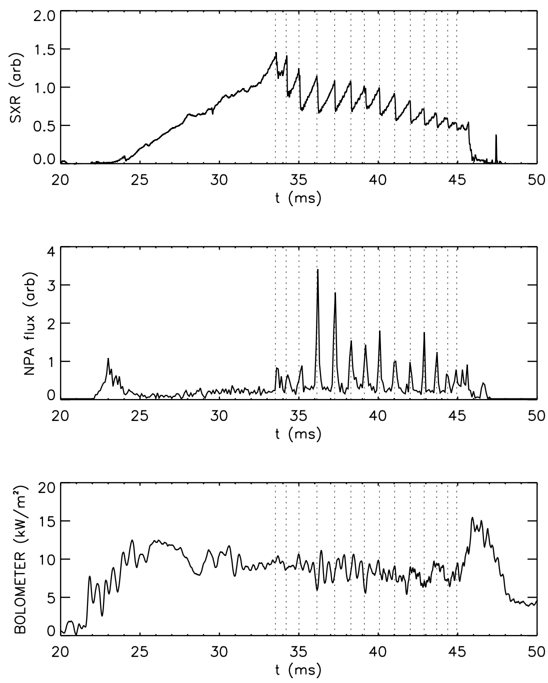

Figure 3. Vertical SXR signal, NPA flux (at 10.4keV, $\mathrm{R_T} = 48\mathrm{cm}$) and bolometer power flux for a discharge from the low β_T shot series.

3. Thermal ion analysis

Due to the transient nature of START NBI discharges, particularly at high β_T, 1-D interpretive confinement analysis is difficult. We have attempted to determine the ion thermal diffusivity profile and have compared results with predictions from neoclassical theory. The only heating source profiles required are from electron-ion exchange and from the neutral beam, this being determined by LOCUST. T_i, T_e and n_e profiles are obtained from charge exchange spectroscopy and Thomson scattering. We estimate n_i by assuming a uniform profile of Z_{eff} $(=2.0)$ across the plasma, a single impurity (carbon), profile similarity, and take the time variation of the particle content and stored energy from chord averaged density and equilibrium reconstruction. Thermal diffusivity χ_i at the plasma periphery tends to be higher than the 'improved' Chang-Hinton neoclassical prediction [5]. The most probable reason for this is charge exchange induced losses or plasma turbulence near the edge. At the plasma core, the converse is the case, ie. neoclassical χ_i is higher than the experimentally determined value, but within experimental errors. Lower values of central $Z_{\rm eff}$ and higher values of edge $Z_{\rm eff}$, together with lower q_0, the inclusion of on-axis orbit effects [6] and charge exchange cooling, are likely to yield better agreement.

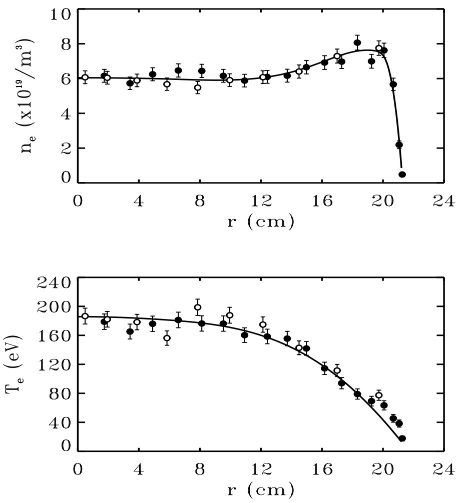

Figure 4. T_e and n_e data inboard (solid) and outboard (open) of $R_{\rm mag}$ together with the EFIT flux surface averaged profile as a function of minor radius.

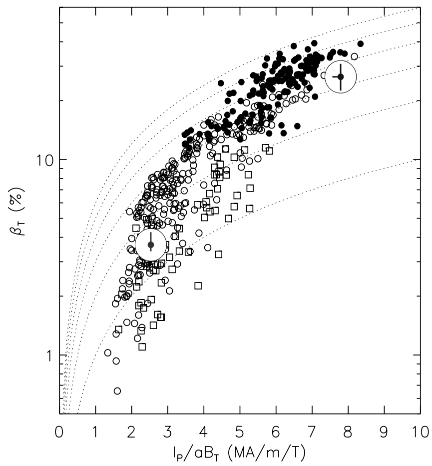

Figure 5. START beta space. Circled points correspond to low and high beta self consistent values with systematic errors determined by relaxing pressure and q_0 fitting constraints. Other points are for magnetics measurements.

4. Discussion

Thermal ion transport analysis shows that χ_i is close to neoclassical but additional effects such as edge turbulence and charge exchange cooling due to the high edge neutral density in START may be required. 30keV fast ion orbits in START occupy a large fraction of the plasma poloidal cross section and need careful treatment due to their extreme topologies. A self consistent picture of the effects associated with high neutral density and NBI in START has been constructed by careful study of experimental data and the development of a number of numerical models in full 3D START geometry. Some discharges show the ejection of fast ions due to sawtooth activity, however the redistribution and loss of fast ions from the plasma core is estimated to be small. Typically, at $I_P \approx 300{\rm kA}$, β_T of around 30-40% can be achieved with $\eta_{\rm NBI} \leq 84\%$, together with record central betas of around 100%. Record β_T and β_n values determined using magnetics alone are confirmed by fully self-consistent calculations using the calculated beam ion pressure and measured thermal temperature and density profiles.

Acknowledgements

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