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Neutral Beam Ion Confinement and Current Drive in the Spherical Tokamak

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Auxiliary heated discharges have been created in the START spherical tokamak (ST) using a 30keV, high power (∼800kW) neutral beam injector. Due to the low magnetic field (∼0.3T), fast ions traverse a large fraction of the poloidal cross section and are non-adiabatic, ie. the first order term of the magnetic moment expansion ($\mu_0 = m_H v_\perp^2/2B$) is not a constant of motion. Figure 1 a) shows a typical 30keV H^+ orbit resulting from tangential *co-injection* together with the variation of μ_0 with time. Figure 1 b) shows a typical 15keV orbit resulting from *counter-injection* where the H^+ ion was born at the inboard mid-plane. The particle performs four poloidal revolutions until the gyro-phase is such that it undergoes a transition into the trapped, unconfined region of velocity space. Only a small fraction of counter injected fast ions in the plasma core are confined and stable from such non-collisional stochastic transitions into the loss cone. Confinement of counter injected fast ions in START then is extremely poor (4% compared with 57% for co-injection into the same plasma (#35533)). All START, MAST (the Mega-Amp Spherical Tokamak, in construction at Culham) and NSTX (National Spherical Torus Experiment, in construction at PPPL) simulations discussed in this paper are for tangential co-injection and have been studied using the LOCUST Monte Carlo gyro-tracking code [1] to allow for this non conservation of μ_0. For MAST, co-injection is predicted to result in much higher absorption efficiencies, typically of the order 70% compared with 23% for counter-injection.

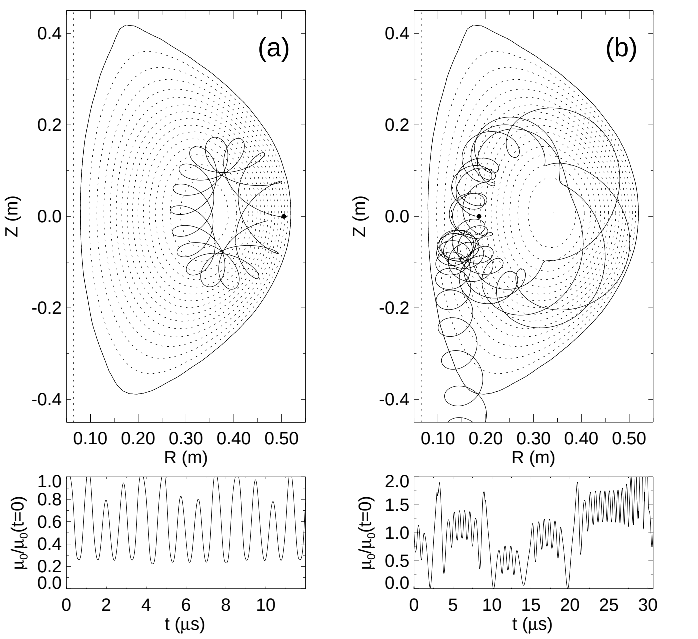


Figure 1: *Typical* H^+ *orbits in START (discharge #35533 @ 38.02ms). a) is for 30keV co-injection, b) is for 15keV counter.* $I_P = 247kA$, $B_0 = 0.17T$.

1 Modelling of START, MAST and NSTX heating and NBCD

In order to validate the LOCUST model and to determine whether fast ions in START evolve solely due to Coulomb collision processes and charge exchange collisions, a series of similar, low beta (β_T =3.5%) START plasmas was studied. The NPA was scanned through the mid-plane and the multi-point Thomson scattering system set to fire at 30ms (prior to the commencement of sawtooth relaxations). Figure 2 illustrates a typical discharge evolution and figure 3 NPA spectra at 30ms and various tangency radii. Points represent the experimental flux and the solid line is the LOCUST prediction, convoluted with the experimental instrument function and scaled to minimise χ^2 (the absolute

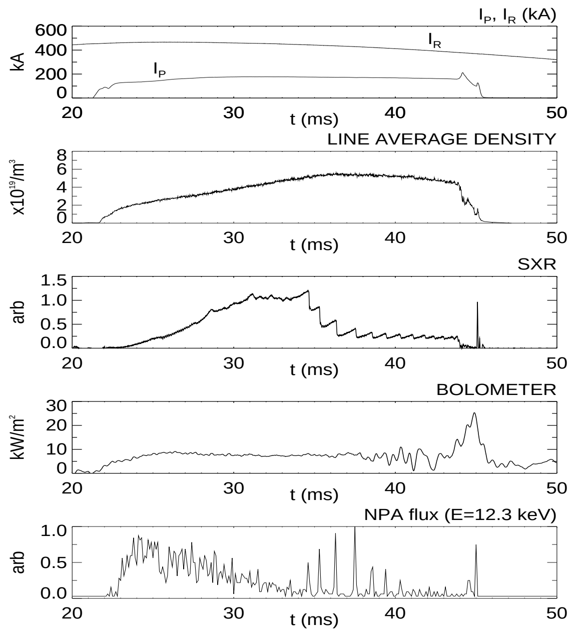


Figure 2: *Typical discharge evolution of shot series #34966 to #35096. I_P is plasma current, I_R rod current.*

calibration of the NPA is not known). To calculate the fast ion beta, q_0, the radial pressure profile and the plasma mid-plane outer edge were all constrained in the magnetic reconstruction, total pressure being determined by iterating the reconstruction and execution of LOCUST. Thermal electron data were taken from Thomson scattering, T_i information from charge exchange spectroscopy and $Z_{\rm eff}$ was taken to be 2.0 (consistent with spectroscopy assuming C impurity). Atomic neutral density information was taken from experimental inversion of D_α array data. Predictions from the HSLAB [2] neutral density model are in excellent

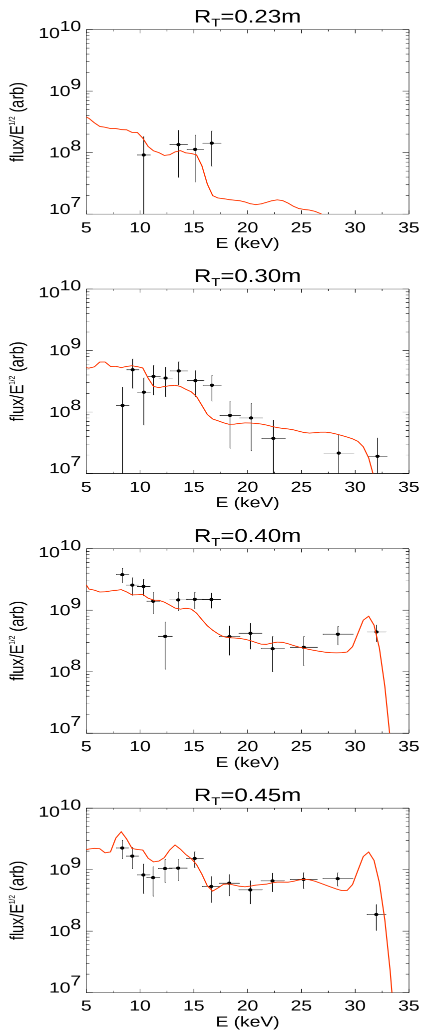


Figure 3: *Experimental (points) and model (solid line) NPA spectra for START discharge series #34966-#35096.*

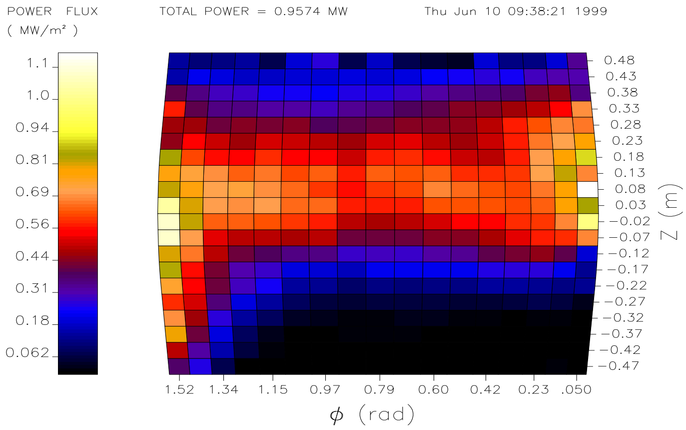
agreement with measured profiles (typically n_H is $\sim 10^{17}$ at the plasma edge). The updated analysis now includes the molecular density profile, inferred using a fast ion gauge mounted at the vessel wall together with a pressure balance model for extrapolation into the plasma. In START, the majority of the charge exchange loss is driven by the high value of n_{H_2} in the plasma periphery (of the order $10^{18} - 10^{19} m^{-3}$). The electric field from the applied loop voltage is now also included (approximated as constant across the plasma). This is important in START as high resistivity means that typically 20-40kW of the ohmic power can be transferred to the fast ions ($\sim$10% of the absorbed NBI heating power). The LOCUST model flux is now in excellent agreement with experiment using experimentally determined neutral density profiles, given the systematic uncertainties in model input and shot to shot plasma variation. Data then suggest that fast ions in START evolve predominantly due to collisional deceleration and charge exchange driven cross field transport and loss.

Equilibrium reconstruction using magnetic measurements alone as a function of time, together with the observation that increased flux recorded by the NPA during sawtooth crashes (fig 2) rapidly returns to its pre-crash level (together with no observable variation in flux emanating from the plasma centre) [1] , indicates that sawtooth redistribution of the fast ion population does not cause serious degradation of core fast ion confinement. Assuming that fast ion evolution occurs mainly due to collisions and charge exchange processes, one can compare the LOCUST-EFIT self consistent equilibrium reconstruction β_T with β_T reconstructed using magnetic diagnostics alone (as in [1]). For example, for high beta discharge #35533 at 38.02ms, LOCUST predicts $\beta_T = 20.8 \pm 2.8$ compared with 23.6 using magnetics alone during the sawtoothing phase of the discharge prior to disruption. Diamagnetic flux for the self consistent reconstruction is in excellent agreement with the experimentally measured flux and q is in agreement with the sawtooth inversion radius taken from soft X-ray cameras and qualitatively with predictions of the accessibility into optimized shear regimes at high β [3]. Again, data support the assertion that fast ions in START evolve predominantly due to collisional and charge exchange processes.

The two new Mega-Amp spherical tokamaks currently being commissioned (MAST and NSTX) will use NBI for auxiliary heating and current drive. Provided MHD redistribution due to sawteeth, Alfvénic activity etc. are, as in START, benign [4], one can predict the attainable fast ion pressure, NBCD efficiency etc. The beam systems being deployed on MAST and NSTX are both capable of delivering 5MW of neutral beam - in MAST using two ORNL injectors modified to deliver a primary energy of 70keV (D) and in NSTX, a TFTR 3-source injector set to inject at 80keV (D). The MAST beam tangency radius has been optimised at 0.7m for maximal heating efficiency, current drive and fast ion heating peakedness in the plasma core [5]. We have recently coupled the LOCUST code to the SCoPE code [3] in order to examine the accessibility of steady state regimes in MAST with pulse lengths of up to 5s (with $E_0 \sim 60$keV, 4MW injection). Simulations have been carried out with fixed total plasma confinement time (30ms) (discussed in detail in [3]), compatible with ITER scalings. Central density was fixed at $4 \times 10^{19}\mathrm{m}^{-3}$ and central temperature allowed to rise from 300eV to a saturation value of 2.3keV at 200ms. NBCD reaches a value of 0.38MA at 200ms, approximately 44% of the total plasma current. Injection and critical energies are such that the ratio of ion to electron heating is 65% compared with typically 15% in START. The plasma reaches pseudo-steady state after 0.5s allowing a further 4.5s within which to study steady state issues such as divertor power loading and plasma control.

2 First wall power loading due to finite Larmor radius

As in START, a significant fraction of the fast ion population in both MAST and NSTX crosses the last closed flux surface in the equatorial plane. This necessitates 3D calculations of losses due to charge exchange and the interception of ion trajectories with close fitting components. For example, figure 4 shows the LOCUST model power flux to the NSTX RF antenna for an optimized shear ($q_0 > 2$) high beta ($\beta_T = 40\%$) equilibrium with $T_e(0) = 3$keV, $n_e(0) = 3.8 \times 10^{19}\mathrm{m}^{-3}$. LOCUST calculation of the driven NBI current is 0.32MA ($I_{tot} = 1$MA) (very similar to the achievable NBCD and fast ion toroidal beta in MAST) and fast ion β_T is 16%.



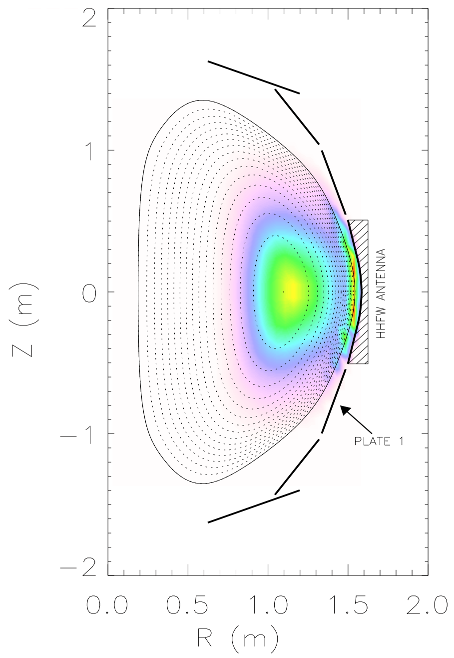


Figure 4: *Charged particle power loading to the NSTX HHFW antenna for an optimized shear, 40% toroidal beta plasma. Also shown is a poloidal cross section of the NBI power deposition together with passive stabilisers and antenna.*

Power flux in the mid-plane from all three beam sources is $\sim$0.6MW/m^2 and peak flux is $\sim$1.1MW/m^2 due to clockwise and anti-clockwise precession of the outermost portions of the orbits of the two groups of lost particles responsible for the heating peak at each end of the Faraday shield. Similarly, the first passive stabiliser plate (plate 1) passed by the fast ions receives a peak power loading of 3.8MW/m^2. Although not insignificant, these power fluxes are tolerable provided discharges are of $\leq$0.5s duration. For longer discharges, the HHFW antenna Faraday shields and stabilisation plates will be water cooled.

3 Conclusions

An intensive modelling/experimental campaign on START has yielded an understanding of the physics of NBI heating and current drive in the ST, highlighting the outstanding success of NBI in START and its applicability for auxiliary heating and current drive in the new generation of Mega Amp Spherical Tokamaks. This understanding is being used to study the accessibility of steady state regimes in MAST, the attainable NBCD and fast ion beta etc. and to help in the design of close fitting plasma facing components such as the HHFW antenna in NSTX.

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