H-mode and confinement studies in the START spherical tokamak

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Abstract
Ohmic discharges on START exhibit both linear Ohmic confinement (LOC) and saturated Ohmic confinement (SOC) regimes. At densities above roughly one-half of the Hugill limit, the energy confinement degrades. This is believed to be due to a combination of factors including enhanced ion neoclassical transport and radiation losses. In both Ohmic and NBI heated plasmas clear H-mode signatures have been observed, including ELMs, a sharply defined plasma edge, steepening of the edge profiles, especially n_e, and rapid poloidal rotation and associated radial electric field. When $I_p \geq 250$kA, the H-mode regime is accompanied by a clear increase in energy confinement time.

Introduction
High performance of STs in terms of β have been demonstrated [1]. However, to contribute to the physics and scaling of tokamaks as a whole and to assist in the design of future large STs it is necessary to investigate energy confinement behaviour in START. It was well equipped for this purpose, possessing auxiliary heating in the form of a ~1MW NBI injector (~35kV), as well as appropriate diagnostics including 30-point Thomson scattering[2], 20-chord charge-exchange spectroscopy[3], fast Doppler spectrometry and the EFIT equilibrium reconstruction code.

Confinement
Confinement data has been obtained for both Ohmic and additionally heated discharges over a wide range of current, density and toroidal field parameters, although the NBI data are restricted to $I_p >$ 120kA in order to obtain reasonable beam absorption. Two distinct types of Ohmic discharge are considered: "pure" Ohmic discharges and "beam-conditioned" Ohmic discharges. The latter are discharges in which NBI power is applied but only during the plasma formation time. The fast ion thermalisation time is typically 2ms and similar to the energy confinement time, so after about 5ms following the

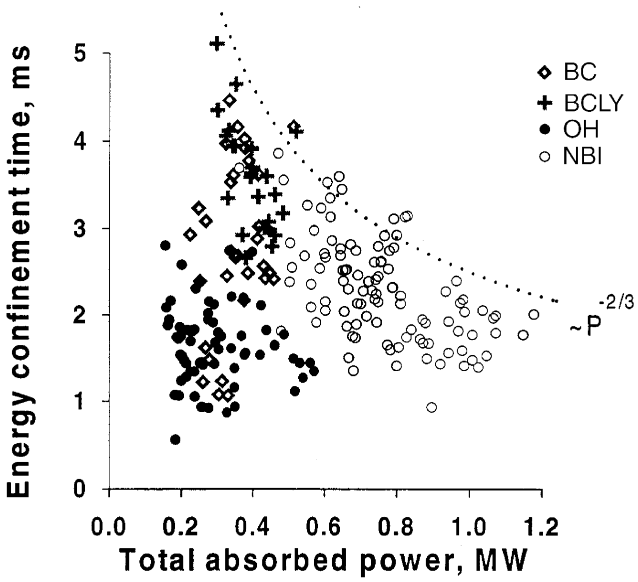

Figure 1 Measured τ_E for beam-conditioned (BC), BC ELMy (BCLY), Ohmic (OH) and NBI plotted against the total input power.

beam cut-off, the discharge is essentially Ohmic. The effect of the short NBI pulse can be seen in Fig. 1. This diagram shows energy confinement time plotted against of total absorbed power. The confinement time has an upper bound which roughly scales as $P^{-2/3}$, although a full regression analysis would be required to determine the actual power dependence. The pure Ohmic discharges have poorer confinement than those with additional heating, contrary to experience on conventional tokamaks, while the beam-conditioned Ohmic discharges have the best confinement. This effect will be discussed below.

Ohmic Confinement

The energy confinement time is plotted against density (normalised to the Hugill limit, $n_H = I_p/\pi a^2\kappa$) in Fig. 2 for both pure and beam-conditioned Ohmic discharges, some of which exhibited ELMs. A limit to the confinement is represented by:- $\tau_E(\mathrm{START}) = 0.07\, \bar{n}_{e20}\kappa a R^2 q_{95}$. This "START scaling" may be an ST-compatible version of the neo-Alcator scaling[4]. A general degradation in confinement may be observed at higher densities ($n_e/n_H \geq 0.6$). Most of the pure Ohmic discharges appear to exhibit SOC (saturated Ohmic confinement) for n_e/n_H as low as ~0.15, while the majority of the beam-conditioned discharges exhibit LOC (linear Ohmic confinement) at n_e/n_H up to ~0.3, with SOC becoming apparent at higher densities. The beam-conditioned minority of discharges generally reach the highest confinement times.

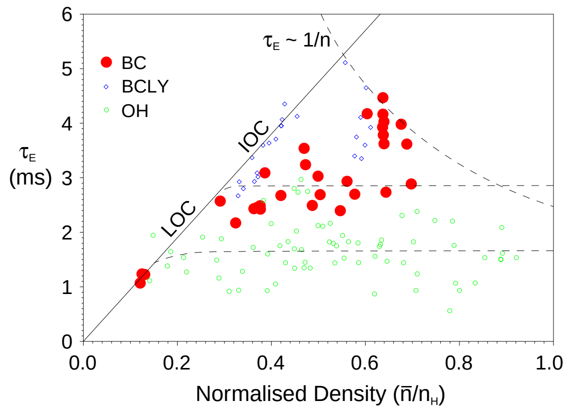

Figure 2 Measured τ_E plotted against Hugill normalised density ($n_H = I_p/\pi a^2\kappa$) for beam-conditioned (BC), BC ELMy (BCLY) and Ohmic (OH) plasmas.

We have performed ASTRA transport calculations for a density scan at typical START Ohmic discharge conditions: B_0=0.317 T, I_p=193 kA, R=0.313 m, a=0.231 m, κ=1.7, δ=0.3, q_{95}=11.2. The transport model assumes neoclassical ions and Goldston's neo-Alcator model [4] for anomalous electron transport: $\chi_e = (7.0/\, n_e)\,(0.56/R)^2\,(r/0.05)$ in MKS units and$10^{19}m^{-3}$.

The results of some ASTRA simulations are shown in Fig. 3. The simulations show that in the no-impurity case for START-like parameters, an initial LOC phase is followed by a reduction due to the onset of high ion-channel losses as the density is increased. Inclusion of impurities in the simulations predicts a degradation of confinement with increasing density due to radiation and ion neoclassical losses.

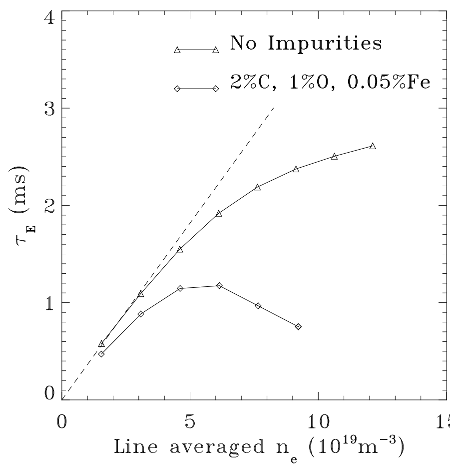

Figure 3 Calculations from ASTRA of confinement with and without impurities.

H-mode

The power input to START substantially exceeds the predicted threshold power, P_{thr}, required for L - H transition in conventional tokamaks. For representative parameters of $n_e = 5.10^{19}$ m^{-3}, $B_T = 0.28T$, $R = 0.3m$, the ITER-EPS97 scaling [5]

$$P_{thr} = 0.76\, n_e^{\ 0.79}\, B_T^{\ 0.76}\, R^{1.95}$$

[MW, 10^{20} m^{-3}, T, m] yields P_{thr} ~ 18kW, which is a factor of ~ 40 lower than the total input power (i.e. including Ohmic) of ~ 800kW for these auxiliary heated discharges. Even pure Ohmic heated discharges exceeded this threshold by a large margin (typical Joule heating ~ 400kW).

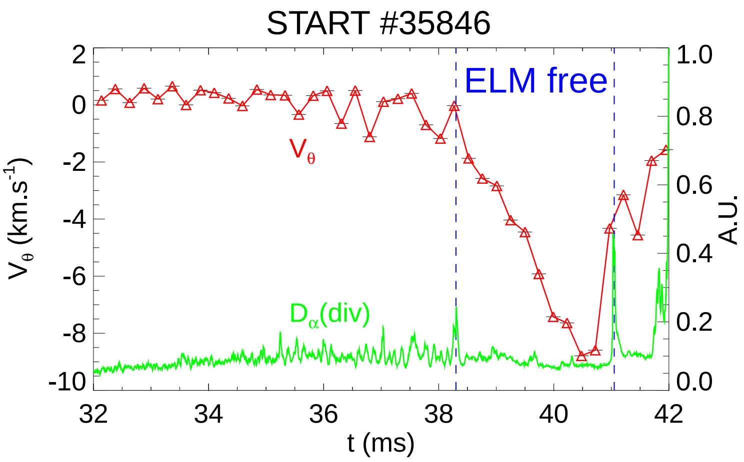

Figure 4 Poloidal velocity excursion in an inter-ELM period

However, none of the usual H-mode signatures was observed before the high-β campaign which combined high current and density with improved wall conditioning (boronisation, Ti gettering and GDC). New features were exhibited, including a sharply defined plasma edge, a steepening of edge profiles (esp. n_e), poloidal rotation and ELMs [6]. ELMy H-modes have occurred in both NBI-heated and beam-conditioned-Ohmic discharges, with $I_p > 190$kA and line averaged density in the range of $3.8\text{-}6.2 \times 10^{19}$m^{-3}.

Doppler poloidal rotation data (C^{2+} emitting ~2cm inboard of the separatrix) during H-modes are shown in Fig. 4. During the inter-ELM period a rapid poloidal acceleration is observed terminated by the appearance of another ELM or the reversion to the L-mode regime. The plasma acceleration was found to be fairly reproducible, summarised in Fig. 5, for inter-ELM period, from three separate discharges. Results from a series of H-mode discharges give apparent accelerations of ~4km.s^{-1}/ms in the for inter-ELM periods up to ~3ms. The deduced maximum radial electric field is relatively small, approximately –1kV/m (pointing inwards), which is a factor of ~ 20 smaller than in the similarly sized, but conventional aspect ratio, COMPASS-D tokamak. These observations suggest that the build-up of the poloidal velocity is a relatively gradual affair, at least over the viewing spatial resolution, ~1-2cm. The behaviour of the poloidal velocity with regard to the L-H transition is similar to that observed on COMPASS-D [7] particularly that the acceleration commences at the L-H transition. These observations suggest that the poloidal velocity change is not the bifurcation event, for all tokamaks, but rather that it builds up, in extent or magnitude, after the L- to H-mode transition has occurred.

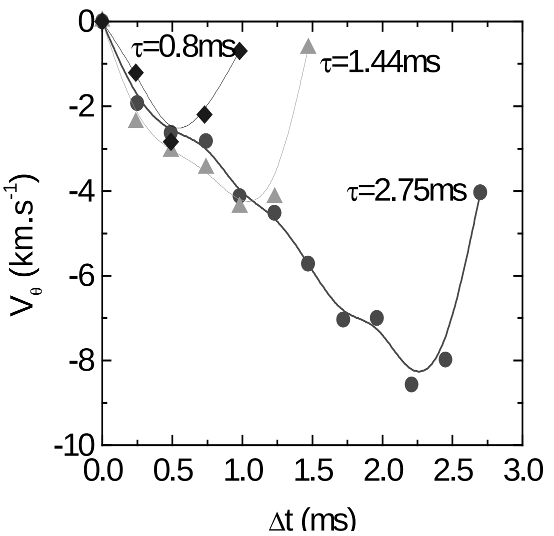

Figure 5 Acceleration of V_θ (C^{2+}) between ELMs where τ is the time separating ELMs.

Energy confinement in H-mode discharges

A scatter plot comparing the energy confinement time of NBI heated discharges in START with the predictions of the ITERH97 scaling is shown in Fig. 6. Over the totality of discharges, those having ELMs show no clear enhancement in confinement compared to other auxiliary heated shots. However, selecting those discharges with plasma currents > 250kA, a clear increase in confinement of approximately 50% over the corresponding L-mode shots is apparent. At high-β, the H-mode energy confinement is comparable to the ITER97H scaling [8], which was a key factor in the achievement of record β values of β_T ~ 40%, $\beta_N \geq 5.5$.

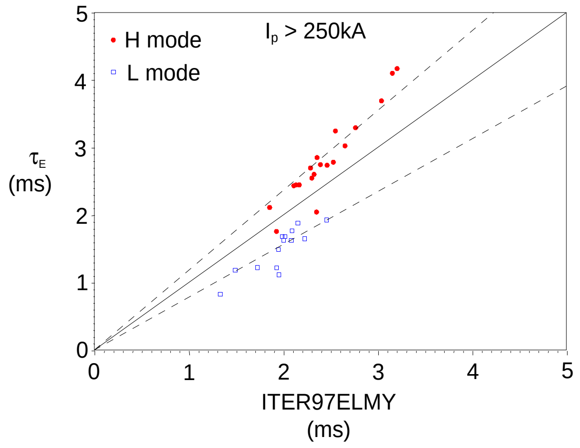

Figure 6 Energy confinement Vs ITERH97 prediction for all H-mode (solid symbols) and L-mode (open symbols) discharges having I_p > 250kA .

Conclusions

A database is available from START for use with other STs or conventional aspect ratio tokamaks over an extensive range of confinement regimes. The confinement behaviour compares favourably with the scaling laws derived from other tokamaks and can be modelled with transport codes which include tight aspect ratio effects. H-mode conditions are shown to be accessible in both Ohmic and NBI heated discharges in START accompanied with the usual H-mode signatures found in conventional tokamaks. For plasma currents in excess of 250kA, there is a clear ~50% increase in confinement time compared with the equivalent L-mode shots and exceeding the prediction of H-mode ITER scalings such as ITER97H (ELMy).

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