Confinement in L and H mode MAST plasmas


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Introduction

The first demonstration that H-mode operation was accessible in the Spherical Tokamak (ST) [1] was provided by the prototype START experiment [2], where it was shown that confinement is well represented by the ITER98py(y,2) scaling [3], even though this scaling law has been developed at conventional aspect ratio. The successor to START, the MAST device, has similarly reported the first observations of H-mode [4,5] in plasmas with significantly higher currents and at lower collisionality. When compared with START, MAST [6] can generate plasmas with a factor of ten increase in plasma volume (with poloidal cross section comparable to DIII-D and ASDEX-U), improved vacuum conditions, and can produce keV temperature plasmas (both electrons and thermal ions). Following boronisation, which produced a ten-fold reduction in a number of measured impurity lines (notably carbon and Oxygen), H-mode plasmas have been achieved in Neutral Beam Injection (NBI) heated plasmas with modest auxiliary heating power [4,5]. The NBI system, on loan from ORNL, produced typically 500-700kW of power in campaign I, and up to 2MW in campaign II. The H-mode plasmas reported here were generated in campaign I and hence have a beam power comparable to the Ohmic heating power.

L-H transition and H-mode phenomenology

Transition from L to H-mode in MAST is demonstrated for discharge 2952 in figure 1. The total input power was ~1.3MW (0.6MW Ohmic + 0.74MW NBI), with NBI termination at 0.30s. Figure 1a) shows the increase in measured global energy confinement time following transition at ~190ms (although interestingly for this discharge, energy confinement appears to increase slightly preceding the transition). L-H transition for this plasma was triggered by a sawtooth crash, this being typically the case for MAST H-mode plasmas achieved to date. Accompanying the observed increase in energy confinement is a sharp increase in line integrated electron density (figure 1b). This can be modelled using a simple 1D diffusion model where an increase in fuelling efficiency and a decrease in the peripheral particle diffusivity are required to take place L-H transition. The increase itself is manifest as ‘ears’ at...
the plasma edge together with a steep edge density gradient and a correspondingly large edge pressure gradient $dP_e/d\psi_n \approx 8 \text{ kN/m}^2$ (where $\psi_n$ is normalised poloidal flux) which remains constant throughout the H-mode phase of the discharge. Further details of this phenomenon, together with results of the 1D modelling are reported in [7].

Figure 1c) shows the $D_\alpha$ emission, highlighting a sudden drop when the edge pedestal begins to form as well as the presence of large Edge Localised Modes (ELMs) and grassy or dithering ELMs towards the end of the discharge following termination of the NBI.

A preliminary edge-ballooning stability analysis indicates that the large ELM signature appears when the plasma periphery is close to marginal stability; the ELMs are therefore likely of Type I classification. The resultant plasma energy loss is typically $\sim 2\text{kJ}$ ($\sim 4.5\%$ of total), comparable to that observed for type-I ELMs in conventional tokamaks but not, however, in agreement with scaling law predictions developed at large aspect ratio [3] which predict a significantly higher loss of $\sim 8\%$. Figure 1d) shows the reduction in high frequency activity recorded by the
MAST homodyne reflectometer (which measures fluctuations in the plasma periphery, operating at 33GHz in X-mode with a pass-band of 50-125kHz and corresponding density cut-off of 1x10^{19}/m^3). This most probably indicates a decrease in turbulence, since the edge profiles change relatively slowly (although the cut-off location does move radially outwards over ~7ms by ~10% w.r.t. poloidal flux [5]). Figure 1e) shows the rapid onset and saturation of the edge poloidal flow, which like on START, and the conventional aspect ratio tokamak COMPASS-D begins at the L-H transition and not preceding it [2,8,9].

An important issue associated with the edge density evolution and corresponding reduction in turbulence, is the degree by which the divertor heat deposition width changes. Figure 1f) shows the ratio R_{oi}, of total power deposited between the outer and inner strike points for discharge 2951 (the companion shot to #2952 which undergoes L-H transition at the same time), having an average value of ~19.3 in L-mode, but falling by a factor ~5 to around 3.6 during the L-H transition. This is very close to the ratio of outboard to inboard separatrix surface areas, which varies from ~3.1 to ~3.5. A possible explanation for the relative increase in inboard power efflux lies, therefore, in the reduction in turbulent losses from the outboard side (tentatively inferred from the homodyne reflectometer), whereas the inboard side, which is in the good curvature region, may be comparatively unaffected.

**Confinement scaling**

Figure 2 shows ‘thermal’ confinement times for the plasmas studied (averaged over suitable time windows) against those predicted by the international scaling IPB98(y,2) [3], together with data from START. Calculations have been validated by comparing the plasma energy from EFIT with that from kinetic evaluation, i.e. by combining data from Thomson scattering, the Neutral Particle Analyser [10] and fast ion modelling using the LOCUST code [11] (assuming ion-electron temperature and density profile similarity). Results of this study are shown in figure 3, indicating good agreement. Here, error bars are due only to the random error on the core T_i (as measured by the NPA) and do not reflect the full systematic uncertainty. \( \tau_E \) has been evaluated over periods during which the loop voltage remained approximately constant, stored energy being determined by removing the fast ion energy calculated by LOCUST (blue bars in figure 3) from the EFIT stored energy (yellow bars). Figure 3 was generated using the assumption that all of the injected beam power was absorbed, this being broadly supported by the two highly suprathermal discharges 2945 and 2946 (i.e. where the NBI fast ion population is a large fraction of the total plasma energy and there is no overestimate of the stored energy when compared with EFIT). In any case, such an assumption will lead to a conservative underestimate of the confinement time.

For MAST, the edge safety factor \( q_{95} \) varied between 2.9 and 7.5 for L mode plasmas and 4.1 and 5.5 for H-mode shots. Greenwald numbers \( (=n_{e20}\pi a^2/I_p) \) for the H-mode plasmas ranged from 0.25 to 0.85, there being no clear evidence of confinement degradation as density increased. The marked improvement in energy confinement at transition on MAST is in contrast to results from START, where clear improvement was only observed for the highest current discharges [2]. This difference may be due in part to the high neutral density in START, which is predicted to have caused a significant increase in convective losses as the
plasma edge density increased following transition. Dotted lines in figure 2, connecting the MAST L to H-mode phases, indicate that the increase in confinement is mainly due to an increase in $H_H$ and not simply due to an increase in plasma volume and density (radial position feedback control not having been applied).

**Conclusions**

We have discussed the phenomenology of H-mode formation in MAST. Clear improvements in both energy confinement and particle confinement are observed, global energy confinement in H-mode agreeing well with IPB(y,2) scaling predictions. Clear ELMs, most probably of type-I origin, are observed, resulting in power ejection below the level predicted by conventional scalings. Following L-H transition, a clear reduction in high frequency activity, recorded by a homodyne fluctuation reflectometer is seen, most probably due to a reduction in turbulence near the edge. Plasma edge poloidal rotation rapidly increases and saturates and a reduction in outboard-inboard power flux asymmetry is observed down to a ratio close to that of the outboard to inboard separatrix surface areas, very likely due to a reduction in the peripheral turbulence.

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**References**