DENSITY LIMITS IN MAST
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Abstract Good density control is achieved in MAST plasmas despite the large vessel to plasma
volume ratio. High normalised densities can be readily attained in Ohmic and NBI heated L-
Mode DND discharges at moderate plasma current \( I_p < 0.6 \text{ MA} \) and at higher currents the
maximum density achievable is limited by a combination of the available heating power and
discharge length. This paper presents the operating space of the MAST spherical tokamak
achieved during its first experimental campaign. The relationship to a theoretical model for
density limits in tokamaks, based on ideal MHD ballooning stability, is introduced.

1 MAST Operating Space

The Mega-Ampere Spherical Tokamak (MAST) is one of the new generation of large tight
aspect-ratio devices (spherical tokamaks or ST's) built to verify and extend the remarkable
results of the START prototype experiment [1]. First physics results have been reported
in [2]. Since the fusion power produced per unit volume of plasma is proportional to
the square of the plasma density, it is clear that maximising density is desirable, and its
control is crucial to tokamak performance.

The effects of the presence of high density gas in proximity to the plasma edge have
generally been investigated in the tokamak divertor chamber (e.g. [3]), where there is high
recycling of particles from the unconfined outer plasma edge (scrape-off layer) and where
a high density of particles is desirable for more effective pumping and extraction of the
exhaust particles [4]. In MAST, where the plasma volume is \( \sim 1/10 \) of the vessel volume,
the divertor configuration is 'open' and the fuelling source is far from the plasma edge, the
effects of the neutral gas accumulated in the tank play a significant role in the refuelling
and recycling dynamics of density control. Modelling of this plasma/gas envelope/wall
system for the particular MAST case [5] indicates that at sufficiently high neutral gas
density, this 'blanket' can be an extra limiting factor to achieving good plasma density
control and neutral beam transmission. Hence the importance of surface conditioning to
achieve strong wall pumping.

Experimentally, good density control is currently achieved on MAST plasmas despite
the large vessel to plasma volume ratio (figs 1 and 2). Boronisation (using deuterated
trimethylboron) together with inter-shot helium glow discharge cleaning results in pumping
walls (plasma density decay \( \tau_{\text{decay}} \geq 100 \text{ ms} \) ) and low tank \( D_2 \) neutral density during
discharges \( (<10^{18} \text{ m}^{-3}) \), adequate for good neutral beam transparency.
Referring to figure 1, high normalised densities \( G \equiv \pi_e/n_G \) where \( n_G \equiv I_p/\pi a^2 \times 10^{20} \text{ m}^{-3} \)
up to \( \approx 1.8 \) can be routinely attained in Ohmic and NBI heated \((P_{\text{NBI}} \leq 2 \, \text{MW})\) L-mode DND discharges at relatively low plasma current \((I_P < 0.6 \, \text{MA})\), appearing to be limited by internal reconnection events. At higher currents (up to 1 MA), the maximum density achievable is set by a combination of the available heating power and limited discharge length \((< 500 \, \text{ms})\) with the present gas-puff fuelling rates available. MARFEs (localised regions of high radiation loss) near the mid-plane, are also observed at high Murakami numbers \((M = \bar{n}_e \, [10^{19} \, \text{m}^{-3}] \, R_0/B_T)\). This density range corresponds to absolute densities less than \(8 \cdot 10^{19} \, \text{m}^{-3}\) and neutral gas ‘blanket’ densities \(\leq 4 \cdot 10^{18} \, \text{m}^{-3}\), beyond which the modelling [5] shows significant degradation of density control.

As yet, H-mode discharges have been achieved over a relatively small operating window, reaching Greenwald fractions \(G \approx 0.9\) in large volume tight aspect-ratio plasmas, although low volume H-mode plasmas at higher aspect ratio reach \(G \approx 1.4\) during the current decay phase of the discharge. Typical high density plasmas \((G \geq 1)\) achieve \(\beta_N \approx 2 \, (\beta_T \sim 3\%)\), just above half of the Troyon limit.

### 2 A Theoretical Limit to Density

Murakami has suggested that density is limited by disruptive instabilities, the limit scaling as \(B_t/R\), and Hugill showed the dependence on plasma current, \(n_H \propto B_t/(R q_b)\), where \(q_b\) is the safety factor at the edge of the plasma (minor radius \(a\)). Greenwald’s empirical derivation \(\bar{n}_G\) removed the dependence on the plasma elongation \(\kappa\), is indepen-
dent of heating power, and is generally taken as a common reference point for comparing tokamak performance ([6] and references therein).

In [7] a density limit is derived for additionally heated L-mode plasmas, assuming that the ideal MHD ballooning limit criterion on pressure gradient sets an ultimate density limit at the plasma edge. The model considers two operating regimes. In the first there is energy transport from a core plasma, where additional external heating is assumed to be deposited, with cross-field thermal diffusivity \( \chi \perp \) towards the plasma edge where the energy sink is due to impurity radiation loss in a thin radiative layer. The density limit is then found to be

\[
n_a = \left( \frac{P_{\text{tot}}}{8 \pi^2 R a \sqrt{\kappa}} \right)^{2/3} \left( \frac{1}{k \chi_{\perp a} \sum f_z L_z} \right)^{1/3}
\]

(1)

where \( n_a \) is the plasma density of the thin radiative layer at the edge; total heating power \( P_{\text{tot}} = 4 \pi^2 R \int_0^\rho P(\rho) d\rho \) (\( R \) major radius); \( \rho \) a flux surface label such that \( S = \pi \rho^2 = \pi k a^2 \); \( k \) is Boltzmann’s constant; \( f_z = n_z/n \) is the fractional density of impurity species (of atomic number) \( Z \) and \( L_z(T) = 3.7 \cdot 10^{-33} T^{1/2} Z^3 \) Wm\(^3\)eV (\( T \) in eV) is the radiative energy loss term [8]. The density limit increases with \( P_{\text{tot}}^{2/3} \) and depends weakly on \( \chi_{\perp a} \). Once the power increases above a critical value \( P_{\text{crit}} \), then the model is subject to the ideal MHD ballooning stability condition, \( \alpha(\rho) \equiv -2 \mu_0 (R B^2) d\rho/d\rho < \alpha_c(\rho) \), where \( p(\rho) \) is the plasma pressure and \( \alpha_c \) is the critical pressure gradient at which ballooning modes occur, itself being a function of magnetic shear, \( s = (1/q) dq/d\rho \). In this regime, energy transport (gradient) is no longer set by thermal diffusivity \( \chi \perp \) but by the ballooning stability criterion. The heat flux balance then gives the density limit:

\[
n_a = \left( \frac{\alpha_c P_{\text{tot}} B^2}{32 \pi^2 \mu_0 k \sqrt{\kappa a R^2 B^2} \sum f_z L_z} \right)^{1/3}
\]

(2)

for \( P_{\text{tot}} > P_{\text{crit}} \) where \( P_{\text{crit}} \) is defined as

\[
P_{\text{crit}} = \frac{2.5 \alpha_c \sqrt{\kappa R^2 I_p^2 \chi_{\perp a}}}{a^3 (1 + \kappa^2)^2}
\]

(3)

with \( P \) in MW, \( I_p \) in MA.

The MAST data set can then be reformatted in terms of this density, defining \( C = n_e/n_c \) where \( n_c \) is given by equation 2 and assuming \( n_e \sim 4n_a \) (figure 3).
3 Discussion

Experimental results show that MAST plasmas achieve high densities, normalised to the empirical Greenwald value, for plasma currents < 0.6 MA (figs 1 and 2). At higher currents, normalised densities are less than 1, being limited by available additional heating power and discharge duration. MARFEs tend to appear at high densities. A density limit model is introduced, based on balancing energy transport from the plasma core to the edge with radiative losses and imposing the ideal MHD ballooning stability criterion as a limit on edge pressure gradient.

Comparison with experimental data shows that at low heating power, this density limit is approached, whereas at higher power, normalised densities are ≤ 70% of the theoretical limit (fig 3). These limits are subject to uncertainties in (mainly) the thermal diffusivity and critical pressure gradient, the values $\chi_{\perp} \simeq 5 \, \text{m}^2\text{s}^{-1}$ and $\alpha_c \simeq 1.2$ for $s \simeq 2$ used as a first approximation corresponding to conventional tokamak estimates. The more recent discharges clearly indicate progress towards higher densities and it appears MAST has not yet reached a density limit. Current experimental conditions (surface conditioning and plasma densities $\leq 5 \cdot 10^{19} \, \text{m}^{-3}$ resulting in strong wall pumping and low gas ‘blanket’ densities $n_{D_s} \leq 4 \cdot 10^{18} \, \text{m}^{-3}$) have not yet reached the situation modelled by [5], where the gas envelope would significantly degrade density control.

However, with increasing heating power (up to 2 MW of neutral beam in the present experimental campaign and 5 MW eventually) and longer discharge durations (up to 5 s design duration), the present limiting factors would be removed. Then future high density experiments could be limited by the predicted degradation. Enhanced fuelling aimed at reducing the gas ‘blanket’ density (pellet injection, convergent-divergent nozzle gas collimation, inboard fuelling) are now being commissioned and will help the operating space to approach and test the radiative ballooning model theory.

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