THE EFFECT OF PLASMA SHAPE ON DENSITY AND CONFINEMENT OF ELMY H-MODES IN JET.

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1. Global Performance of high δ plasmas. This paper presents the results of experiments carried out in JET to investigate the confinement properties of NB heated high density ELMy H-modes, focusing on the effects of plasma triangularity δ on the relationship between energy confinement and density.

Previous experiments in JET [1] and other divertor tokamaks have shown that the thermal energy confinement time and the maximum density achievable in steady state for a given confinement enhancement factor increase with δ. Recent experiments in JET have confirmed and extended these earlier results, up to a plasma triangularity of δ~0.5 (κ~1.75), achieving a line average density ne~1.1nGR and H97~0.85 (Fig.1). In this plasma configuration, at 2.5MA/2.7T (q95~3), a line average density ~90% nGR with H97=1 and βN~2 are obtained, matching or exceeding the global plasma parameters required for the Q=10 ITER-FEAT operation [2]. Moreover, the plasma thermal stored energy content is approximately constant with increasing density (Fig.2, δ=0.47), as long as the discharge maintains Type I ELMs [3], up to nped~nGR (and n~1.1nGR).

In the next sections it will be shown that with the highest triangularity, we observe an increase in the pedestal pressure with density, possibly due to marginal access to second stable region (ideal ballooning), as well as an improved core transport.

![Figure 1: Confinement enhancement factor (H97) as function of the Greenwald number n_e/n_Gr. The new data for δ=0.47 are compared to triangularity scans from JET MKII experiments [1].](image1)

![Figure 2: Thermal plasma stored energy W_th for the same discharges as in Figure 1 (2.5MA/2.7T), plotted against the normalized pedestal density n_ped/n_Gr. Each point represents a different discharge.](image2)

2. Edge pedestal, ELMs and stability. This section analyses the results of gas/density scans carried out for 2.5MA/2.7T and 2.0MA/2.7T plasmas, δ~0.5 and 15MW of NB additional heating. The discharges were fuelled with constant gas flow from the inner divertor, for improved efficiency [4]. Figure 3 shows the inner divertor Dα emission for 5 representative discharges of the 2.5MA series. The usual relationship between Type I ELM frequency and density (f_ELM increasing with density) is
The JETTO code plasma analysis coupled to the ideal ballooning code IDBALL [8] for the case shows access to ideal ballooning second stability, at least over part of the edge pedestal region ($\psi > 0.97$). This result is qualitatively consistent with the observed increase of the pedestal pressure and the decrease of the Type I ELM frequency with density. Unfortunately, the measurement of the pressure gradients with the edge LIDAR [9] is limited by the space resolution of the system, thus precluding a direct comparison with the JETTO computed pedestal pressure profiles.

Figure 3: $D_\alpha$ emission from the inner divertor (a.u) as function of time for a subset of discharges at 2.5MA/2.7T, $\delta$-0.5, for increasing gas fuelling rates.

Figure 4: Time evolution of the $T_e$ at the top of the pedestal and of the outer divertor $D_\alpha$ for two 2.0MA/2.7T ($q_{95}$=3.8), $\delta$-0.5 pulses: 52997 ($n_{ped}$=72% $n_{GR}$) and 52995 ($n_{ped}$=48% $n_{GR}$). Note the enhanced $D_\alpha$ levels in pulse 52997.

Figure 5: $n_e$-$T_e$ diagram for a gas/density scan for 2.0MA/2.7T, $\delta$-0.5, 15MW $P_{in}$. Values at the top of the pedestal. All the discharges are in the Type I ELM regime.
In fact, for the 2.5MA case with Type I ELMs, the measured pressure gradient \( V_{ped} \) in the pedestal region is always at least 240 kPa/m, and any change of the gradient with density is not resolved. This is not any more the case during the Type III ELMs phase, such as in pulse 52739 after 19s (Fig 3). This transition corresponds to a reduction of the pressure gradient in the pedestal region down to \( \sim 180 \text{kPa/m} \), indicating indirectly that the edge pressure gradient sustained during the enhanced \( D_a \) phases is substantially higher than for Type III ELMs.

3. Core profiles and transport. The loss of \( p_{ped} \) with density is smaller at high \( \delta \) compared to standard JET ELMy H-modes, in particular when the Type I ELM frequency starts to decrease at high \( n_{ped} \). Nonetheless, for increasing density, \( p_{ped} \) is somewhat reduced compared to the unfuelled reference case, and of course, the pedestal temperature reduced compared to reference. It follows that the experimental observation that the total stored energy is \( \sim \) constant with density implies that the core confinement of these discharges is constant up to the highest density. Therefore, in this section we analyse the changes in the core density and temperature profiles, for the 2.5MA/2.7T series of discharges with \( \delta \sim 0.5 \) and \( P_{in} = 15 \text{MW} \).

The variation in density in the scan is quite large, from approximately 6 to \( 10 \ 10^{19} \text{ m}^{-3} \) at the pedestal. This implies that the central NB power and particle deposition profiles varied considerably (the central power density gradually decreases, down by \( \sim 2 \), and becomes very flat). In first approximation, if the core temperature profiles were self-similar, the combination of constant \( W_{th} \) and off-axis heating should imply self-similarity in the density profiles or density peaking with density. The analysis of the \( n \) profiles shows that the characteristic timescale for the evolution of the density profile in the high \( \delta \) discharges, at constant \( P_{in} \) and \( \Phi_{GAS} \) is of the order of \( 3s \), corresponding to \( 6-7 \tau_C \).

In contrast, the pedestal density reaches quasi-steady state on a shorter time scale, typically \( \sim 1s \). The density of most of these plasmas does not reach true steady state in the \( \sim 6s \) of additional heating although the “residual” time evolution is quite small and the peaking constant, hence the term quasi steady state used above. The final peaking factor \( n_{peak} \) (defined as the ratio of the central to the pedestal line average density) decreases with \( n \) from pulse to pulse, as shown in the inset of Fig. 5 (for the analysis of spontaneous density peaking, see [10]). The current density profile is of course evolving in these discharges, but normal sawtooth activity is maintained in all pulses.

Ion and electron temperature are coupled in these discharges, due to the high density, and decrease for increasing density, from \( \sim 5 \text{keV} T_i \sim 4 \text{keV} T_e \) at \( 80\% n_{GR} \) to \( \sim 2.2 \text{keV} \) at \( n = 1.1 n_{GR} \), but they exhibit different profile behaviour. We find that the ECE \( T_i \) profiles are self-similar, at least up to \( n = 90\% n_{GR} \) (beyond that ECE emission is cut-off) whilst, as shown in Fig. 5, the \( T_i \) profiles are not stiff, and they become more peaked as the density increases (each trace in Fig. 5 is the average of 3 profiles taken at the end of the constant power phase of each discharge, plotted on the region outside the sawtooth inversion radius), consistently with the reduction in \( n_{peak} \) at \( n = \text{constant} \ W_{th} \). Preliminary TRANSP analysis of these discharges indicates a reduction of \( \chi_{eff} \) across the radius of the plasma for the discharges at the highest density. The interpretation of this unusual result is in progress, but the phenomenology of the high \( \delta \) high density discharges studied here seems to be different from what reported from other experiments. In particular, in [11], the good energy confinement of DIII-D gas fuelled ELMy H-modes at \( n > n_{GR} \) is ascribed to the increased density peaking, with stiff \( T_i \) and \( T_e \) profiles, in contrast with our finding. For a discussion of the role of input power, refer to [3].

4. Plasma geometry effects. The role of plasma shape in the pedestal and global confinement at high density has also been investigated by comparing plasmas with the same upper \( \delta \), but with different lower \( \delta \) (Fig 6), at the same \( I_p, B, \) and similar NB power (15 vs. 16.5 MW). Although the geometry of the two configurations is different near the X-point (\( \delta_1 \) reduced from 0.4 to 0.3), the variation in the

Figure 5: CX \( T_i \) profiles for a subset of the \( \delta \sim 0.5 \) discharges in Fig. 1. Each trace is the average of 3 profiles, taken \( >90\% \) into the ELM cycle, and normalised to its maximum. The inset shows, \( n_{peak} \) vs \( n_{ped} \) for the same discharges and time slices.
average equilibrium properties near the edge is small, with the shear and $q$ (at 95% of the flux) differing by $<10\%$. Nonetheless, the configuration with higher $\delta_i$ (and higher $<\delta_i>$) achieves higher confinement at higher density, as well as higher pedestal pressures. The $n_e - T_e$ diagram for the two gas/density scans (top of the pedestal values, constant $P_m$) is shown in Fig 8. The lower $\delta_i$ plasmas have, for a given $n_{ped}$, lower $T_{ped}$, and reduced pedestal pressure across the density range. Moreover, the transition to lower confinement, Type III ELMs, occurs at lower density for the lower $\delta_i$ plasmas.

The “anomaly” in the Type I ELM frequency at high density, described in Section 2 is observed also at low $\delta_i$, although this change in ELM behaviour for the low $\delta_i$ occurs very near the Type I-III transition, and is sustained in a much reduced $n_{ped}$ window. The lower $\delta_i$ has a strong effect on both the Type I ELM frequency and prompt energy loss per ELM. In particular at high $n_{ped}$ ($n_{ped} \sim 90\% n_{GR}$, $\sim 9 \times 10^{19} m^{-3}$), $f_{ELM}$ for $\delta_i=0.3$ is $\sim 40\text{Hz}$, to be compared to $\sim 12\text{Hz}$ for $\delta_i=0.45$. The respective ELM energy losses are 4-5% and 8-9% of $W_{ped}$.

ELM losses of about 4% are very close to the acceptable value for the ITER W divertor (3.6%), although in the experiment this is obtained at the cost of $\sim 10\text{-}15\% W_{th}$ reduction. This reduction in the total stored energy content and its trend with density (Fig 9) for the low $\delta_i$ plasmas is consistent with the reduced pedestal pressure.

5. Conclusions. The positive effect of plasma shaping for achieving high density with high confinement in ELMy H-modes has been confirmed and extended in recent JET experiments. Plasma with $\delta$ and $\kappa$ close to the ITER specifications have achieved $n/n_{GR}$, $H$ and $\beta_V$ required for the $Q=10$ ITER operation.

For $n_{ped}>70 n_{GR}$, the frequency of Type I ELMs decreases with density. Specific MHD broadband fluctuations and enhanced $D_e$ are observed in the inter-ELM period. Similarities with Type II ELMs and EDA regimes are observed, although total Type I ELM suppression has not been achieved. 2-D stability calculations indicate a possible access to second stability.

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