Steady State H-modes at high plasma density in JET

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1. Introduction

One of the reference ITER operating scenarios [1] is a high confinement regime with H_{93} =0.9 to 1, $Z_{eff} \leq 1.8$ and plasma density at or above the Greenwald density limit (GDL) in steady state. However, as reported already by JET [2] and other Tokamaks [3], the plasma steady state density of ELMy H modes saturates at values below the GDL, due to a progressive loss of confinement (H mode density limit). Dedicated experiments have been carried out in the JET Mark II (MkII) divertor campaign to study the confinement of Type I ELMy H-modes at high density, under steady state conditions ($t>4\ \tau_E$).

The basic type of plasma studied is a 2.5MA/2.5T discharge (q_{95}=3.4) with 12 MW of Neutral Beam injected power, where D_2 gas fuelling scans were performed. The experiment studied the effects of the magnetic configuration and divertor plasma geometry, including low and high triangularity discharges (Δ = 0.2 and 0.3), and variation of the position of the separatrix (horizontal or vertical plates of the divertor).

Confinement data have been compared to the ITERH93-P ELM-free scaling for ELMy discharges (τ_{ELMy}=0.85 $\tau_{ELM\text{-}free}$). The plasma stored energy is corrected for the fast ion contributions, unless otherwise stated, and fast ion orbit losses are taken into account. For all the pulses analysed, the fast energy fraction is small and varies between 15% at low densities ($\approx 4\times10^{19}\ m^{-3}$) to approximately 5% for densities above $7\times10^{19}\ m^{-3}$.

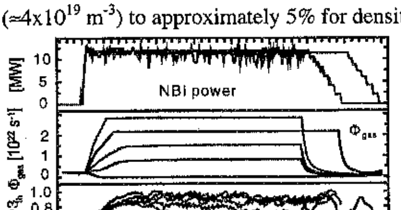


Figure 1: Typical D_2 gas scan for an high triangularity configuration. NBI power input, gas rates, H93, density (& Greenwald density) and Z_{eff}

2. General results

Fig. 1 shows the time traces for a series of discharges with high triangularity, where the gas input was varied from pulse to pulse from zero to $2.8\times10^{22}s^{-1}$. ELMs are produced during the whole heating phase, with a frequency increasing with fuelling from 12 to 46Hz. The energy and particle confinement deteriorate for the higher fuelling rates, and the line averaged density stays below the GDL. Similar results are observed in all configurations.

In general, the total fraction of radiated power varies with the plasma configuration, and is between 20-35% (no gas) and 50-60% (maximum fuelling). Increasing gas fuelling does not change the fraction of bulk radiation

(10-30%), while the X-point radiation increases steadily. Divertor MARFEs are not observed. The impurity content is low, with Z_{eff} usually around 1.3-1.4 with gas fuelling.

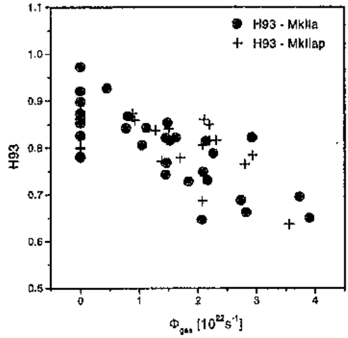
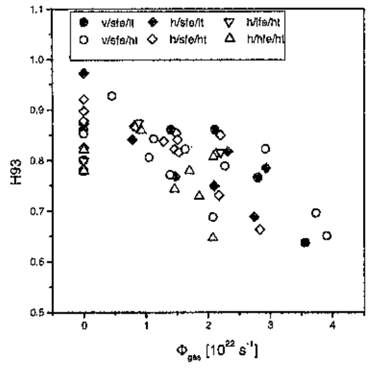


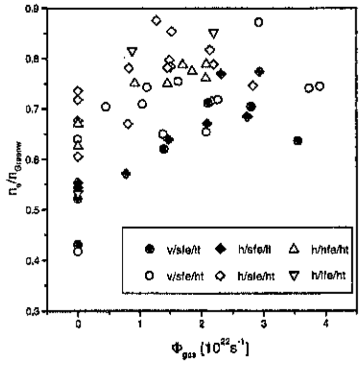
Figure 2: H93 before (MkIIa) and after (MkIIap) the closure of the by-pass leaks. Each point is a plasma discharge.

One effect of increasing the gas fuelling rate (and density) is an increase of the ELM frequency. We find that the total particle loss per ELM is a weak function of density and/or gas fuelling therefore as the fuelling is increased, the maximum achievable density saturates and then decreases. The high ELM frequency and loss of confinement result in a net loss of density. The maximum density achieved with gas fuelling saturates below the GDL and is determined by the balance between fuelling and confinement losses (see figs 3 and 4). The roll-over of n_e and H93 corresponds to a transition from Type I to Type III ELMs.

The effect of neutral pressure on the density limit and the confinement was studied before and after the closure of the by-pass leaks around the structure of the MkII divertor. The closure resulted in a decrease of the edge neutral pressure in the midplane (30%) while the divertor neutral pressure remained the same. However, the global confinement did not change appreciably (fig 2).

3. Effect of configuration on density and confinement





Figures 3 and 4: Thermal confinement degradation and maximum achieved density (expressed as a fraction of the GDL) for all the magnetic configurations studied (h-v = horizontal-vertical target, lt-ht = high-low Δ, lfe-sfe-hfe = low-standard-high flux expansion)

Fig 3 illustrates that the energy confinement does not depend on the magnetic configuration, whereas fig 4 shows that triangularity affects the maximum density achievable in steady state. In fact, for the same value of H93, the high triangularity discharges reach up to ≈ 90% of the GDL, while at low triangularity they achieve only 75%.

Most of the discharges analysed are characterised by an initial hollow density profile. This is also the case for no additional gas fuelling hence we conclude that edge recycling is responsible for the hollow profiles. The effect of recycling is evidenced by the fact that the initial density rise is about twice the beam fuelling, also in the absence of additional gas fuelling. Usually, the density profile fills up during the discharge and is flat in steady state. In some cases however, (medium gas fuelling, high Δ), the steady state n_e profile peaks. For these discharges, the GDL is exceeded locally in the central 10% of the plasma volume, while the edge density and the overall average density remain below the Greenwald density.

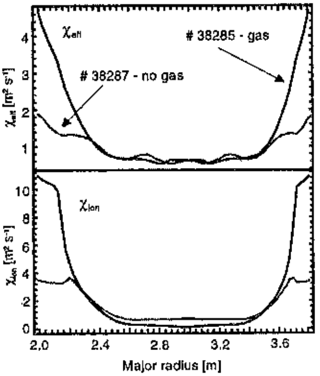


Figure 5: Radial profiles of χ_{eff} and χ_{ion}, calculated by TRANSP.

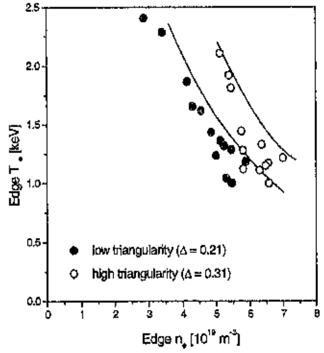


Figure 6: Empirical stability plot for Type I ELMs in low and high Δ discharges, in steady state.

4. TRANSP code analysis.

Figure 5 illustrates the results of TRANSP simulations of two discharges, on the horizontal plates and at low Δ, with zero and high gas fuelling (2.7×10^{22} s^{-1}), with H93(no gas)=0.83 and H93(gas)=0.69. The calculated profiles of the transport coefficients show that the lower confinement of the fuelled discharge is accounted for by enhanced energy transport in the edge (outermost 20% of the plasma radius), while the central confinement is not affected. This result seems to contradict the Kotschenreuther-Dorland model [4].

There are indications that the change in transport occurs mainly in the ion channel. Additional TRANSP runs were carried out to test the sensitivity of these results to the assumptions on particle recycling. These simulations, where the energy of the recycling particles or the particle confinement time were varied (fixed τ_P or $\tau_P \propto \tau_E$), confirm that the changes in the edge transport are relatively insensitive to the assumptions on the edge recycling in the code.

5. ELMs and edge parameters

The pedestal electron density and temperatures have been analysed for gas scans at low and high triangularity. In the edge n_e/T_e diagram [5,6], the experimental stability limit for type I ELMs is found to increase with plasma triangularity (i.e. shear), as expected (fig 6). Moreover, as shown in fig 7 for a gas scan (subset of fig 6), there is a correlation between the confinement of a discharge and its position in the stability diagram, with low confinement corresponding to a cool and dense edge. In fact, the increase of the gas fuelling results in the rise of the edge density at the expense of the edge temperature, at approximately constant pressure. The lower confinement point shown in the figure corresponds to a change from type I to type III ELMs. The crucial role of the edge temperature is confirmed by the analysis of the

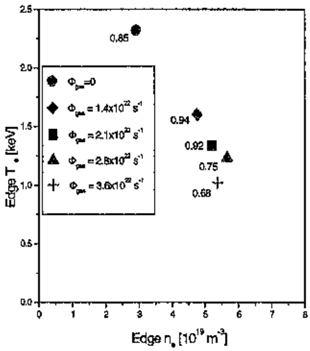


Figure 7: Variation of H93 for a gas scan at low Δ. H93 is calculated without subtraction of the fast ions energy.

time evolution of the edge n_e and T_e for low and high Δ discharges. This shows that for low Δ, n_e and T_e increase similarly between ELMs, until the stability limit is reached, whereas for high Δ, the pedestal temperature clamps after an initial rise, and the stability limit is reached due to the increase in n_e. The clamping of T_e is correlated with the occurrence of high frequency MHD modes (60-80 kHz), possibly located in the edge. The clamping of the edge temperature is consistent with the observation that high Δ plasmas have a lower energy confinement between ELMs than low Δ discharges.

In the high density ELMy H modes, partial detachment at the inner divertor is observed between ELMs. The degree of detachment [7,8] is quite low in all cases and there is no unique correlation between detachment and confinement degradation. At high triangularity, some detachment can be sustained without loss of confinement.

6. Summary

The H mode density limit is a confinement limit. The decrease in energy confinement at high density cannot be explained by the loss of fast ion contributions (typically around 10% or less). The maximum plasma density achieved in H mode is ≈ 90% of the GDL, with H93 ≈ 0.75 - 0.8. Discharges with high triangularity (edge shear) reach higher densities than low triangularity plasmas, for the same global confinement.

The core confinement of high density, low edge temperature pulses (H93=0.65) is comparable to the unfuelled reference case (H93>0.83), and the reduced confinement is accounted for by the enhancement of the edge transport (outer 20% of plasma radius).

Experimental data in steady state discharges confirm that the edge stability for type I ELMs increases with edge shear. The degradation of confinement is related to a trajectory in the n_e/T_e space toward low pedestal temperature, consistent with the existence of a minimum critical edge temperature for H mode confinement.

Clamping of the edge T_e between ELMs is observed in high triangularity discharges. In this case, the stability limit is determined by the density rise between ELMs, and not by re-heating. Divertor detachment and MARFE formation do not account for the observed loss of confinement.

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