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INTRODUCTION

In the ELMy H-mode regime, a degradation of the plasma energy confinement enhancement factor at high density is observed in most experiments [1.2], in contrast with the positive density dependence predicted by the energy confinement global scaling. In JET, when the density is increased at constant input power, some reduction of the stored energy (≤10%) is observed [1]. As the density is increased further, the plasma usually makes a transition from the Type I to the Type III ELMy H-mode regime. This transition occurs when the pedestal temperature falls below a critical temperature, T_{crit}, which is, at high density, independent of density [3]. The transition to Type III ELMs is accompanied by a further large reduction of the stored energy and often also by a decrease in density. Therefore, the Type III ELMy H-mode regime represents a confinement limit for high density ELMy H-modes. In the edge operational diagram n_e-T_e, T_{crit} limits the best operating point in terms of the combination of high density and good confinement (Type I ELMs). If T_{crit} does not depend strongly on plasma triangularity, δ, increased δ is likely to extend the operational space for Type I ELMs at high density, through the increase in pedestal pressure. Similarly, an increase in pedestal temperature for a given density could be expected at higher input power, P_{IN}, hence increasing the achievable density in Type I ELMs. On the other hand, the ability to operate in the Type I ELMy regime is likely to depend on the lower boundary of the ELM cycle more than on the upper one, and effects of the ELM frequency, f_{ELM}, on the fuelling efficiency could also play a role.

Due to the very limited P_{IN} available in JET, in the majority of the high density ELMy H-mode experiments previously carried out [1], P_{IN} (=P_{loss}, since the discharge is in steady state) was less than twice the predicted H-mode threshold power, $P_{L\text{-}H}$, at the highest density. Previous JET results also showed that, at low density, where the critical temperature for the stabilization of Type III ELMs decreases with density ($T \propto 1/n$), an input power $P_{in} > 2\ P_{L\text{-}H}$ was required to obtain and maintain the Type I ELMy regime at low δ (δ ≅ 0.2). A reduction of the power threshold for Type I ELMs with increased d was also observed at low density [4]. This paper presents the result of an experiment to study how $P_{IN}/P_{L\text{-}H}$ and d affect the high density ELMy H-mode operational space in the Type I ELMy regime, that is, with good confinement.

1. EFFECT OF INPUT POWER

In a series of discharges at 1.9MA/2.0T (q_{95} ~3.4), with moderate shaping (δ~0.33) and P_{IN} ~ 15 and 17MW NBI, the density was increased from pulse to pulse with increased D_2 gas fuelling at constant rate. In this experiment, the ratio $P_{IN}/P_{L\text{-}H}$ was maintained above 2.6 even at the highest densities. Another density scan was carried out with identical discharge parameters but lower P_{IN} (8MW), so that $P_{IN}/P_{L\text{-}H}$ was reduced to 1.6 at the highest density. A similarly low margin above the threshold at high density was obtained in a further density scan with high P_{IN} (15MW), by increasing B_τ to 2.4T at constant q_{95}. The results of this experiment are summarized in Fig.1, Fig.2 and Fig.3.

In all the three densities scans, the relative decrease in thermal stored energy, W_{th}, with respect to the plasma at the lowest density is ≤10% in the Type I ELMy regime. Nevertheless, increasing the margin above the L-H threshold power extends the range of densities achievable with Type I ELMs.

In fact, when the ratio P_{IN}/P_{L-H} is maintained above 2.4 at high density (density scan with P_{IN}=15), Type I ELMs are obtained up to the Greenwald density, n_G. Moreover, after an initial limited decrease, W_{th} recovers at high density, so that the relative loss in W_{th} between the plasma with n_e = 60% n_G and the plasma with $n_e = n_G$ is less that 5%. $n_e = n_G$ was achieved with H97 = 0.88 and β_N = 2.2. The pedestal density reaches 85% of n_G. The density could not be increased further at this high PIN because the NBI pulse length is limited by the restriction in the maximum beam duct pressure. In contrast, in the gas scans at lower P_{IN}/P_{L-H}, Type I ELMs are maintained only up to n_e = 90%n_G in the core and n_e = 70%n_G in the pedestal with 10% decrease in W_{th}, before the transition to Type III ELMs and large loss of confinement.

2. EFFECT OF TRIANGULARITY

The effect of δ and margin above the threshold power on the maximum achievable density in the Type I ELMy H-mode regime is summarized in Fig.4. The only experiment aimed specifically at the investigation of the role of power is the one described above. At δ = 0.25 and P_{IN}/P_{L-H} of 2, the maximum densities achieved with Type I ELMs are 80%n_G in the core and 60%n_G in the edge, better than previous JET results with the same triangularity but lower margin above the threshold [1]. An attempt to substantially increase P_{IN}/P_{L-H}, at δ =0.25, by reducing I_p and B_t from 2.5MA 2.7T to 1.7MA/1.8T with P_{IN} =17MW did not result in an increase of the maximum achieved normalized density. It is possible that the improvement observed with increased P_{IN}/P_{L-H} saturates above a certain power. Another possibility is an inherent dependence upon I_p. This could enter via the current dependence of transport in the barrier, the ELM stability limit or the Type I to Type III transition.

Operation at 1.7MA/1.7T was also difficult since many discharges were affected by NTMs. The recent results for high δ plasmas (d ≅ 0.5) are described in detail in [6]. With this high δ, a very large increase in the edge and core density with good confinement is achieved at relatively low P_{IN}/P_{L-H}. In fact, at 2.5MA/2.7T, with a margin above the threshold of only 1.4 and a core density $n_e = n_G$, the pedestal density reached n_G, almost twice as much the pedestal density of the plasma without external fuelling. This result confirms that lower power is required to maintain Type I ELMs at high δ. Similarly to the low δ results, a reduction in I_p to 2.0MA (at constant B_τ) resulted in a lower fraction of n_G both in the core and at the edge.

3. PEDESTAL PARAMETERS, CONFINEMENT AND ELMS

Fig. 5 shows the pedestal evolution of the edge T_i as the density is increased, for the gas scans at 2MA/2T at high and low power. At high power, after an initial decrease in pedestal pressure, and above an edge density of 70%n_G, n_e increases with little degradation of T_i. T_i remains above the critical temperature for Type III ELMs. This behavior of the pedestal parameters is very similar to what observed at high density in the ITER-like high • configuration [6].

Also similar to what is observed at high δ, is the unusual decrease of f_{ELM}, associated with the increase in pedestal pressure at high density. In fact, f_{ELM} has a maximum as a function of density, so that f_{ELM} at the highest density is similar to f_{ELM} at low density. The broadband fluctuation in between ELMs is, for this high density discharges, different from the characteristic one of both Type I and Type III ELMs [6]. In agreement with the observation that the relative ELM losses ($\Delta W_{ped}/W_{ped}$) depend on the pedestal collisionality before the ELM crash [7], the relative stored energy loss at an ELM is seen to decrease as the collisionality increases, independent of f_{ELM}, (see Fig.6). A change of stability could be associated with the change in ELM behavior [8], with access to second stability in some region of the pedestal. Whilst there are some similarities between those observation and the "mixed Type I and Type II" ELMs regime observed in other machines [9,10], the fact that it is observed, in this experiment, at relatively low δ and q_{95} might suggest otherwise. Nevertheless, whether due to a stability change or to the ability to maintain Type I ELMs, this "anomalous" ELM behavior is associated with high pedestal pressure (and pressure gradient) and good core confinement at high density. In these high power plasmas, the peaking of the density profile is constant during each discharge. Broadening of the density profiles and peaking of the ion temperature profiles is observed with increasing density. As opposed to what is seen at low power, at high power the effective heat diffusivity decreases (by 30%, from TRANSP code results) at high density, consistent with lower pedestal temperature at the edge and similar thermal stored energy.

CONCLUSIONS

In ELMy H-mode**s,** most of thermal stored energy loss at high density is observed at the transition from Type I to Type III ELMs. In the Type I ELMy regime the reduction in W_{th} as the density is increased is limited to ≤10%. Therefore, extending the range of density for operation in the Type I ELMy regime extends the range of density achievable with good energy confinement. High triangularity is observed to be beneficial in this respect. The maximum pedestal pressure is higher at higher δ. Moreover, the reduction of ELM size with collisionality, combined with the observation that the main contribution in ΔW_{ped} comes from the temperature drop [6], favours high δ for maintaining $T>T_{crit}$ at the pedestal. In fact, if the other plasma parameters are fixed, an increase in δ results in an increase in density at constant temperature, reducing the relative ELM size and therefore the absolute temperature drop at the ELM. As a consequence, if T_{crit} does not depend strongly on δ, the margin between the lower boundary of the ELM cycle and T_{crit} is increased. In terms of global parameter, less power is required to maintain Type I ELMs at higher δ. Another way to extend the range of densities achievable in Type I ELMs is by operating at high input power, or at an "optimum" power, since in the experiment P_{IN} was not increased further in order to establish if there is saturation. At a given δ, this "optimum" power can be empirically expressed in terms of margin above the L-H power threshold P_{IN}/P_{L-H}. At higher P_{IN}/P_{L-H}, not only the maximum achieved density in Type I ELMy regime was increased by ≅10%, the confinement was also better at the highest density, with less than 5% relative drop in W_{th}. In a similar fashion as for the high triangularity plasmas, at high P_{IN} (and moderate δ), the good confinement at high density is associated with high pedestal pressure (increase of pedestal density at constant temperature), reduced ELM frequency and reduced relative ELM size. The reduction in absolute ELM size at high density could results from similar pedestal stored energy being achieved at higher collisionality. High I_p seems to be also advantageous for maintaining Type I ELMs at high density. The critical density for the transition to Type III ELMs at high collisionality has been derived from two models [5,11, see also 12], which fit well the JET data. According to both models (assuming ideal ballooning for the Type I ELM limit), an increase in I_p would open up the operational space for Type I ELMs ($n_{crit} \propto B^{\alpha}/q^{\beta}$, α, b≥1). How this translates in the achievable density normalised to n_G, depends on the predicted B_τ and q_{95} dependencies relative to the Greenwald scaling. The trade off between high P_{IN} and high δ, as well as the role of q_{95}, B_τ and I_p in the relative changes of the Type III ELM boundary and the upper and lower boundary of the Type I ELM cycle, needs further experiment to be clarified.

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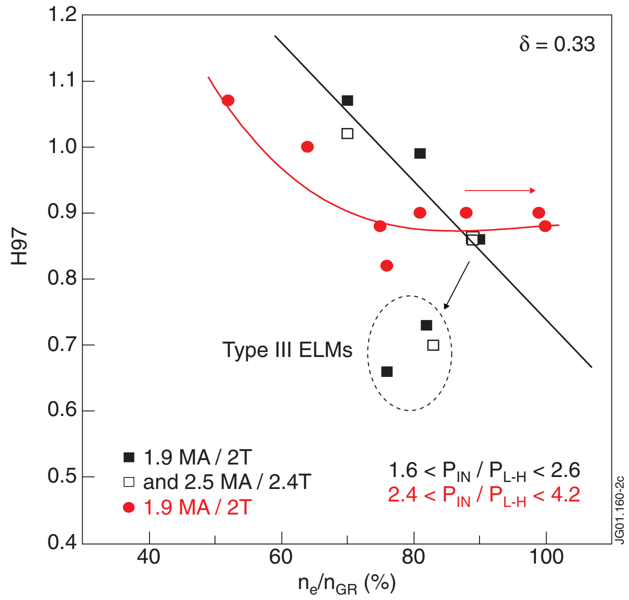

Figure 1: *Energy confinement time enhancement factor (H97) versus normalized density for the density scans at* ***high*** *(15 and 17MW at 1.9MA/2T, circles) and* ***low*** *(8 MW at 1.9MA/2T, solid squares, and 15MW at 2.5MA/2.4T, empty squares)* $\boldsymbol{P_{IN}/P_{L\text{-}H}}$

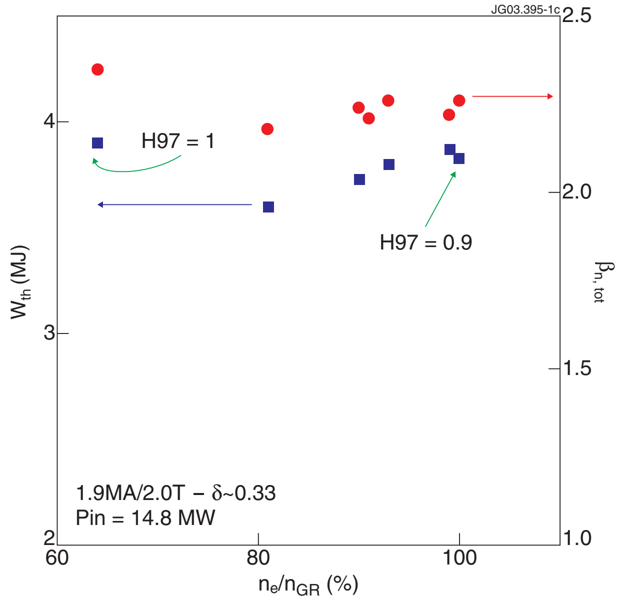

Figure 2: Thermal stored energy and normalized β *versus normalized density for a scan with high* $P_{IN}/P_{L\text{-}H}$ *of Fig.1:* $P_{IN} \cong 15MW$ *at 1.9MA/2T. The scan with* $P_{IN} \cong 17MW$ *was not completed for lack of experimental time.*

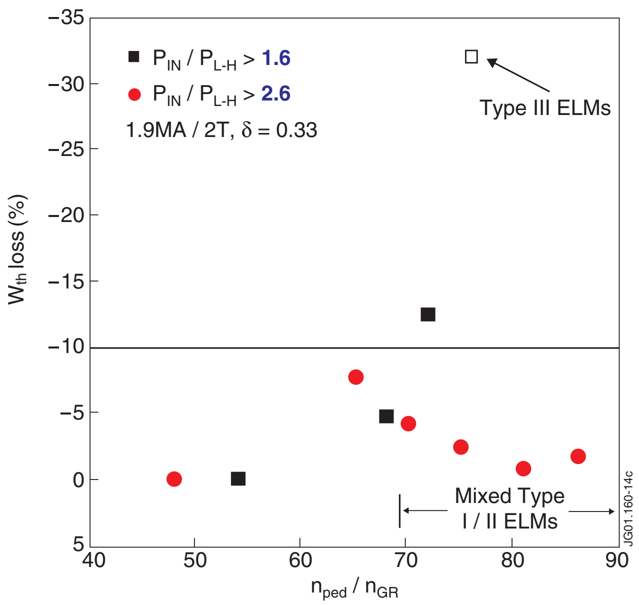

Figure 3: Thermal stored energy loss (relative to the discharge with higher stored energy: With loss (%) $=-((W_0-W)/W_0)*100$ *versus normalized* n_{ped}/n_G*, for the density scans at 1.9MA/2T,* P_{IN} *= 8 & 15MW*

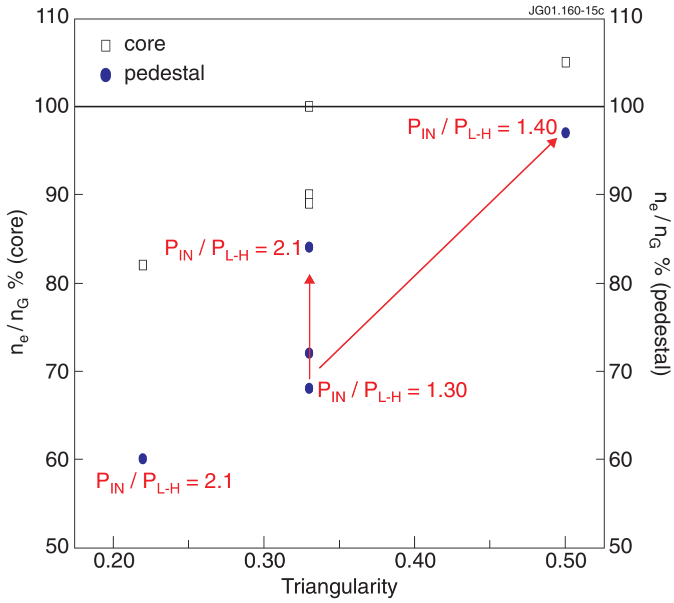

Figure 4: Maximum normalized pedestal and core densities vs triangularity. The vertical line indicates the effect increased $P_{IN}/P_{L\text{-}H}$*, the other line indicates the effect of increased d at similar* $P_{IN}/P_{L\text{-}H}$

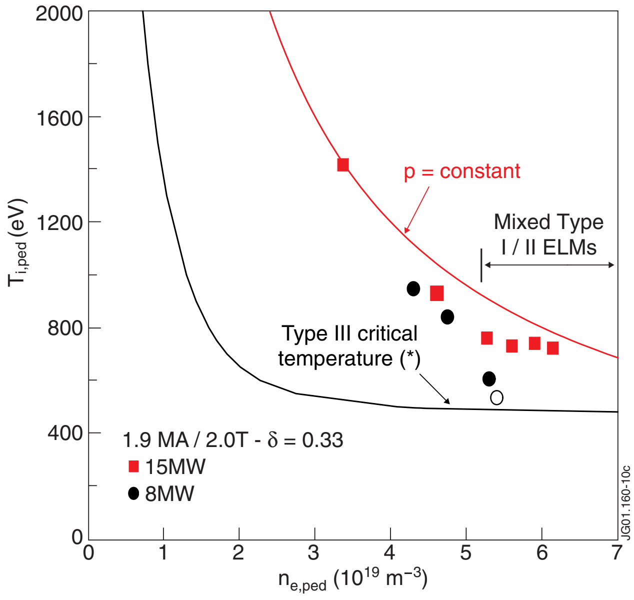

Figure 5: Pedestal T_i (from edge Charge Exchange versus n_e (n_e from the FIR interferometer outermost channel) for the gas scans at 8 and 15MW. The curve for T_{crit} is predicted by the model of Ref [5]. The empty symbol is a Type III ELM (steady state).

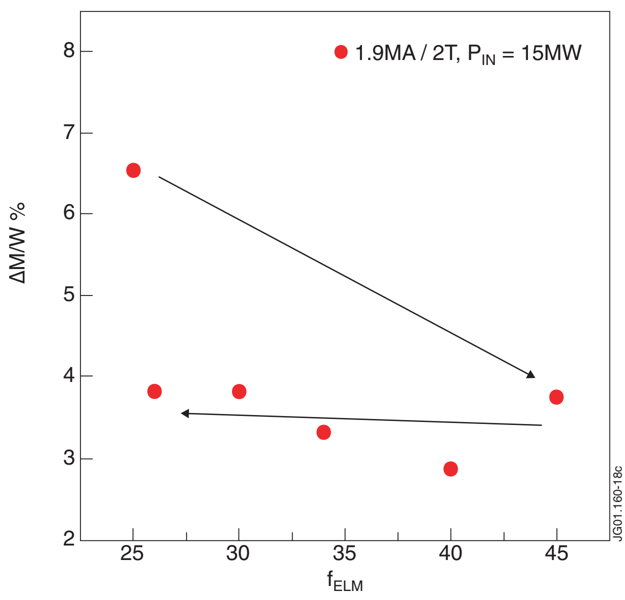

Figure 6: ELM losses relative to the total stored energy versus ELM frequency for the gas scan at 15MW. The pedestal parameters are described in Fig.5 The arrows indicates increasing density.