JET–CP(98)32

High Density ELMy H-modes Studies at JET in ITER Relevant Scenarios

G Saibene, A V Chankin, S Clement, G D Conway, N C Hawkes[1], L D Horton, J Lingertat, R D Monk, R Sartori, R Smith, G C Vlases.

JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA,
[1]UKAEA/Euratom Association, Culham, Abingdon, Oxfordshire, OX14 3DB, UK.

1. INTRODUCTION.

ELMy H-modes are currently the favoured plasma operating regime with a proven capability for steady state performance. The confinement of these plasmas in standard conditions (mainly Neutral Beam heating NB, density far from the Greenwald limit [1], moderate edge shear, type I ELMs) has been studied, and the results used within the Multi-Machine Confinement database from which the latest confinement scaling law (H97) has been derived [2]. The projection of the performance of ELMy H-modes to ITER show that the plasma density required to achieve high Q or ignition is near or above the Greenwald density n_{GR}. Moreover, Type I ELMy regimes may not be suitable for a reactor, unless the peak power load on plasma facing components is reduced [3].

This paper reports on experiments carried out in the JET MkIIA campaign with high density ELMy H-modes. In particular, we focus on the edge pedestal characterisation and on the study of the transition from type I to type III ELMs at high density. The effects of the plasma edge magnetic shear on density, confinement and ELM power losses are also discussed.

2. GENERAL RESULTS.

Gas fuelling scans are used systematically in JET to study the behaviour of ELMy H modes with varying density. In this paper we analyse the response to density increase of neutral beam heated discharges, in pure Deuterium, for a series of scans in power, plasma current, toroidal field, q_{95} and plasma edge shear Sh_{95}.

The general result, that holds independently of the geometry of the divertor, the additional heating method, the plasma current and/or toroidal field and the plasma shape, is that the energy confinement degrades for increasing density [4,5]. This is in contrast with the confinement scaling laws, that predict an increase of the plasma stored energy proportional to the density ($W_{97} \propto n_e^{0.4}$, for instance).

With no or little gas fuelling, the steady state phase of these discharges is characterised by regular type I ELMs, with a frequency that increases with density. At high density, but still below n_{GR}, a transition to Type III ELMs occur, characterised by a loss of pedestal pressure associated with further edge cooling, compared to the type I ELM phase. If the fuelling is increased further, the discharge may revert to L-mode [6].

3. CONFINEMENT AND LOCAL EDGE PARAMETERS.

The decrease of H97 with increasing density is not just an artefact of the functional dependence of the confinement scaling laws on n_e, but reflects a reduction in the plasma stored energy content. This reduction is already observed while the discharge maintains type I ELMs, but worsens with the transition to type III ELMs (figure 1). One can separate out the contribution of the edge and of the core to the total stored energy, by writing the total stored energy $W_{th}=W_{ped}+W_{bulk}$, where $W_{ped}=3/2\ P_{ped}V_p$ (V_p plasma volume), and the pressure $P_{ped}=P_e+P_i$, calculated at the top of the edge pedestal. Since, for the type of discharges analysed in this paper, $T_e \sim T_i$ at the pedestal top, we take $P_{ped} \sim 2P_e$, to benefit from the higher time resolution of the T_e measurements compared to T_i. As expected, we find that the average W_{th} is proportional to W_{ped} (steady state, averaged over 1s), and that the degradation of the total energy confinement is reflected by a reduction of the pedestal energy content.

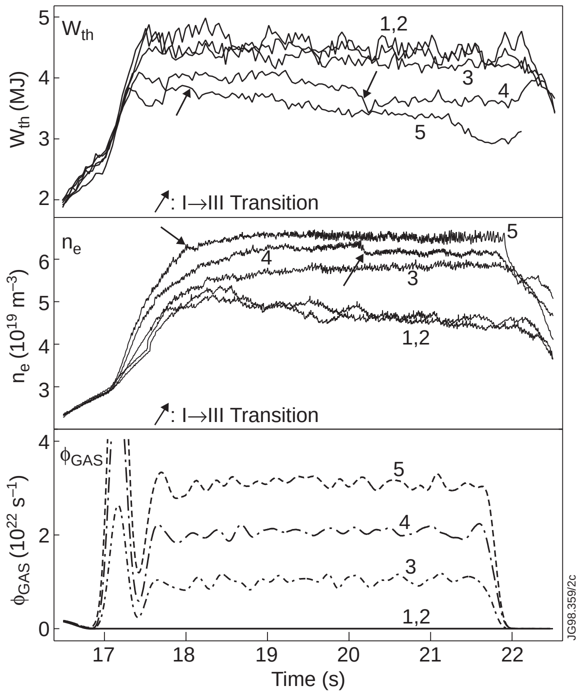

Figure 1:Thermal stored energy, line average density and D fuelling rate for a gas scan at I_p=2.6MA, B_t=2.7T, NB power =11 MW, δ=0.22.

Taking the no gas case as a reference, one can compare the total and the pedestal energy as the density increases. With little fuelling, the loss of pedestal energy accounts for the global plasma energy losses. This is consistent with the reduction of the maximum stable pressure (gradient) caused by a narrowing of the pedestal width induced by edge cooling [7]. In contrast,at high densities, in particular after the transition to type III ELMs, the decrease in W_{ped} accounts for only ~50% of the total plasma energy degradation (compared to the no gas case), indicating that the reduction of confinement is not limited to the pedestal region and that an enhanced transport region exists inside the barrier region.

Figure 2 shows W_{th} vs. W_{ped} (steady state, average values) for H-mode fuelling scans carried out at three different levels of input power (8, 11 and 14 MW of NB). The plasma current, toroidal field and plasma edge shear were fixed for all discharges (I_p=2.6MA, B_t=2.7T, Sh_{95}=3.2 with triangularity of the plasma boundary δ=0.22). We observe that $\langle P_{ped} \rangle$ is higher for higher input power. This fact can be reconciled with the picture that the maximum edge pressure gradient is determined by an ideal ballooning instability assuming that the pedestal width Δ increases with input power. Our analysis for type I ELMs shows that the changes in the peak pedestal pressure (just before the ELM) with input power can be understood if

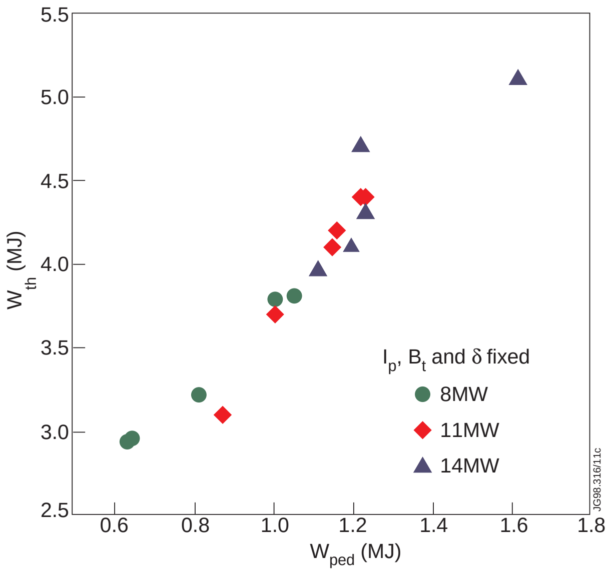

Figure 2: W_{th} vs W_{ped}, for a series of gas scans at I_p=2.6MA, B_t=2.7T, δ=0.22, with input power at 8, 11 and 14 MW NB.

one assumes that Δ scales as $(T_{edge})^{\sim 0.5}$, i.e. assuming a dependence of Δ on the thermal poloidal Larmor radius ρ_L. A scaling of Δ with the Larmor radius of the fast ions [7] is not ruled out, but provides a less satisfactory fit to the data.

Another way to increase P_{ped}, is to increase the edge magnetic shear. Gas scans at fixed I_p, B_t and NB power (2.6MA, 2.7T and 11-12 MW) where carried out, with Sh_{95} varying from 2.9 to 4.1. The corresponding maximum W_{ped} increased from ~1.2 to 2.4 MJ. In this case we find that the peak P_{ped} is proportional to $(Sh_{95})^2$. The drop in the maximum edge pressure with type III ELMs is not well represented by these simple scalings.

4. TYPE I TO TYPE III ELMS TRANSITION.

A model proposed in JET for the interpretation of the ELMy H-mode n_e-T_e operational diagram [8] assumes that the transition from type I to type III ELMs, observed at high density, corresponds to a transition from an ideal to a resistive mode. The similarity parameters describing the two modes are derived from the ideal ballooning limit $F_\beta = q^2 R \nabla \beta / f(s)$ (*f(s)* is a function of the shear) and collisionality $\nu^* = Z_{eff} nqR / T_e^2$. Fixing the two similarity parameters gives a scaling for $n_{e,crit} \sim B^{\alpha} q^{-\beta} R^{-\gamma}$, close to the Greenwald-Hugill scaling, with α~1 but β slightly above and γ slightly below 1, for most of the transport models analysed in [8]. Good agreement with JET data is obtained using the collisional skin-depth model ($\chi_e \sim Z_{eff}/T_e^{3/2}$), that gives:

$$n_{e,crit} \propto \frac{Bf(s)^{1/2}}{q^{5/4} R^{3/4} Z_{eff}^{1/4}} \qquad (1)$$

and

$$T_{e,crit} \propto \frac{B^{1/2} R^{1/8} Z_{eff}^{3/8}}{q^{1/8}} \qquad (2).$$

An example of a transition from type I to type III ELMs is shown in figure 3. The change in the D_α emission from the divertor gives a very good indication of the change in the ELM character. Typically, after the transition the density rise slows down, and in general T_e, T_i and P_{ped} decrease compared to their values before the transition. Characteristically, the edge collisionality increases sharply in coincidence with the change in the D_α signature. The scaling for the critical edge parameters at which the transition occurs (Eqs. (1) and (2)) have been verified in gas scan experiments where, at constant input power and shear, we varied I_p and B_t. The results of these experiments are summarised in figures 4 and 5, where the edge n_e and T_e are those at the transition. The proposed scaling of $n_{e,crit}$ with $Bq^{-5/4}$ is in good agreement with the experimental data. The measured critical edge T_e (values near the separatrix, extrapolated from divertor target Langmuir probe measurements) is consistent with the proposed scaling, within the uncertainty of the data.

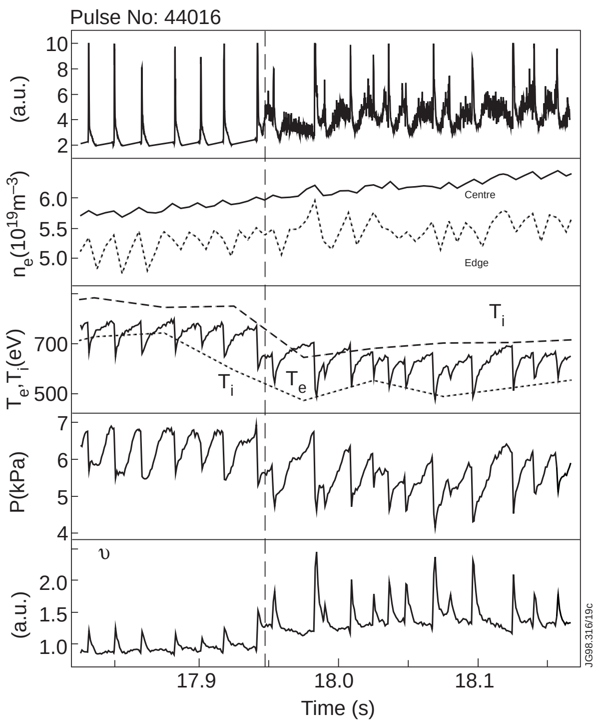

Figure 3: D_α emission from the divertor, densities, edge temperatures, edge pressure and collisionality at the type I to III ELM transition.

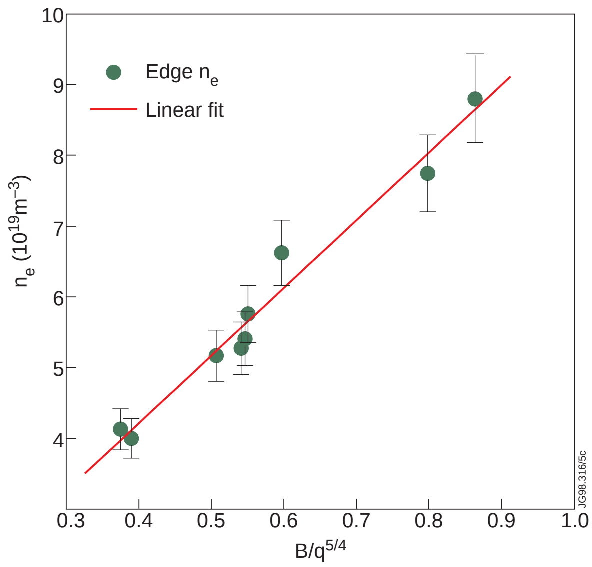

Figure 4: Scaling of the edge pedestal n_e according to eqn. 1, for fixed Sh_{95}. Density taken at the top of the pedestal.

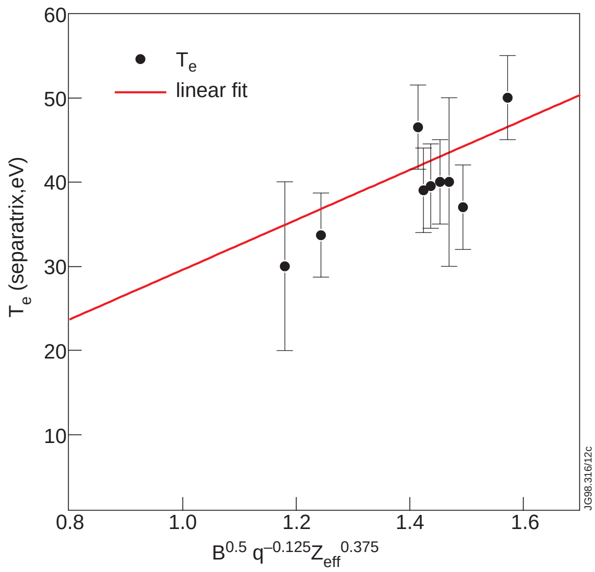

Figure 5: Scaling of the edge T_e, according to eqn. 2, same pulses as figure 4. T_e taken close to the separatrix.

5. EFFECTS OF THE PLASMA EDGE SHEAR.

The density of ELMy H-mode plasmas changes with Sh_{95}, both without gas and in response to fuelling. Figure 6 shows the variation of H97 for the gas scans described at the end of section 3 (δ=0.14, Sh_{95}=2.9 - δ=0.23, Sh_{95}=3.2 - δ=0.38, Sh_{95}=4.1). The natural density (i.e. no gas) of the discharge increases for higher shear, consistent with the higher stable P_{crit}. The degradation of confinement with density occurs in all cases, but at high Sh_{95} the plasma can sustain a higher density for a given confinement. Taking into account the density dependence of H97, this translates into higher plasma stored energy at higher density.

The scaling for the $n_{e,crit}$ for the transition from type I to type III ELMs predicts that the density at the transition should increase as $f(s)^{0.5}$, or, taking into account that, experimentally, $P_{ped} \propto (Sh_{95})^2$, we expect $n_{e,crit} \propto Sh_{95}$. The experimental data confirm this prediction, and $n_{e,crit}$ increases linearly from ~5 to ~6.8 10^{19} m^{-3}, for Sh_{95} varying from 2.9 to 4.1. The plasma stored energy at the transition increases likewise, from ~3.3 to 4.8 MJ, at constant input power.

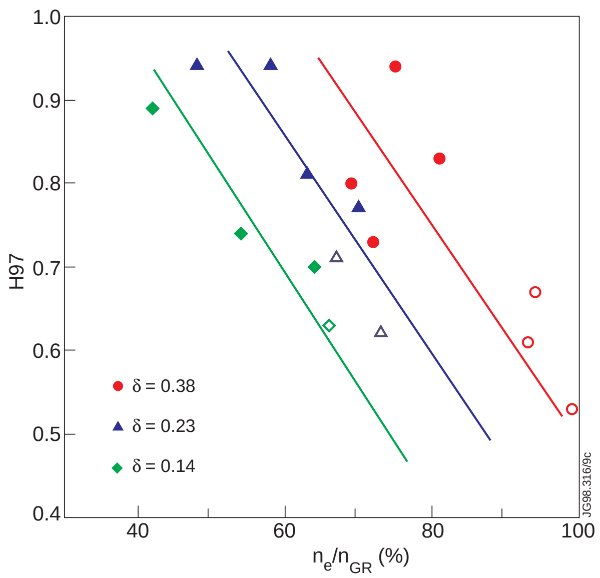

Figure 6: H97 vs. fraction of the Greenwald limit, for gas scans with different edge shear. Open symbols: H97 during type III ELMs.

It is well known that increasing the edge shear of an ELMy H-mode causes a reduction in ELM frequency, due to the higher edge stability. Without additional gas fuelling, the average prompt plasma energy loss per ELM, ΔW/W, approaches 10% for Sh_{95}=3.8, compared to ~4% at the lowest shear. The addition of gas reduces the ΔW/W. Just before the type I to III ELM transition, ΔW/W is reduced to <3% for all plasma shapes.

6. CONCLUSIONS.

The confinement of gas fuelled, high density ELMy H-modes does not follow the predictions of current confinement scaling laws, since the plasma stored energy decreases instead of increasing with density. The reduction of plasma stored energy at high fuelling rates/density is only partially accounted for by the loss of pedestal pressure (<50%).

The increase of P_{ped} with power at constant I_p, B_t and Sh_{95} is consistent with type I ELMs being triggered at constant P_{ped}/Δ, if the pedestal width scales with the thermal Larmor radius. Increasing the edge shear at constant power also increases P_{ped}, proportionally to $(Sh_{95})^2$.

At high density/high fuelling rates we observe a transition from type I to type III ELMs. A model developed in JET assumes that this transition is caused by increased edge collisionality. The edge n_e and T_e at the transition are found to be in good agreement with the scaling derived in the model.

Experiments in JET have shown that the plasma stored energy and density can be increased at the same time by increasing the edge stability, i.e. by operating at high edge shear. High Sh_{95} results in an increased critical edge density for the transition from type I to type III ELMs and high stored energy at the transition (H97~0.7-0.8). At the same time, the energy loss per ELM just before the transition is reduced to ~ 3% of the peak stored energy. For a reactor, operation at high shear and high density (just before the transition to type III ELMs) may provide both acceptable plasma performance and tolerable power loads to first wall components.

REFERENCES

[1] Greenwald M et al, Nucl Fusion **28** 2199, 1988

[2] ITER Confinement Database and Modelling Group, Plasma Phys Control Fus **39** B115, 1997

[3] Clement S et al, tbp in Jour Nucl Materials 1998

[4] Saibene G et al, Europhys Conf Abstracts, **21A** part I 49, 1997

[5] The JET Team, IAEA-CN-64/A1-4, Fusion Energy 1996, **1** 371, 1996.

[6] Saibene G et al, JET-AUG Workshop on Plasma Edge and Divertor Physics, IPP Garchin, D, 1998.

[7] Lingertat J et al, tbp in Jour Nucl Materials, 1998

[8] Chankin A V, Saibene G, submitted to Plasma Phys Control Fus.