CONFINEMENT DEGRADATION OF ELMY H-MODES AT HIGH DENSITY AND/OR RADIATED POWER FRACTION

The JET Team[1]
(Presented by G.F.Matthews)

JET Joint Undertaking,
Abingdon, Oxfordshire,
United Kingdom.

Abstract

High density, high radiated power fraction and small ELMs are key elements of the current ITER design. In JET, these conditions are shown to be associated with high ELM frequency, low pedestal pressure and correspondingly reduced global energy confinement time. This paper reviews our current understanding of the connections between these parameters.

1. INTRODUCTION

The existing ITER design requires a density at or above the Greenwald density limit ($f_{GL} = \bar{n}_e / \bar{n}_{e,Greenwald} > 1.1$) [1], combined with a high energy confinement time (for ignition $f_{GL} H_{97} > 1.1$ using the ITERH-97P(y) scaling[2]). High total radiated power fraction is also required to protect the divertor [3] (excluding bremsstrahlung, $f_{rad} \geq 0.75$). There are three critical issues which have not received much attention in energy confinement scaling studies: (1) degradation of τ_E with f_{GL} [4,5], (2) degradation of τ_E with f_{rad} and (3) failure of f_{GL} to increase with gas fuelling rate [4,5,6]. The first two of these problems form the subject of this paper.

Figure 1(a) shows the variation of the normalised Lawson product $f_{GL}H_{97}$ as a function of the Greenwald density fraction f_{GL} for low triangularity H-modes ($\delta < 0.24$). These pulses were either unfuelled, had strong deuterium fuelling or seeding with neon or nitrogen impurity (points selected with total radiated power fraction $f_{rad} > 0.4$, excluding neutral losses). Deuterium gas fuelling results in a modest increase in density but the normalised Lawson product is not increased. At higher fuelling rates the

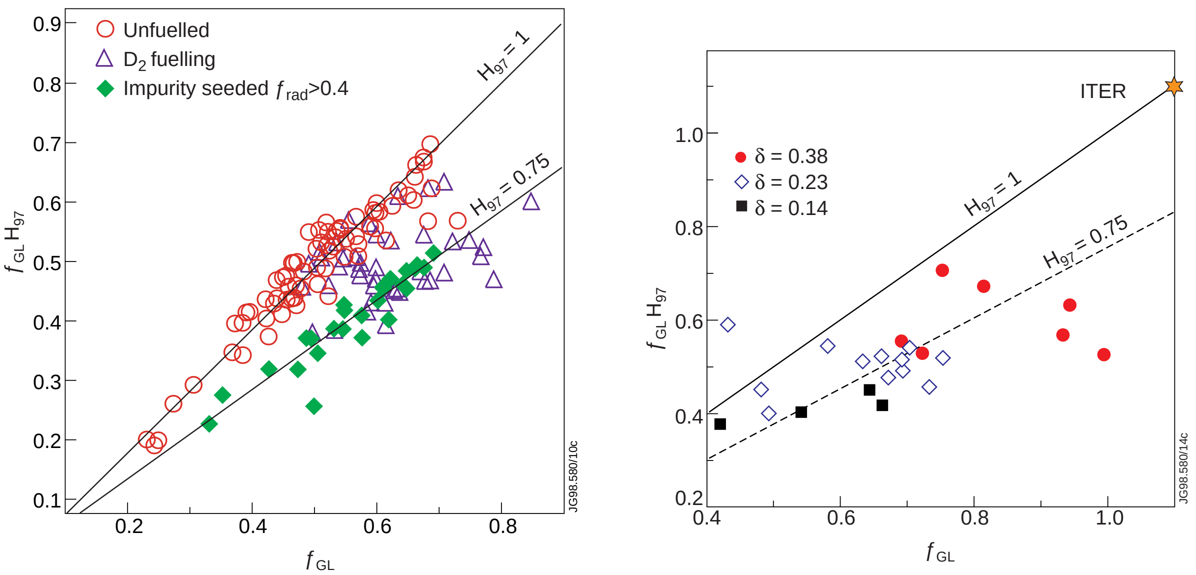

Fig.1 (a) Showing $f_{GL}H_{97}$ vs f_{GL} for unfuelled, impurity seeded and D_2 fuelled H-modes in the JET MkI and MkIIa divertor for I_p = 1.9-2.9MA and triangularity $\delta < 0.24$. (b) $f_{GL}H_{97}$ vs f_{GL} for a triangularity scan in MkIIa with deuterium fuelling for identical I_p and P_{NBI} [7].

[1] See Appendix to IAEA-CN-69/OV1/2, The JET Team (presented by M.L.Watkins)

discharges return to L-mode and disrupt in exactly the same way as L-mode discharges [8]. The upper limit in density and confinement is very similar for impurity seeded and deuterium fuelled discharges. As deuterium fuelling rate is increased the type I ELM frequency rises until at some point the frequency jumps up due to the onset of higher frequency type III ELMs. It is at this point that the greatest loss in energy confinement is observed [4, 5]. With impurity seeded discharges, without significant deuterium fuelling, the type I ELM frequency decreases until there is a sudden jump to high frequency type III ELMs at which point ~ 25% of the stored energy is lost [9]. In both cases intermediate states can also be produced where there are compound ELMs which appear to be a mixture of type I and type III ELMs.

Figure 1(b) shows data from deuterium fuelling scans into 2.5MA/2.5T H-modes in MkIIa in which the plasma triangularity was varied [7]. This data shows that increasing the plasma triangularity raises the main plasma density at which the confinement degrades. High triangularity pulses have a lower ELM frequency for a given gas fuelling rate and plasma density.

2. DEGRADATION OF THE H-MODE PEDESTAL

2.1 Relationship between ELM frequency and confinement

The rollover in energy confinement at high density and/or radiation appears to be dominated by changes in time averaged pedestal pressure with ELM frequency, f_{ELM} [10]. Figure 2(a) shows this relationship for D_2 and N_2 seeded discharges at fixed current and input power.

The pedestal pressure cycles seen in JET during ELMs have an asymptotic form which for given field and current are independent of ELM frequency, as in the example of Fig. 2(b). The equation describing this time evolution is [10]:

$$P_{ped}(t) = P_{min} + \left(P_{max} - P_{min}\right)\left(1 - e^{-t/\tau}\right) \tag{1}$$

where P_{min} is the pressure to which the pedestal crashes after an ELM and P_{max} is the saturation pressure which would pertain in the absence of an ELM and τ is the edge reheat time. From a time average of (1) an equivalent expression for confinement time can be derived [10]:

$$H_{93} = f_{93}^{prof} - f_{93}^{ped}\left(f\tau\left(1 - e^{-1/(f\tau)}\right)\right) \tag{2}$$

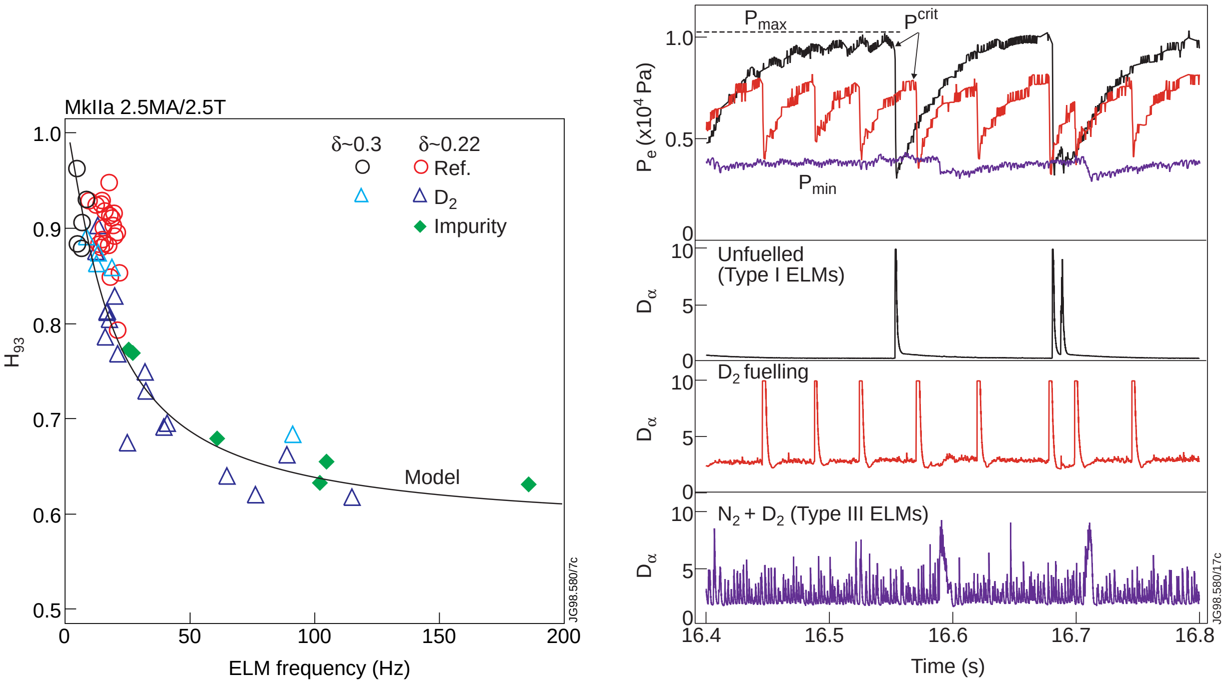

Fig.2(a) H_{93} vs. ELM frequency from experiment and model and (b) pedestal pressure cycles and divertor D_α vs. time for an unfuelled discharge and identical pulses with D_2 and D_2+N_2 fuelling [10].

where, f is the ELM frequency, f_{93}^{prof} is thecontribution to the H-factor from the core profile and f_{93}^{ped} is the maximum contribution from the pedestal. It is more consistent to apply this model to the ELM-free ITERH-93P scaling since ITERH-97P(y) is already a fit to an ELMy data set. Figure 2(a) compares equation (2), using $\tau = 0.034$, $f_{93}^{prof} = 1.02$ and $f_{93}^{ped} = 0.44$, with data from the JET MkIIa campaign (I_p = 2.5MA, B_T = 2.5T and P_{NBI} = 12MW). Both low and high triangularity pulses fit the model well. The main effect of increasing the triangularity is to lower the ELM frequency at a given density. The same model fits a wider range of plasma current (1.8-4.8MA) and neutral beam power with the additional assumption that $\tau/\tau_E = 14$ [10].

2.2 Pedestal width scalings and the Type I to Type III ELM transition

The relationships discussed in the previous sections show how confinement varies with ELM frequency but what controls ELM frequency? Good confinement is generally associated with type I ELMs which are thought to occur when the edge pressure gradient reaches the ideal ballooning limit. If this is true then the critical pressure gradient for type I ELMs is expected to scale as [11]:

$$P^{crit} / \Delta \propto I_P^2 S^y \tag{3}$$

where I_p is the plasma current, S is the magnetic shear and Δ is the pedestal width. The edge pressure evolves with time according to equation (1) until the edge pressure reaches P^{crit}, Fig.2(b). Figure 3 shows fits to the P^{crit} data for type I ELMs in unfuelled discharges for a range of S, I_p and isotopic mass (H, D, T) assuming that Δ is proportional to either the fast ion Larmor radius $P^{crit} \propto I_P^2 S^2 \rho_{i,\,fast}$ or the thermal ion Larmor radius $P^{crit} \propto I_P^2 S^2 \rho_{i,thermal}$.

Although in this data set the fit which assumes that the width is proportional to $\rho_{i,fast}$ is slightly better than that for $\rho_{i,thermal}$, the uncertainties are such that one cannot use this method to distinguish between the two models. A similar analysis of gas-fuelling scans shows a better fit to the scaling with $\rho_{i,thermal}$ than $\rho_{i,fast}$[12]. This difference might be attributed to the effect of gas fuelling on the fast particle population but the issue is as yet unresolved. The attraction of the fast particle picture is that it allows a qualitative explanation of other phenomena. For example:

- In hot ion H-mode tritium neutral beam injection into a deuterium plasma produces a similar pedestal pressure to T injection into T plasma which is higher than D injection into D [13, 14].
- In hot ion H-mode, P^{crit} for the first ELM is higher for 140keV neutral beam injection than it is for 80keV at identical edge ion temperature.
- On axis ICRH heating which produces relatively low edge fast particle populations is characterised by high frequency type III ELMs and correspondingly low edge pressure when compared with neutral beam heated discharges at the same input power, Fig. 4.

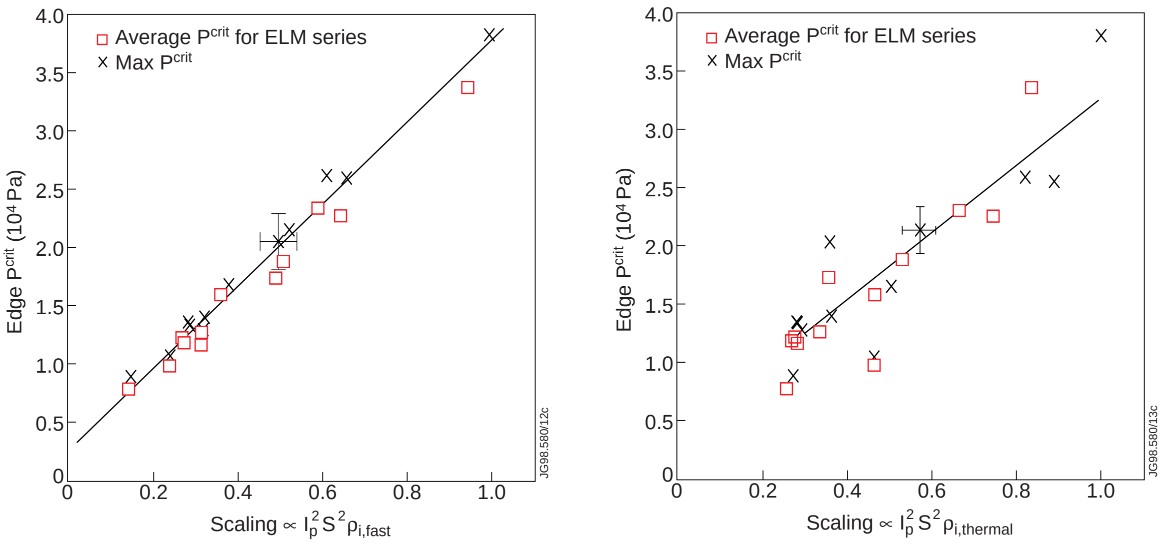

Fig.3 (a) P_{crit} vs. normalised scaling expression for fast ions and (b)thermal ions [11].

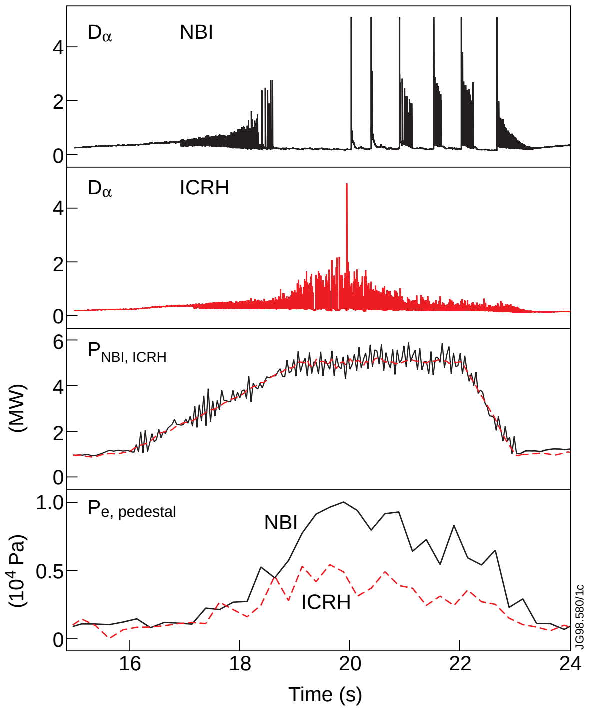

Fig.4 Comparison of RF and NB ELMs edge pressure and D_α.

Whether the pedestal width scales as the fast or thermal ion poloidal Larmor radius, the loss in confinement and rise in type I ELM frequency with gas fuelling can be associated with a cooling of the edge. In the limit of low or high T_e, the energy of fast particles is expected to be constant. In JET however, the edge plasma is in a transitional regime and the mean fast ion energy derived from Fokker-Planck calculations varies between 30keV and 50keV.

The critical question for understanding the loss of energy confinement at high density and/or radiation is - what causes the transition to type III ELMs? There are two possibilities currently under consideration:

1. Collisionality may be the critical parameter for transition to type III ELMs, perhaps due to the onset of resistive ballooning instabilities [15].
2. Non-ambipolar losses of fast particles within one poloidal Larmor radius of the separatrix may create a radial electric field and hence the velocity shear which stabilises the pedestal region. For this to happen a critical density of fast particles at the edge of the pedestal would be required. Strong gas fuelling may deplete the fast particle population through charge exchange processes thus leading to a transition from type I to type III ELMs [14].

Deuterium fuelling of type I ELMy H-modes clearly raises the collisionality at the pedestal. Impurity seeding, combined with low deuterium fuelling rates, can however produce type III ELMs at much lower line average density, Fig. 1(a). It therefore appears to be possible to produce type III ELMs at up to an order of magnitude lower pedestal collisionality ($\propto nZ_{eff}/T_e^2$) than is observed in equivalent type I ELMy discharges. Another argument against collisionality as the sole cause of the type I to type III ELM transition is that type III ELMs are observed in ICRH heated discharges despite lower collisionality. In the example of Fig. 4 the collisionality at the top of the pedestal is ten times lower in the ICRH heated discharge than in the NBI case. If it is the collisionality at the separatrix which matters [15] then the situation is not so clear cut. Our analysis indicates that the collisionality near the separatrix can be very similar with type I and type III ELMs but the analysis is inconclusive.

Despite the loss in pedestal pressure associated with ICRH heated H-modes the global energy confinement time, after corrections for the fast ion contributions to the energy are made, is as good as in the best type I ELMy H-modes with neutral beam heating. Local transport analysis with the TRANSP code shows that the core χ_{eff} profiles in such cases are identical. The reason for the similarity in the global energy confinement time is that the power deposition profile for ICRH heated discharges is strongly peaked on axis while for neutral beam heated ELMy H-modes it is almost flat [11]. Due to the lack of strong profile resilience seen in JET this difference results in a peaking of the core pressure profiles of ICRH heated discharges which almost exactly cancels the loss in pedestal pressure. A lack of a specific description of the pedestal scaling is thus not the only deficiency of existing global energy confinement scalings. The power deposition profile predicted for alpha particle heating in ITER has a shape which lies about halfway between the NBI and ICRH heating profiles in JET. This would be expected to partially offset any loss in pedestal energy associated with the need to operate with small high frequency ELMs.

The hypothesis that depletion of the edge fast ion population is responsible for the type I to type III ELM transition is also difficult to prove. Analysis of trace tritium transport experiments has highlighted the fact that current models do not correctly predict the fast particle population near the edge of the plasma [16]. The observed anomaly is also found to be dependent on gas-puffing. Existing Fokker Planck calculations of the neutral beam deposition do not contain an adequate description of the edge charge exchange losses. They do however show the lowest fast ion energies and densities in the strongly fuelled and impurity seeded plasmas. It is not possible at present to show a causal relationship between fast ion density and the transition from type I to type III ELMs.

3. EFFECT OF RADIATION ON CORE TRANSPORT

3.1 Local transport analysis

Experiments at JET have been aimed at establishing whether the core confinement of strongly radiating pulses is consistent with Gyro-Bohm scaling. Previous global confinement analysis pointed to Bohm-like behaviour which would be very unfavourable for ITER [17]. Recent local transport analysis of dimensionless scaling experiments in the radiative regime [18] has shown that, provided the effect of variations in collisionality can be ignored, the scaling of χ_{eff} in the core with normalised gyro radius ρ^* is most consistent with Gyro-Bohm scaling, Fig. 5. Near the edge of the plasma (r/a>0.75) the transport scaling becomes more Bohm like. How the width of this region scales is not clear at present.

3.2 CDH identity pulses

In highly radiative discharges in JET, type III ELMs and low pedestal pressure are synonymous. This is consistent with the behaviour seen in CDH modes in ASDEX-Upgrade (AUG) [19]. However, in AUG the loss of pedestal pressure is compensated by a slight peaking of the core pressure profile. This effect is not seen in the normal range of JET parameters. Work has therefore started on "core identity" experiments which are intended to match the shape and dimensionless parameters (q_{95}, ρ^*, υ^* and β) of AUG CDH pulses with neon seeding. In JET an AUG shaped, q_{95}=4, low δ equilibrium has been used with B_T/I_p = 1.24/0.88 and P_{NI}=4.6MW. This corresponds to q_{95}=4, low δ equilibrium, B_T/I_p = 2.5/1.0, P_{NI}=7.5MW in AUG. Under these conditions it has been possible to produce a discharge with H_{97}~1 and type III ELMs. After the transition from type I to type III ELMs there is a slight peaking of the pressure

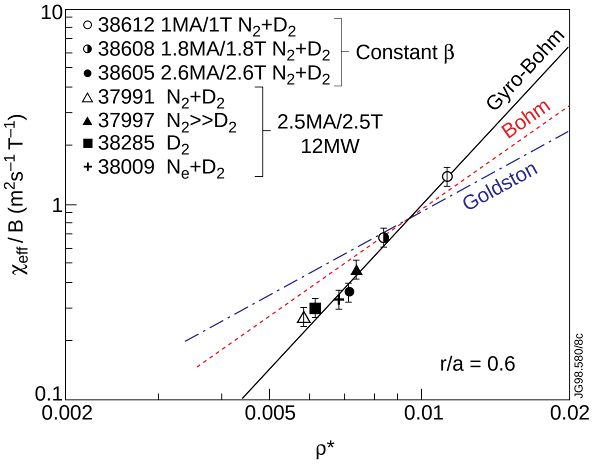

Fig.5 Logarithmic plot of χ_{eff}/B (TRANSP) vs. ρ_* at r/a=0.6 for a variety of impurity and deuterium seeded discharges. Pulses 38612, 38608 and 38605 form a ρ^* scan at constant β (but ν^* varies).

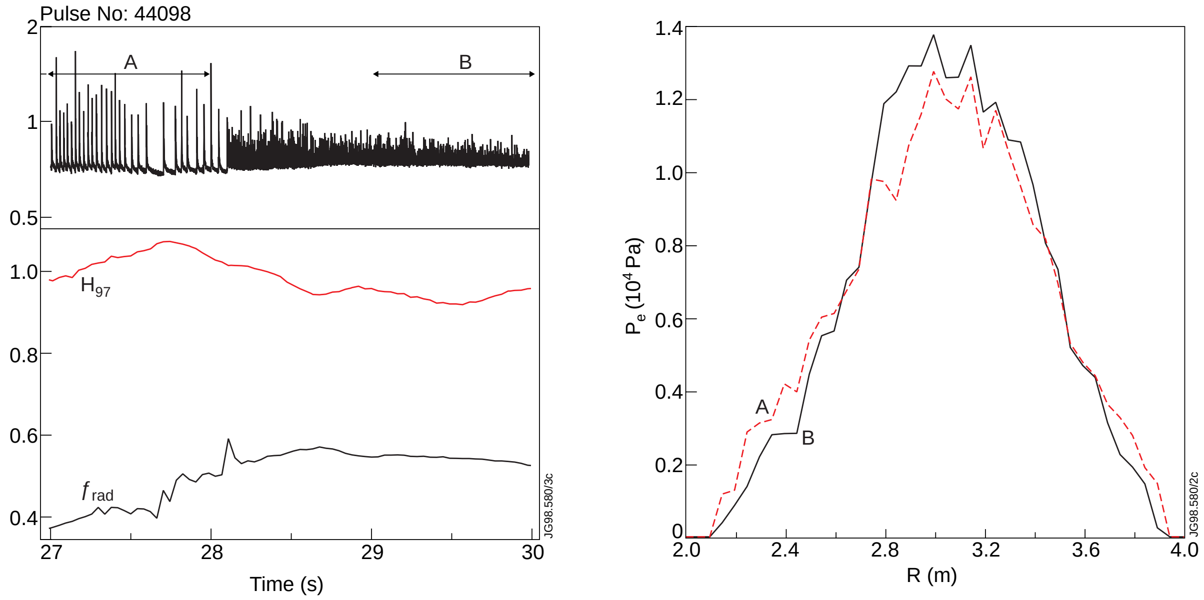

Fig.6 (a) AUG CDH "core identity" experiment in JET in which a transition to type III ELMs is observed without significant loss of global energy confinement. (b) Average electron pressure profiles for the type I and type III ELM phases which peak after the transition.

profile, Fig. 6. As in AUG, this seems to result from a peaking of the density profile which offsets the edge pressure loss. Similar compensation of pedestal losses is seen in ICRH heated H-modes but in this case it is due to a more centrally peaked power deposition profile than in comparable NBI heated plasmas. In the CDH identity pulses there is no significant change in power deposition profile although the sawtooth amplitude increases after the transition to type III ELMs. It is not yet clear whether the peaking effect seen in Fig. 6 has the same origins as that observed in AUG. The phenomenon is not very robust and attempts to raise the density and/or radiated power fraction resulted in a pressure loss across the whole profile and reduced global confinement $H_{97} \leq 0.8$. Experiments with the JET MkIIGB divertor have also failed so far to reproduce this effect.

4. DISCUSSION AND CONCLUSION

High density, high radiated power fraction and small ELMs are key elements of the current ITER design. However, it is clear that in JET there is trade-off between ELM size and τ_E which is represented in Fig. 7. Since ELMs are often irregular the maximum size may be more important than the average and so both values are shown. To get the maximum ELM size below the 2% level thought tolerable for ITER implies a significant loss in global energy confinement.

In JET, the best performance in terms of the normalised Lawson product $f_{GL}H_{97}$ is actually obtained with unfuelled or lightly fuelled type I ELMy H-modes. Strong gas fuelling produces a relatively small gain in density and this is at the price of a reduced energy confinement time. Raising the radiated power fraction to achieve type III ELMs and low divertor power loading results in a 25% reduction in confinement time. The only effective way found to increase the value $f_{GL}H_{97}$ which can be achieved is by raising the plasma triangularity.

These results have been shown to be consistent with a semi-empirical model for the ELM pressure cycles relating the ELM frequency to the average pedestal pressure [10]. It is clear from this work that the scaling of the core and edge contributions to the global energy confinement need to be considered independently [20]. A limitation of the semi-empirical model is that it assumes a knowledge of the ELM frequency, it also assumes that each ELM takes the edge plasma pressure down to a similar base level. Attention has tended to be focused on the scaling of the critical pressure for type I ELMs but this model highlights the fact that the scaling of the lower limit of the pressure cycles is just as important and is currently not understood. The greatest jump in ELM frequency, and hence the largest loss in averaged pedestal pressure, is associated with the transition from type I to type III ELMs. At present there is no conclusive explanation for this transition. Collisionality at the pedestal or further out near the separatrix

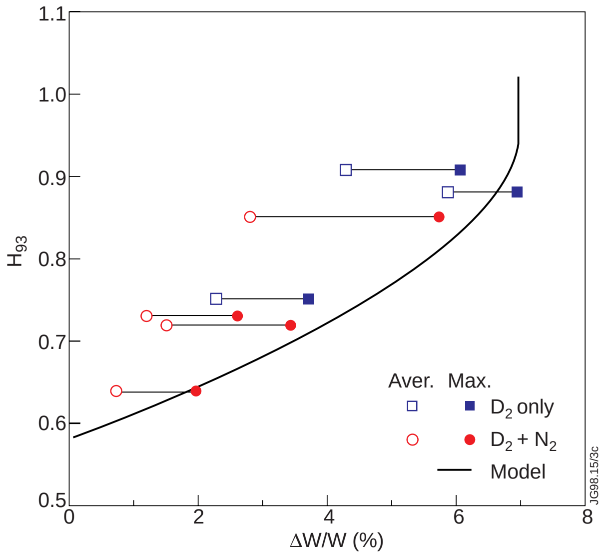

Fig.7 H_{93} vs. ELM size (ΔW/W) for a series of D_2 and N_2 seeded discharges with $\delta \sim 0.23$, $I_p = 2.5MA$, $B_T = 2.5T$ and $P_{NBI} \sim 12MW$. Average and maximum ELM size are compared to the semi-empirical model for the ELM pressure cycles[10].

may play a role does not appear to be the only factor. Ideas about the role of fast particles show promise for understanding why type III ELMs are always seen with ICRH heating and why the neutral beam mass and energy affect the critical pressure for type I ELMs in hot ion H-modes. However, the conclusive experiment involving deuterium beam injection into a hydrogen plasma has yet to be carried out.

The loss of pedestal energy associated with strong gas fuelling and high radiated power fraction may be acceptable for ITER provided the core confinement scaling is Gyro-Bohm, as indicated by recent JET results. Further work is however required to determine how the thickness of the Bohm like region observed near the edge of the plasma scales. The extent to which core peaking can offset confinement losses near the edge and whether this can be scaled to larger devices is currently under investigation.

REFERENCES

[1] GREENWALD, M., et al., Nuc. Fus., **28** (1988) 2199.
[2] CORDEY, J.G., presented on behalf of the ITER Confinement and Modelling Working Group, Plasma Phys. Control. Fusion, **39** (1997) B115-B127.
[3] JANESCHITZ, G., et al., Proceedings of the 16th Int. Conf. on Fusion Energy Montreal, IAEA, Vol. 1 (1996) 755-767.
[4] HORTON, L.D., et al., Plasma Phys. Control. Fusion **38** (1996) A269.
[5] SAIBENE, G., et al., 24th EPS Conf., Berchtesgaden, Vol. 21A Part I (1997) 49.
[6] MATTHEWS, G.F,. et al., Proceedings of the 13th Int. PSI Conf., San Diego, 1998.
[7] SAIBENE, G., et al., 25th EPS Conf., Prague, paper B-26 1998).
[8] MONK, R.D., for the JET Team, this conference, IAEA-F1-CN-69/EX6/4.
[9] MATTHEWS, G.F. for the JET TEAM, Plasma Phys. Control. Fusion **37** (1995b) A227-A239.
[10] FISHPOOL, G., accepted for publication in Nuclear Fusion (1998).
[11] LINGERTAT, J., et al., Proceedings of the 13th Int. PSI Conf., San Diego, (1998).
[12] SAIBENE, G., et al., in preparation for submission to Nuclear Fusion.
[13] PARAIL, V., for the JET Team, this conference, IAEA-F1-CN-69/EX6/1.
[14] PARAIL V., LINGERTAT J., accepted for publication as a Nuclear Fusion Letter (1998).
[15] CHANKIN, A., SAIBENE G., submitted to Plasma Phys. Control. Fusion (1998).
[16] ZASTROW, K.-D., for the JET Team, IAEA-F1-CN-69/EX1/7, this conference.
[17] STORK, D. for the JET Team, 16th Int. Fusion Energy Conf., IAEA, Vol.1 (1996) 189.
[18] MATTHEWS, G.F., et al., submitted for publication in Nuclear Fusion, 1998.
[19] KALLENBACH, A., et al., Nuclear Fusion, Vol. 35, No. 10 (1995) 1231-1246.
[20] CORDEY, J.G., for the JET Team, this conference, IAEA-F1-CN-69/EX7/1.