ITER Shaping and Elongation Experiments on JET

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Abstract The flexibility of the design of JET has made it well suited to exploring the effects of different plasma shapes and elongations on ELMy H-mode plasmas. Over the past few years, a number of experiments [G. Sabeine; Nuclear Fusion 39 (1999) 1133] have measured such effects and attempted to explain the underlying physics. Two of the principal results have been the strong dependence of confinement on elongation and the improvement of confinement, for densities close to the Greenwald density, at higher triangularities. This led to experiments in Autumn 1999, at the request of the ITER project, to measure, independently, the effects of elongation and shaping at constant q and current. Here we draw together these experiments to produce the best measure yet of the elongation and triangularity scaling on JET. By including data from other machines, from the international confinement database [O. Kardaun; Plasma Phys. Control. Fusion 41 (1999) 429], we show this scaling's impact on possible next step machines, especially by means of two term scaling laws.

1. Introduction

The IPB98(y,2) scaling law, based on results from ten ITER similar machines [1], expresses the energy confinement time of a tokamak in terms of eight engineering parameters,

$$\tau_{conf} = 0.0562 \text{ x } P^{-0.69}\, B^{0.15}\, I^{0.93}\, \kappa_a^{\ 0.78}\, n^{0.41}\, a^{0.58}\, R^{1.39}\, M^{\ 0.19} \qquad (1)$$

where τ_{conf} is the energy confinement time in seconds, P is the power in MW, B is the field in Tesla, I is the current in MA, n is the density in 10^{19} m^{-3}, a and R are the minor and major radii in m and M is in the mean atomic mass of the main plasma species. $\kappa_a = \Delta/\pi a^2$, where Δ is the poloidal cross-sectional area, is the preferred elongation measure. One notices the relatively high positive scaling of elongation, which is amplified by the fact that plasma volume increases linearly with elongation and thus a higher elongation enables a higher current for a given minorradius, major radius and q_{95}. Triangularity is not included, however experiments on ASDEX Upgrade [2] and JET [3] have shown evidence for improved confinement with increased triangularity at high densities. With this in mind the ITER-FEAT design has a relatively large elongation (κ =1.85) and triangularity (δ = 0.2). At the request of the ITER team, dedicated experiments were carried out on JET, during the Autumn 1999 campaign, to study the effects of elongation and triangularity on plasma confinement.

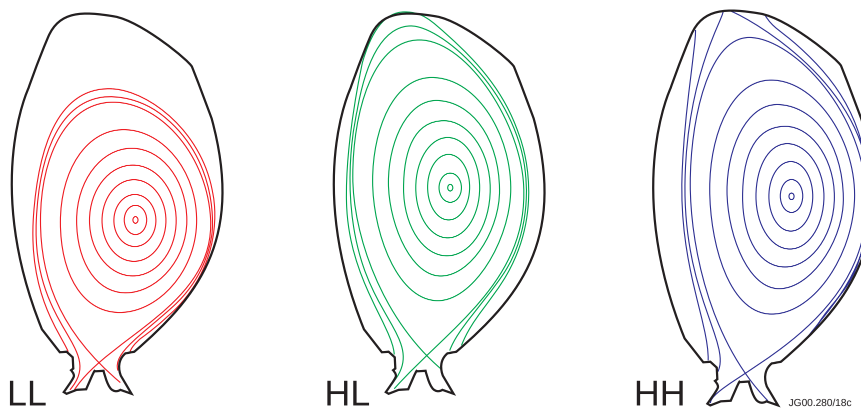

Fig.1: Plasma equilibria used in Autumn 1999 experiments

Three configurations were produced: at low elongation ($\kappa \approx 1.55$) and low triangularity ($\delta \approx 0.2$), LL; at high elongation ($\kappa \approx 1.85$) and low triangularity ($\delta \approx 0.2$), HL; and at high elongation ($\kappa \approx 1.9$) and high triangularity ($\delta \approx 0.35$), HH; all at constant minor radius ($a_{min} \approx$ 84cm). In each configuration, a $I_p \approx 1.8$MA, $q_{95} \approx$ 3.3 scenario was developed and a gas scan of NBI heated ($P \approx 15$MW) ELMy H-modes was made. By comparing the LL and HL scenarios it was possible to study the effects of elongation, whereas comparing the HL with the HH enabled an independent study of triangularity. Two further scenarios were also developed, in the HH configuration, to study the independent effects of current and field scalings, as well as another scenario in the LL configuration to study the effect of current at constant field.

2. Global confinement

To study the effects of shaping, elongation and confinement loss at large density, we normalise the confinement times of the pulses in the experiment as,

$$\tau_{conf}^{norm} = \tau_{conf}\, 0.102 \left(\frac{P_{NBI}}{15MW}\right)^{0.69} \left(\frac{B}{2.1T}\right)^{-0.15} \left(\frac{I_{ped}}{1.8\ MA}\right)^{-0.93-0.41} \left(\frac{R}{3m}\right)^{-1.39} \qquad (2)$$

where we have already noted that a = 84cm and M = 2 are constants across all scans and the extra power in the current term compensates for the change in Greenwald limit between the scenarios.

Figure 2 shows the results from the scans, with one symbol representing each shot. The lowest density points in each scan represent the natural density for the ELMy H-mode, that with no gas fuelling during the main heating phase. We note the increase in natural density between the low shaped LL configuration and the other two. This would appear to be related to elongation. As we move through the scans we notice a sudden fall in confinement in the HH scenarios around 70% Greenwald due to the ELM transition (Fig.3). A similar transition was seen in the other scenarios with a smaller confinement fall. Comparing scans with the same κ and δ we see good confirmation of current and field scaling.

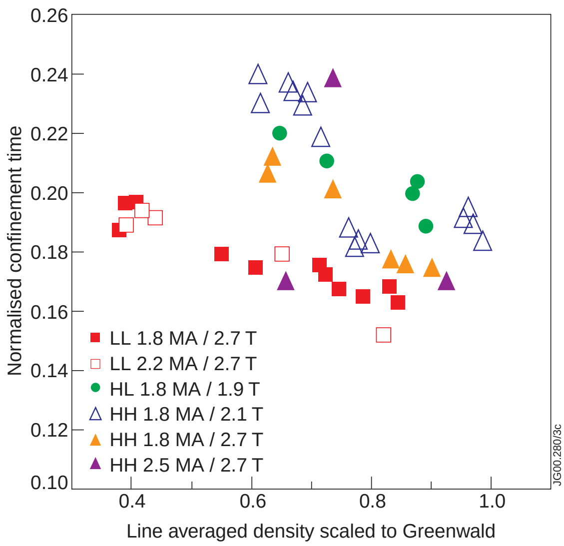

Fig.2: Effect on confinement of shaping, elongation and density

Comparing LL with HL, in the normalised plot, we see a marked improvement in confinement with elongation, consistent with the IPB98(y,2) scaling. Comparing HL with HH, we see little sign of confinement improvement, suggesting the effect of triangularity is small. A power law fit gives

$$\tau_{conf} \propto \kappa_a^{\,0.8 \pm 0.3}\ \delta^{\,0.0 \pm 0.1}$$

We note here that triangularity is not well suited to a power law fit, as reasonable confinement is seen at and below zero triangularity. For the purposes of the Autumn 1999 experiments the fit merely illustrates the weak dependence on triangularity, but for the wider database a linear fit will be used.

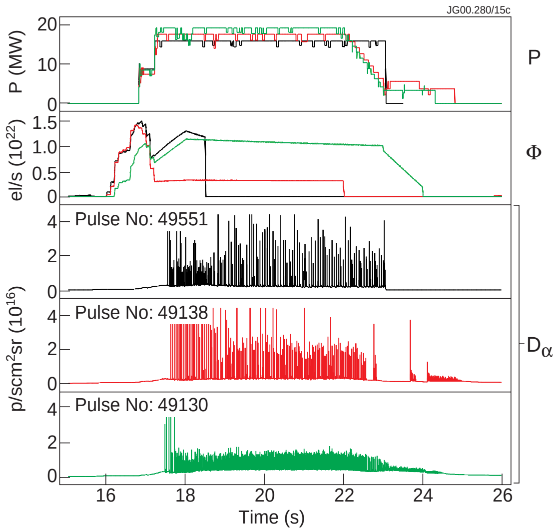

Fig.3: Time traces for three shots in the HH scan at 1.8 MA / 2.1 T

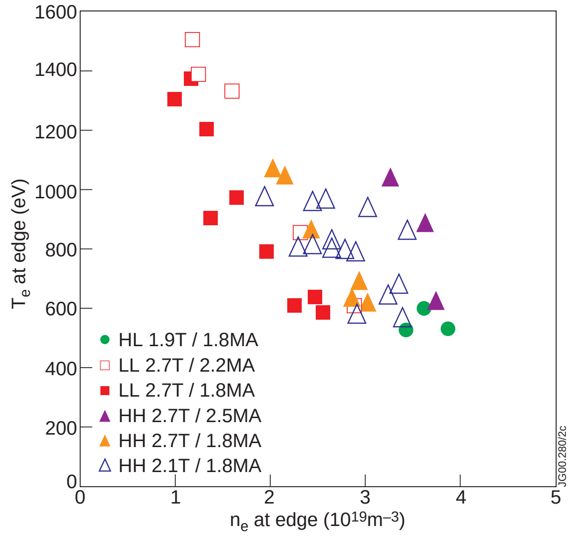

Fig.4: Edge operation diagram for

NTMs were also a feature of some discharges, particularly the HH ones, leading to confinement falls of up to 20%. These discharges have been removed in the analysis here.

3. Pedestal Data

The unusual geometry of the LL and HL configurations meant that measuring the pedestal parameters was difficult. However, data from the edge LIDAR [4] diagnostic enabled a measurement of pedestal density and temperature to be made for all the scans. The resulting edge operation diagram is given in figure 4.

Looking within individual scenarios we see a clear increase in pedestal pressure with current. This is consistent with the linear scaling given in earlier work on JET pedestal data [5]. Once again we see a large improvement between the LL and HL scenarios, indicating a strong elongation dependence. Taking the current and temperature scaling from [5] and fitting κ with a power law dependence δ with a linear dependence we arrive at the following scaling law for the pedestal energy:

$$\left(\frac{W_{ped}}{MW}\right) = 0.102 \left(\frac{I}{MA}\right)^{1.0\pm0.1} \left(\frac{T_{ped}}{keV}\right)^{0.5\pm0.2} (\kappa)^{2.5\pm1.5}\left[1 + (0.15\pm0.1)\,\delta\right] \quad (3)$$

We note that the δ dependence is weak whilst the κ scaling is very strong.

4. Scaling Laws

Following [5] we invert the pedestal energy scaling and include a separately fitted core confinement model which is broadly gyro-bohm. The resulting two term scaling law is:

$$\tau_{conf} = 0.0095 \frac{I^{0.8}\, n^{0.6}\, R^{2.2}}{P^{0.6}} \left(\frac{M}{2}\right)^{-0.2} + 0.045 \frac{I^2 R\kappa^4}{nP^{0.8}} (1 + 0.3\,\delta) \qquad (4)$$

We note that the elongation dependence is exclusively in the pedestal and that the density dependence is produced by a combination of positive scaling in the core and negative scaling in the pedestal.

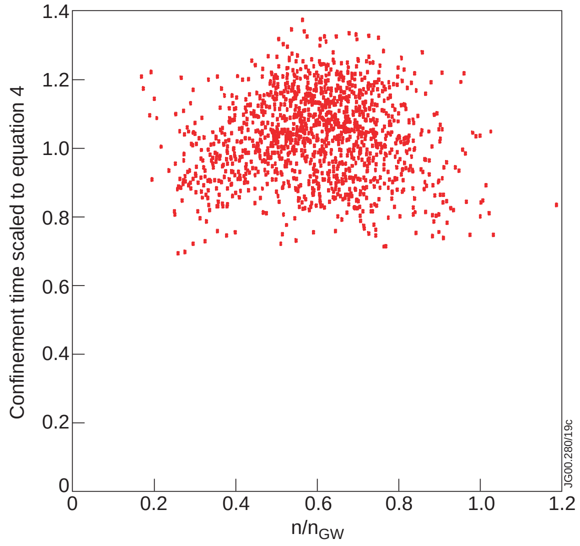

Fig.5(a): Two term scaling law fit to JET ELMy H-modes

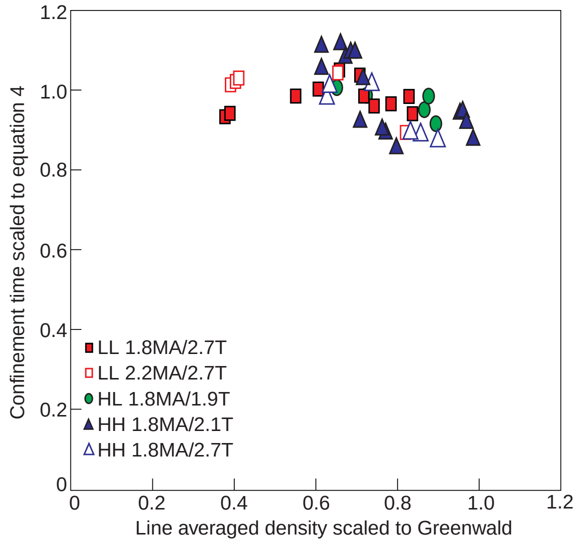

Fig.5(b): Two term scaling law fit to JET ELMy H-modes

Figure 5(a) shows the fit of the two term scaling law to a database of steady state ELMy H-modes on JET. With a root mean squared error of 12.0% this fit is only a slight improvement on that of 12.8% for a simple power law fit, but its real strength comes in its greatly improved description of the density dependence as illustrated in figure 5(b).

If we take ITER like parameters of P = 94 MW, B = 5.3 T MW, I = 15 MA, κ_a = 1.85, δ = 0.49, n = 10^{20}m^{-3}, a = 2.0m, R = 6.2m and M = 2.5 we have a energy confinement time of 3.35 s, slightly lower than that of 3.65 s from the IPB 98(y,2) scaling law. However, the relatively large error bars on the pedestal scaling, particularly that on the edge temperature, mean that the resulting error bars in the confinement time (± 2.4 s) are large. Thus, at present, the two term scaling law does not provide more information than a simple power law. However, we have illustrated how such a fit gives a better description of the density dependence and believe this should be developed further.

5. Discussion

JET experiments have provided a good range of plasmas triangularities and elongations. The experiments discussed here have added considerably to this database. Elongation scaling in the ITER power law is consistent with the results, supporting the scaling used for ITER-FEAT predictions. Study of the pedestal parameters suggests that elongation has its dominant effect there, leading to an increase in pedestal pressure going as $\kappa^{1.5 \pm 0.9}$

Despite a 50% increase in δ between two of the scans, only a weak improvement in confinement was seen. This contrasts strongly with the improvements seen in some other experiments on ASDEX [2] and JET [3], but does appear to be consistent with the wider JET database. Different edge behaviour, as a result of changing strike point positions and angles or outer gaps, may mask the effect. A non-linear response to triangularity, such as a threshold value being required, could also explain the different effects of triangularity in different experiments. Further experiments to study the effects of triangularity on confinement will be carried out on JET throughout 2000 and early 2001.

A clear fall in confinement with density was also a feature of all the gas scans. This is believed to be as a result of pedestal degradation from increased fuelling and is clearly a robust feature with regard to shaping. A two term scaling law has been shown to successfully model this behaviour, although error bars are large.

6. Acknowledgements

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