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Energy Confinement in Steady State ELMy H-modes in JET

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1. INTRODUCTION

During the last seven years an extensive confinement database has been assembled on JET of steady state ELMy H-mode plasmas. The database was started under the JET Joint Undertaking and has been continued under EFDA with the addition of a further 200 pulses. In this paper the database is used to assess the effect of three parameters upon the energy confinement, these are the triangularity δ, the proximity of the density to the Greenwald density limit and the peaking of the density profile. There is clear evidence from single parameter scans that these three variables do influence the confinement, however the present scaling expression, used to predict the performance of ITER, namely IPB98(y,2)[(1)], does not contain these variables.

2. ANALYSIS OF STEADY STATE DATABASE

a) Full Database

The steady state ELMy H-mode database contains some 1228 pulses and includes a wide range of current (1<I<4.5MA), toroidal field (1<B<3.8T), and isotopes H, D, D-T, T. Recently a substantial quantity of high density data has been obtained close to the Greenwald limit ($n_{GR} = I/\pi a^2$), such that the present database now contains pulses with $0.2 < n/n_{GR} < 1.2$, where n is the central line average density. The higher densities being obtained by employing sophisticted gas fuelling and power control techniques[(2) - (6)]. There are both Type I and Type III ELMs and a wide range of configurations with upper triangularity δ_u ranging from $0<\delta_u<0.7$, and the lower triangularity $0.1 < \delta_L < 0.5$ and three divertor types Mark I, Mark II and the gas box MarkGB.

The data is compared with the IPB98(y,2) scaling which has the form

$$\tau_{\varepsilon 98} = 0.0562\, I^{0.93}\, B^{0.15} n^{0.41} P^{-0.69}\, M^{0.19}\, R^{1.97}\, \varepsilon^{0.58}\, \kappa_a^{0.78} \qquad (1)$$

This comparison is shown in Figure 1 versus the density divided by the Greenward density.

The data has been grouped by current and one can see that in the present dataset only the lower current data I < 2.5MA achieves a density above the Greenward limit. The reason for the absence of the high current data with $n > n_{GR}$ is thought to be due to the lack of available input power [(7)] rather than a fundamental limit. We first examine whether there is any dependence of the energy confinement on the divertor type, by examining the dependance of the residuals with respect to the IPB98(y,2) scaling upon the divertor. We find that the Mark I and Mark II divertors are essentially identical and that both have an approximately 5% lower confinement than the gas box. This small difference between the 3 divertors is not thought to be statistically significant and is ignored in this paper, however a further analysis will be completed when data with the septum removed is available next year.

** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Turning to the dependence of the residuals or H factor on triangularity and the vicinity to the Greenwarld limit we find that the H factor increases with triangularity and degrades as the Greenwald limit is approached. The form is

$$H(\equiv \tau_\varepsilon / \tau_{\varepsilon 98}) = 0.93 \pm 0.026 + (0.29 \pm 0.047)\delta_u + (0.28 \pm 0.11)\delta_L - (0.25 \pm 0.024)\, n / n_{GR} \qquad (2)$$

The RMSE of this fit is 12.5% compared with 13.1% in the absence of the triangularity and Greenwald terms where the H factor is 0.92. Inspection of the errors on the coefficients of Eq.(2) reveals that the error on the lower triangularity δ_L is larger than that on δ_u which implies that δ_L is not particularly significant and as a consequence in the future analysis we shall use the upper triangularity δ_u alone. A similar result was found by Kallenbach[8] for specific scans of upper and lower triangularity.

b) Reduced Database

To investigate the role of density peaking on confinement we have to extract a subset from the above dataset for which accurate values of the pedestal density are available. The pedestal density is obtained from the Interferometer vertical line integral located at R = 3.75m. Only pulses in which the last closed flux surface is located at least 5 cms outside of this interferometer line of sight are retained, and furthermore only those in which the line average has been flagged as being of good quality are selected. We also restrict the dataset to type I ELMs only, to avoid those pulses close to the L to H transition. The above selection reduces the dataset to 436 pulses from the original 1228 pulses. The main reduction coming from the requirement to obtain an accurate line average density in the edge region. An example of a pulse in which the above criteria are satisfied is shown in Figs. 2 and 3.

We first examine the database for correlations between density and triangularity. In Fig. 4 the density normalised to Greenwald is shown versus the upper triangularity, with the data again grouped by current. From this figure it can be seen that there is a strong correlation between the lower density (or natural density) and triangularity, the upper density is not so strongly correlated. This is due to the fact that fairly high densities can be obtained even in low triangularity plasmas by carefully tuning the gas fuelling or by the injection of impurities to increase the edge radiation and reduce the deleterious effect of the ELMs.

Fitting the residuals of the H factor as in section (2a) with respect to the upper triangularity δ_u, the Greenwald fraction n/n_{GR} and the density profile peaking n/n_{ped}, where n is the line average through the plasma centre R = 3.02m and n_{ped} is the line average in the edge region (R=3.75m) gives,

$$H = 0.84 + 0.18\delta_u - 0.13\, n / n_{GR} + 0.51\left(\frac{n}{n_{ped}} - 1\right) \qquad (3)$$

with an RMSE of 10.6%.

From Eq. 3 we see that the profile peaking is an important term, the more peaked the profile the better the confinement.

Following the suggestion of Kardaun et al[9] the fit can be further improved by introducing a quadratic term in n/n_{GR}. This term is required to handle the curvature in the H factor versus n/n_{GR} that can be clearly seen in Fig. 1. The resulting fit has the form

$$H = 0.71 + 0.33\,\delta_u - 1.58(n / n_{GR} - 0.63)^2 + 0.58(n / n_{ped} - 1) \qquad (4)$$

with an RMSE of 9.5%.

From this expression we see that once again profile peaking is important. The fit is shown in Fig. 5, clearly the curvature in n/n_{GR} has now been eliminated. Adding other quadratic terms such as δ^2 or $\delta n/n_{GR}$ does not improve the fit any further.

3. ITER PREDICTIONS AND CONCLUSIONS

Using equations (2)-(4) one can make a prediction for the H factor in ITER. If we assume that in ITER δ_u = 0.5, the operational density is n/n_{GR} = 0.85, and there is no peaking, then the H factors from equations (2)-(4) are respectively H = 1.01, 0.81, 0.79. With a modest peaking factor n/n_{ped} = 1.3 both equations (3) and (4) give an improved H factor of 0.96.

Summarising the paper it has been shown that:

1) Increasing the triangularity improves both the access to higher densities and the energy confinement.
2) Peaking the density profile by tuning the gas input or by injecting impurities improves the confinement.
3) The confinement degrades as the Greenwald density limit is approached, and to model this effect one needs to add a quadratic term in n/n_{GR} to account for the curvature in the H factor.
4) All three effects, triangularity, density peaking and proximity to the Greenwald limit are significant and should also be included in fits to the multi-machine database.

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REFERENCES

1) ITER Physics Bases, Nucl. Fusion **39** (1999) 2204.
2) Lomas, P., et al., Plasma Physics. Contr. Fusion **42** (2000) B115
3) Constanza, M., EPS 1999
4) Saibene, G., et al, Nucl. Fus. Vol. 39.
5) Saibene, G., et al., Ibid, EPS 2001, Madeira
6) Valovic, M., et al., Ibid, EPS 2001, Madeira.
7) Sartori, R., et al, Ibid, EPS 2001, Madeira
8) Kallenbach A., Private Communication.
9) Kardaun, O., et al., IAEA Fusion Energy Conference, Sorrento, Italy, 2000.

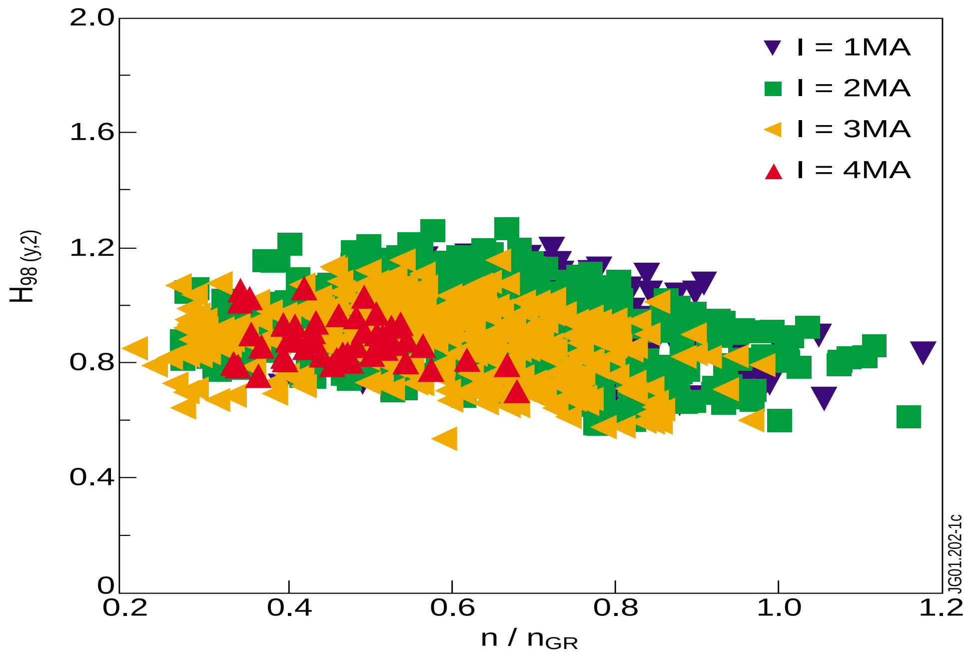

Fig. 1. H_{98} ($\equiv \tau_{th}/\tau_{\varepsilon 98}$) versus n/n_{GR}, the data are grouped by current I in MA 0.5 < I < 1.5, 1.5 < I < 2.5, 2.5 < I < 3.5 and I > 3.5.

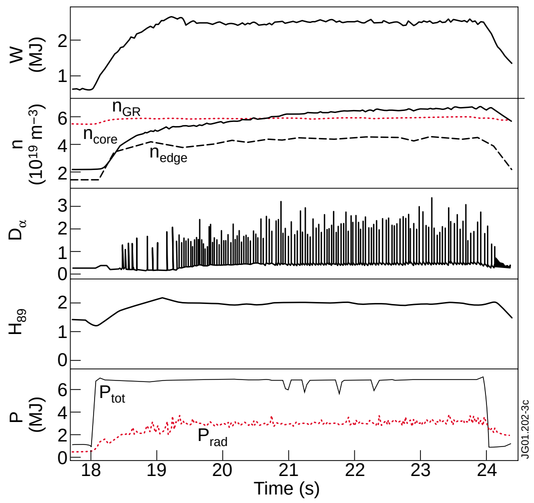

Fig. 2. The time evolution of a typical pulse 48276; the traces are (1) the stored energy (2) the core line average density, the edge line average density (R = 3.78) and the Greenwald density (3) the D^{α} emission (4) the H_{89} ratio ($\equiv \tau_E/\tau_{ITER89}$) (5) the total power input and the radiated power.

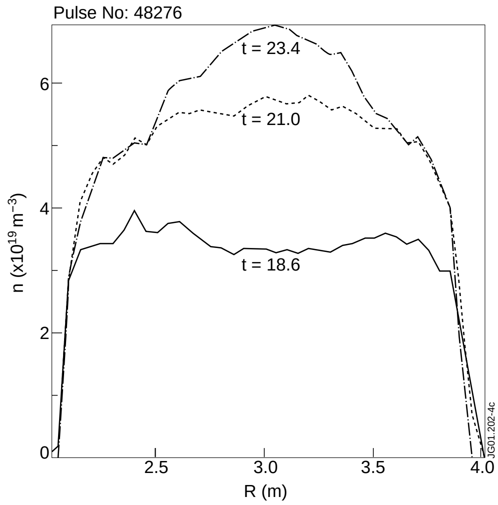

Fig. 3. The electron density profile at three times.

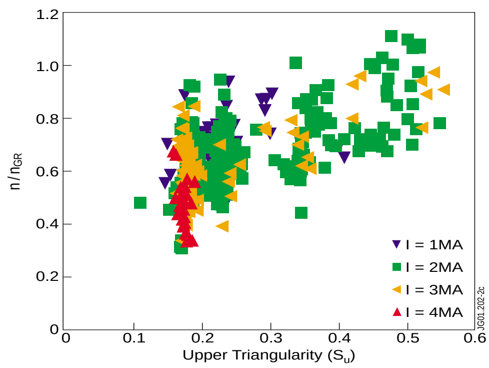

Fig. 4. n/n_{GR} versus the upper triangularity δ_u, current grouping as in Fig. 1

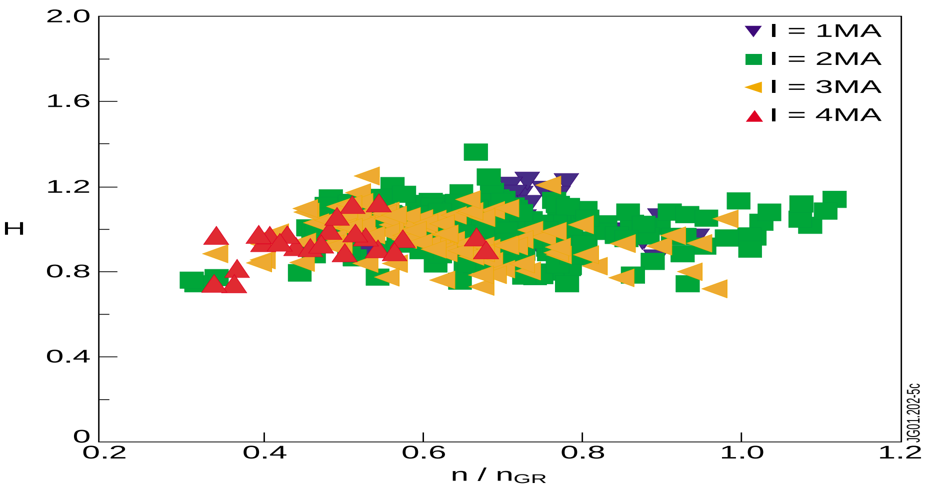

Fig. 5. The fit for the H factor given by Eq. (4) versus n/n_{GR}.