# High $\beta_p$ experiments at high triangularity in JET

F.G. Rimini[1], A. Bécoulet[1], J. Hobirk[4], P.J. Lomas[3],D.C. McDonald[3] , G. Saibene[2],
and JET EFDA contributors*

*[1] Ass. Euratom-CEA, CEA/DSM/DRFC, CEA/Cadarache, 13108 Saint Paul lez Durance, France - [2] EFDA CSU (Garching), 2 Boltzmannstrasse, 85748 Garching, Germany - [3] Euratom-UKAEA Fusion Ass., Culham Science Centre, Abingdon OX14 3EA, UK - [4]Ass. EURATOM-IPP, MPI für Plasmaphysik, 2 Boltzmannstrasse, Garching, Germany * See the Appendix of J.Pamela et al., Nuclear Fusion 45(2005) S63*

## 1. Introduction

One of the important issues for a tokamak power plant is the development of a viable high confinement operating scenario which combines the desired characteristics of high density, high bootstrap current fraction, full non-inductive current drive and moderate ELM activity. In the context of the research effort devoted worldwide to this problem [1,2] high $\beta_p$ experiments have been carried out in JET (2003/2004) in high triangularity ITER-relevant equilibria, $<\delta>$ = 0.4-0.5. A comprehensive characterisation of the ELM activity in these discharges has been published in [3]. Here we will, instead, concentrate on the core confinement analysis in the light of the growing debate about the β dependence of some commonly used dimensionless scaling laws, and address the question of the applicability of existing scaling laws to high $\beta_p$ scenarios.

## 2. The experiments

Experiments were carried out both in sawtoothing discharges, $q_o$<1 $l_i$~1.1-1.2, and with current profiles characterised by $q_o$≥1 and $q_o$~2, zero or reversed shear in the plasma core $l_i$~0.8-0.9, closer to what is envisaged for Hybrid scenarios and Advanced Tokamak (AT) operation. The plasma current and toroidal field are the same for the three sets of discharges, i.e. $I_p$ = 1.2 MA, $B_T$=2.7 T, resulting in $q_{95}$ ~ 7. The sawtoothing discharges were carried out at high density, ne ~ 0.8-1.0 of the Greenwald density $n_{GDL}$, in a quasi-double-null (QDN) configuration. The $q_o$>1 cases, at lower densities ~ 0.6-0.7 $n_{GDL}$, have more conventional high triangularity lower single-null (SN) equilibria Total injected power, a combination of NBI and ICRH, in excess of 20 MW results in $\beta_p$ ~ 2 and thermal $\beta_N$ ~2 (fig. 1).

As shown in figure 2, some of the $q_o$ ~ 2 discharges developed Internal Transport Barriers (ITB) in the Ion energy channel, although not so clearly in the electron energy or in the particle transport channels. The improvement in global stored energy given by these ITBs is up to 20-25% with respect to the other low li scenarios at similar densities. It is also interesting to analyse the relative contribution of the core and pedestal energy in the total thermal stored energy. The pedestal energy is estimated as $W_{ped} = \frac{3}{2} n_{e,ped}\left(T_{e,ped} + T_{i,ped}\right)V_p$ , $V_p$ is the plasma volume, the values of density and temperatures are taken close to the top of the H-mode pedestal, and $W_{core}=W_{th}-W_{ped}$. The proportion of pedestal energy with respect to total thermal energy varies between 20-30% (figure 3) and decreases with increasing density. Within the spread of the experimental data and the error bars of the estimation of the pedestal energy, ~ 15%, it is difficult to assess unequivocally whether the cases with ITBs have a significant improvement in core confinement for similar edge pedestal conditions.

### 3. Global Confinement Analysis

Some of the most popular H-mode scaling laws, like the so-called IPB98(y,2) scaling [4], exhibit a strong degradation of global confinement with β. On the other hand, experimental evidence of dedicated dimensionless single parameter scans [5,6] is mounting in support of a much weaker dependence on β.

The obvious caveat in the comparison with our dataset is that scalings like the IPB98(y,2) have been developed on a database of standard ELMy H-modes, mostly in Single Null equilibria and $q_o<1$, and it is not obvious that such scaling laws could be applicable to our dataset as a whole. As figure 1 shows, however, the beta scan in our database is essentially due to a power scan rather than confinement variations within and between different regimes, which gives us confidence that our dataset can provide a good testing ground for the β dependence of global confinement scaling laws.

First of all, we compare our data to the IPB98(y,2) scaling, on which estimates of the global energy are based for ITER. In engineering variables (see table I for definitions )

$$\tau_{IPB98(y,2)} = 5.62x10^{-2} \cdot P_{LOSS}^{-0.69} \cdot B_o^{0.15} \cdot I_P^{0.93} \cdot k_a^{0.78} \cdot \overline{n}_e^{0.41} \cdot a^{0.58} \cdot R^{1.39} \cdot M^{0.19}$$

or, recast in dimensionless form :

$$B_o \tau_{IPB98(y,2)} \propto \rho^{*-2.70} \cdot \beta^{-0.90} \cdot \nu^{*-0.01} \cdot M^{0.96} \cdot q_{95}^{-3.0} \cdot \varepsilon^{0.73} \cdot k_a^{3.3}$$

As figure 4 shows, when the global confinement time $\tau_{th}$ normalised to $\tau_{IPB98(y,2)}$ is plotted against the normalised toroidal beta, the experimental confinement factor $H_{98(y,2)}$ increases strongly with β. Clearly the confinement times in our dataset are not well described by the IPB98(y,2) scaling and one possible interpretation for this disagreement is that the β dependence of the scaling is incorrect, resulting in an overestimate of the confinement for the low β cases.

In response to the doubts about IPB98(y,2), global scalings laws have been recently developed which have intrinsically a weak or zero β dependence.

We consider next a scaling derived using the same multi-machine H-mode confinement database DB3v5 that originated IPB98(y,2) by imposing both the Kadomtsev and electrostatic constraints [6] . In engineering variables, this ES scaling is

$$\tau_{ES} = 4.87x10^{-2} \cdot P_{LOSS}^{-0.55} \cdot B_o^{0.09} \cdot I_P^{0.72} \cdot k_a^{0.74} \cdot \overline{n}_e^{0.51} \cdot a^{0.78} \cdot R^{1.36} \cdot M^{0.10}$$

and in dimensionless variables, expliciting the *zero* dependence on β

$$B_o \tau_{ES} \propto \rho^{*-2.8} \cdot \beta^{0} \cdot \nu^{*-0.09} \cdot M^{1.62} \cdot q_{95}^{-1.51} \cdot \varepsilon^{-0.44} \cdot k_a^{2.02}$$

The behaviour of $H_{ES}=\tau_{th}/\tau_{th,ES}$ is given in figure 5 as function of β. There is still a residual β dependence but it seems to be reduced with respect to the IPB98(y,2) trend.

A similar fit procedure to the ITER database DB3v5, imposing both the Kadomtsev and electrostatic constraints and the gyro-Bohm constraint, yields another zero- β-dependence fit as

$$\tau_{th}^{EGB} = 0.028 \cdot P_{LOSS}^{-0.55} \cdot B_o^{0.07} \cdot I_P^{0.83} \cdot k^{0.75} \cdot \overline{n}_e^{0.49} \cdot a^{0.30} \cdot R^{1.81} \cdot M^{0.14}$$

or

$$B_o \tau_{th}^{EGB} \propto \rho^{*-3.0} \cdot \beta^0 \cdot \nu^{*-0.14} \cdot q_{95}^{-1.7} \cdot M^{0.82} \cdot \varepsilon^{-1.31} \cdot k^{2.29}$$

which proved to well desccribe the β dependence of the confinement in the dedicated DIII-D and JET scans [5]. The residual β dependence is very similar to that of the ES scaling, which is not surprising given that the two scalings have basically the same dependences on the parameters with larger variation in the database, $P_{loss}$ and density. The H factors with the ES and EGB scalings are in the range 0.6-1.0, so even these scalings tend to overestimate somewhat the confinement at low β.

## 4. Some Conclusions

A set of data spanning a significant β range at constant current and toroidal field has been used as basis for assessment of the accuracy of the beta dependence of three commonly used ELMy H-mode scaling laws. The discharges are characterised by different current profiles, to the point that some of them develop ion Internal Transport Barriers, but the beta variation in the database is due mainly to the input power variation. The dataset has been found to be poorly described by the IPB98(y,2) scaling, used in the ITER design, with a clear trend for the observed confinement to be poorer than the scaling prediction at low beta values. Some of the alternative scaling laws, developed within the contraints of an electrostatic relation, have a much better fit to the β dependence in dedicated dimensionless parameter scans and are an improvement with respect to the IPB98(y,2) law, but they still seem pessimistic in their β dependence when compared to our database. This may suggest that, if the other parametric dependences in the scaling are correct, then the β dependence may be stronger than $\beta^0$.

## References

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[4] ITER Physics Basis, Nucl. Fusion 39 (1999) 2175
[5] Petty C.C. et al, Physics of Plasmas vol 11 No. 5 (2004) page 2514
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**table I**

| | | | |
|---|---|---|---|
| $P_{loss}$ [MW] | loss power through the separatrix | $B_o$ [T] | toroidal vacuum magnetic field |
| $I_p$ [MA] | plasma current | $k_a$ | Elongation |
| $n_e$ [1019 m-3] | line av. electron density | a [m] | minor radius |
| R [m] | major radius | M | atomic no. of ion isotope |
| ρ* | norm. ion Larmor radius | β | norm. plasma pressure |
| ν* | norm. collision frequency | $q_{95}$ | safety factor |
| ε | inverse aspect ratio | | |

legend :

○ : $q_o$<1 - type I ELMs & no ITB

● : $q_o$<1 - grassy ELMs & no ITB

□ : $q_o$≥1 - type I ELMs & no ITB

△ : $q_o$~2 - type I ELMs & no ITB

▲ : $q_o$~2 - type I ELMs & Ion ITB

the error bars on the scatter plots are indicative of the typical measurement errors

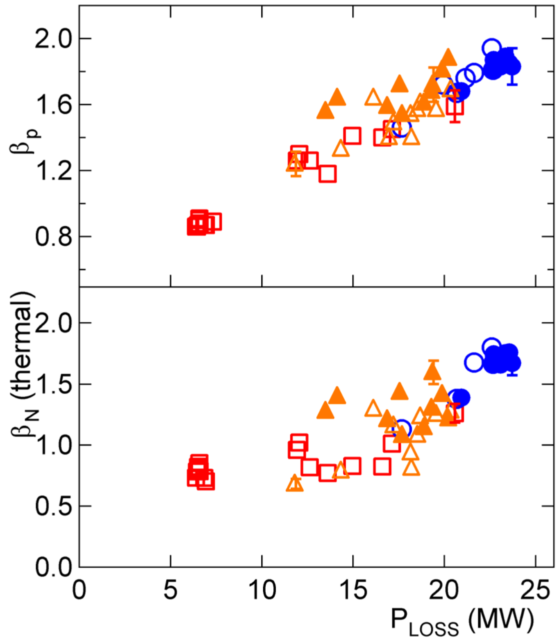


*Fig. 1 : poloidal β and normalised β for the different scenarios in the dataset as function of loss power*

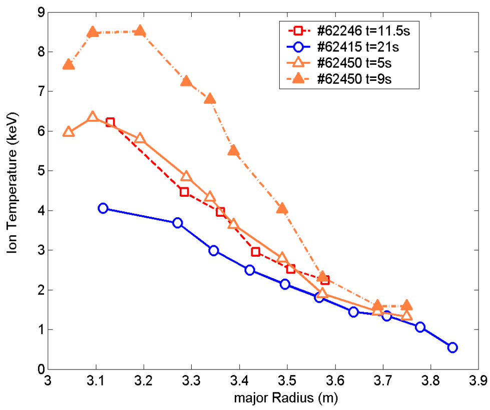


*Fig. 2 : ion temperature profiles for representative discharges in the dataset (symbols and colors are as in the scatter plots )*

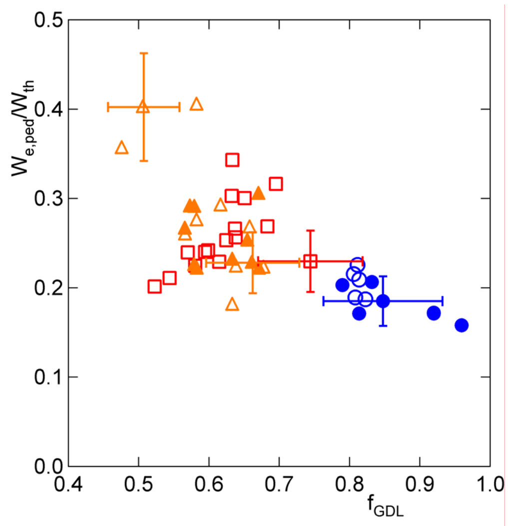


*Fig. 3 : ratio of electron pedestal energy to thermal energy vs. density normalised to $n_{GDL}$*

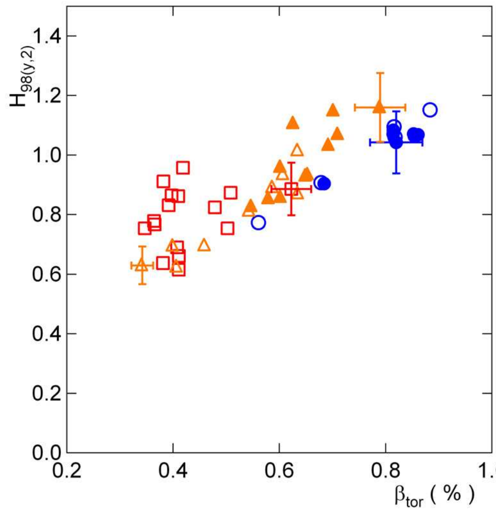


*Fig. 4 : $H_{98(y,2)}$ confinement factor vs. thermal β*

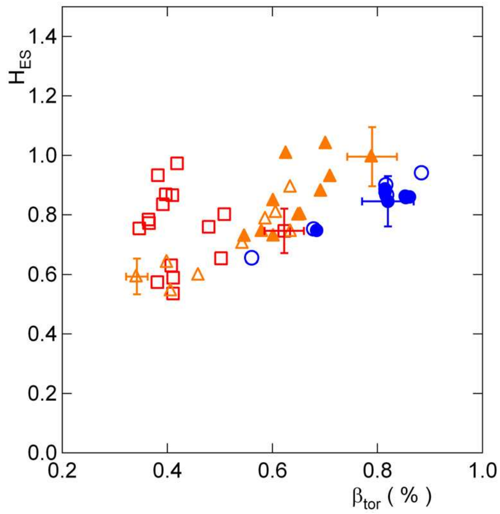


*Fig. 5 : $H_{ES}$ confinement factor vs. thermal β*