JET–C(98)62

JG Cordey and the JET Team

H-mode Power Threshold and Confinement in JET H, D, D–T and T Plasmas

JET–CP(98)62

H-mode Power Threshold and Confinement in JET H, D, D–T and T Plasmas

The JET Team[1]
presented by J G Cordey

JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA,
[1]See appendix to The JET Team presented by M L Watkins

ABSTRACT

The scaling of both the L-H threshold and confinement with the mass M of the hydrogenic isotopes is discussed. The confinement in the core and edge are found to scale differently with M and a two region model is developed to represent the physical behaviour of each region. Identity pulses with the same profiles of the dimensionless physics parameters ρ*, ν* and β are obtained with different isotopes, H and D; this result suggests that there is no explicit mass dependence of the transport in either the core or edge regions.

I. INTRODUCTION

A series of steady state ELMy H-mode plasmas with differing hydrogenic isotopes D, D-T and almost pure T were completed during the main JET D-T campaign; these were then supplemented with a series of ELMy H-mode hydrogen pulses. The range of currents, fields and powers of these pulses are listed in Table I and their general properties have been described previously [1, 2]. In the present paper the scaling of the L-H transition and the confinement with respect to the dimensionless physics variables $\rho^*\left(\equiv \rho_i / a\right)$, $\nu^*\left(\propto na / T_e^2\right)$ and $\beta\left(\propto \frac{nT}{B^2}\right)$ are examined in greater detail, in an attempt to obtain a better understanding of the underlying physics.

Table I

Parameter	Value
R (M)	2.88
a (M)	0.93
κ/δ	1.7/0.2 – 0.3
B (T)	1 – 4
I (MA)	1 – 4.5
P (MW)	4 – 25
<n> ($10^{19}m^{-3}$)	1.8 – 8
q_{95}	2.7 – 3.4

The paper is organised in the following manner. In section II, the scaling of the edge dimensionless physics parameters at the L-H transition is determined. In section III, the scaling of the energy confinement in the steady state ELMy H-mode phase is discussed. The most significant point is the different scaling of transport in the core and edge plasmas, where it is found that the core confinement degrades with isotope mass in contrast to the edge whose confinement improves strongly with mass. This behaviour is in line with present theoretical expectations of gyro-Bohm transport in the core and the edge transport being dominated by MHD events such as the ELMs.

In section IV we examine whether identity pulses can be obtained having the same dimensionless physics parameters (ρ^*, ν^*, β etc.) with different isotopes. Initial indications are that this is indeed a possibility provided strong gas puffing is used to control the ELM behaviour in the heavier isotope pulses.

II. THE SCALING OF THE EDGE PARAMETER AT THE L-H THRESHOLD

The scaling of the power threshold P_{thr} with the effective isotope mass M has been discussed previously by Righi et al.[1]. In that paper it was shown that $P_{thr} \propto 1/M$. In the present paper the scaling of the edge parameters with isotope mass is examined in greater detail in an attempt to identify which physics parameters control the transition.

The only edge profile measurement routinely available on JET is the electron temperature which is measured using a high resolution 48 channel radiometer[4]. A set of radial profiles from this instrument at different times is shown in Fig. 1. In the analysis which follows, the temperature at which the transition takes place is taken at the position of the knee in the fully developed pedestal $R=R_{ped}$. Unfortunately at the present time there is no measurement of the density profile in this region, however a vertical line integral measurement from the FIR interferometer is available at the position R=3.75 which is close to the knee in the temperature profile (see Fig. 1). This particular line integral is used throughout the paper as being representative of the edge density, n_{ped}.

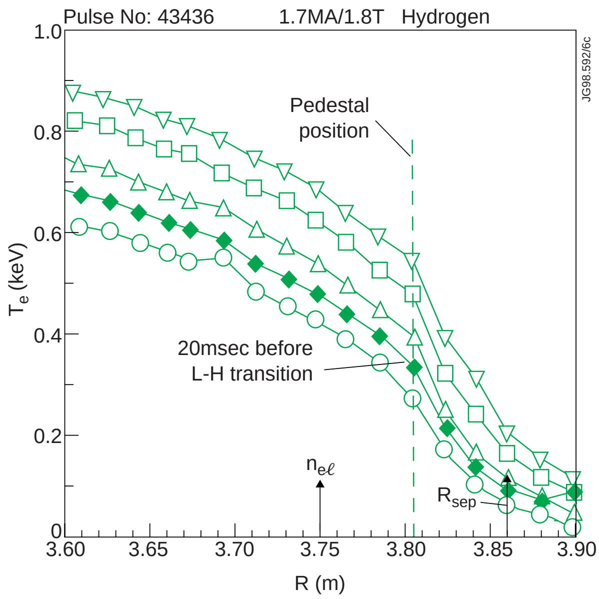

Fig. 1. Radial profiles of the electron temperature from the heterodyne radiometer at a series of times through the L-H transition. For this particular pulse the location of the pedestal is taken at R=3.8m.

A database has been assembled, containing the edge pedestal values from some 23 pulses in which the toroidal field ranges from 1.8 to 3.8T with the isotope mass ranging from 1 to 2.9 (hydrogen to almost pure tritium). The best fit to the temperature at the pedestal in terms of the variables B (toroidal field T), n_{ped} (line average density at R = 3.75m) and isotope mass M has the form:

$$T_{e\,ped} = 0.07\, B^{2.26}\, n_{ped}^{-0.23}\, M^{-0.6} \qquad (1)$$

The strong dependence on B and weak n dependence have been seen previously in JET deuterium data [5], the new element in Eq. (1) is the inverse mass dependence.

The free fit Eq. (1) is compared in Table II with three physically constrained fits.

Table II. Scaling of the electron temperature at the L-H transition. The units are $T_{e\,ped}$ (KeV), n_{ped} (10^{19} m^{-3}), B (T).

Type of fit	$T_{e\,ped}$ fit	RMSE (%)
Free	$0.07\, n_{ped}^{-0.23}\, B^{2.26}\, M^{-0.6}$	18
$\rho^* \propto M^{\alpha}$	$0.08\, B^2\, M^{-0.54}$	18
$\beta \propto M^{\alpha}$	$0.1 \frac{B^2}{n} M^{-0.21}$	32

In the second fit, of Table II, it is assumed that the transition occurs at a critical value of ρ* which is isotope dependent. For the third fit which is similar to the form proposed by Pogutse [6], it is assumed that the transition occurs at a critical value of β which is isotope dependent. The results in Table III should only be regarded as indicative; and not conclusive, since the data set is very small at the present time. The best of the physics fits ($\rho^* \propto M^{\alpha}$) is shown in Fig. 2.

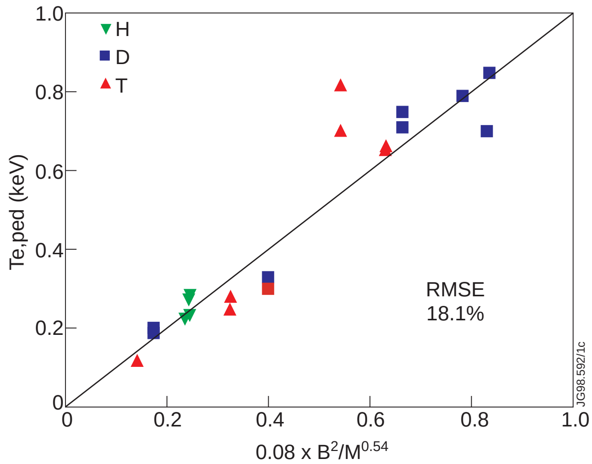

Fig. 2. The electron temperature at the transition versus the fit 0.08 $B^2/M^{0.54}$. The symbols are H=Hydrogen, D=Deuterium and T=Tritium.

III. THE SCALING OF CONFINEMENT WITH ISOTOPE MASS

The general properties of the JET steady state ELMy H-mode isotope data set are described in Cordey et al.[2]. The energy confinement time fits the scaling expression $\tau_{ITERH-EPS97(y)}$, used to predict the confinement in ITER, fairly well. This scaling expression [7] has the form:

$$\tau_{ITERH-EPS97(y)} = 0.029\, I^{0.90}\, B^{0.20}\, P^{-0.66}\, n^{0.40}\, R^{2.03}\, \varepsilon^{0.19}\, \kappa^{0.92}\, M^{0.2} \qquad (2)$$

where the variables (units) are τ_{th}(s) energy confinement time, I (MA) current, B(T) toroidal field, P(MW) loss power, n ($\times\, 10^{19}$ m^{-3}) density, R(m) major radius, ε inverse aspect ratio a/R, κ elongation and M the effective mass. Although Eq. (2) has a close to gyro-Bohm form as far as the P, I, n and R scaling are concerned, its mass dependence should be $\tau_E \propto M^{-0.2}$ for a gyro-Bohm scaling rather than a positive scaling with mass.

To understand the origin of the τ_E dependence on mass, we separate the stored energy into two components, the core and the pedestal. These two regions are shown schematically in

Fig. 3. To calculate the stored energy in the pedestal the ECE and FIR interferometer measurements are used as described in the previous section along with assumption that $T_i = T_e$ in this region. The pedestal energy is then defined as $W_{ped} = 3\, n_{ped}\ T_{e\,ped}\, V$, where V is the plasma volume, $T_{e\,ped}$ is the time averaged electron temperature at the knee of the profile (see Fig. 1) in the steady state ELMy phase, and n_{ped} is the line average density at R = 3.75m. The core energy is then calculated by subtracting the pedestal energy from the total stored energy.

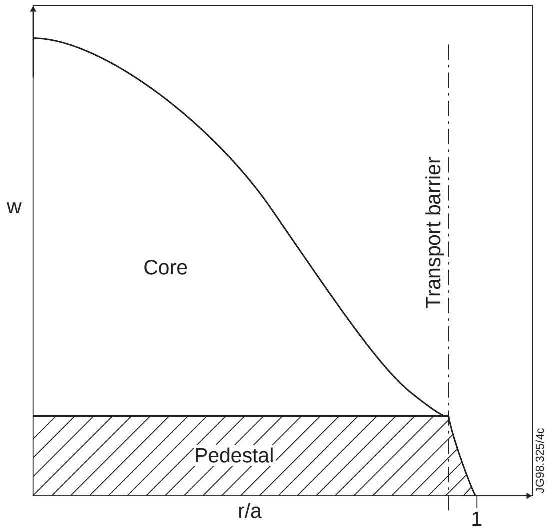

Fig. 3. A schematic representation of the stored energy density versus radius, the shaded region is the stored energy in the pedestal and the unshaded region is the stored energy in the core.

The scaling of the pedestal energy W_{ped} can be obtained from a free fit to the variables I, M, T_{ped}; the free fit can then be constrained to a variety of physical models. The fits and their RMSE are given in Table III. The second fit in Table III is equivalent to the ballooning limit with the gradient width D proportional to the thermal ion Larmor radius. The third fit has D proportional to the fast ion Larmor radius, and the fourth fit has D proportional to the major radius. The main point to emerge from Table III is the fairly strong and positive mass dependence of all of the forms which have a good fit to the data. The best physics fit, the second in Table III, is shown in Fig. 4.

Table III. Scaling of the pedestal energy. The units are W_{ped} (MJ), I (MA) T_{ped} (KeV) respectively.

Type of fit	W_{ped}	RMSE (%)
Free fit	$0.6\, I^{0.81}\left(\frac{M}{2}\right)^{0.63} T_{ped}^{0.74}$	16
Ballooning limit $\Delta \sim \rho_{ith}$	$0.54\, I^2\left[\left(\frac{M}{2} T_{ped}\right)^{1/2} / I\right]$	18
Ballooning limit $\Delta \sim \rho_{ifast}$	$0.14\, I^2\left[\left(\frac{M}{2} E_{fast}\right)^{1/2} / I\right]$	27
Ballooning limit D ~ R	$0.23\, I^2$	41

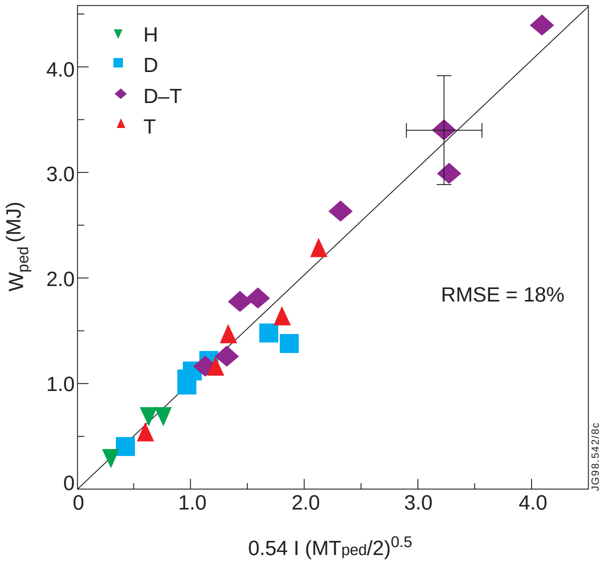

Fig. 4. Scaling of the stored energy in the pedestal (MJ) versus the fit 0.54 I $(MT_{ped}/2)^{0.5}$. The symbols are H=Hydrogen, D=Deuterium, D-T=50:50 D-T mixture and T=Tritium.

For the scaling of the core plasma, the confinement time $\tau_{core} = (W_{th} - W_{ped})/P$ is compared with a pure gyro-Bohm scaling form:

$$\tau_{core} = C\frac{I^{0.8}n^{0.6}R^{2.2}\kappa^{0.5}}{P^{0.6}\left(\frac{M}{2}\right)^{0.2}} \qquad (4)$$

This expression gives a good fit to the complete dataset, as can be seen from Fig. 5.

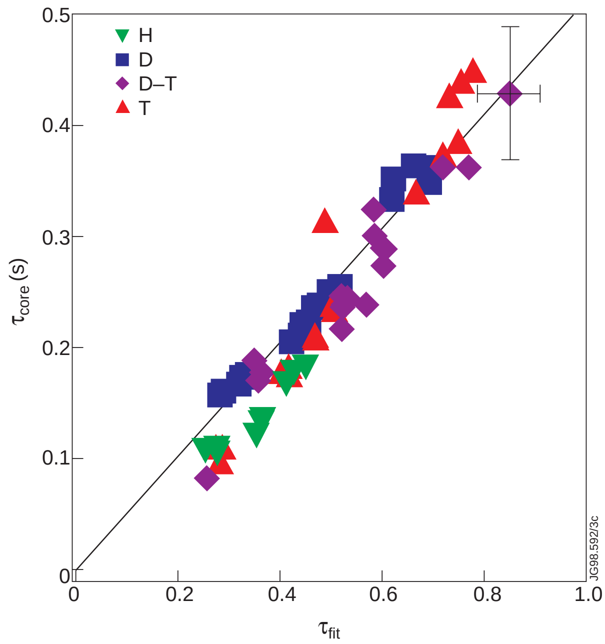

Fig. 5. Core confinement time versus the pure gyro-Bohm fit form Eq. (4). The symbols are the same as for Fig. 4.

From Eq. (4) and the second expression in Table III, an expression can be derived for the global τ_E

$$\tau_{E\,ON} = 0.0185\frac{I^{0.8}n^{0.6}R^{2.2}\kappa^{0.5}}{P^{0.6}\left(\frac{M}{2}\right)^{0.2}} + 0.95\frac{I^2}{nP}\left(\frac{M}{R}\right) \tag{5}$$

where the first term is the core confinement term and the second term the edge confinement, the units are as in Eq. (2). The constants in front of the two terms are obtained by fitting to the complete JET dataset. The above form is of the offset nonlinear type and has some similarity with the form derived by Takizuka[8].

Eq. (5) can be used to predict the performance of ITER. For the basic FDR design parameters, I = 21MA, B = 5.7T, $n = 1 \times 10^{20}$, P = 180MW, κ = 1.73, R = 8.14m, a = 2.8m, Eq. (5) predicts a confinement time of 4.8 secs. The equivalent prediction from the simple power law form Eq. (2) is 5.8 secs. The reason for the lower prediction is due to the fact that the contribution from the pedestal becomes very small in ITER.

One other interesting feature of Eq. (5) is its dimensionless physics form, which can be expressed in terms of the average $<\rho^*>$ and normalised βn as:

$$\omega_c\tau_E \propto <\rho^*>^{-3}\left(1 + c<\rho^{*2}>/\beta^2\right) \tag{6}$$

where the first term is the gyro-Bohm core transport term and the second term is from the pedestal. From Eq. (6) we can see that for fixed ρ^* the confinement time degrades with β_n. This degradation of τ_E with β_n has always been a feature of the simple power law forms [9] and we now see that the origin of this degradation is from the pedestal.

IV. IDENTITY PULSES WITH DIFFERENT ISOTOPES

If the plasma confinement is not explicitly dependent on the isotope mass as suggested by Eq. (6), then it should be possible to create pulses with the same radial profiles of ρ^*, ν^* and β for the different isotopes. To match the ρ^* and β in the edge region it was found that strong gas puffing was needed for the high mass isotope pulses. The strong gas puffing increasing the ELM frequency and reducing the β of the pedestal. The best match obtained so far was a Hydrogen pulse at 1.7T matched to a strongly gas puffed Deuterium pulse at 2.6T. The main parameters of the two pulses are given in table IV, where it can be seen that the dimensionless confinement times $B\tau_E/M$ are reasonably well matched and the dimensionless ELM frequencies are close also. The profiles of ρ^*, β and ν^* are also well matched as can be seen from Fig. 6, as are the dimensionless thermal conductivities Fig. 7.

Note if one compares the hydrogen pulse with a non gas-puffed Deuterium pulse having the same average ρ^*, normalised β and average collisionality, the dimensionless confinement times would differ by a factor of 2 and the dimensionless ELM frequencies by a factor of 10.

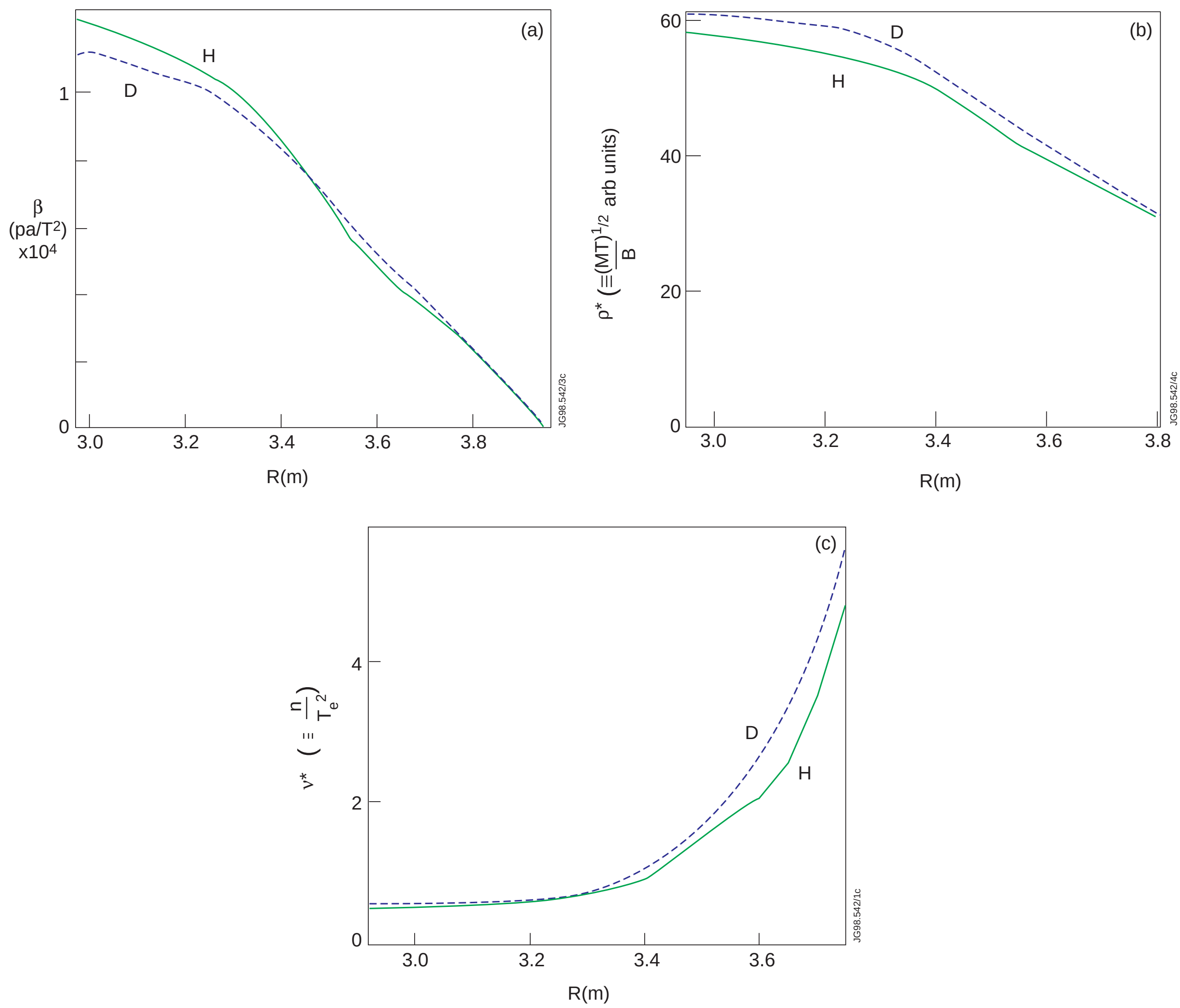

Fig. 6. (a) Radial profile of β versus major radius for the H (solid) and D (dashed) pulses. (b) Radial profile of ρ versus major radius for the H (solid) and D (dashed) pulses. (c) Radial profile of ν* versus major radius for the H (solid) and D (dashed) pulses.*

Table IV

#	Isotope	B(T)	<ρ*>	βn	<ν*>	$\frac{B\tau_\varepsilon}{M}$	$\frac{M f_{elm}}{B}$
43403	H	1.69	**0.45**	**1.43**	**11**	**0.44**	**24**
43153	D	2.58	0.46	1.31	13	0.47	35

This is because the profiles of β and ρ* are not propertly matched, with both β and ρ* being larger in the edge region for the Deuterium pulse.

Thus it appears that identity pulses can be obtained with different isotopes provided the profiles of ρ*, β and ν* are matched throughout the radius. This result suggests that there is no need for any explicit mass dependence in the scaling of the transport in either the core or edge regions.

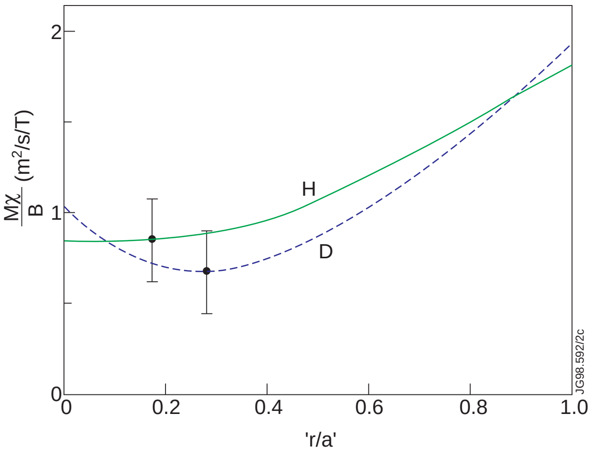

Fig. 7. The normalised effective conductivity Mχ/B versus the radial variable ‘r/a’.

REFERENCES

[1] Righi, E., et al. “Isotope Scaling of the H-mode Power Threshold in Plasmas in JET”. Accepted for publication in Nucl. Fusion.

[2] Cordey, J.G., et al., “Plasma Confinement in JET H-mode Plasmas with H, D, D-T and T isotopes”. Accepted for publication Nucl. Fusion.

[3] Christiansen, J.P., et al., Nucl. Fusion **31** (1991) 2117.

[4] Bartlett, D.V., et al., Proc. 9th Int. Workshop on ECE and ECRH, Borrego Springs, U.S.A. (1995).

[5] Righi, E., et al., “Dedicated ITER H-mode Power Threshold Experiments with the Mk1 Pumped Divertor”, JET-P(97)18, submitted to Plasma Physics and Controlled Fusion.

[6] Pogutse, O., et al., 24th EPS Conference on Controlled Fusion and Plasma Physics, Bertchesgaden (1997), III p1041.

[7] ITER Confinement Database and Modelling Working Group, presented by J.G. Cordey, Energy Confinement Scaling and the Extrapolation to ITER, Plasmas Phys. Control. Fusion **39** (1997) B115-B127.

[8] Takizuka, T., An Offset Non-linear Scaling for ELMy H-mode Energy Confinement, Plasmas Phys. Control. Fusion (Proc. 6th H-mode Workshop Gut Ising, 1997) (to appear).

[9] Valovic, M., et al., EPS, Prague (1998).