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Scaling of confinement in the ITPA L-mode database with dimensionless variables

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Introduction

The International Tokamak Physics Activity (ITPA) L-mode database has been augmented with several new contributions since the previous release of an L-mode scaling expression [1]. Among the issues that this database allows us to address, the scaling of the energy confinement time with dimensionless parameters (ρ^*, β, ν^*) is of physical importance and of some interest for extrapolation to Next Step machines. Recently, this scaling has been revisited for the H-mode regime, following dimensionless scaling experiments on JET and DIII-D which showed a weak impact of β on the confinement, in contrast to the strong β degradation featured by the IPB98(y, 2) scaling expression [2]. It has been found that including the errors on the experimental measurement in the analysis could change the β-dependence of the scaling expression: the exponent of the β-dependence can be reduced down to a negligible value, while at the same time a degradation with the effective collisionality ν^* appears [3]. In this work, the same statistical methods are applied to the new version of the L-mode database, in order to investigate the possible changes on the β-dependence of the L-mode scaling expression.

Description of the L-mode data base

The L-mode database DB3v1 used in this paper features now about 3000 L-mode entries, including recent contributions from HL-1M, NSTX and JET. The different variables used in the analysis are:

W_{th}	The thermal stored energy (MJ)	n	the central line average density (10^{19} m^{-3})
P	the loss power (MW)	I	the current (MA)
R	the major radius (m)	B	the toroidal field (T)
a	the minor radius (m)	M	the isotope mass
A	the cross sectional area (m^2)	τ_{th}	the thermal energy confinement time

The selection criteria are standard L-mode only (no improved confinement discharge), hydrogenic discharges only, semi-stationary, $0.4 \leq T_{i0}/T_{e0} \leq 2.5$ and $0.5 < li \leq 2$. Then, the number of observations by tokamak and their relative weights, deduced by $w_j \sim (2 + N^{½}/4)^{-1}$, are:

	N_j	w_j
ASDEX	237	*0.17*
CMOD	225	*0.17*
D3D	124	*0.21*
FTU	6	*0.38*
HL-1M	4	*0.40*
JET	714	*0.12*

	N_j	w_j
JFT2M	127	*0.21*
JT60	174	*0.19*
NSTX	8	*0.37*
PDX	32	*0.29*
RTP	10	*0.36*
T10	28	*0.30*

	N_j	w_j
TdeV	7	*0.38*
TEXTOR	81	*0.24*
TFTR	400	*0.14*
TSUPRA	75	*0.24*
Total	2252	

Scaling laws of confinement

In this configuration, the standard log-linear method gives the scaling law of confinement below:

$$\tau_E = 0.016\ I^{0.84} B^{0.12} R^{1.55} n^{0.46} a^{-0.83} A^{0.63} M^{0.21} P^{-0.76}$$

Then, for non-dimensional parameters, the law becomes:

$$\omega_c \tau_E \propto \beta^{-1.55} \rho*^{-1.84}\ \nu*^{0.38}$$

This scaling law is similar to the ITERL-97P one [1]:

$$\tau_E = 0.011\ I^{0.96} B^{0.03} R^{1.77} n^{0.40} a^{-1.22} A^{0.64} M^{0.20} P^{-0.73} \qquad \omega_c \tau_E \propto \beta^{-1.39} \rho*^{-1.98}\ \nu*^{0.19}$$

- **Error in Variable**

The error in variable technique (EIV), introduced to plasma physics in Kardaun et al. [4] and subsequently in Cordey et al. [3] weightens measurements with their average errors given in the above table:

	δR	δa	δA	δB	δI	δn	δM	δP	δW_{th}
Average error	1.3%	2.9%	4.7%	1.5%	1.3%	5.0%	8.4%	14.2%	14.1%

For the same assumptions on the data errorbars as used for the H-mode DB analysis, the original β-degradation of the energy confinement time is reduced to -0.77 while the ν*-dependence is almost null and the ρ* one is nearly constant (Bohm scaling). This result is qualitatively similar to what has been obtained for the H mode DB, i.e. the EIV method provides a reduction of the α_β exponent and simultaneously decreases the ν* exponent.

$$\tau_E = 0.0041\ I^{0.73} B^{0.16} R^{1.97} n^{0.43} a^{-2.18} A^{1.14} M^{0.39} P^{-0.66} \qquad \omega_c \tau_E \propto \beta^{-0.77} \rho*^{-2.07}\ \nu*^{0.08}$$

The results of the EIV method depend on the set of estimated errors, as shown in figure 1. To entirely eliminate the β-degradation, the estimated loss power error must be increased and/or the estimated stored energy error decreased. For $\delta P = 28.8\%$ and $\delta W_{th} = 11\%$, we obtain:

$$\tau_E = 0.0020\ I^{0.64} B^{0.07} R^{2.12} n^{0.29} a^{-3.00} A^{1.35} M^{0.62} P^{-0.41} \qquad \omega_c \tau_E \propto \beta^{-0.00} \rho*^{-2.20}\ \nu*^{-0.87}$$

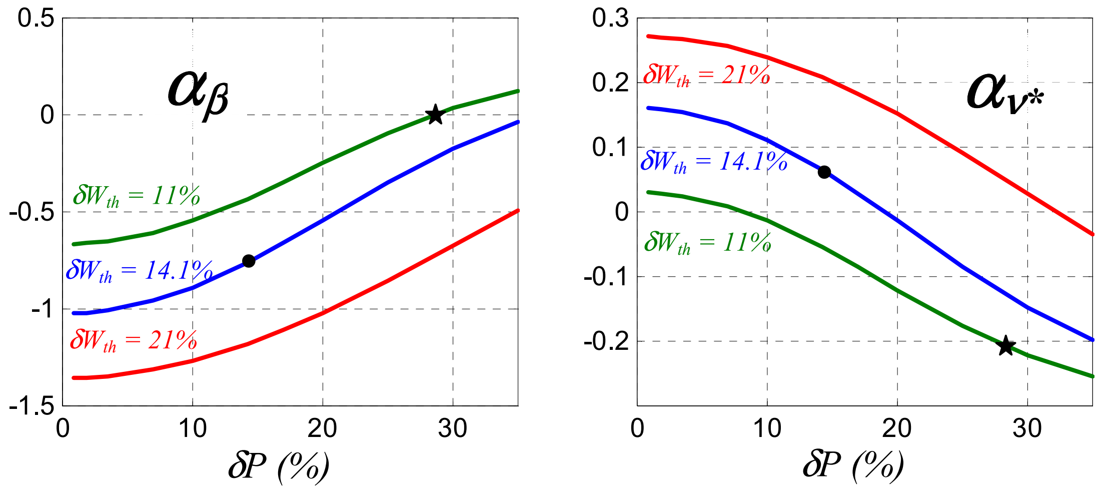

Fig. 1 – The exponents of β and ν versus the estimated error on the loss power δP for different values of the uncertainty on the thermal energy δW_{th}. The stars indicate a possible couple (δP, δWth) that gives zero β-dependence; the dots correspond to the error dataset used for the H-mode DB analysis.*

- **Sensitivity of the β exponent**

The form of the scaling is $\tau_E = C\, I^{\alpha_I} B^{\alpha_B} R^{\alpha_R} n^{\alpha_n} a^{\alpha_a} A^{\alpha_A} M^{\alpha_M} P^{\alpha_P}$ and $\omega_c \tau_E \propto \beta^{\alpha_\beta} \rho^{*\alpha_{\rho*}} \nu^{*\alpha_{\nu*}}$; the relations between the engineer exponents and the non-dimensional exponents can be written:

$$\alpha_\beta = \frac{7\alpha_P + \alpha_I + \alpha_B + 1 + 4\alpha_n}{4(1+\alpha_P)} \qquad \alpha_\rho = -\frac{9\alpha_P + 3(\alpha_I + \alpha_B + 1) + 4\alpha_n}{2(1+\alpha_P)} \qquad \alpha_\nu = -\frac{3\alpha_P + \alpha_I + \alpha_B + 1}{4(1+\alpha_P)}$$

From these expressions, we can deduce that α_β is very sensitive to α_P especially when this one is close to –1. For exponents in the range of the L-mode scaling law ($\alpha_P \sim -0.7$), a variation of 0.01 on α_P induces an approximate variation of 0.1 on α_β!

Application to ITER configuration

Table beside shows the confinement time for different scaling laws when the loss power is equal to 28 MW (corresponding to an additional power of 32 MW which is just below the transition limit $P_{L\text{-}H}$ calculated with $B = 5.3$T, $n = 5.10^{19}$m^{-3}, R = 6.2m, a = 2m, M = 2.5 $I = 5$ MA, $A = 22$ m^2).

	τ_E	β_N
ITERL-97P	2.82	0.44
Log-linear	2.42	0.39
EIV	3.24	0.51

Discussion

The high sensitivity of the α_β exponent to the value of α_P explains why α_β can be significantly reduced by applying the EIV method. Nevertheless, even with the EIV method, a quite large value of δP and simultaneously a somewhat reduced value of δW_{th} have to be chosen in order to eliminate completely the β-degradation. Therefore the standard L mode dataset suggests that a β-degradation has still to be expected in L mode.
This result is in contrast to the H mode database, where using the EIV method with a realistic set of assumed errors is able to eliminate entirely the β-degradation.

The large variation of α_β and α_ν as a function of the error in P has only a limited influence on the prediction for ITER FEAT, see [3].

The β-degradation remains even if the high β shots are removed from the scaling. Therefore, the β-degradation of the global dataset is not due to a change of the physics at high β. Likely L-mode discharges do not have high enough pressure to get close to ballooning stability limits.

Since there seem to be significant a scatter of the predicted τ_E, scaling with respect to the measured value at high τ_E (in particular JET and TFTR data), we have applied log-linear regression independently to JET and to TFTR data. The two machines have enough entries in the database so that the regression is statistically relevant, once having removed the geometry scale parameters R, a and A. The result of these specific device regressions gives also reduced β-degradation with respect to the one obtained for the whole dataset (-0.5 for JET and -0.8 for TFTR). These values are of the same order than what is given by the EIV method for the whole database using the standard error set.

Dedicated L-mode β scaling experiments on various tokamaks yielded quite contrasted results on the β-degradation: DIII-D found $\alpha_\beta \sim 0$ [5], TFTR ~ -0.5 [6], while Tore Supra indicated a much larger β-degradation $\alpha_\beta \sim -1.3$ [7]. Further experiments are needed in the various tokamaks in order to clarify this issue of β-degradation. Indeed, a clear guidance from experiments is needed in order to optimize the statistical treatment to apply to the global database.

τ_E, standard log-linear scaling

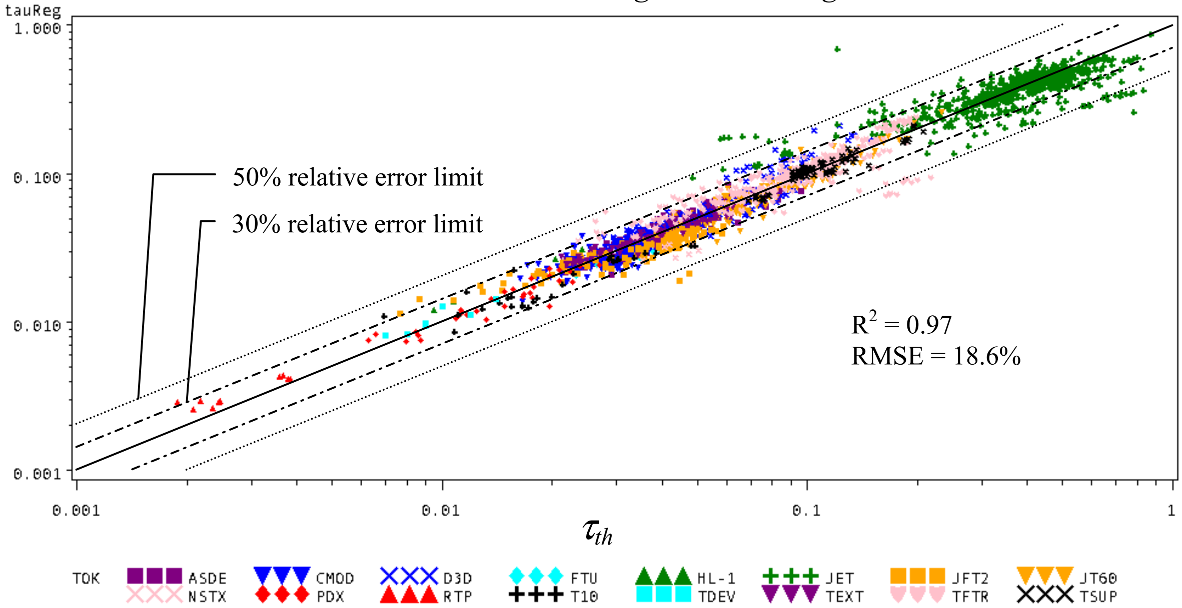

Fig. 2 - τ_E scaling for log-linear regression vs. estimated τ_{th}.

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