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ENERGY CONFINEMENT SCALING AND THE EXTRAPOLATION TO ITER

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By the **ITER Confinement Database and Modelling Working Group***

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Abstract

The fusion performance of ITER is predicted using three different techniques; statistical analysis of the global energy confinement data, a dimensionless physics parameter similarity method and the full 1-D modelling of the plasma profiles. Although the three methods give overlapping predictions for the performance of ITER, the confidence interval of all of the techniques is still quite wide.

1. Introduction

In the last few years there has been considerable progress in the understanding of the transport processes taking place in a tokamak. In the theoretical area large codes have been developed which simulate the turbulence and ensuing radial transport. The main source of turbulence is thought to be due to the ion temperature gradient instability and as we shall see in Section IV there has been some success in comparing theoretical models which contain this type of turbulence with the data (1). However at the present time a complete and fully validated 1-D model describing the transport throughout the radial region is not yet available.

Thus to predict the performance of ITER three different techniques are currently being used; a) the global energy confinement scaling method; b) the dimensionless physics parameter similarity technique; and c) the full 1-D modelling of the plasma profiles. The latest results from each of the techniques will be briefly reviewed in this paper.

Each of the techniques has its own strengths and weaknesses. The main strengths of the global energy confinement scaling are its simplicity and the fact that all the physical processes are contained within the data. Its main weakness is that the modelling of the energy confinement time τ_{th} by a simple log-linear form, or even by more sophisticated forms, can only, at best, be a very approximate description of the physical processes taking place, since no knowledge of the heating, temperature or density profiles or atomic physics processes for that matter, are built into the analysis. Nevertheless this technique has a good track record (2) and as will be shown in section II the addition of data from new machines ASDEX-U, C-MOD, COMPASS-D, JT-60U and TCV as well as new data from DIII-D and JET has improved the condition of the database from that used to derive the scalings ITERH93-P(3) AND ITERH92-P(Y)(7) etc.

The lack of profile information in the global energy confinement time approach can be overcome by extrapolating the profile data using the dimensionless parameter similarity technique. In this approach discharges which have similar dimensionless parameters to those of ITER are set-up. In principle it is possible to keep all of the key physics dimensionless parameters such as β, ν^*, q etc. fixed at their ITER values apart from the dimensionless Larmor radius ρ^* ($\equiv \rho_i/a$). The ρ^* dependence of the confinement is then determined by scaling experiments in which β and ν^* are kept fixed. These experiments have been completed on several devices (4-6). For ELMy H-modes it has been found in DIII-D (4) and JET (5) that both the global and local confinement is close to gyro-Bohm ($B\tau_{th} \propto \rho^{*-3}$) and also in ASDEX-U (6) the local confinement has been shown to be gyro-Bohm.

Using this information the temperature profiles in ITER can then be obtained from those of present experiments by a simple linear scaling and the power to achieve these profiles can also be obtained in a simple fashion as will be shown in section III. However the error in the estimate of the power requirements is quite large when scaling up from a single machine and it will be necessary to form a database using data from different size machines to obtain an accurate estimate of the fusion performance of ITER using this technique.

DISCLAIMER

The main strength of the 1-D modelling approach is that in principle all of the transport processes and all of the sources and sinks could be included in the model. The present weakness is that, although significant progress has been made in modelling the transport in the plasma core, we still do not have a good validated edge model, and as will be shown in section IV, the prediction of the performance of ITER is extremely sensitive to the edge conditions for some of the models. In particular, those models that have very strong profile stiffness lead to a very pessimistic ITER prediction if the predicted edge pedestal temperature is low.

II. Analysis of the global confinement H-mode data

As mentioned in the introduction substantial additions have been made to both the ELMy and ELM-free database DB2 $^{(7-8)}$ in the last year. Five new machines have contributed data; ASDEX-U, C-MOD, COMPASS-D, JT60-U and TCV, and DIII-D and JET have submitted additional pulses. A standard data sub-set has been assembled which consists of the same subset that was taken from DB2 $^{(7)}$ plus a new subset which includes other forms of heating; ICRH and ECRH as well as NBI. In addition the ohmic H-mode data from COMPASS-D (ELMy and ELM-free) and TCV (ELM-free) was also included in an effort to improve the condition of the standard dataset. The new dataset consists of 1112 ELM-free discharges and 1190 ELMy discharges which is roughly a 50% increase in the total number of data points over the DB2 database.

The condition of both the ELM-free and the ELMy database is significantly better than DB2. The two weakest principal components have a very similar form to those of DB2

$$PC_7 \sim Bn/R\kappa^2$$

$$PC_8 \sim aB/I$$

The number of standard deviations to ITER of the most important one (PC_7), has been reduced from 8 to 4 though. The main reason for this reduction is due to the introduction of the C-MOD data which has a high B/R compared to the other tokamaks in the database. The weakest PC_8 has a q like dependence and is not so important since the data base includes some data at the ITER value of q. In terms of the physical variables ρ^* and β the new devices C-MOD, ASDEX-U and TCV have filled in the gap between JET and DIII-D and the smaller devices. This can be seen in Fig. 1, where the full database for the ELM free and ELMy data is shown in ρ^*, β space.

The conventional log-linear fits to the ELM-free and ELMy data sets are as follows;

$$\tau_{th} = 0.031\ I^{0.95}\ B^{0.25}\ P^{-0.67}\ n^{0.35}\ R^{1.92}\ \varepsilon^{0.08}\ \kappa^{0.63}\ M^{0.42} \qquad (1)$$

for the ELM-free data set with an RMSE of 16%;

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

for the ELMy with an RMSE of 15%.

Both of these forms satisfy the high β Kadomtsev constraint and writing them in terms of the dimensionless physics parameters, they have the form:

$$B\tau_{th} \propto \rho^{*-2.94}\ \beta^{-0.87}\ \nu^{*-0.13} \qquad \text{ELM}-\text{free} \qquad (3)$$

$$B\tau_{th} \propto \rho^{*-2.88}\ \beta^{-0.69}\ \nu^{*-0.08} \qquad \text{ELMy} \qquad (4)$$

The ELM-free fit is similar to ITERH93-P and, as can be seen in Table 1, the ITER prediction is very close to that of ITERH93-P. The only difference is the slightly weaker β dependence. The DB2 ELMy fit ITERH92-P(y) did not satisfy the Kadomtsev constraint. The fact that the ELMy fit now satisfies the constraint is due to the inclusion of the C-MOD data. The ELMy fit is shown in Fig. 2.

In deriving the fits of equations (1) - (4) each point in the database has equal weight. However, there are only a small number of points from COMPASS-D and JT-60U, so to strengthen up the contribution from these, a fit is completed in which each tokamak is weighted equally. This fit, which is for the ELMy dataset, is presented in its engineering and physics forms in equations (5) and (6), respectively.

$$\tau_{th} = 0.029\ I^{0.99}\ B^{-0.06}\ P^{-0.69}\ n^{0.61}\ R^{2.11}\ \varepsilon^{0.22}\ \kappa^{0.7}\ M^{0.11} \qquad (5)$$

$$\beta\tau_{th} \propto \rho^{*-3.21}\ \beta^{-0.41}\ \nu^{*0.13} \qquad (6)$$

This tokamak weighted form is very similar to that of equations (3) and (4) and, as can be seen in Table 1, the ITER prediction is also very similar.

Several other log-linear regressions have been completed using different data selections and normalisations. The main ones that reduce the ITER confinement predictions are 1) omission of the COMPASS-D ELMy data, this reduces the τ_ε by 0.4s 2) changing the normalisation of the PDX data from the TAUC93[3] correction used in this paper to the earlier TAUC92[7] correction reduces τ_ε by 0.7s. The addition of auxiliary heated data from COMPASS-D could assist in resolving the PDX data normalisation problem.

We now turn to the error in the ITER prediction and the results of other models, an expression for the 95% confidence interval for a log-linear form is [8]

$$\frac{\delta\tau}{\tau} = \frac{2\sigma}{\sqrt{N_{eff}}}\left(1+\sum_{\delta=1}^{n}\frac{\lambda_{ITERj}^2}{\lambda_{pcj}^2}\right)^{1/2} \tag{7}$$

where λ_{pcj} is the standard deviation of the jth principal component and λ_{ITERj} is the distance from the centre of the database to ITER in the direction of the jth principal component. N_{eff} is the number of independent data points and, as in the past, we assume N_{eff} ~ N/4 where N is the total number of data points and the factor of 4 accounts for correlations between data points, such as those taken during the same pulse.

Table I

ITER parameters are R=8.14m, a=2.8m, κ=1.73, B=5.68T, I=21MA, n=9.7×10^{19} m^{-3}, M_{eff}=2.5 and P_{loss}=180MW.				
Type of model and reference	Principal Authors and reference	Database used	RMSE %	ITER τ_{th} (s)
log-linear	This paper	DB3 ELM-free*	16.0	6.0
log-linear	This paper	DB3 ELMy	15.0	5.8
log-linear Tokamak Equal Weighting	This paper	DB3 ELMy	16.1	6.2
log-linear	ITERH93-P[3] ITERH-92P(y)[7]	DB2 ELM-free* DB2 ELMy	12.3 14.3	6.0 5.7
offset-linear	O. Kardaun (14)	DB2 ELM-free*	11.0	8.0
log-nonlinear	W. Dorland and M. Kotchenreuther (15)	DB2 ELM-free*	11.4	4.3

offset-nonlinear	T. Takizuka (16)	DB2 + JT-60U		4.7
Near Neoclassical	J.P. Christiansen(13)	DB2 ELMy		8.8

* multiplied by 0.85 to account for ELMS.

Expression (7) is only valid if all the major influences on τ_{th} are included in the regression.

For the data selection used in deriving equations (1) - (4) it is found that $\delta\tau/\tau = \pm 17\%$ for the ELMy dataset and ±18% for the ELM-free data set. These values are smaller than those obtained from DB2 (~29%) and this is due to the increased number of data points and the improved condition of DB3 with respect to the ITER extrapolation.

Several non log-linear models have also been fitted to the previous database DB2 and the ITER predictions for these models are listed in Table I, along with those from the log-linear models of this section. From the table, one can see that there is quite a range in the predicted performance of ITER. In view of this wide range; the group recommends ITER to consider contingency scenarios based on a confinement time interval of ± 45% about the point prediction from expression (2) (τ_{th} = 5.8 secs). In view of the improved condition of DB3 it may be possible to reduce this range; however, until the differences between the various scalings have been understood and a full statistical analysis has been completed it is prudent to keep the same interval.

The consequences for the fusion performance of ITER of the two intervals are shown in Fig. 3. For the narrow interval of the log-linear forms ITER would ignite, but with the wider region at the low confinement end the performance drops to Q of 5, which illustrates the importance of determining more precisely the confidence interval.

III. Dimensionless Physics Parameter Similarity Approach

The theoretical basis of this technique is described in the review by Cordey (10). The basic idea is to set up discharges with the same shape as ITER in which as many of the dimensionless physics profiles such as those of β, ν^*, q, κ, ε are kept at their ITER values. An example of such a discharge in the JET tokamak is shown in Figs. 4 and 5. This particular discharge is at a field of 1.7T and current of 1.7MA has the same β_n (β_n = 2.5) and the same collisionality as the ignited ITER.

The only dimensionless physics parameter that cannot be fixed at its ITER value in present experiments is the dimensionless Larmor radius ρ^* ($\equiv\rho_i/a$). This parameter is a factor 3.5 larger in JET than ITER and a factor 7 larger in DIII-D. Thus we need to determine the scaling of the confinement with the parameter ρ*. The first experiments on the ρ* scaling of ELMy H-modes were completed on DIII-D (4), where the confinement, both globally and locally, was found to have a gyro-Bohm scaling ($B\tau_{th} \propto \rho^{*-3}$). Similar experiments on JET (5,11) were completed at 1MA/1T and 2MA/2T and these also showed a close to gyro-Bohm scaling ($B\tau_{th} \propto \rho^{*-2.7}$). The range of ρ* in the JET experiments has recently been extended to 3MA/3T and the close to gyro-Bohm scaling is maintained.

Experiments in both JET and DIII-D on the scaling of confinement with the other dimensionless parameters β and ν* were reported recently (11,12). The scaling of $B\tau_{th}$ with ν* and β was found to be very weak. The weak scaling with β is in contradiction to the global database scaling studies of equations (3) and (4) and the original ITERH93-P scaling which had a very strong β scaling, $B\tau_{th} \propto \beta^{-1.2}$. This discrepancy is under active investigation by the group and possible reasons for it are discussed in Christiansen et al. (13). Forcing the fit to the ELMy data set DB2 to be gyro-Bohm and independent of β gives a scaling of the form $B\tau_{th} \propto \rho^{*-3} \nu^{*-0.2}$, and an energy confinement time, which is given at the end of Table I, of 8.8 secs.

We now turn to the prediction of the performance of ITER using this technique and the errors in the prediction. For a pulse which has the same β and ν* the dimensionless Larmor radius ρ* scales as $B^{-2/3}\ a^{-5/6}$. If we then express the confinement scaling in the form:

$$B\tau_{\varepsilon} \propto \rho^{*-\alpha} \equiv \left(B^{2/3}\ a^{5/6}\right)^{\alpha} \qquad (8)$$

α = 3 for gyro-Bohm, α = 2 for Bohm and α =1 for stochastic transport.

Using equation (8) and the confinement time of the ITER demonstration pulses in DIII-D (4) and JET (11), one can calculate the confinement time in ITER, assuming an H-mode like discharge is obtained, using the value of α derived from the scaling studies in each experiment. The results are given in Table II.

Table II

Tokamak	βn	ρ^*/ρ^*_{ITER}	α	$\delta\alpha$	τ_{th} ITER	$\delta\tau$ (s)
DIII-D	2.1	7.7	3.1	± 0.3	28	±18
JET	2.2	5.5	2.7	± 0.22	6.4	± 3

The errors in $\delta\tau$ are assumed to come entirely from the errors in the determination of the parameter α in the ρ^* scaling experiments. For a standard error of ± 15% (2σ) in the stored energy, the error in the parameter α will be $\delta\alpha = \pm\ 0.3$ for DIII-D and $\delta\alpha = \pm\ 0.22$ for JET. The reason that the errors are so large is due to the fact that the range in ρ^* is very small in the experiments (DIII-D; $\rho^*_{1T}/\rho^*_{2T} = 1.6$ and JET; $\rho^*_{1T}/\rho^*_{2T} = 1.9$).

To reduce the error in the prediction of the confinement it will be necessary to complete a joint ρ^* scan on at least two machines of different sizes to increase the range of ρ^*. Ideally the joint scan would contain an identity pulse in which all of the dimensionless physics parameters ρ^*, ν^*, β are identical. Such pairs of discharges have been developed jointly by DIII-D and JET [(12)] at lower values of β than that of ITER. It was found that the confinement times in the two machines did vary inversely with field as expected from theory and the scaled effective thermal diffusivities also matched. This does not imply that the three dimensionless parameters ρ^*, ν^* and β are all that is required to describe the confinement behaviour of ELMy H-modes. Further identity experiments need to be completed between other pairs of experiments to investigate this question.

Several theoretical papers have proposed that the turbulence in a tokamak can be quenched by shear in the toroidal flow. This implies that the Mach number $M \equiv V_\phi/V_e$ is an important dimensionless parameter. This is certainly not being kept constant in the ρ^* scaling experiments completed so far, which use neutral beam injection heating. Clearly experiments in which the Mach number is varied whilst ρ^*, β and ν^* are kept fixed are required. There are several possibilities here; co versus counter and balanced injection NBI, comparisons of NBI and ICRH, and the breaking of the toroidal rotation by toroidal field ripple. Although work is proceeding in all these areas a clear conclusion has yet too emerge.

IV. The 1-D modelling approach

Work has continued on the systematic testing of the eleven 1-D models listed in Table III against the data in the profile database using the systematic testing procedure described in Connor et al (1). The profile database has now also been extended to include fully documented discharges from 9 tokamaks: DIII-D, JET, TFTR, JT-60U, ASDEX-U, T-10, TEXTOR, TORE SUPRA and RTP.

The different transport codes used by the modellers are being benchmarked against each other. This benchmarking process is almost completed among the subset of transport codes that only evolve the electron and ion temperatures, as seen in Fig.6. Here three different codes from this subset using the IFS/PPPL model give approximately the same prediction of the ion and electron temperature profiles for a JET pulse.

Table III

Model	Modeller	Physics
Turner	M. Turner (EU), S. Attenberger (US)	Semi-empirical
Turner-IFS/PPPL	M. Turner (EU), S. Attenberger (US)	Semi-empirical
Itoh	A. Fukuyama (JAP), S. Attenberger (US), D Mikkelsen (US), R. Waltz (US)	Current Diffusive Ballooning Modes
T11/SET	A. Polevoi (RF)	Semi-Empirical
RLW B	D. Mikkelsen (US), D. Boucher (JCT)	Semi-Empirical
Waltz	R. Waltz (US)	ITG
mixed Bohm gyro-Bohm	A. Taroni (EU)	Semi-Empirical
mixed-shear	G. Vlad/M. Marinucci (EU)	Semi-Empirical
IFS/PPPL	M. Turner (EU), S. Attenberger (US), B. Dorland (US), D. Mikkelsen (US), R. Waltz (US).	ITG
Weiland	J. Weiland (EU), D. Mikkelsen (US), R. Waltz (US)	ITG

Multi-	J. Kinsey et al (US)	Weiland + Resistive Ballooning

Some transport models have also evolved in the last year; E×B flow has been added to both to the IFS/PPPL model and the GLF23 model of R. Waltz. The addition of E×B flow appears to improve the fit to the data for the GLF23 model but not the IFS/PPPL model, at least for the sub set of mainly H-mode discharges considered in this paper. For most L- and H-mode discharges ExB effects are less than a 20% effect on the temperature profiles; however, the effect is quite dramatic for NCS and ERS discharges as demonstrated for the DIII-D NCS shot #84736 (t=1.3 secs) shown in Fig.7.

In the limited space available in this paper it is only possible to present a small fraction of the results and summarise the general trends. A number of tests of each model against the ion and electron temperature profile data have been carried out and an example of one of these tests for four of the models is shown in Fig.8. Here the offset in the stored energy $W_{simulation}/W_{exp}$ - 1 is shown for a selection of 46 pulses from the database containing both L-modes and H-modes. The goodness of fit is tabulated in Table IV.

Table IV

	$<R_W>$	ΔR_W	$<R_{Winc}>$	ΔR_{Winc}
Multi-mode	0.96	0.15	0.94	0.23
IFS-PPPL	0.94	0.22	0.90	0.35
IIF (recalibrated)	0.97	0.24	0.92	0.38
GLF23 (+ w/ExB)	1.05	0.27	1.10	0.43
IFS-PPPL (w/ExB)	1.20	0.37	1.35	0.64

	σT_e	σT_i	$<fT_e>$	$<fT_i>$
Multi-mode	0.17	0.22	-0.05	0.01
IFS-PPPL	0.28	0.26	-0.04	–0.07
IIF (recalibrated)	0.25	0.39	-0.05	–0.02
GLF23 (+ w/ExB)	0.32	0.34	0.02	0.03
IFS-PPPL (w/ExB)	0.53	0.34	0.17	0.08

$\langle R_W \rangle = \sum_i (W_{si} / W_{xi}) / N$ (average); $\Delta R_W = \sqrt{\sum_i (W_{si} / W_{xi} - 1)^2 / N}$ (average error);

$f_T = \sum_i (T_s - T_x) / \sqrt{\sum_i T_x^2}$ (offset); $\sigma_T = \sqrt{\sum_i (T_s - T_x)^2} / \sqrt{\sum_i T_x^2}$ (rms error);

W_{inc} is the incremental stored energy W-$W_{pedestal}$.

On the basis of these tests it would appear that the Multi-mode model performs best of the four, independent of which figure of merit is chosen: ΔR_W, σ_{Te} etc. However the results are not decisive in indicating a best model since most models are able to match the stored energy to within 20-30%, and it is possible that uncertainties in the experimental inputs could generate discrepancies of this magnitude. What is required is clearly more stringent tests such as the response of the models to localised perturbations produced by pellets or highly localised heating sources such as ICRH or ECRH.

A further difficulty with using these models in ITER predictions is that a model of the plasma edge pedestal is required since they only deal with the region $0.2 < r/a < 0.9$. In fact in comparing the results of these models with the global energy confinement approach, it is the quantity ΔR_{Winc} which ranges from 23-64% that should be compared with the RMSE of 11-16% of the simple Log-linear scalings of section II. Although it is not quite as simple as this, since knowledge of the type of pulse L or H is built into the log-linear scalings.

Turning to the prediction of the fusion performance of ITER using these 1-D models in Fig.9 the fusion power output for each model is given. These models cover a very wide range with the most optimistic being the Itoh-Itoh-Fukuyama model, which ignites whatever the edge temperature (at r/a = 0.9), down to the IFS/PPPL model which has only Q=1 for a pessimistic 1KeV edge temperature. The strong sensitivity of the performance of the IFS/PPPL and GLF23 models to the edge temperature is due to the stiff nature of these models, and as mentioned earlier, experimental tests of this profile stiffness are urgently needed.

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Figure aptions

Fig. 1. ersus β_n for the combined ELM free and ELMy datasets.

Fig. 2. rsus the scaling expression of Eq. (2) for the ELMy dataset.

Fig. 3. nction of the fusion power versus HH factor (τ_{th}/τ_{th} scaling (Eq. 2)). The ses are for n = $n_{Greenwald}$, solid squares and n = n_{free}, open squares. The line is the ignited range.

Fig. 4. development of the JET ITER similarity pulse 38409. Stored energy, me average density, D^α, neutral beam power versus time. On the l.h.s. ET values are given on the rhs are the projected ITER values.

Fig. 5a. on and ion temperature versus radius for #38409. On the l.h.s. the JET es are given on the r.h.s. are the projected ITER values.

Fig. 5b. ron density versus radius for #38409. On the l.h.s. the JET values are n on the r.h.s. are the projected ITER values.

Fig. 6. parison of the electron and ion temperature profiles produced by three ent codes (the Boucher SMC, Dorland NT. Kinsey MLT codes) using FS/PPPL model with ExB shear flow and the experimental data from ulse 19649.

Fig. 7 effect of the introduction of ExB shear flow in the GLF23 model on the on and ion temperature profiles. The pulse is a DIII-D negative central discharge.

Fig. 8. Offset in the total stored energy between the prediction of a model and the experimental data for a subset of 46 pulses. Four models are shown: GLF23 with ExB shear flow, IFS/PPPL without ExB shear flow, the Multi-mode model and the recalibrated Itoh-Itoh-Fukuyama model.

Fig. 9. Variation of the fusion power versus the HH factor defined in terms of the ITERH93-P scaling expression for several different 1-D models with different edge temperatures.