27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol. **24B** *(2000) 964 -967*

A Dimensional Extrapolation Technique based on a System Code applied to the ITER H-mode Energy Confinement Database

P.Barabaschi[1]

[1]*ITER Joint Central Team, Joint Work Site, D-85748 Garching, Germany*

Abstract

In this paper a novel methodology for the extrapolation of the performance of ITER-class machines is introduced. This procedure utilizes the ITER Elmy H-mode database by means of a similarity approach where every shot is extrapolated to a machine satisfying the ITER performance requirements through the use of the tokamak system code developed during the course of the ITER design evolution. This approach attempts, amongst other things, to overcome the difficulty associated with the simultaneous choice of non-dimensional parameters which, in particular when close to their respective limits, may have some significant mutual interactions affecting the energy confinement time. The methodology is applied with the use of ITER Physics Basis scalings as well as developing a non-statistical approach where the fusion power is extrapolated at constant beta and the confinement is assumed to follow a gyroBohm form. In both cases, out of more than a thousand shots in the ELMy H-mode database, less than half turn out to extrapolate to a Q=10 machine whose major radius is smaller than 8m. However, a significant number extrapolates to a Q=10 machine with R<6.2m. This strengthens our confidence in the present choice of the ITER parameters. In addition, from this analysis, it has been possible to identify a set of high performance "ITER relevant" shots from a number of machines, which could be used as starting points for investigation of further improvements in confinement.

Introduction

This novel approach tries, amongst other things, to overcome the difficulty associated with the simultaneous choice of non-dimensional parameters ($A = R/a$, κ, δ, q_{95}, $ß_N$, n/n_{GW}) which, when close to their respective limits, may have some significant hidden interactions which affects the energy confinement. As an example, this is observable in the effect of shear (triangularity, q, κ, A) on confinement in high density discharges, or the effect of sawteeth on low edge safety factor discharges at high elongation and triangularity [1,2,3,4].

In addition, the proposed methodology addresses, in part, the fact that the enhancement factor H_H cannot be treated as a simple scalar because it may hide some additional variables as well as explicitly treated terms (in the energy confinement formula), for example the density or elongation, the influence of which on the energy confinement time may not be mathematically expressed in a simple monomial form within the empirical formula for energy confinement time. The employed procedure is as follows:

- each shot in the database is evaluated by extracting all of its parameters and sizing by means of the system code (in accordance with the ITER criteria) for a Q = 10 machine with the same geometry (k, δ, A=R/a) , q_{95}, and n/n_{GW}: these parameters are then assumed to come as a "package";
- the extrapolation in the energy confinement time is performed based on the empirical scaling coefficients applied only on the parameters not kept constant, and by using relative ratios. There is no need for H_H.

The energy confinement time empirical scaling then becomes:

$$\tau_{E,Q10} = \tau_{E,DBSHOT}\left(\frac{I_{Q10}}{I_{DBSHOT}}\right)^{\alpha_I}\left(\frac{P_{Q10}}{P_{DBSHOT}}\right)^{\alpha_P}\left(\frac{B_{Q10}}{B_{DBSHOT}}\right)^{\alpha_B}\left(\frac{R_{Q10}}{R_{DBSHOT}}\right)^{\alpha_R}\left(\frac{M_{Q10}}{M_{DBSHOT}}\right)^{\alpha_M}\left(\frac{n_{Q10}}{n_{DBSHOT}}\right)^{\alpha_n} \quad (1)$$

where :

- the subscript "Q10" refers to the Q = 10 machine designed from the shot in the H-mode database and indicated with the subscript "DBSHOT".
- The α_i exponents are the same exponents found in the empirical scaling law for the correspondent parameters.

In addition, considering then the following relationships:

$$q = \frac{BR}{I} * f(\delta, \kappa, A) \quad ; \quad n_{GW} = \frac{I}{\pi a^2} \qquad (2,3)$$

equation (1) further simplifies, because q_{95}, geometry, and normalized density are fixed in the extrapolation, to:

$$\tau_{E,Q10} = \tau_{E,DBSHOT}\left(\frac{P_{Q10}}{P_{DBSHOT}}\right)^{\alpha_P} \cdot \left(\frac{B_{Q10}}{B_{DBSHOT}}\right)^{\alpha_B+\alpha_n+\alpha_I} \cdot \left(\frac{R_{Q10}}{R_{DBSHOT}}\right)^{\alpha_R-\alpha_n+\alpha_I} \cdot \left(\frac{M_{Q10}}{M_{DBSHOT}}\right)^{\alpha_M} \qquad (4)$$

Considering, for example, the IPB-98y2 empirical scaling law for ELMy H mode:

$$\tau_{E,th}^{IPB98(y,2)} = 0.0562 H_H I^{0.93} B^{0.15} P^{-0.69} n_{19}^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78} \qquad (5)$$

then expression (4) becomes:

$$\tau_{E,Q10} = \tau_{E,DBSHOT}\left(\frac{P_{Q10}}{P_{DBSHOT}}\right)^{-0.69} \cdot \left(\frac{B_{Q10}}{B_{DBSHOT}}\right)^{1.49} \cdot \left(\frac{R_{Q10}}{R_{DBSHOT}}\right)^{2.49} \cdot \left(\frac{M_{Q10}}{M_{DBSHOT}}\right)^{0.19} \qquad (6)$$

Of the more than a thousand shots in the ELMy H-mode database, less than half turn out to extrapolate to a Q = 10 machine whose major radius is smaller than 8 m, however about 70 extrapolate to a Q = 10 machine with R < 6.2 m.

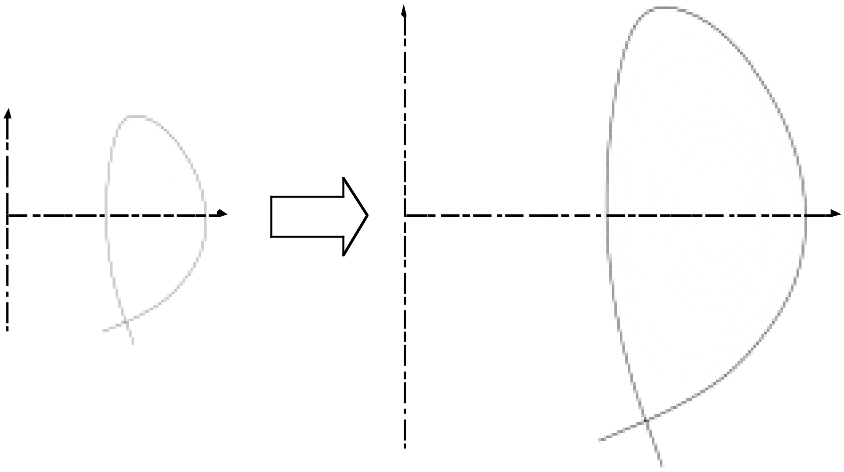

Figure 1:Extrapolation performed with same geometry, q_{95} and n/n_{GW}

Figure 2 shows the major radius of the extrapolated Q = 10 machine versus the edge safety factor q_{95} of the analyzed shots. It is apparent that there are a good number of shots, from DIII-D, JET, and ASDEX-U, which confirm the robustness of the ITER-FEAT design in reaching the Q = 10 objective on the basis of the existing experimental results. Of particular interest are those DIII-D shots which are capable of being extrapolated to a competitive Q = 10 device, even at a rather large edge safety factor. It is nevertheless clear that the choice of a safety factor of about 3 is sound.

As an even more general simplification to the proposed approach, the use of an empirical scaling formula for the energy confinement time can be completely avoided if the extrapolated device is sized based on a fusion power requirement and not on the amplification factor Q. In order to do so, the above-mentioned, non-dimensional parameters are chosen to be kept constant, based on the consideration that the most unpredictable, from first principles, turbulent, phenomena taking place in the plasma are mostly influenced by stability and even more so by the geometry of the magnetic field, q and shear profiles. In addition, in this second methodology, the value of $ß_N$ observed in the extrapolated experiment is also fixed. This last hypothesis implies that the magnetic and pressure profiles in the experiment in question and the larger extrapolated device are completely self similar. The pressure scales then as:

$$p \propto B^2 \tag{7}$$

And, for a DT experiment, the fusion power then scales approximately as:

$$P_f \approx p^2 \cdot V \propto B^4 R^3 \tag{8}$$

However, considering that the total fusion power is not exactly proportional to T^2, it is in principle necessary, but not too important for the result, to choose an operating density. This can be taken assuming also in this case the same density normalized to the Greenwald density scaling as:

$$n \propto \frac{I}{a^2} \propto \frac{B}{R} \tag{9}$$

Figure 3 shows the machine major radius versus the safety factor at the edge. Also in this case, a number of shots extrapolate to a 500 MW device with a major radius smaller than the one of ITER-FEAT. In summary, also in accordance with this alternative design methodology, the ITER-FEAT design seems to be soundly based on the extrapolation of many high performance ELMy H-mode shots from JET, DIII-D, and ASDEX-U.
The procedure above thus enables the fusion power to be extrapolated but not the transport losses and thus the value of Q to be predicted. However, by considering that the temperature scales as:

$$T \propto \frac{p}{n} \propto BR \tag{10}$$

and assuming that τ_E scales as gyroBohm, we have:

$$\tau_{E,GyroBohm} \propto \frac{a^2}{\rho^* \cdot \chi_{Bohm}} = \frac{R^2}{\frac{\sqrt{MT}}{\varepsilon RB}\left[\frac{T}{B}\right]} \propto R^{1.5} \cdot B^{0.5} \cdot M^{-0.5} \tag{11}$$

The inverse isotopic mass dependence, shown in equation (11) is not supported by the empirical scaling laws, which typically have a positive exponent. This could be because the positive mass dependence of the pedestal edge width shown in experiments [9] is neglected whereas it is thought that the edge pedestal width scales with a complex function of magnetic shear, machine size and thermal ion Larmor radius. Considering equation (11) for the evaluation of the energy confinement time, the lowest *cost* shots turn out to have a value of Q in the range between 4 and 15.
The scaling derived above can be compared with the different scaling laws expressed in the ITER Physics Basis [5]. By assuming the usual set of non-dimensional parameters equation (6) above becomes:

$$\tau_{E,Q10} = \tau_{E,DBSHOT} \cdot \left(\frac{B_{Q10}}{B_{DBSHOT}}\right)^{\frac{\alpha_B+\alpha_n+\alpha_I+2\alpha_P}{1+\alpha_P}} \cdot \left(\frac{R_{Q10}}{R_{DBSHOT}}\right)^{\frac{\alpha_R-\alpha_n+\alpha_I+3\alpha_P}{1+\alpha_P}} \cdot \left(\frac{M_{Q10}}{M_{DBSHOT}}\right)^{\frac{\alpha_M}{1+\alpha_P}} \tag{12}$$

Figure 4 compares the various empirical laws with the one derived on the basis of gyroBohm scaling, all under the assumptions of freezing the same non-dimensional parameters (A, k, δ, q_{95}, $ß_N$, n/n_{GW}) in the extrapolation. With the exception of the scaling IPB98(y,3), where a free fit without Kadomtsev constraint was performed, all scalings are very similar in the coefficients γ_B and γ_R. It is worth noting that for a given engineering approach the relation between R and B is, to a first approximation, of proportionality, when aspect ratio and elongation are constant. This means that the sum $\gamma_B + \gamma_R$ is the single most important coefficient in the scaling. When compared with eq. (11), the scalings 98(y), 98(y,1) give a more favorable size/field effect whereas scaling 98(y,2), 98(y,3), and 98(y,4) yield the opposite result.

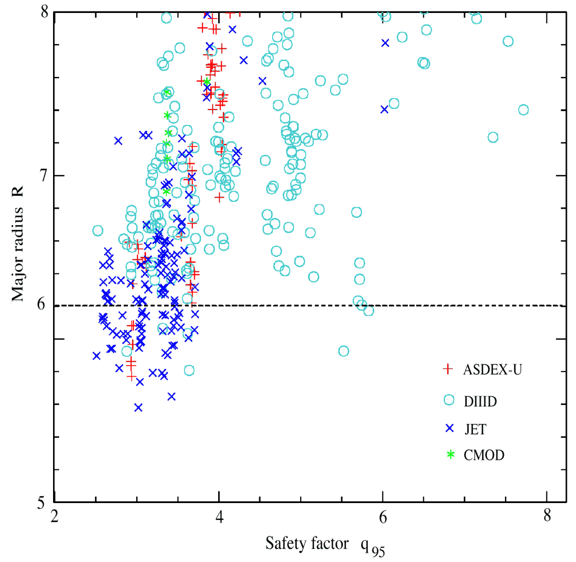

Figure 2: Major Radius of Q = 10 Machine vs. q_{95} Obtained with Dimensional Extrapolation Methodology

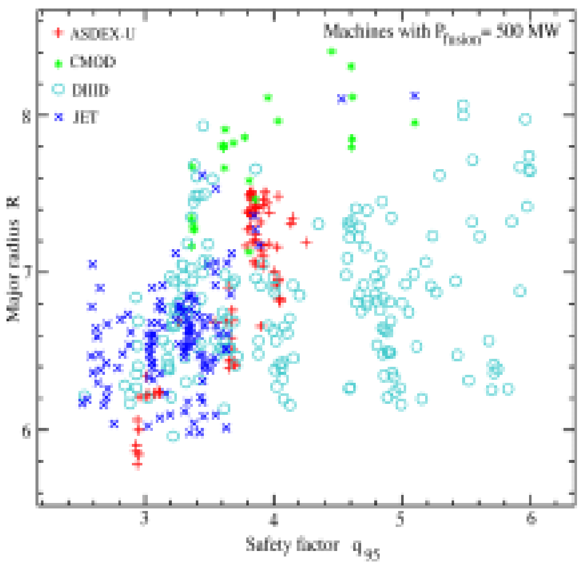

Figure 3: Major Radius of 500 MW Fusion Power Device versus Safety Factor in the Database under the Assumption of Constant Beta

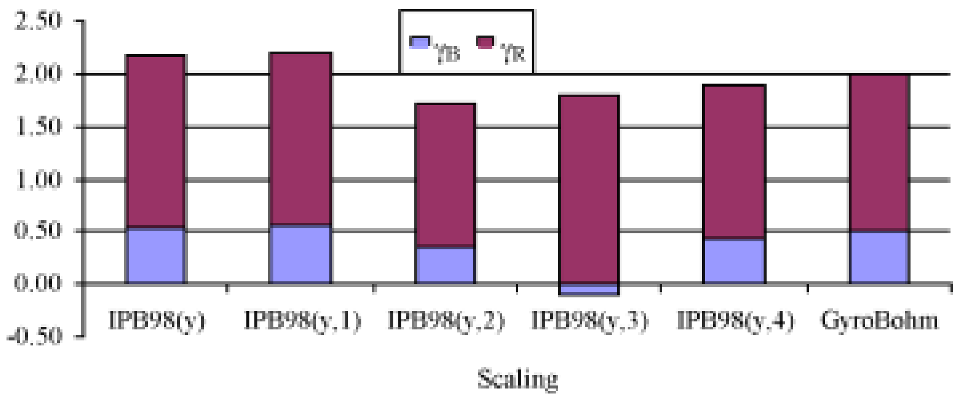

Figure 4: Comparison of Gyrobohm scaling versus IPB empirical scalings at constant n/nGW, betaN, and magnetic field geometry.

References

[1] Saibene G. et al, Nuclear Fusion 39, 1133 (1999)
[2] Stober et al, 26th EPS conf. on controlled fusion, Maastricht (1999)
[3] Kamada Y.et al, 14th. IAEA Conf. Plasma Physics, Wuerzburg (1992)
[4] Horton L.D. et al, Nuclear Fusion, 39 993 (1999)
[5] ITER Expert groups et al, *Nucl. Fusion* to be published (1999) , ITER Physics basis
[6] ITER EDA Document GA0RI199-02-12 W0.2 Study of RTO/RC ITER Options
[7] ITER EDA Document Technical Basis for the ITER FEAT Outline design, to be published, IAEA, Vienna.
[8] Boucher D., IAEA Meeting on Advances in Simulation and modeling of thermonuclear plasmas, vol 1 1992
[9] Cordey J et al, JET P98(53) , Submitted to Nuclear Fusion.
[10] C.C.Petty, T.C. Luce, Nuclear Fusion, Vol 37, No1 (1997)
[11] Kadomtsev, B.B., Sov. J. Plasma Physics Vol 1 (1975)