ITER Simulation Experiments on JET of the H-mode Power Threshold, Confinement Scaling and βeta Saturation

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I. Introduction. At the request of the ITER confinement and transport expert group, a series of experiments has been carried out on JET in which the dimensionless geometrical parameters are kept at their expected ITER values. Similar experiments have been completed on DIII-D and are expected to be completed on other machines shortly. The main objective of these experiments is to improve the accuracy of the extrapolation in size.

Three aspects of H-mode physics are examined, the power threshold, the Larmor radius scaling of ELMy H-modes and the β limit. The implications of the results for ITER are briefly discussed in the final section.

II. The threshold scaling studies. The ITER like geometry is single null with the ∇ B drift towards the target plates with an elongation $\kappa \sim 1.7$ and low triangularity $\delta \sim 0.2$. Three sets of currents and fields have been used 1MA/1T, 2MA/2T, 3MA/3T to give the same $q_{\psi 95} \sim 3$. Further details of these experiments may be found in the paper by E. Righi et al$^{(1)}$. In this note we concentrate on comparisons with the scaling expressions being used to predict the threshold in ITER$^{(2)}$.

In Fig. 1a the power threshold is first compared with the expression $P_{THRI} = 0.3\, n_{20} B_T\, R^{2.5}$ (MW $10^{20}/m^3$, T, m) which gives the best fit to the whole ITER threshold data base. The ITER simulation pulses are fairly well described by this scaling expression; however there is evidence at both low and high densities of a departure from strict linearity with n in the 3MA/3T data. Comparing the data in Fig. 1b with the more optimistic threshold scaling form $P_{THRII} = 0.016\, n^{0.75}\, B_T\, S$ (MW $10^{20}/m^3$, T, m^2), which has a weaker length scaling (S is the surface area), it can be seen that the ITER simulation pulses are substantially above the scaling. Previously in the 91-92 experimental campaign when the plasma had a 30% larger surface area S, under some conditions transitions were obtained close to 0.016 line. This may indicate that the S dependence is incorrect and that the R dependence (which is unchanged in JET between 91 and 95) is the more correct dependence, or that the wall conditioning was superior in 1991.

III. Larmor radius scaling of ELMy H-modes. Previous Larmor radius scaling experiments completed on TFTR, JET and DIII-D were done in an L-mode plasma and the scaling of the global confinement was found to be Bohm-like and in agreement with the ITER89P L-mode scaling expression. The operational regime, proposed for ITER is the ELMy H-mode regime and the scaling in this regime derived by the ITER data base$^{(3)}$ group is the ITERH93-P scaling expression. This latter expression is close to a gyro-Bohm scaling ($\chi \sim \chi_{Bohm}\, \rho^{*0.8}\, \beta$). To confirm this scaling a series of pulses were set up with the same β and ν^* at different values of current and field 1MA/1T, 2MA/2T, 1.6MA/1.7T and 2.8MA/3T. The first set had a $q_\psi = 3.4$ and the second set $q_\psi = 3.7$. The main plasma parameters are listed in Table I and further details on these pulses can be found in the paper by B. Balet(4). For the first pair of pulses 1MA/1T, 2MA/2T it can be seen that globally at least the τ_{th} increases linearly with toroidal field which indicates a gyro-Bohm dependence (gyro-Bohm $\tau_{th} \propto B$, Bohm $\tau_{th} \propto B^{1/3}$, stochastic $\tau_{th} \propto B^{-1/3}$), in agreement with the ITERH93-P scaling expression. A local analysis by the TRANSP code further confirms this result: for example in Fig. 2 the ratio of the χ's of the 2T and 1T pulses can be seen to scale as gyro-Bohm for a large fraction of the radius.

Table 1

Pulse no.	B_T(T)	I_p (MA)	$<n_e>/10^{19}$ M^{-3}	P(MW)	W_{th}(MJ)	τ_{th} (S)
35171 (25.8s)	1	1	2.2	4.85	0.84	0.17
35156 (16.1s)	2	2	5.5	9.18	3.2	0.35
33140 (16.6s)	1.7	1.6	3.6	6.3	2.3	0.36
33131 (15.6s)	3	2.8	7.6	19.6	7.3	0.37

Turning to the second pair of pulses 33131 and 33140 it can be seen that the global energy confinement scales as $B^{0.05}$ giving a scaling worse than Bohm ($\tau_\varepsilon \propto B^{1/3}$). This difference in the global energy confinement scaling between the two sets of pulses can be attributed to a difference in the ELMing behaviour. In the 3T pulse the ELMS are of the compound type with the plasma returning to the L-mode state following each ELM for a significant period. The reason for this is thought to be due to the fact that the 2.8MA/3T pulse is very close to the H-mode threshold whilst the lower field pulses are well above the H-mode threshold.

To illustrate this feature we express the threshold scalings of section II in terms of the dimensionless variables ρ^*, β and ν^* and one dimensional variable which we choose to be the minor radius a.

The two threshold forms given in section (II) have the form (4)

$$P_{THRI} \sim a^{-3/4}\, \rho^{*-7/2}\, \nu^{*-1/4}\, \beta^{5/4}, \qquad (1a)$$

$$P_{THRII} \sim a^{-3/4}\, \rho^{*-3}\, \nu^{*-1/4}\, \beta \qquad (1b)$$

Similarly one can express the standard confinement scaling expression such as ITER89-P and ITERH93-P in the same form

$$P_{ITER89\text{-}P} \sim a^{-3/4}\, \rho^{*-5/2}\, \nu^{*-1/2}\, \beta^2 \qquad (2a)$$

$$P_{ITERH93\text{-}P} \sim a^{-3/4}\, \rho^{*-3/2}\, \nu^{*-0.65}\, \beta^3 \qquad (2b)$$

where P is the power required to reach a given β, ρ^*, ν^* etc. assuming the particular confinement scaling law is correct. It can be seen from Equations (1) and (2) that both threshold scalings have a much stronger ρ^* dependence than that of the H-mode scaling expression ITER93H, and so as ρ^* is reduced by increasing the magnetic field in these similarity discharges at some stage the ITERH93-P scaling will be lost. The influence of the threshold on the JET data is shown in Fig. 3 where the normalised power is shown versus the threshold scaling P_{THRI}. Well above the threshold a gyro-Bohm dependence with $P \propto \rho^{*-3/2}$ is clear for both JET and DIII-D however close to the threshold the gyro-Bohm scaling is lost.

IV. The scaling of confinement with β. With the power levels currently available it has only been possible to obtain a β saturation in the 1MA/1T series. For this plasma configuration a total β_n normalised of 3.8 was achieved using 18MW of beam power(6) while the thermal β_{nth} was 2.5. Since a thermal $\beta_{nth} = 2.3$ was achieved with only 9 MW of injected power we are clearly approaching a β saturation. The sudden loss of confinement is illustrated in Fig. 4 where the confinement time is shown versus β_{nth} for the 1MA/1T series. The ITERH93-P scaling expression can be written in dimensionless form as $\tau_\varepsilon B \sim \rho^{*-3} \nu^{*-0.6} \beta_n^{-1}$. From Fig. 4 it appears that the β_n^{-1} dependence in ITERH93-P, which is shown in the figure, is connected with the approach to an MHD β limit.

V. The implications for ITER. Turning to the consequences for ITER, in Fig. 5 we first expand Fig. 3 to include the ITER operational point and we also include the JET higher β points. Taking the value of $\beta_n = 2.3$ in ITER and extrapolating the $\beta_n = 2.3$ line to the operating density of ITER it can be seen that 60 MW of additional heating would be sufficient to maintain the β. The alpha heating would then increase the β to the saturated value (~2.5). The α heating at this value of β would be slightly higher than the nominal 300MW, assuming the same impurity conditions etc. This of course would be the ideal stable burn scenario. The key issue for ITER though is the scaling of the threshold; and it should be noted that the optimistic form P_{THRII} has been used in Fig. 5.

References

1) E. Righi, et al., EPS Bournemouth 1995.
2) F. Ryter and the ITER data base working group. IAEA H-mode workshop proceedings PPPL 1995.
3) S. Kaye, et al., IAEA-CN-60/E-P-3, Seville (1994).
   D. Schissel, et al. EPS Lisbon (1993).
4) B. Balet, et al., EPS Bournemouth 1995.
5) C.C. Petty, T.C. Luce, K.H. Burrell, et al., Physics of Plasmas, Vol. 2, 2342 (1995).
6) C.D. Challis, et al., EPS Bournemouth 1995.

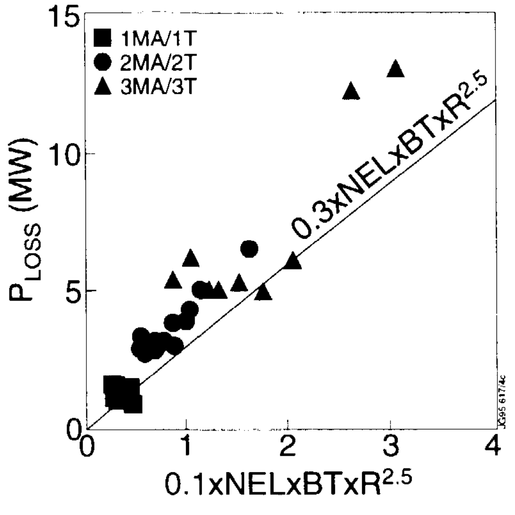


Fig.1a: The loss power P_{loss} versus the power threshold expression $<n_{20}>B_TR^{2.5}$ from reference (2).

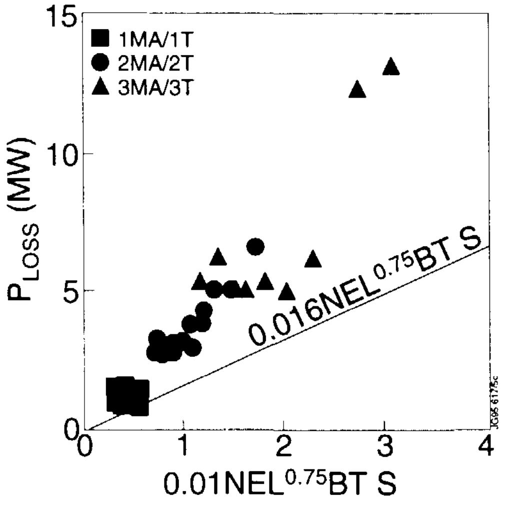


Fig.1b: The loss power P_{loss} versus the power threshold expression $n_{20}^{0.75}$ B_T S (S is the plasma surface area) from reference (2).

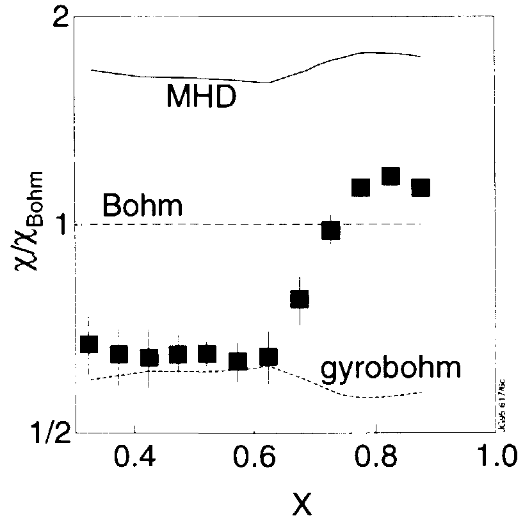


Fig.2: Ratio of the "effective thermal diffusivities" versus the normalised radial co-ordinate χ for the 2T and 1T pulses. The lines are the expected ratio for gyrobohm, Bohm and Stochastic (MHD) scaling.

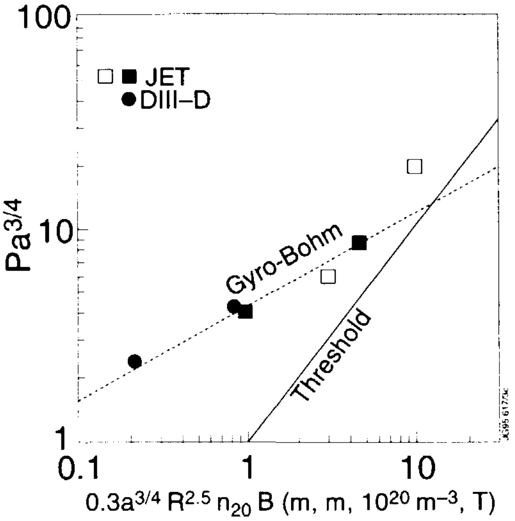
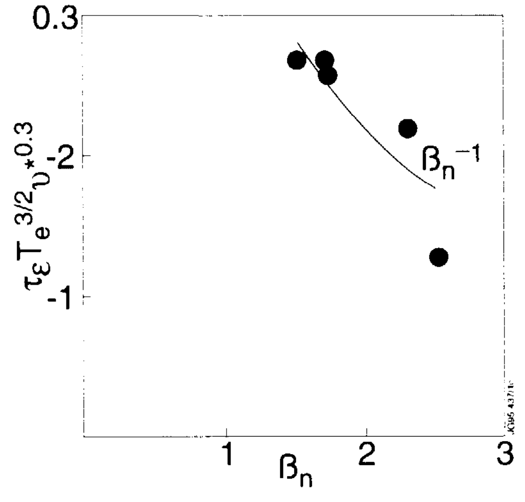


Fig.3: Normalised power $Pa^{3/4}$ versus 0.3 $a^{3/4}R^{2.5}n_{20}$ B, the H-mode power threshold expression from Ref.2, the DIII-D points are from C. Petty et al(5).



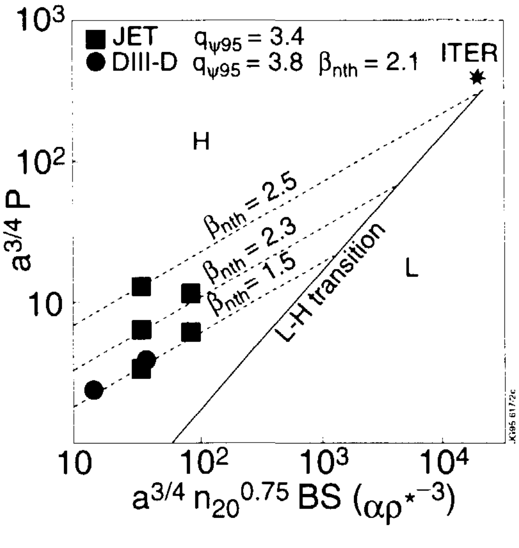


Fig.4: Normalised confinement time versus β_n for the 1MA/1T pulses.

Fig.5: Normalised power $Pa^{3/4}$ versus $a^{3/4}n_{20}^{0.75}BS$.