

THRESHOLD POWER AND ENERGY CONFINEMENT FOR ITER

ITER CONFINEMENT DATABASE AND MODELLING EXPERT
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Abstract

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In order to predict the threshold power for L-H transition and the energy confinement performance in ITER, assembling of database and analyses of them have been progressed. The ITER Threshold Database includes data from 10 divertor tokamaks. Investigation of the database gives a scaling of the threshold power of the form $P_{thr} \propto B_t n_e^{0.75} R^2 \times (n_e R^2)^{\pm 0.25}$, which predicts $P_{thr} \approx 100 \times 2^{0 \pm 1}$ MW for ITER at $n_e = 5 \times 10^{19} \text{ m}^{-3}$. The ITER L-mode Confinement Database has also been expanded by data from 14 tokamaks. A scaling of the thermal energy confinement time in L-mode and ohmic phases is obtained; $\tau_{th} \sim I_p R^{1.8} n_e^{0.4} P^{-0.73}$. At the ITER parameter, it becomes about 2.2 sec. For the ignition in ITER, more than 2.5 times of improvement will be required from the L-mode. The ITER H-mode Confinement Database is expanded from data of 6 tokamaks to data of 11 tokamaks. A τ_{th} scaling for ELMy H-mode obtained by a standard regression analysis predicts the ITER confinement time of $\tau_{th} \approx 6 \times (1 \pm 0.3)$ sec. The degradation of τ_{th} with increasing $n_e R^2$ (or decreasing ρ_*) is not found for ELMy H-mode. An offset-linear law scaling with a dimensionally correct form also predicts nearly the same τ_{th} value.

1. INTRODUCTION

In order to achieve its long-time, high-Q mission, an improved confinement with an H-factor ($= \tau_E / \tau_E^{ITER89P}$) above 2 will be indispensable for ITER. The ELMy H-mode is considered to be the most suitable for this purpose. Accurate predictions of the energy confinement as well as of the H-mode transition threshold power are urgently required for ITER EDA. This paper presents recent results of the predictive studies of threshold power and energy confinement for ITER and updates former publications by the H-mode Database Working Group [1-5].

2. THRESHOLD POWER

The change of confinement regime from L to H mode occurs after certain conditions of plasma parameters or plasma profiles are satisfied. A heating power exceeding a threshold, P_{thr} , is necessary to obtain these conditions. For the prediction of P_{thr} in ITER, the size dependence of P_{thr} is required which can only be obtained from a multi-machine database, e.g., the ITER Threshold Database [5]. Data from 10 divertor tokamaks are included in the database; Alcator C-Mod, ASDEX, ASDEX Upgrade, COMPASS-D, DIII-D, JET, JFT-2M, JT-60U, PBX-M.

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and TCV. Since the scattering in data points was rather large, it was difficult to determine uniquely the size dependence of P_{thr} so far.

By introducing a dimensional consideration, we can obtain a P_{thr} scaling with uncertainty in the density and size dependencies [5]. The total heat flux through the separatrix surface is assumed to be given as $P \propto n_e T^{1.5} R^2 F(\rho_*, \beta, \nu_*)$, where n_e is the electron density, T is the temperature, and R is the major radius. A nondimensional function $F(\rho_*, \beta, \nu_*)$ represents the transport process near plasma edge, where $\rho_* \propto T^{0.5} / B_t R$ is the normalized Larmor radius, $\beta \propto T n_e / B_t^2$ is the beta value and $\nu_* \propto n_e R / T^2$ is the collisionality. Considering a Bohm diffusion, for example, F is proportional to ρ_* and $P \propto n_e T^2 R / B_t$. The condition for L-H transition is also assumed to be given by a nondimensional equation, $G(\rho_*, \beta, \nu_*) = 1$. Since $F \propto T^f$ and $G \propto T^g$, we can eliminate T from P at the transition by dividing P by $G^\gamma (= 1)$ with $\gamma g = 1.5 + f$. The threshold power is then given as a function of R , B_t and n_e , $P_{thr} \propto B_t^Z n_e^X R^Y$, where a relation $8X - 4Y + 5Z = 3$ should hold. Although we do not know exact forms of F and G at present, we can find values of X , Y , and Z from the analysis of the ITER Threshold Database.

As for the B_t dependence, a linear relation is clearly observed from data of each tokamak with the density nearly constant, as shown in Fig. 1. The loss power in the figure is defined as $P_L = P_{NB} + P_{RF} + P_{OH} - dW/dt$, at the L-H transition (P_{NB} is the neutral beam heating power, P_{RF} the RF heating power, P_{OH} the ohmic heating power, and dW/dt is the time derivative of the stored energy).

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Putting this linear B_t dependence ($Z = 1$), we obtain a following scaling with an arbitrary power α of $(n_e R^2)$,

$$P_{thr} = C(R/a, \kappa, q, \alpha) B_t n_e^{0.75} R^2 \times (n_e R^2)^\alpha, \quad (1)$$

where C is a nondimensional coefficient including the aspect ratio R/a , elongation κ , the safety factor q , and α . Hereafter, the following notations and units are used; the power P in MW, major radius R in m, minor radius a in m, line averaged density n_{20} in 10^{20} m^{-3} (n_{19} in 10^{19} m^{-3}), magnetic field B_t in T, plasma current I_p in MA.

The non-dimensional quantity, $n_e R^2$, is proportional to β / ρ_*^2 , and this value for ITER is much larger than its value for present tokamaks. Therefore, the uncertainty of the order of $(n_e R^2 / \langle n_e R^2 \rangle)^\alpha$ becomes large for the prediction of P_{thr} in ITER, where $\langle n_e R^2 \rangle$ represents the average of $(n_e R^2)$ in the ITER Threshold Database.

The limits of α value are determined from data analysis. Figure 2 shows P_L normalized by (a) $B_t n_e^{0.5} R^{1.5}$, (b) $B_t n_e^{0.75} R^2$, and (c) $B_t n_e R^{2.5}$. A black circle represents to the average of normalized P_L for a fat tokamak ($R/a < 3.5$) and a diamond corresponds to that for a slender tokamak ($R/a > 3.5$). Note that the lower half of error-bar region for a tokamak is used for comparison, when the error bar of a tokamak is large. One can see that the normalized P_L for the case (a) increases with R , i.e., $R^{1.5}$ dependence of P_L is optimistic. Data of COMPASS-D (double circle) and of TCV (double diamond) exhibit higher thresholds than other data, especially for P_L normalized by $B_t n_e R^{2.5}$. These data, however, are taken into account only lightly to determine the scaling at present, because the number of data points are small and the following reason: These two devices are of small size, have open divertor configurations, and are therefore expected to be more sensitive to neutrals which are known to increase generally the threshold power. Neutral density measurements, not yet available in these devices, would be required to address this question quantitatively. Figure 3 shows the change of the standard deviation $\Delta\sigma$ with the variation of the n_e dependence of $P_{thr} \propto n_e^X$, where σ is defined as $\sigma^2 = N^{-1} \{ \hat{P}_L / \langle \hat{P}_L \rangle - 1 \}^2$, N is number of data points, and $\hat{P}_L \equiv P_L / B_t n_e^X R^Y$. The standard deviation increases with the stronger n_e dependence of P_{thr} except Alcator C-Mod. Therefore the scaling of the form $P_{thr} \propto B_t n_e R^{2.5}$ is not reliable.

According to the results of Figs. 2 and 3, the limits of α value are evaluated as ± 0.25 . Assuming that C is independent of R/a , κ , and q , for simplicity, value of C is estimated from Fig. 2 as

$$C = (0.45 \pm 0.1) \times 0.6^\alpha \quad \text{with } -0.25 \leq \alpha \leq 0.25, \quad (2)$$

where the unit of line averaged density n_e is 10^{20} m^{-3} . There is seen the dependence of C on R/a and κ in Fig. 2 (a) for $X = 0.5$ and $Y = 1.5$, but is not especially seen in (c) for $X = 1.0$ and $Y = 2.5$. As for the q dependence of C , a clear dependence $C \propto q^{0.5-1}$ is found in JET data, while no clear dependence is observed in other tokamaks. Data from JT-60U suggest very weak q dependence of C [6]. One of considerable reasons of P_{thr} decreasing at smaller q is that a sawtooth crash sometimes causes the L-H transition.

The regression analyses give the similar results to the above. Using the equal weighting for all data, we obtain a relation; $P_{thr} \sim B_t n_e^{0.7} R^2$. When we use a $(1/N_{tok})$ weighting for each data point, we obtain another relation; $P_{thr} \sim B_t n_e^{0.9} R^{1.8}$, where N_{tok} is the number of data points from a tokamak, and this

method weights each machine equally. It is confirmed by these analyses, that Eqs. (1) and (2) are reliable for the scaling of threshold power. Figure 4 shows the comparison of experimental data from 10 tokamaks to the scaling, $P_{thr} = 0.45 B_t n_{20}^{0.75} R^2$. The data are found to be fitted well by this formula.

In order to predict P_{thr} in ITER, dependencies of C on R/a , κ , and q are not so important, because many data points cover the parameter region of ITER; $R/a \approx 3$, $\kappa \approx 1.7$, and $q \approx 3$. The predicted value of P_{thr} in ITER ($B_t = 5.7$ T and $R = 8.1$ m) at $n_e = 0.5 \times 10^{20} \text{ m}^{-3}$ is obtained from Eqs. (1) and (2) as $100 \times 2^{0 \pm 1}$ MW. There still remains a large uncertainty, $50 \text{ MW} < P_{thr} < 200 \text{ MW}$.

Being aware of the importance of radiation losses, edge plasma density and neutral density, efforts have been made to include these elements into the database. The analysis of this new version of the database, including a more physical approach of analyzing the edge data, is progressing to reduce the uncertainty in the prediction. Data analysis on P_{thr} for the H-L back transition is also in progress. It is necessary to investigate theoretically whether the condition for L-H-L transitions is really determined by three parameters (ρ_* , β , v_*) but independent of other parameters, such as normalized mean-free-path λ_{*CX} against charge-exchange reactions.

3. L-MODE CONFINEMENT

A basis of the confinement performance has been historically given by a total energy confinement scaling for L-mode plasmas. One of the well-known scaling for total energy confinement time τ_E is ITER89-Power law scaling [7],

$$\tau_E^{\text{ITER89P}} = 0.048 M^{0.5} I_p^{0.85} R^{1.2} a^{0.3} \kappa^{0.5} n_{20}^{0.1} B_t^{0.2} p^{-0.5}, \quad (3)$$

where τ is in the unit of sec and M denotes the ion mass number.

It is more useful to have a basis given by a thermal energy confinement scaling for evaluating the performance of ITER. For this purpose, the L-mode confinement data from 14 tokamaks are assembled in the ITER L-mode Confinement Database [4], where ohmic confinement data are also included; Alcator C-Mod of L-mode and ohmic data, ASDEX (L, OH), Doublet III (L), DIII-D (L), FTU (OH), JET (L, OH), JFT-2M (L), JT-60 (L, OH), PBX-M (L), PDX (L, OH), T-10 (L, OH), TEXTOR (L, OH), TFTR (L), and TORE SUPRA (L, OH). The standard linear regression analysis of the L-mode data yields the following scaling,

$$\tau_{th}^L = 0.023 M^{0.2} I_p^{0.96} B_t^{0.03} \kappa^{0.64} R^{1.89} a^{-0.06} n_{19}^{0.4} p^{-0.73}, \quad (4)$$

which has rather strong density dependence and strong power degradation compared with the τ_E scaling. This difference is due to the effect of high energy ion component in the total energy. The formula of Eq. (4) indicates the L-mode confinement being Bohm-type, $\tau_{th}^L \sim \tau_{Bohm} \times (v_*^{0.18} / \beta^{1.34})$, as the same as the ITER89-Power law scaling, $\tau_E^{\text{ITER89P}} \sim \tau_{Bohm} \times (1/v_*^{0.28} \beta^{0.56})$, where $\tau_{Bohm} \propto R^2 B_t / T$ denotes the Bohm confinement time.

The above scaling fits well not only the L-mode thermal confinement time but also the ohmic confinement time as shown in Fig. 5, where only the ohmic data of TEXTOR (dotted squares) deviate remarkably from the scaling. This scaling is similar to a dimensionally correct scaling, $\tau_{th}^{\text{JT-60}}$, based mainly on JT-60 data [8] except the q dependence and stronger power degradation. The present scaling gives a

smaller standard deviation against total data points, though it fits JT-60 data worse a little than the previous JT-60 scaling.

For the ITER parameters, $M = 2.5$, $I_p = 21$ MA, $B_t = 5.7$ T, $\kappa = 1.7$, $R = 8.1$ m, $a = 2.8$ m, $n_e = 1.3 \times 10^{20} \text{ m}^{-3}$, and $P = 190$ MW, Eq. (4) predicts $\tau_{th}^L = 2.3$ sec. This value is nearly the same as $\tau_E^{ITER89P} = 2.3$ sec, and $\tau_{th}^{JT-60} = 2.4$ sec when the Bohm-type confinement criterion is imposed. Since the minimum confinement time of 5.6 sec is required for ignition in ITER, an enhancement factor of about 2.5 over L-mode will be necessary. Even for the L-mode phase at $n_e = 0.5 \times 10^{20} \text{ m}^{-3}$ with additional heating power of 100 MW, the fusion power of about 150 MW can be produced with $\tau_{th}^L \approx 2$ sec and the averaged temperature $\langle T \rangle \approx 5$ keV. Since expected alpha heating power from an L-mode plasma is less than 40 MW, the uncertainty in the prediction of P_{thr} should be reduced within this range.

4. H-MODE CONFINEMENT

On the basis of the ITER H-mode Confinement Database, a scaling of the thermal energy confinement time for H-mode has been studied. A standard regression analysis of data, from ASDEX, DIII-D, JET, JFT-2M, PDX, and PBX-M, gave a scaling of τ_{th} for ELM-free H-mode called ITER93-H [2, 3],

$$\tau_{th}^{ELM-free} = 0.036 M^{0.41} I_p^{1.06} B_t^{0.32} \kappa^{0.66} R^{1.9} a^{-0.11} n_{19}^{0.17} P^{-0.67}. \quad (5)$$

A scaling for ELMy H-mode, τ_{th}^{ELMy} , was also given in Refs. [2, 3], and it can be simply evaluated as $\tau_{th}^{ELMy} = 0.85 \times \tau_{th}^{ELM-free}$. This scaling of $\tau_{th}^{ELM-free}$ suggests a gyro-Bohm-type transport in H-mode plasmas, $\tau_{th}^{ELM-free} \sim \tau_{Bohm} \times (1 / \rho_*^{0.8} v_*^{0.28} \beta^{1.19})$, while the L-mode $\tau_E^{ITER89P}$ scaling represents a Bohm-type transport. In ITER plasmas, values of β and v_* will take almost the same values in present H-mode plasmas. On the other hand, the value of ρ_* will become smaller than present values, and the H-factor in ITER is expected to become larger than that in present tokamaks by a factor $1 / \rho_*^{0.8}$. The predicted value of τ_{th}^{ELMy} in ITER becomes up to 6 sec (H-factor ~ 2.5). This value is fairly optimistic for the ignition in ITER. If τ_{th} is reduced by 30%, the fusion multiplication factor Q will decrease to around 10.

It is necessary to examine whether systematic degradation of τ_{th} from the above scaling is probable or not with the decrease of ρ_* . From the experimental viewpoint, ρ_* scaling experiments have been performed in DIII-D, JET, and JT-60U. Here we study the ρ_* dependence of $F \equiv \tau_{th} / \tau_{th}^{ELM-free}$ in the database. Recently many scalings have been proposed, which describe the degradation with the increase of $n_e a^2 \propto \beta / \rho_*^2$. An example of such scaling expressions is $\tau^{fit} = F \times \tau_{th}^{ELM-free}$ with $F \propto (n_e a^2 g)^{-0.17}$ and $\ln g = (n_e a^2)^{-0.5} \ln(2 q_{eng})$. This scaling predicts very pessimistic performance of ITER.

Figure 6 shows F of experimental data for ELM-free (open circle) and ELMy (closed circle) H-modes with $3^2 q_{95}^2 4$ as functions of (a) $n_e a^2$ and of (b) ρ_* , where q_{95} is the safety factor at the 95% flux surface and about 1.4 times larger than $q_{eng} \equiv 5 \kappa a^2 B_t / R I_p$ for ITER like configuration. The value of ρ_* is evaluated from the thermal stored energy. Note that new data from Alcator C-Mod, ASDEX Upgrade, COMPASS-D are used in this figure, which have recently been included in the database. Since the ratio $F_{ELMy} / F_{ELM-free}$ for JET data (largest $n_e a^2$ and smallest ρ_*) is nearly unity but is clearly less than unity for other data, dependencies of F on

$n_e a^2$ and on ρ_* are opposite between for ELM case (solid line) and ELM-free case (broken line); $F_{ELMy} \propto (n_e a^2)^{0-0.08} \propto \rho_*^{-0.04-0}$, and $F_{ELM-free} \propto (n_e a^2)^{-0.12-0} \propto \rho_*^{0-0.2}$. From this analysis, we find that the use of a scaling, $\tau_{th}^{ELMy} = 0.85 \times F_{ELM-free} \times \tau_{th}^{ELM-free}$, is not proper for the ITER prediction, where $F_{ELM-free}$ degrades with increasing $n_e a^2$ (or decreasing ρ_*). The uncertainty in the ITER prediction (expected values are pointed by dotted circles in Fig. 6) can be estimated as $\pm 30\%$ at the present situation.

The H-mode confinement scaling is reexamined from the view point of the offset-linear expression. It is found that the dependence of τ_{th} on P is different among tokamaks; $\tau_{th}^{ELM-free} \propto P^{-\alpha_P}$. Figure 7 shows results of DIII-D ($I_p = 2\text{MA} / B_t = 2.1\text{T}$), JET ($3\text{MA} / 2.3\text{T}$), JFT-2M ($0.25\text{MA} / 1.3\text{T}$), and PBX-M ($0.34\text{MA} / 1.4\text{T}$), where $\alpha_P = 0.45 \pm 0.3, 0.44 \pm 0.12, 0.70 \pm 0.13,$ and 0.76 ± 0.24 for DIII-D, JET, JFT-2M, and PBX-M, respectively. This fact indicates that a simple power law like Eq. (5) is not the best suited, and an offset linear law is more suited for the scaling expression [9-11]. As a result, several kinds of offset-linear expressions have given smaller standard deviation against the H-mode database than that given by ITER93-H scaling. Those expressions, however, are not dimensionally correct. A dimensionally correct form of the offset-linear law scaling is the following,

$$\begin{aligned} \tau_{th} = & C_0 I_p B_t R^2 (n_{19} R^2)^{x_0} (B R^{1.25})^{y_0} P^{-1} \\ & + C_1 I_p R^{1.5} (n_{19} R^2)^{x_1} (B R^{1.25})^{y_1} . \end{aligned} \quad (6)$$

The simplest set of the coefficients is given by $C_0 = 0.05, x_0 = y_0 = 0, C_1 = 0.04, x_1 = 0,$ and $y_1 = -0.3$. This formula is similar to the previous offset-linear expression given in Refs. [9, 10] where $(B R^{1.25})$ is replaced with $R^{2.1}$. The predicted value of $\tau_{th}^{ELM-free}$ for ITER is 7.3 sec, which is nearly the same as that predicted by the power law scaling Eq. (5).

In order to improve the reliability of the ITER prediction, new data from DIII-D and JET have been included in the H-mode database. Data from Alcator C-Mod, ASDEX Upgrade, COMPASS-D, JT-60U, and TEXTOR have also increased the range of the database recently. Detailed analysis of this database is underway specifically taking into account the effects of smaller ρ_* and higher density.

5. Summary

Databases called the ITER Threshold Database, the ITER L-mode Confinement Database, and the ITER H-mode Confinement Database have been developed, and have been analyzed to give scalings for the prediction of ITER performance. A scaling of the threshold power of the form $P_{thr} \propto B_t n_e^{0.75} R^2 \times (n_e R^2)^{\pm 0.25}$, which predicts $P_{thr} \approx 100 \times 2^{0 \pm 1}$ MW for ITER at $n_e = 5 \times 10^{19} \text{ m}^{-3}$. This scaling is derived from experimental data and dimensional consideration, and has large uncertainty at present. The thermal energy confinement time in L-mode and ohmic phases is expressed by $\tau_{th} \sim I_p R^{1.8} n_e^{0.4} P^{-0.73}$, which has rather strong density dependence and strong power degradation. At the ITER parameter, it becomes about 2.2 sec which is nearly equal to $\tau_E^{ITER89P}$. For the ignition in ITER, more than 2.5 times of improvement will be required from the L-mode. The ITER H-mode Confinement Database is expanded from data of 6 tokamaks to data of 11 tokamaks. A τ_{th} scaling for ELMy H-mode obtained by a standard regression analysis predicts the ITER confinement time of $\tau_{th} \approx 6 \times (1 \pm 0.3)$ sec. The degradation of τ_{th} with increasing $n_e R^2$ (or decreasing ρ_*) is not found for ELMy H-mode. An offset-linear law scaling with a dimensionally correct form also predicts nearly the same τ_{th} value.

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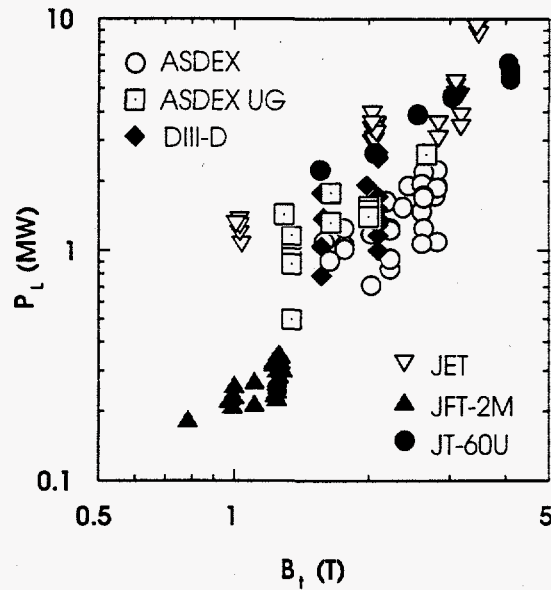


Fig. 1 Dependence of P_L on B_t . Density regions are chosen as $(2.5-3.0) \times 10^{19} \text{ m}^{-3}$ for ASDEX, $(4.0-5.5)$ for ASDEX Upgrade, $(3.0-3.5)$ for DIII-D, $(2.3-3.0)$ for JET, $(2.0-2.5)$ for JFT-2M, and $(1.4-2.1)$ for JT-60U.

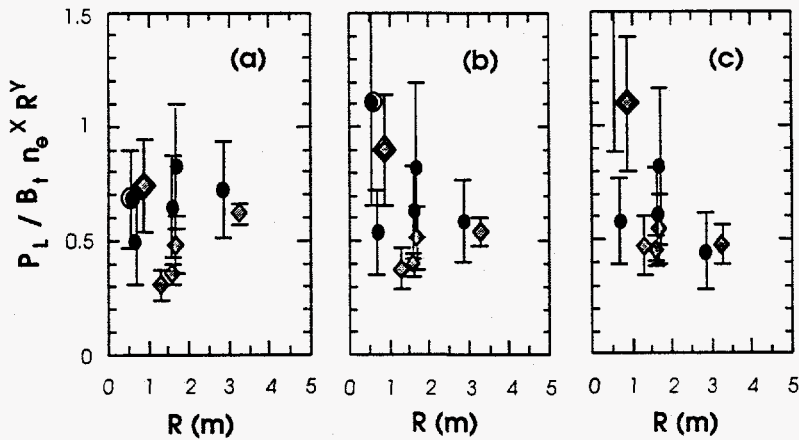


Fig. 2 Loss power P_L normalized by $B_t n_e^X R^Y$ vs major radius R . A black circle represents to the average for a fat tokamak ($R/a < 3.5$) and a diamond to that for a slender tokamak ($R/a > 3.5$). Data of COMPASS-D (double circle) and of TCV (double diamond) exhibit higher thresholds than other data, especially for P_L normalized by $B_t n_e R^{2.5}$.

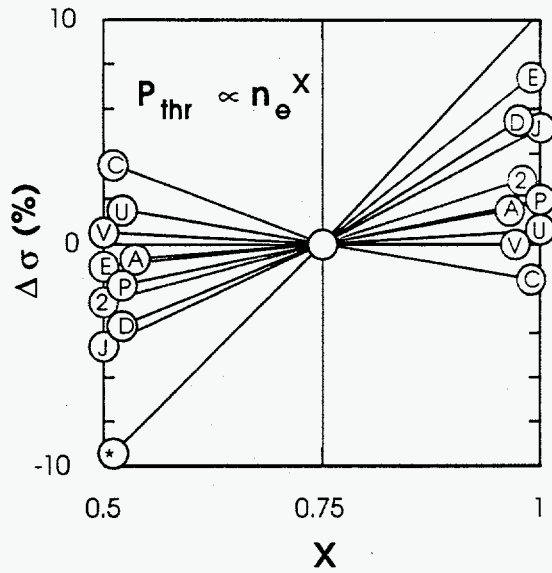


Fig. 3 Change in standard deviation $\Delta\sigma$ with various n_e dependence of P_{thr} . Symbol (C) represents Alcator C-Mod, (U) to ASDEX Upgrade, (V) to TCV, (A) to ASDEX, (E) to JET, (P) to PBX-M, (2) to JFT-2M, (D) to DIII-D, (J) to JT-60U, and (*) to COMPASS-D.

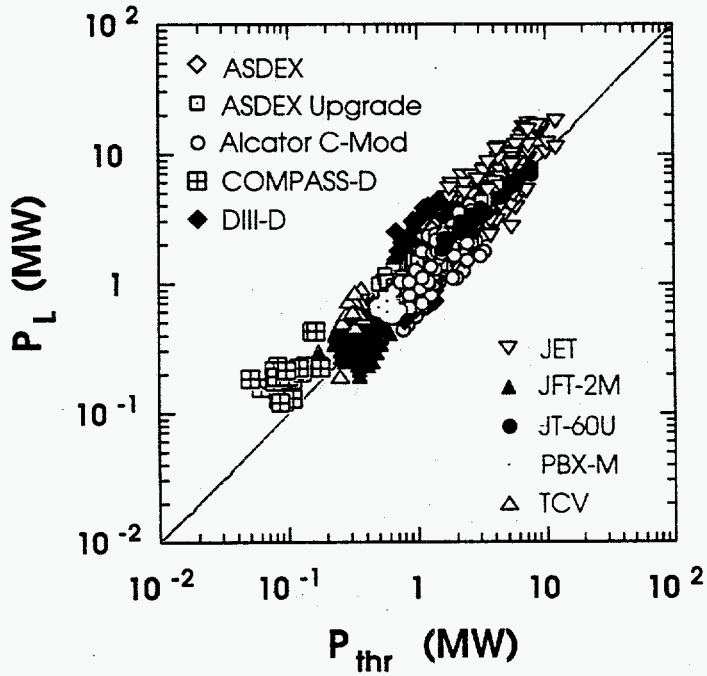


Fig. 4 Comparison of experimental data from 10 tokamaks to a scaling $P_{thr} = 0.45 B_t n_{20}^{0.75} R^2$.

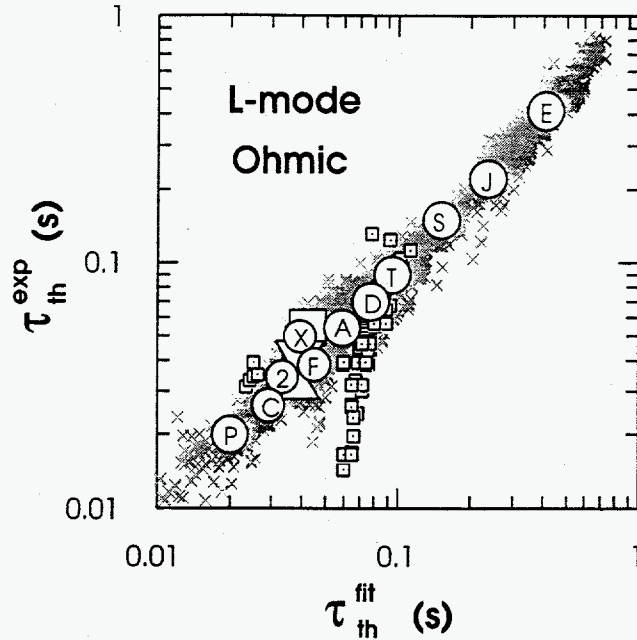


Fig. 5 Thermal energy confinement time τ_{th} for L-mode and ohmic phases. Scaling expression τ_{th}^{fit} of Eq. (4) fits well experimental data. A symbol represents averaged position of data from a tokamak; (E) denotes JET, (J) JT-60, (S) TORE SUPRA, (T) TFTR, (D) DIII-D, (A) ASDEX, (X) TEXTOR, (F) FTU, (2) JFT-2M, (C) Alcator C-Mod, and (P) PDX. Square corresponds to PBX-M, reversed triangle to Doublet III and triangle to T-10. Only the ohmic data of TEXTOR (dotted squares) deviate remarkably from the scaling.

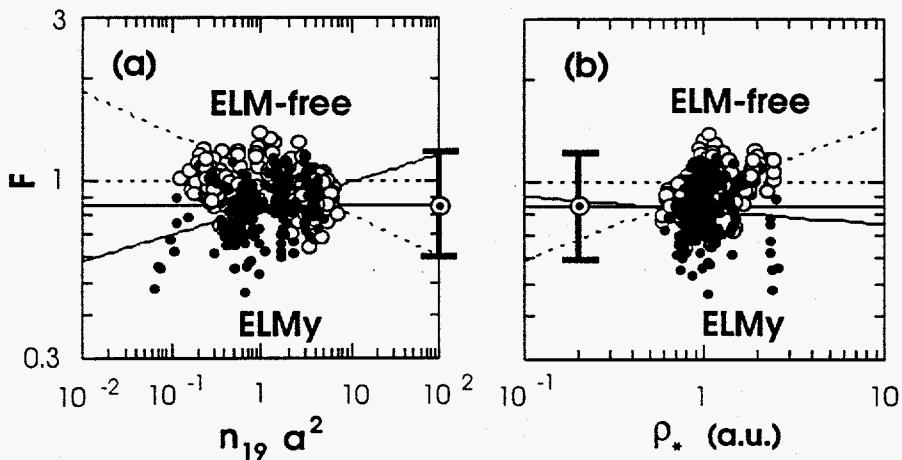


Fig. 6 Dependencies of $F \equiv \tau_{th}^{experiment} / \tau_{th}^{ELM-free}$ on (a) $n_e a^2$ and on (b) ρ_* for ELM-free case (open circle and dashed line) and ELMy case (closed circle and solid line). Expected values for ITER are pointed by dotted circles. Uncertainty in the prediction is estimated as $\pm 30\%$.

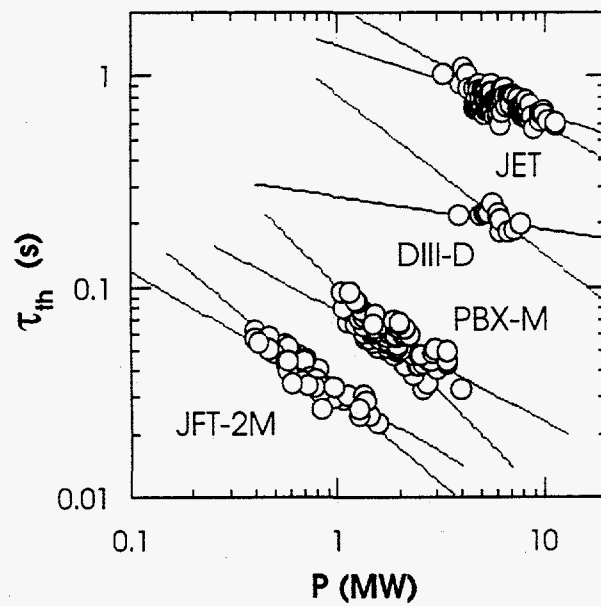


Fig. 7 Power dependence of τ_{th} for ELM-free H-mode. The dependence is different among DIII-D ($I_p = 2 \text{ MA} / B_t = 2.1 \text{ T}$), JET ($3 \text{ MA} / 2.3 \text{ T}$), JFT-2M ($0.25 \text{ MA} / 1.3 \text{ T}$), and PBX-M ($0.34 \text{ MA} / 1.4 \text{ T}$).