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Considerations on Energy Confinement Time Scalings using Present Tokamak Databases and Prediction for ITER Size Experiments

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Abstract

The thermal energy confinement time for ITER size experiments is based on power law scalings obtained using datasets of present tokamak results in specific regimes, the most relevant being the ELMy H-mode regime [1]. A thorough statistical approach has provided a best fit to these data with an estimation of the error bars which forms the basis for the ITER-EDA design parameters. In this report, the range of variation of the main parameters in the database are studied individually and are used to reduce the number of variables in the power law scaling. In this way, we show that the four variables ($a\ \kappa\ B$), n, $P^*=P_L/V$ and q_{eng} are good parameters which provide a simple fit to the data, namely: $\tau_{th}= 0.0307\ (a\kappa B)\ n^{1/2}\ /\ (P^{*2/3}\ q_{eng})$, which satisfies the high β or Kadomstev constraint. This fit is as good as the best log-linear fit, using the 8 variables I, B, R, ε, P, κ, M, n, over the full set of devices used in the databank and it yields the same prediction for the ITER-EDA confinement time. It turns out that this simple best fit is a gyro-Bohm scaling. We also show that small changes in the density, n, and P^* exponents can give a Bohm like scaling, which is less accurate and is pessimistic, but can be used as a lower bound prediction. The use of this simple scaling law is illustrated by a proposal to slightly reduce the size and magnetic field of the ITER-EDA design.

1. Introduction

Even though important progress has been made in recent years in first principles determination of the dependence of the energy confinement time on plasma parameters [2], it is not yet possible to rely on these simulations to predict energy confinement times of experiments of the size of the International Thermonuclear Experimental Reactor (ITER) [3]. Therefore a large effort has been put into assembling data sets with many different discharges from different size and shape tokamaks. These have been classified in specific regimes, namely the low confinement (L) and the high confinement (H) mode with or without edge localized modes (ELM). We shall only consider the ELMy H-mode database in this study as it is the regime of interest for large scale experiments. Recently this database, ITERH.DB3, has been updated and it now includes 1398 ELMy H-mode observations from 11 Tokamaks: Alcator C-Mod, ASDEX, ASDEX-Upgrade, COMPASS-D, DIII-D, JET, JFT-2M, JT60-U, PBX-M, PDX and TCV. These 1398 observations (1 ECRH, 4 ECRH off-axis, 45 ICRH, 1273 NBI, 52 NBI+ICRH, 23 Ohmic) are part of 924 different discharges and they are described in details in Refs. [1, 4]. The ELMy H-mode thermal energy confinement power law fit obtained in terms of the full set of "engineering parameters" characterizing a discharge is given by the following so-called "IPB scaling law":

$$\tau_{th,IPB} = 0.0365\ I^{0.97}\ B^{0.08}\ P_L^{-0.63}\ n^{0.41}\ M^{0.20}\ R^{1.93}\ \varepsilon^{0.23}\ \kappa^{0.67} \qquad (1)$$

where I[MA], B[T], P_L[MW], n[$10^{19}m^{-3}$], M[AMU], R[m], $\varepsilon = \frac{a}{R}$ and κ are the plasma current, vacuum magnetic field at the major radius, loss power, line averaged electron plasma density, effective mass of the gas, major radius, inverse aspect ratio and elongation respectively.

Using the physics variables instead of engineering parameters, namely $\beta \sim nT^2$, $\rho_* \sim \sqrt{T}/aB$ and $\nu_* \sim nqR/T^2\varepsilon^{3/2}$, respectively the normalized plasma pressure, toroidal Larmor radius and collisionality, one obtains:

$$\tau_{th,IPB} \sim \tau_B\ \rho_*^{-0.83}\ \beta^{-0.50}\ \nu_*^{-0.10} \qquad (2)$$

where $\tau_B = a^2\ B\ /\ T$ is the Bohm time. Therefore one sees that Eq.(2), and thus Eq.(1), is dimensionnaly correct and satisfies the high β or Kadomstev constraint [5, 6]. We also note that the ρ_* exponent, -0.83, is closer to a gyro-Bohm type scaling, which would have an exponent of -1, than to a Bohm type scaling independant of ρ_*. In order to have a better understanding of such a scaling law with so many free variables and non-integer exponents, we shall first describe in more details the range of variation of the various plasma parameters in the database in Sec. 2. Then, in Sec. 3, we shall propose a simpler fit which enables one to see better the main dependencies and illustrates possible variations of exponents in the power law while keeping a good fit to the data. We also show how one can slightly change the exponents to obtain a gyro-Bohm or a Bohm like scaling law, and we discuss the predictions obtained for the ITER-EDA design parameters. In Sec. 4, we suggest how one can change the design parameters to reduce the cost of the machine, in view of the results presented in Sec.2 and 3, while keeping a good performance. In particular we show that the plasma elongation has to be increased, consistent with the database. Finally conclusions are presented in Sec. 5.

2. Plasma parameters in the ITERH.DB3 database

We shall present in this Section different plasma parameters in terms of the experimental thermal energy confinement time of the ELMy H-mode dataset. We include the following ITER-EDA parameters as we want to use the dataset to predict ITER-EDA performances:

$$R=8.14\text{m},\ a=2.8\text{m},\ B=5.68\text{T},\ \kappa=1.73,\ I=21\text{MA},\ P_L=200\text{MW},\ n=13\cdot10^{19}\text{m}^{-3},\ M=2.5,\ V=1969\ \text{m}^3,\ q_{eng}=2.25, \quad (3)$$

where $q_{eng}=5\ B\ a^2\ \kappa/(I_{MA}\ R)$ and κ is the elongation at the plasma separatrix as used in Eq. (1) and in this report.

Let us first consider the plasma current as it has an exponent of nearly one in Eq. (1). We see in Fig. 1 that there is indeed a roughly linear dependence between I and τ_{th} of each machine and in between machines, with a variation over a factor of 30 in the database while the ITER point is only another factor 4 further. Therefore the plasma current is a good parameter and its linear dependence quite solid. As we know that the highest current for a given tokamak is limited to q_{eng} around two or slightly below, it is worthwhile to replace I_p by $5\ B\ a^2\kappa\ /\ R\ q_{eng}$. In this case Eq. (1) becomes, replacing ε by a/R:

$$\tau_{th,IPB} = 0.1739\ q_{eng}^{-0.97}\ B^{1.05}\ P_L^{-0.63}\ n^{0.41}\ M^{0.20}\ R^{0.73}\ a^{2.17}\ \kappa^{1.64} \quad (4)$$

In Fig.2 we plot q_{eng} vs. τ_{thexp}, the experimental energy confinement time, which shows that the database covers very well both sides of the ITER design value (q_{eng} = 2.25), and therefore one has confidence in obtaining $q_{eng} \approx 2$ in any machine. In using q_{eng} as fitting variable, we avoid the large extrapolation in the plasma current, but one should remember to keep $\tau_{th} \sim 1/q_{eng}$ as it comes from the linear dependence on the plasma current. Note that the very low values of q_{eng} are due to PBX-M and its strong shaping. We also see from Fig. 2 that we could restrict the dataset to $q_{eng} \leq 3$, for example, and remove it from the fit, in order to avoid a possible non-power law dependence of τ_E on q_{eng} near the lower limit. This will be discussed in the next Section.

Another important quantity is the amount of loss power, P_L, which has been reduced by the radiated power for the ITER-EDA design point, Eq. (3). Figure 3(a) shows P_L vs $\tau_{th,exp}$ where one sees the power degradation of each machine individually, while of course the power increases with increasing size. This latter remark suggests that the power density would be a better parameter and is actually a better "engineering" variable in order to evaluate a machine efficiency. This is why we define $P^* = P_L$ / Volume, which is also more closely related to the local transport properties of the plasma. We see in Fig. 3(b) that P^* varies only over 1-2 orders of magnitude, in contrast to P_L in Fig. 3(a), including the ITER point. Moreover, Fig. 3(b) shows that all the JET data are around the ITER value. Therefore one could restrict P^* around 0.1 and eliminate it from the fit. This will be discussed in the next Section. We now replace P_L by P^* ($2 \pi^2$ R a^2 κ) in Eq. (4) and obtain:

$$\tau_{th,IPB} = 0.0266\ q_{eng}^{-0.97}\ B^{1.05}\ P_*^{-0.63}\ n^{0.41}\ M^{0.20}\ R^{0.10}\ a^{0.91}\ \kappa^{1.01} \qquad (5)$$

Let us now consider the size dependence. The dependence of the energy content to the volume size is already included in P*. Therefore one easily sees from Eq. (5) that there stays only a linear dependence of τ_{th} on the size. As the aspect ratio does not vary a lot over the database (Fig. 4) one can easily exchange small exponents in between a and R. They are therefore not well defined. Moreover the a and κ dependence of the IPB scaling suggests, replacing $\kappa = b/a$ in Eq. (5), that reducing a with b fixed would increase the confinement time. Of course the edge κ is limited by ideal MHD to below 2.2-2.3 [7] and $q_{eng} \cong 2$, but this $a^{-0.10}$ dependence should be avoided. Moreover as the B exponent is also very close to one, we suggest to keep ($aB\kappa$) as only one independent variable in the q_{eng}, P* power scaling. In order to be complete, we plot a, κ, B in addition to ($a\kappa B$) in Fig. 5. We see that a varies over a wide range in the database but is about constant for each individual machines (Fig. 5(a)). The elongation κ, Fig. 5(b), has most its values within 1.6 to 2 and is therefore more or less constant except for the ASDEX and PDX data. Note that DIII-D and JET have most of their data around 1.8 to 1.9. This is also why we shall suggest to use a higher elongation, up to 2, for the ITER design point (Sec. 4). The magnetic field B does not vary a lot over the database, Fig. 5(c), as compared to the ITER point, apart from the Alcator C-mod data. Finally we see that (aκB), Fig. 5(d), is able to reduce the dispersion in the data as compared to a and B, as it even nicely includes the Alcator C-mode data. Moreover, it varies by more than one order of magnitude over the database for less than a factor of four between JET and ITER. In addition it does suggest a linear dependence of $\tau_{th,exp}$ with (aκB), at least in between machines.

We still have two more variables to discuss, namely the effective mass M and the electron density n. As most of the points in the database have M = 2, we think it is wise, at this stage, not to count on a positive mass dependence. Therefore we shall eliminate M from the fits. For the density, the main question is its value with respect to the Greenwald limit. This is why we plot n/n_G vs $\tau_{th,exp}$, $n_G = 10\ I_{MA}/\pi a^2\ [10^{19} m^{-3}]$, in Fig. 6(a). Even though recent experiments have achieved good confinement with n/n_G as high as 1.5 [8], this is still hard to achieve experimentally. Figure 6(a) shows well that prediction for $n/n_G \sim$ 1-1.5 are not well supported by the database. This is an area where clearly more results are needed. However, as the exponent of the density is small and as the values of n in the database reach values close to that of ITER, Fig. 6(b), we keep n as such. We shall use the relative insensitivity of τ_{th} on n in order to adjust the n exponent to satisfy the Kadomtsev constraint.

3 Scaling laws in reduced set of engineering variables

3.1 Best fit

Motivated by Eq. (5) and Figs 1, 3(b), 5(c) we fit the thermal energy confinement time in terms of the following variables:

$$\tau_{th}^{fit*} = c\ (a\kappa B)^{\alpha_{aB}}\ n^{\alpha_n}\ P^{*\alpha_P}\ q_{eng}^{\alpha_q} \qquad (6)$$

while imposing the Kadomtsev constraint, ensuring that Eq. (6) will give a "dimensionnally correct" scaling:

$$-\ \alpha_{aB} - 15\ \alpha_P - 8\ \alpha_n = 5 \qquad (7)$$

The best fit using Eqs (6-7) and no other constraints gives

$$\tau_{th}^{fit*} = 0.02976\ (a\kappa B)^{1.036}\ n^{0.459}\ P^{-0.647}\ q_{eng}^{-0.896} \qquad (8)$$

with an RMSE value of 15.5%, very close to the value of 15.8% for the IPB scaling, Eq. (1). We see that the linear dependence on (aBκ) is confirmed, as well as the inversely dependence on q_{eng} which we had to obtain as noted above. Therefore we propose to set $\alpha_{aB} = 1$ and $\alpha_q = 1$ in addition to Eqs. (6-7) and we obtain the following simple fit for the ELMy H-mode thermal confinement time:

$$\tau^*_{th,Best} = 0.0307\ \frac{(a\kappa B)\ n^{0.5}}{q_{eng}\ P^{*2/3}} \qquad (9)$$

which has an RMSE value of 16.0%.

This log-fit has only one free exponent, as α_n and α_P were free but Eq. (7) was imposed. It nevertheless has essentially the same RMSE value as the IPB scaling. Note also that this best fit in n,P* when written in "physics" parameters gives:

$$\tau^*_{th,Best} \sim \beta^{-0.5}\ \nu_*^0\ \rho^{-1} \qquad (10)$$

that is a gyro-Bohm scaling.

The ITER-EDA prediction using Eq. (1) gives $\tau_{EDA,IPB}$ = 6.34 s while Eq. (9) gives 6.20 s, even though the mass dependence has been ignored. We plot in Fig. 7(a) τ_{Exp} vs $\tau_{th,IPB}$, including the ITER point, setting $\tau_{ITER,Exp}$ = 6.34 s. In Fig. 7(b) we show the experimental τ_{th} vs the fit defined in Eq. (9). This shows that our simple fit is essentially as good as the IPB fit and that it has captured all the complicated dependencies involved in Eq. (1). As it gives the same prediction for ITER-EDA as the IPB scaling, its value lies only in its simplicity and in reducing drastically the number of free variables to only three (including the Kadomtsev constraint).

3.2 Bohm or Gyro-Bohm?

Another interesting question is if one can use a fit similar to Eq. (9) with an additional constraint on the ρ^* dependence of the fit in "physics" variables. In order to obtain a gyro-Bohm like fit one has to satisfy also:

$$- 9\,\alpha_{aB} - 30\,\alpha_P - 22\,\alpha_n = 0, \tag{11a}$$

and to have a Bohm like scaling one needs:

$$- 4\,\alpha_{aB} - 10\,\alpha_p - 7\,\alpha_n = 0. \tag{11b}$$

As discussed above our best fit is already gyro-Bohm as the exponents satisfy Eq. (11a).

Using Eqs (11b) and (7) one obtains a Bohm scaling. Keeping $\alpha_{aB} = 1$, it gives $\alpha_n = 0$ and $\alpha_P = 0.4$. The best fit with these values is obtained with α_q=-0.906, c=0.0853, RMSE = 25.4% and a prediction to ITER of 2.81 s. The fit is not as accurate and therefore one has to use the best fit for the Bohm scaling, using only Eqs. (6), (7) and (11b) which yields:

$$\tau^*_{th,BestBohm} = 0.0512\,\frac{(akB)^{0.9}\,n^{0.2}}{q_{eng}^{0.8}\,P^{*0.5}} \tag{12}$$

with RMSE = 24.3% and a prediction for ITER-EDA equals to 2.77 s. This fit is plotted in Fig. 8, which shows that even if the data points are relatively well aligned, the lower slope of the diagonal exhibits that the fit is too pessimistic for large scale experiments. However, it could be viewed as a lower bound and is actually close to the lower bound estimated in Ref. [1].

A legitimate concern of such scaling laws is if the resulting fit depends mainly on data points which are actually far from the predicted regime of ITER. First one does not know yet the main auxiliary heating scheme for ITER. Moreover, the heating profiles due to the alpha particles are quite different from the NBI heating used in present day experiments. This is why we show in Fig. 9(a) our best fit, Eq. (9), as in Fig. 7(b) but selecting only the points with electron or ion cyclotron heating. There are only 50 such data, as the fit is dominated by the NBI only heated plasmas (1273 data out of 1398). However Fig. 9(a) shows that the non-NBI shots are nevertheless close to the fitted value.

We have shown in Sec. 2 that the range of q_{eng}, P* and κ surround well the values expected for ITER. Moreover we noted that the confinement time might degrade when n/n_G is too close to one. Therefore we plot in Fig. 9(b) the data points which have these parameters close to the ITER-EDA values, namely:

$$\kappa > 1.5;\ P^* < 0.3;\ q_{eng} < 2.8 \text{ and } \frac{n}{n_G} > 0.5 \qquad (13)$$

which gives 135 pts, that is about 10% of the points. We see in Fig. 9(b) that the points are very well aligned with the fit (RMSE=11.1%), in particular and more importantly, the JET data points. Of course one obtains the same with the IPB scaling law (RMSE=10.4%). Figure 9(b) adds confidence in the fact that the fits obtained are not biased by data points outside ITER relevant parameters.

4 Modifying ITER parameters

Many parties are interested in slightly modifying the ITER-EDA design parameters such as to reduce its cost by about 30-40% while maintaining an operating space centered around $Q = P_{fusion}/P_{aux}$ = 20-30. It is out of the scope of this study to give self-consistent new parameters. However, in view of the plasma parameters of present experiments, as presented in Sec. 2, and of the simple scaling law given by Eq. (9), one can make a few suggestions.

The most important suggestion is certainly that the elongation should be increased to as much as the vertical feedback control allows it, ideally to as much as κ = 2-2.1 (edge value). On the MHD point of view we are very confident that there is no deviation from the Troyon scaling up to $\kappa \cong 2.2$ [7]. This was actually predicted in 1988 for TCV [9] and confirmed experimentally in 1997 [7]. Moreover there are many observations in the database which are between 1.8 and 2. Therefore no extrapolation is needed.

Let us define an enhancement factor $F \geq 1$ for the elongation κ:

$$\tilde{\kappa} = F\,\kappa \qquad (14)$$

Then we would like to reduce the cost without reducing too much the size, in order to stay in a reactor-like scale. Therefore one would rather reduce the magnetic field, as the supraconducting coils account for about 30% of the total cost of ITER. Therefore let us reduce B by F:

$$\tilde{B} = \frac{B}{F} \tag{15}$$

As we want to keep q_{eng} constant we need

$$\frac{B\, a^2 \kappa}{I\, R} = \frac{\tilde{B}\, \tilde{a}^2\, \tilde{\kappa}}{\tilde{I}\, \tilde{R}} \Rightarrow \tilde{a}^2 \sim \tilde{I}\, \tilde{R} \tag{16}$$

On the other hand as $\tau_{th} \sim (a\kappa B)$, one wants to reduce a as little as possible. One can have either $\tilde{a} = a/\sqrt{F}$ or $\tilde{a} = a/F$ as first simple trials.

This would lead to either

$$\begin{aligned} &\tilde{I} = I/\sqrt{F} \quad \text{and} \quad \tilde{R} = R/\sqrt{F} \\ \text{or} \quad & \\ &\tilde{I} = I/F \quad \text{and} \quad \tilde{R} = R/F \end{aligned} \tag{17}$$

The Greenwald density limit would then increase as $\tilde{n}_G = \sqrt{F}\, n_G$ or $\tilde{n}_G = F\, n_G$, respectively. This favourable dependence is due to the increase in κ. Due to the decrease in B, β_N will be the most restricting parameter. However, as in both cases,

$$\frac{\tilde{I}}{\tilde{a}\tilde{B}} = F\, \frac{I}{aB} \tag{18}$$

the pressure needs only to decrease as F rather than F^2. Altogether, one would have a relatively small decrease in confinement time with a strong decrease of B, thanks to the increase in κ. Using F = 1.16, this would lead to the following indicative parameters:

$\tilde{a} = a/\sqrt{F}$	$\tilde{a} = a/F$
$\tilde{\kappa}$ = 2.0	$\tilde{\kappa}$ = 2.0
$\tilde{B}$ = 4.91 T	$\tilde{B}$ = 4.91 T
$\tilde{a}$ = 2.60 m	$\tilde{a}$ = 2.42
$\tilde{R}$ = 7.57 m	$\tilde{R}$ = 7.04
$\tilde{I}$ = 19.53 MA	$\tilde{I}$ = 18.17 MA
$\tilde{q}_{eng}$ = 2.25	$\tilde{q}_{eng}$ = 2.25
$\tilde{n}_G = 9.2 \bullet 10^{19} m^{-3}$	$\tilde{n}_G = 9.9 \bullet 10^{19}\, m^{-3}$

Note also that q_{eng} can be reduced by 10%, a fortiori if κ is increased. The confinement time in both cases should be above 4.5 s, but a complete study needs to be carried out.

5. Conclusions

We have analyzed the range of variations in the ITER-HDB3 ELMy H-mode database of the main plasma parameters, "engineering" variables, used in the usual power scaling laws. We have shown that using $1/q_{eng}$ and $P^* = P_L/V$ enables one to capture the linear dependence on the plasma current and the main dependence on the major radius. Moreover, the predicted value of these two parameters for ITER-EDA, $q_{eng} = 2.25$ and $P^* = 0.1$ MW/m^3, are well within the range of the database values. Therefore, no extrapolation is needed in contrast when using I, P_L and R. Keeping a small dependence on the plasma density, we suggest to use only one main free parameter, $(a\kappa B)$, over which an extrapolation to ITER size experiments is needed. We find that a nearly linear dependence of τ_{th} on $(a\kappa B)$ gives the best fit. Imposing a linear dependence on $(a\kappa B)$ and on $(1/q_{eng})$, the best fit with only the n and P^* exponents as free parameters, satisfying the Kadomtsev constraint, yields (Eq. (9)):

$$\tau^*_{thBest} = 0.0307 \frac{(a\kappa B)\, n^{1/2}}{q_{eng}\, P^{*2/3}}$$

This fit gives essentially the same prediction as the IPB scaling. Moreover it is just as good as the IPB fit even though it has only three independent exponents instead of seven. Note that replacing q_{eng}, it can be rewritten as:

$$\tau^*_{thBest} = 0.00614 \frac{I_{MA}}{\varepsilon} \frac{n^{1/2}}{P^{*2/3}}$$

which exhibits better the main extrapolation in current.

This scaling in "physics" variables goes as $\beta^{-0.5}\, \nu^0_\alpha\, \rho^{-1}_\alpha$, that is a gyro-Bohm like scaling. It does also capture the small β and ν_* dependence as the one obtained from recent experiments [10, 11]. Imposing a Bohm-like scaling gives a fit with a much larger RMSE value and which is below almost all the JET results. However, it gives a lower bound value for the ITER prediction of about 3 s, similar to the lower limit given in Ref. [1].

Finally, the range of values of κ in the database, the linear dependence of τ_{th} on ($a\kappa B$), at fixed q_{eng}, and the strong agreement of ideal β limits calculations in highly elongated plasmas with experiment strongly suggests to increase the design κ. The κ_{edge} value can easily go up to 2 and the vertical control should be accommodated as such. This will enable to reduce the magnetic field, for example, without great loss of performance. It may avoid a too large reduction in size in order to decrease the cost.

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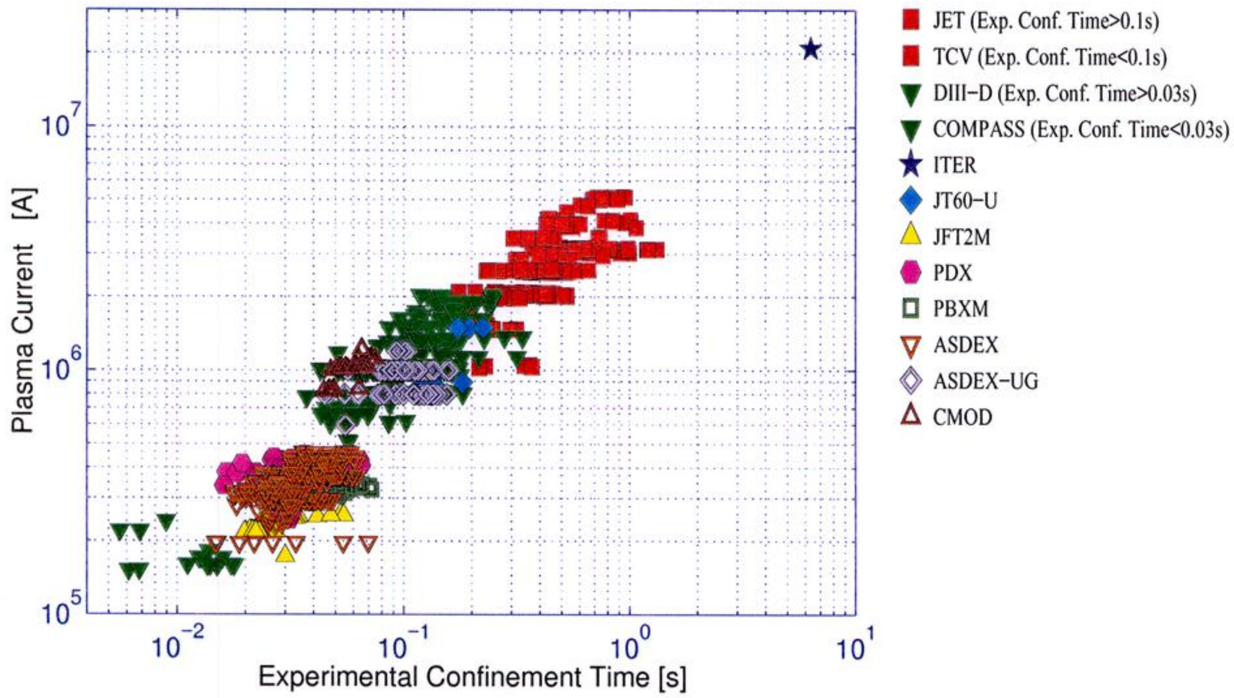

Figure 1: Plasma current, I_p [A], vs. experimental confinement time $\tau_{th,exp}$ from the ITER-HDB3 ELMy H-mode database - 1398 points -. The ITER value for $\tau_{th,exp}$=6.34 s is taken from the IPB scaling, Eq.(1), using the EDA design parameters, Eq.(3).

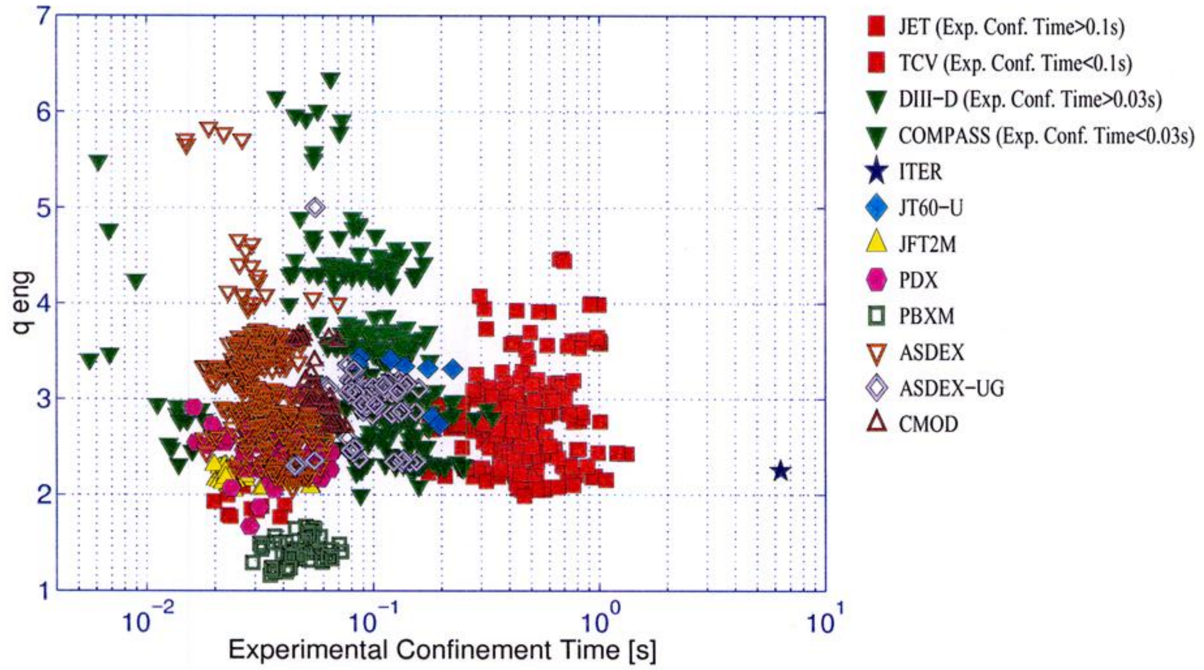

Figure 2: Same as Fig.1, but for $q_{eng} = 5\ B\ a^2\ \kappa\ /\ (\ I_p\ R\ )$ vs. $\tau_{th,exp}$.

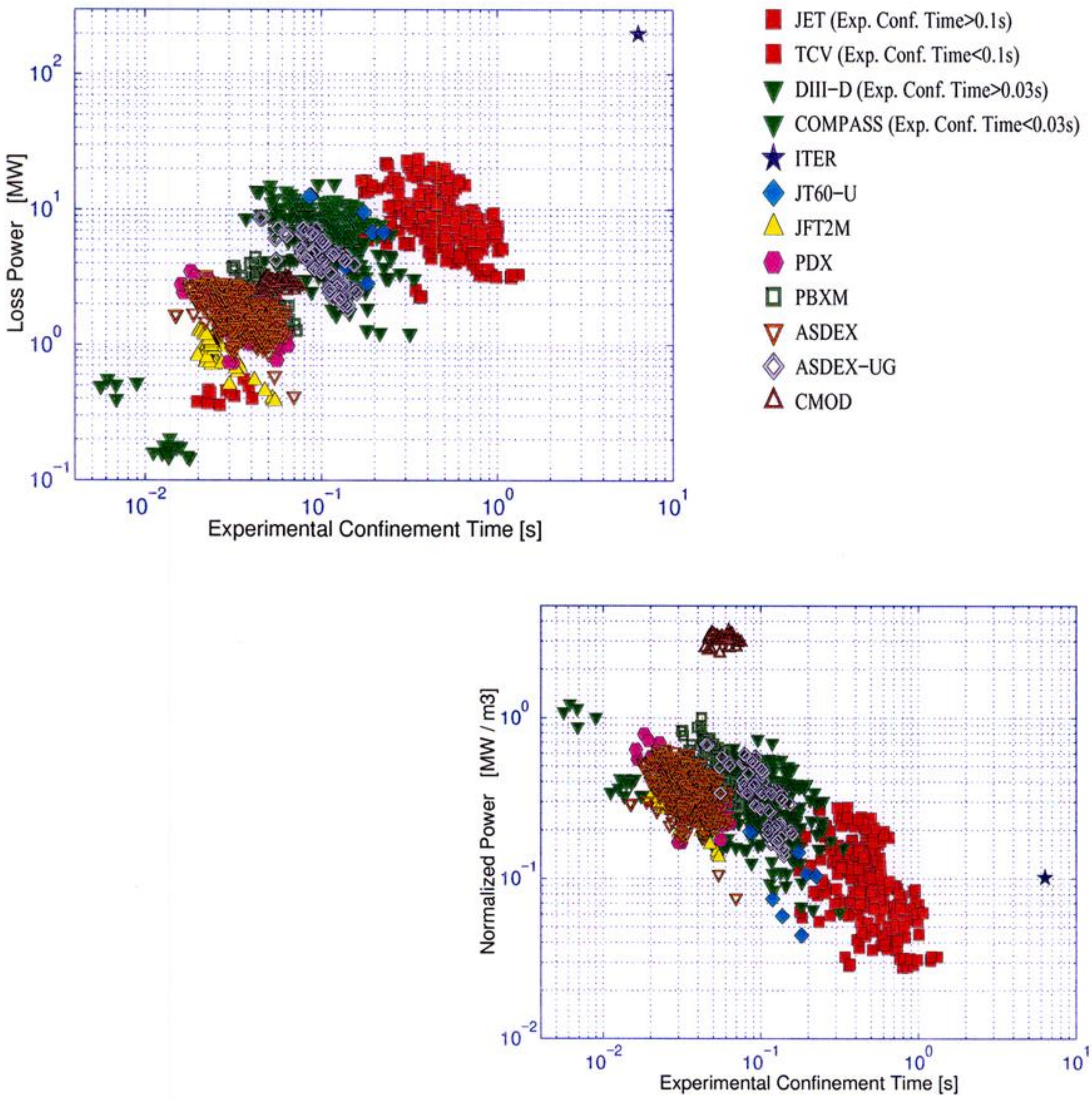

Figure 3:

a) Same as Fig.1, but for the loss thermal power $P_{LTH} = P_{tot} - dW_{th}/dt$ [MW] vs $\tau_{th,exp}$.
For ITER the radiated power is also substracted from P_{LTH} yielding P_{LTH}=200MW.

b) Same as Fig.1, but for $P^*=P_{LTH}$ / Volume [MW/m^3] vs $\tau_{th,exp}$.

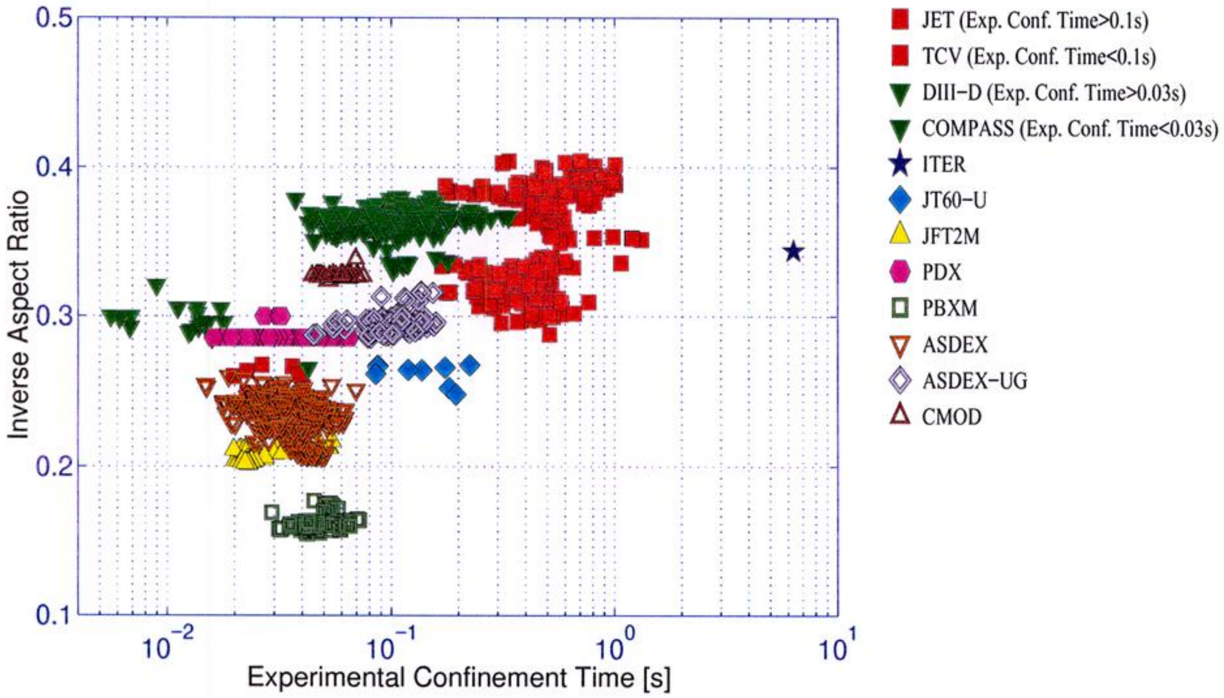

Figure 4: Same as Fig.1, but for the inverse aspect ratio $\varepsilon = a/R$ vs $\tau_{th,exp}$.

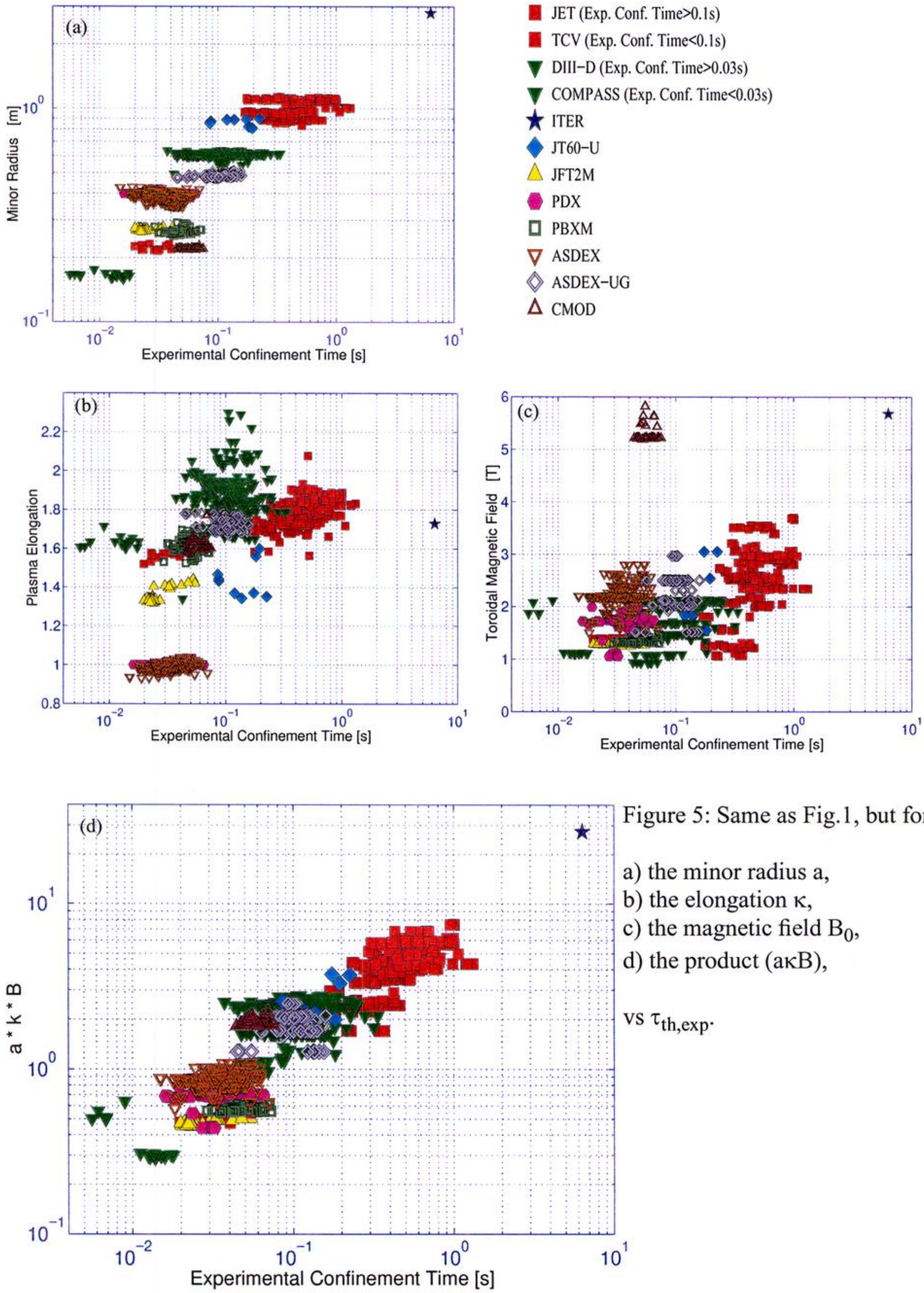

Figure 5: Same as Fig.1, but for:

a) the minor radius a,
b) the elongation κ,
c) the magnetic field B_0,
d) the product (aκB),

vs $\tau_{th,exp}$.

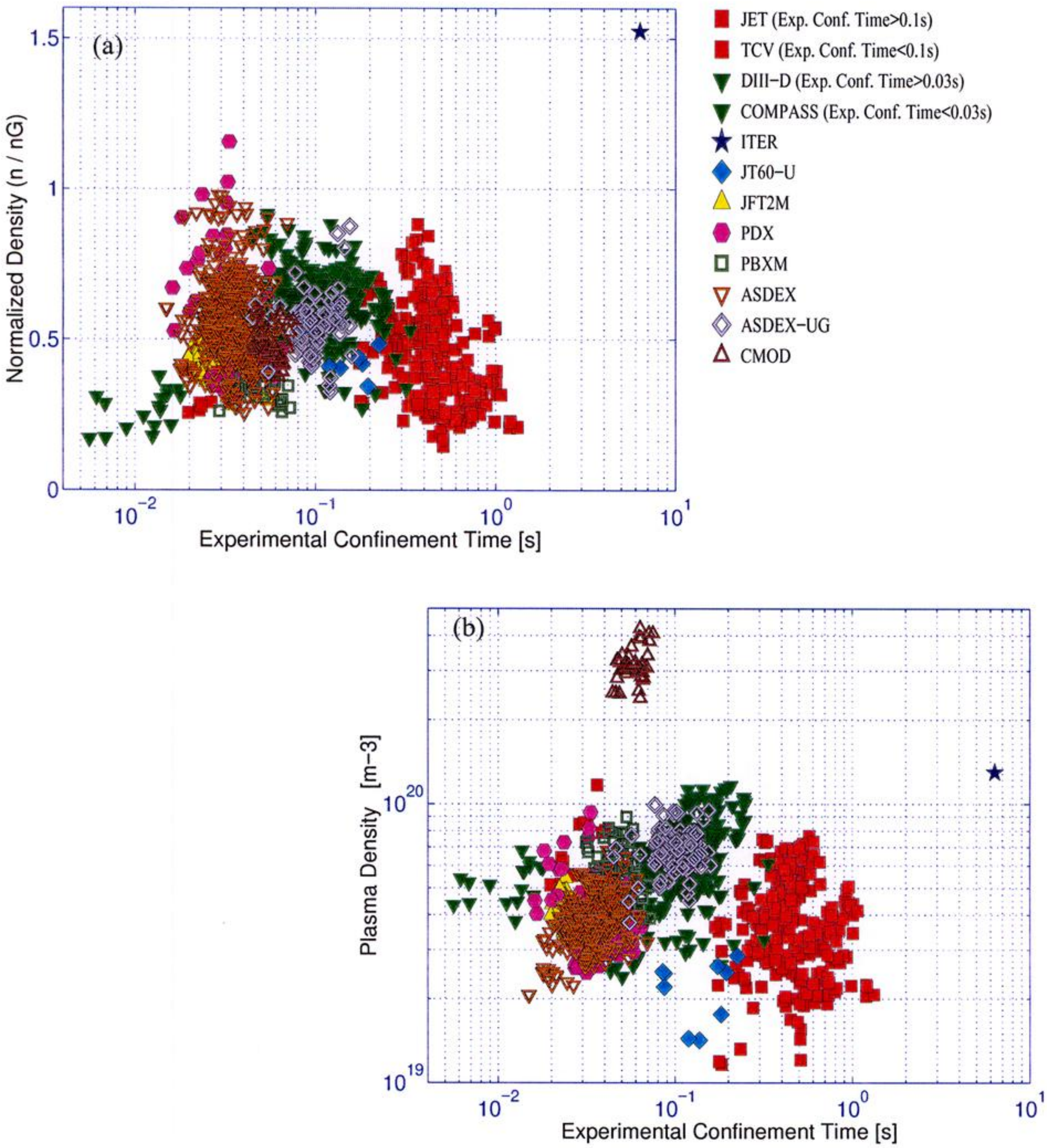

Figure 6: Same as Fig.1, but for

a) the line averaged electron density normalized to the Greenwald density $n_G = I_p / (\pi a^2)$ $[10^{20} m^{-3}]$,

b) the line averaged electron density,

vs $\tau_{th,exp}$.

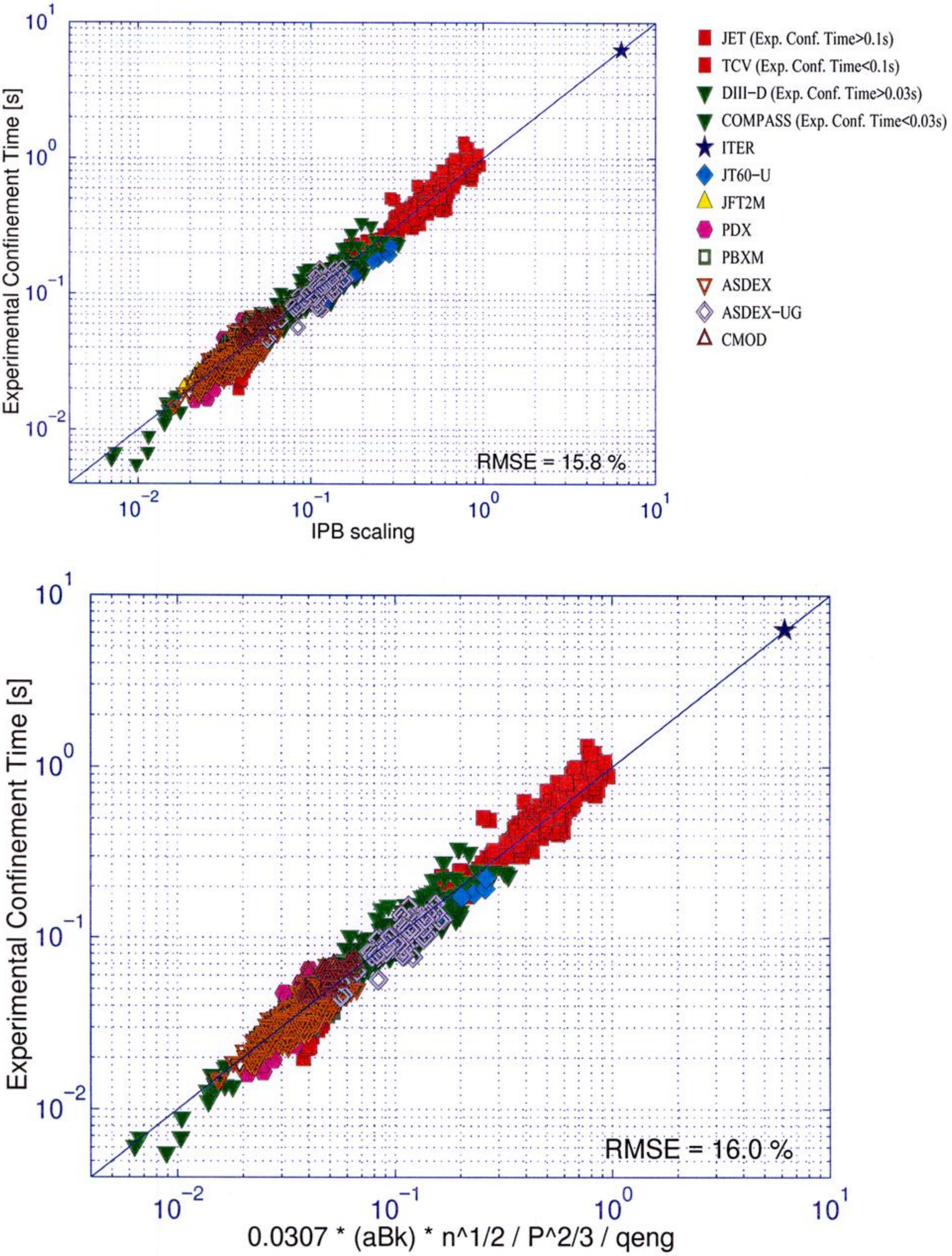

Figure 7: Experimental confinement time, $\tau_{th,exp}$ vs. (a), τIPB, obtained from the IPB scaling law, (b) tqP* obtained from the scaling law given in eq.(9).

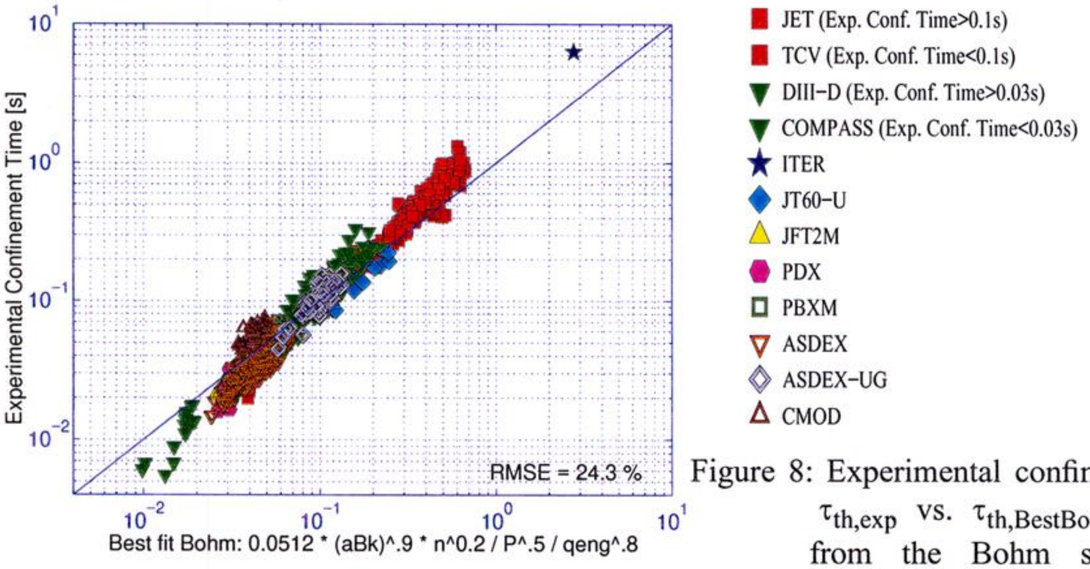

Figure 8: Experimental confinement time, $\tau_{th,exp}$ vs. $\tau_{th,BestBohm}$ obtained from the Bohm scaling law, eq.(12).

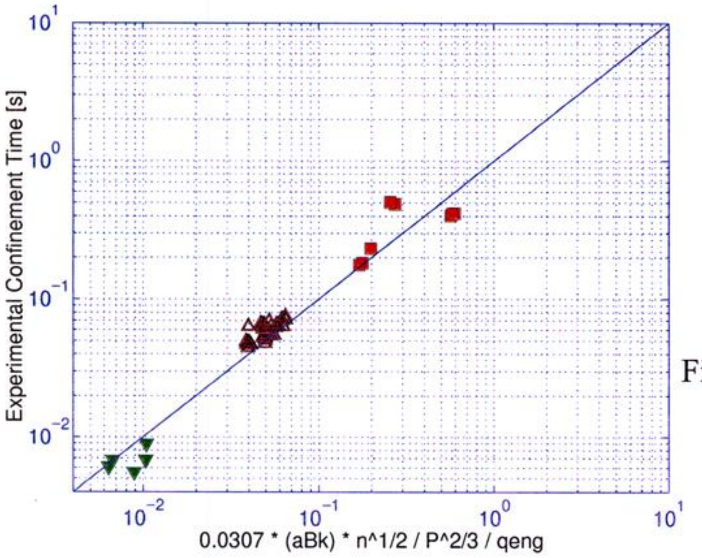

Figure 9(a): Same as in Fig.(7b) but for the data obtained with only ICRF and/ or ECRF auxiliary heating.

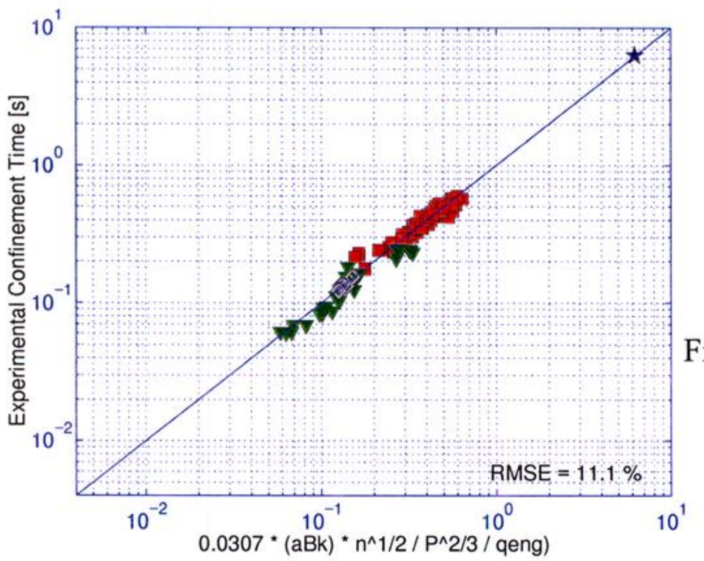

Figure 9(b): Same as Fig.(7b) but showing only data satisfying the conditions of eq.(13). Those are points close to the ITER-EDA parameters.