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Power requirement for accessing the H-mode in ITER

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Abstract. The input power requirements for accessing H-mode at low density and maintaining it during the density ramp in ITER is addressed by statistical means applied to the international H-mode threshold power database. Following the recent addition of new data, the improvement of existing data and the improvement of selection criteria, a revised scaling law that describes the threshold power required to obtain an L-mode to H-mode transition is presented. Predictions for ITER give a threshold power of ~52MW in a deuterium plasma at a line average density $n_e = 0.5\times10^{20}\text{m}^{-3}$. At the nominal ITER H-mode density, $n_e = 1.0\times10^{20}\text{m}^{-3}$, the threshold power required is ~86MW. Detailed analysis of data from individual devices suggests that the density dependence of the threshold power might increase with the plasma size and the magnetic field. On the other hand, the density at which the threshold power is minimal is found to decrease with the plasma size and increase with magnetic field. The influence of these effects on the accessibility of the H-mode regime in ITER plasmas is discussed. Analyses of the confinement database show that, in present day devices, H-modes are generally maintained with powers exceeding the threshold power by a factor larger than 1.5, and that, on the other hand, good confinement can be obtained close to the threshold power although rarely demonstrated.

1. Introduction

Transitions from a standard confinement mode (L-mode) to an improved confinement regime (H-mode), called L-H transitions, are observed in most tokamaks. Although progress is being made in understanding the physics underlying L-H transitions, the lack of model based predictions for ITER leads to the requirement of extrapolations from present-day devices.

The international H-mode threshold database (DB) collects data from the widest possible range of tokamaks to provide a statistical approach to the L-H transition studies. The current version of the DB is populated by 7700 time slices from 14 tokamaks. Several time slices, recording values taken just before the L-H transition and labelled accordingly, are used in the statistical analysis of the threshold power such as the evaluation of an expression in the form of a power law scaling. The scaling law is then used to estimate the threshold power in ITER. The DB also contains data taken during the L-mode or H-mode phases, or at the transition from H-mode back to L-mode (H-L transitions). These data can be used, for instance, to characterise the power required to stay in the H-mode.

Although known to depend on many parameters, it is widely accepted that the L-H transition threshold power strongly depends on the plasma density, toroidal magnetic field and plasma size. A series of power law scalings, estimating the threshold power on the basis of these parameters, were published following the evolution of the DB content [1, 2, 3, 4, 5, 6]. More recently, new data from spherical tokamaks (MAST and NSTX) have widened the parameter ranges allowing for the analysis of the effect of the aspect ratio [7, 8]. On the other hand, other dependences were searched in the goal of reducing the uncertainty in the power law coefficients [9], but with limited success. Therefore, an alternative approach has been considered consisting of the extraction of power law coefficients from a reduced dataset including only ITER-like conditions [5]. For the scaling analysis of the H-mode energy confinement time, a similar approach using the ITER-like subset of the database was accomplished [8, 10].

The estimated power law scalings of the L-H transition threshold power are used to predict the power requirement, for a new device such as ITER, to enter the H-mode. The predicted power should allow the access to the H-mode but, if the power remains close to the threshold power value, the discharge would generally remain in a regime with type III Edge Localised Modes (ELMs) according to the widely accepted picture of the different ELM type characteristics [11]. This ELMy regime is characterised by only a moderate increase in the energy confinement time compared to the L-mode regime. Good confinement values, those used in the energy confinement time scalings for instance, are generally obtained when the power is significantly larger than the threshold to reach a type I ELM regime. Therefore, the power required to achieve a good confinement in ITER might then be larger than that estimated by the scaling law. The overall description of the behaviour is complicated by the power reduction due to the hysteresis effect. Indeed, once in the H-mode the required power to keep the same plasma conditions is reduced since the energy confinement time increases. This has been clearly seen for the Ohmic H-mode transition, where the loop voltage and Ohmic heating power P_{OHM} drop sharply [12]. For the additional heating cases, the net power through the plasma surface, $P_{\mathrm{L}} = P_{\mathrm{OHM}} + P_{\mathrm{abs}} - \mathrm{d}W/\mathrm{d}t$, is reduced after the L-H transition because the growth of the stored energy W becomes more rapid than that before the transition.

The paper addresses these issues within the following structure: in section 2, the scaling obtained with a reduced data set is presented followed by the effect of the most recent contributing device, CHS, in section 3. Individual density dependences of the threshold power for several devices are considered in section 4. In section 5 the way in which the critical density for minimum threshold power is related to device size and magnetic field is explored. Then section 6 discusses the issue of the power required in stationary phase in H-mode regimes with good confinement properties in all devices. All results are discussed and summarised in terms of predictions for ITER in section 7.

2. Threshold power estimation

Since the last paper published at the IAEA Fusion Energy Conference in 2004 [8], the main modifications to the International Global Threshold DataBase (IGDBTH) have been the addition of new time slices (ts), corrections of existing ts and improvement of the selection criteria. New ts have been provided by NSTX, JFT-2M and CHS teams. The DB now contains 7700 ts taken during the different phases of the discharges evolution: L-mode (2357 ts), L-H transition (2667), H-mode (2268), H-L transition (404). It includes contributions from: Alcator C-Mod (1227 ts / with 334 ts at L-H transition), ASDEX (600/122), ASDEX Upgrade (636/237), CHS (6/6), Compass-D (46/30), DIII-D

(752/178), JET (3111/1291), JFT-2M (1019/241), JT-60U (109/81), MAST (20/20), NSTX (13/11), PBXM (5/5), TCV (131/94), TUMAN-3M (15/15). Corrections were applied to ASDEX-Upgrade data (injected power, absorbed power) and Alcator C-Mod data (absorbed power, plasma density, ion grad B drift direction).

A new selection criteria (SELEC2007) has been defined to select ITER like plasmas only from the DB. This was done with the aim of reducing the uncertainty in the threshold power scaling coefficient estimation. It is based on the selection criteria SELDB2 [1], made on a series of 10 binary conditions, which selects single null configurations (except PBX-M) with ion grad B drift towards the X point, deuterium plasmas, and rejects ts with too low plasma density (Alcator C-Mod: n_{e20}(unit of 10^{20}m^{-3}) < 0.8, ASDEX Upgrade: $n_{e20} < 0.2$, DIII-D: $n_{e20} < 0.2$, JET: $n_{e20} < 0.1$, JFT-2M: $n_{e20} < 0.2$, JT-60U: $n_{e20} < 0.1$), too low safety factor at the 95% flux surface ($q_{95} < 2.5$), too close to the beginning of heat pulse, too large counter-NBI fraction ($P_{ctr}/P_{NB} > 0.8$), too small gaps between plasma surface and wall (d < 5 cm), too high radiation losses ($P_{rad}/P_L > 0.5$). SELEC2007 furthermore rejects transitions obtained in Ohmic conditions since they are not relevant for ITER and also rejects Electron Cyclotron only heated discharges since this heating scheme, mainly used in small devices, regularly leads to high threshold power values (as far as the present database displays). Note that the prediction of the threshold power for ECRH in ITER is allowable with the present scaling because the equalization between T_e and T_i can be established in large devices. Configurations different from single null and plasma elongation lower than 1.2 have also been rejected.

Applying this selection criteria, one obtains the following distribution: Alcator C-Mod (115 ts), ASDEX Upgrade (175 ts), DIII-D (56 ts), JET (562 ts), JFT-2M (58 ts), JT-60U (58 ts). The large fraction of JET data sometimes plays like a fulcrum for the extrapolation to ITER.

The H-mode threshold power is known to depend on the plasma density, magnetic field and plasma size. Two descriptions of the plasma size have been used so far, the couple of major and minor plasma radii and the plasma surface area. The latter comes from threshold studies in ASDEX [13] and DIII-D [14] while the former is more appropriate to describe the effect of the aspect ratio. This description however is not useful in the frame of this study since the aspect ratio covers a rather limited range in the selected ITER like plasma configurations. A power law scaling, including the line average plasma density, the magnetic toroidal field and the plasma surface area, is then used for fitting the experimental threshold power more precisely defined as the loss power P_L which equals the sum of the ohmic power P_{OHM} and absorbed power P_{abs} minus the time variation of the total plasma energy dW/dt, minus the power loss by fast ions due to unconfined orbits and charge-exchange processes:

$$P_L = P_{OHM} + P_{abs} - \mathrm{d}W/\mathrm{d}t - P_{Floss}\ . \quad (1)$$

Fitting the power law expressions via their corresponding logarithmic expressions in the least square sense over the 1024 ts data set leads to the following expression:

$$P_{Thresh} = 0.0488\ \mathrm{e}^{\pm 0.057}\ n_{e20}^{\ 0.717\pm 0.035}\ B_T^{\ 0.803\pm 0.032}\ S^{0.941\pm 0.019}\ , \quad (2)$$

where P_{Thresh} is the threshold power expressed in MW, n_{e20} the line average electron density in 10^{20}m^{-3}, B_T the magnetic field in T and S the plasma surface area in m^2. The uncertainties in the exponents correspond to the standard errors and the RMS value of the fit is 30.8%. This expression was estimated without the Kadomtsev constraint, but the resulting exponents almost verify it: if the density and magnetic field exponents were considered as correct ($\alpha_n = 0.717$ and $\alpha_B = 0.803$), the surface area exponent α_S would be 0.844 to satisfy the dimensionality of the expression; $8\alpha_n + 5\alpha_B - 8\alpha_S = 3$.

Another fitting expression with the use of the minor radius a (m) and the major radius R (m) instead of the surface area S is also obtained as follows:

$$P_{Thresh} = 2.15\ \mathrm{e}^{\pm 0.107}\ n_{e20}^{\ 0.782\pm 0.037}\ B_T^{\ 0.772\pm 0.031}\ a^{0.975\pm 0.08}\ R^{0.999\pm 0.101}\ . \quad (3)$$

The RMS value of this fit is 29.5%. The reduction of the RMS value can be brought by the increase of the fitting parameters [4]. Because this reduction is only a little, we use hereafter the former expression with minimum fitting parameters (n_e, B_T and S) as a basic scaling.

The predictions for ITER are expressed in table 1, for 2 values of the plasma density while the magnetic field and surface area values are 5.3T and 678m^2, respectively. At the beginning of its operation ITER will have 73MW of additional power. This table indicates that entering the H-mode at low density of deuterium discharges should certainly be possible, but H-mode access at higher density might become marginal.

Table 1. Threshold power predicted by the scaling (2) and 95% confidence interval for ITER at two different densities of deuterium discharges.

Density [10^{20}m^{-3}]	Predicted threshold power [MW]	95% confidence interval [MW]
0.5	52	28 - 96
1	86	46 - 160

The above scaling expressions are obtained from the data of deuterium discharges and of deuterium plasmas heated by hydrogen beam. The latter plasmas are considered to consist mainly of deuterium at the L-H transition. It is widely known that the L-H transition occurs easily at a lower heating power in deuterium discharges than in hydrogen discharges. It is also found in JET that the threshold power in tritium discharges becomes further lower. The dependence of the threshold power on the ion mass number M was roughly given by $P_{\mathrm{Thresh}} \propto 1/M$ [15]. When this mass dependence is applied to the deuterium-tritium discharges for ITER, the above predicted values of P_{Thresh} can be reduced by ~ 20%.

3. Effect of CHS data

CHS is a compact, low aspect ratio, helical system with a major radius, R ~ 1m [16]. In neutral beam heated discharges, H-modes have been obtained after the formation of an edge transport barrier (ETB). Many similarities with H-modes in tokamaks were found in this helical device such as the presence of a threshold power which depends on the plasma density, magnetic field and magnetic configuration [17]. Six time slices from CHS have been included in the DB. These discharges were performed in hydrogen. The experimental threshold power value, P_L, is compared to the estimation done with the scaling (2), P_{Thresh}, as shown in figure 1. CHS data, represented by crosses, lie significantly above the scaling line. Even when their values are reduced by half in accordance with the possible mass dependence, they are still larger than the scaling. It is worth noting that these points lie close to those from MAST and NSTX, the spherical tokamaks of the DB, while the tokamak data, used for evaluating the power law scaling, are obviously found closer to the scaling line. It was suggested that the lower aspect ratio or the lower untrapped-particle fraction could increase the threshold power [7]. The data of CHS and the spherical devices, though they are not taken into account to establish the present scaling, might help the understanding of the global behaviour of the H-mode accessibility. This remains for the future work.

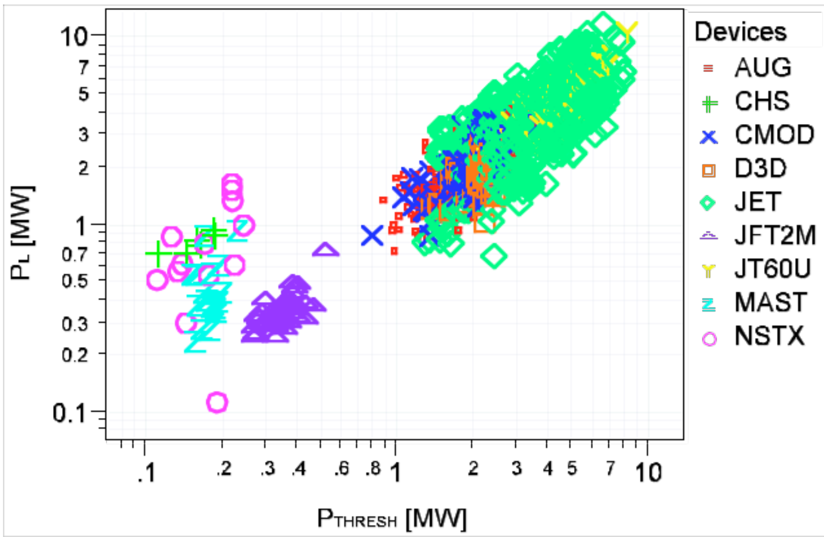

Figure 1. Actual versus fitted threshold power for tokamak time slices used in the fit (Alcator CMod, ASDEX Upgrade, DIII-D, JET, JFT-2M, JT-60U). In addition, spherical tokamaks and helical system threshold power are superimposed to show their distance to the fit (MAST, NSTX, CHS).

4. Individual density dependence

The density dependence of the threshold power plays an important role in the predictions for ITER since its planned density range will be rather large. It is currently envisaged that an H-mode in ITER will be accessed via an L-H transition at low density, followed by a ramp to the vicinity of the Greenwald density limit, while relying on possible hysteresis in power to maintain the H-mode since the power available at the beginning of ITER's operation will remain below the estimated threshold power at high density. With a mild density dependence of the threshold power the hysteresis effect might be sufficient to maintain the plasma in H-mode while the density is increased. However, if the threshold power strongly depends on the density, the hysteresis effect might not be sufficient to maintain the H-mode or even less to access good confinement. The auxiliary input power could fall below the H-L transition level as P_{Thresh} increases with density causing an H-L transition. Detailed studies of fitting residuals and recent results from individual devices revealed that the density dependence in individual devices might differ from the average dependence obtained in the global fit [18, 19]. Therefore, the density dependence is now analysed for each device, from the data contained in the threshold DB.

The density dependence was evaluated by fitting the threshold power with the plasma density and magnetic field for each individual datasets, with the same selection criteria as before, assuming that the plasma surface area S does not vary significantly for one device. The obtained density dependences show some increase with the plasma size. Alcator C-Mod data with high B_T demonstrate a strong density dependence despite its relative small size indicating an additional magnetic field influence. These density exponents α_n are shown in figure 2 as functions of (a) the plasma minor radius a and (b) the product of a and B_T, where the different symbols correspond to different values of the magnetic field for different devices as indicated in the legend. The error bars indicate the uncertainty in the exponents obtained from the fit. One can see that the gentle increase in density exponent with plasma size and magnetic field emerges over the uncertainty range.

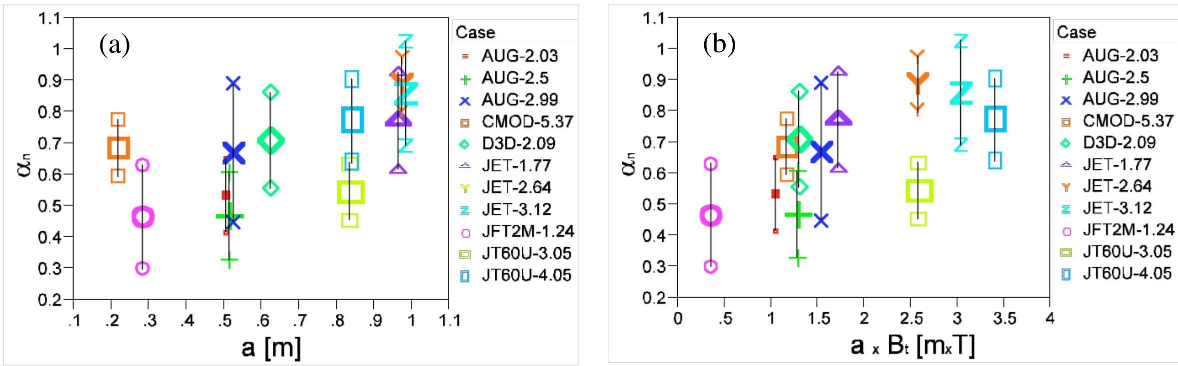

Figure 2. Dependence of density exponent α_n in P_{Thresh} on (a) the plasma minor radius a and (b) the product of a and B_T, for different devices and magnetic field values as indicated in the legend under the form 'device'-'toroidal magnetic field in T'.

Since ITER has a large radius and will operate at a high magnetic field, a strong density dependence might be expected. Extrapolations from the dataset of figure 2 lead to a density exponent of 1.3 for ITER at its nominal toroidal field value (B_T = 5.3T), with an RMS value of 10%. This estimation has to be compared to the global fit value of ~0.75. Although this new estimation of α_n = 1.3 might contain a large uncertainty, the threshold power is predicted to reach 135MW at n_e = 1.0×10^{20}m^{-3}, instead of the ~90MW prediction based on the global scaling. The pivot for the calculation of the high density case is fixed at the low density value (0.5×10^{20}m^{-3}) because this point approximately corresponds to the overall average density value of full selected dataset.

One of the reasons of the increase of density exponent for large devices was supposed that the edge density n_e^{edge} increases rapidly with the increase of the averaged density n_e, such as $n_e^{edge} \propto n_e^{1.4}$, and as a result the threshold power governed by n_e^{edge} could increase rapidly with n_e; $P_{Thresh} \propto (n_e^{edge})^{0.7} \propto n_e^{1.0}$ [18]. On the other hand, it has been reported that the density becomes peaked with the decrease of collisionality [20]. In the ITER plasma, the collisionality will be much lower than the present plasmas and n_e^{edge} cannot rapidly increase compared with n_e. This means that the density exponent is expected to remain ~0.7 without increasing up to ~1.3. From the above considerations, uncertainty in the prediction, P_{Thresh} = 46 - 160MW at n_e = 1.0×10^{20}m^{-3}, is really to be taken into account for the planning of ITER operation.

5. Density at the minimum threshold power

Most devices have observed the presence of a minimum in the threshold power as a function of the plasma density [21 and references therein]. This reference indicates that the minimum threshold is found at very low edge density (~0.1×10^{20}m^{-3}) in JET. In contrast, Alcator C-Mod results show that, at their high magnetic field values, the density of the minimum threshold power rises up to 0.8-1.0 $\times10^{20}$m^{-3} [22]. Since ITER will operate at high field as well, the access to the H-mode at low density might be an issue. The threshold power DB is analysed to search for a global picture of the minimum threshold density in all devices.

For each device having data used for the global scaling (Alcator C-Mod, ASDEX Upgrade, DIII-D, JET, JFT-2M and JT-60U), one takes all L-H transition data since the absolute minimum is the interesting value. Then, for each device, a series of datasets were selected, all presenting a concentration of time slices around a particular value of magnetic field. In all these data sets, one takes the average density (and its standard deviation) of the 10 time slices with the lowest threshold values. An example for JET is given in figure 3.

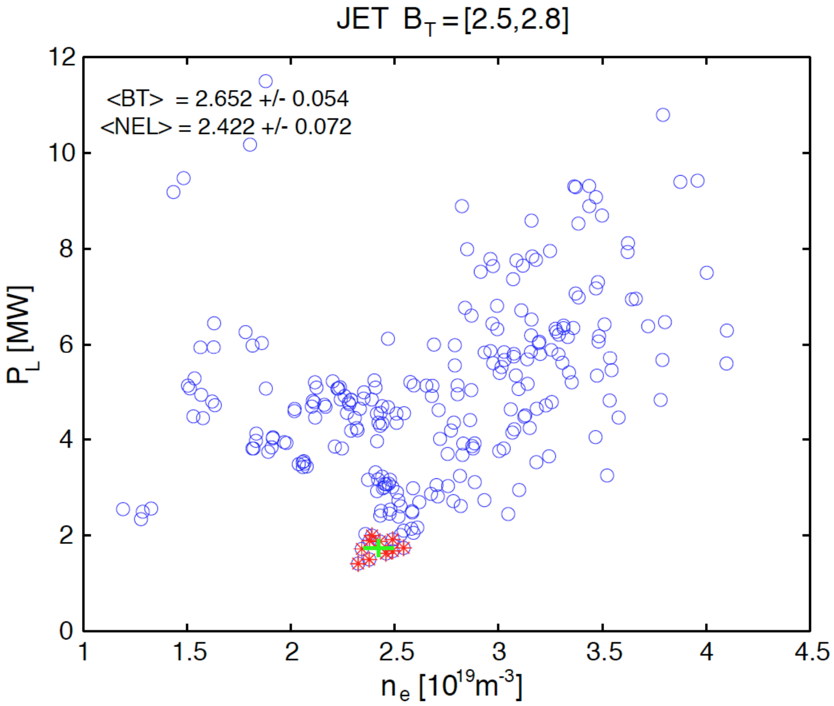

Figure 3. Threshold power as a function of plasma density n_e for JET data with toroidal field B_T in the range 2.5 - 2.8T. Red stars indicate the tens points with lowest threshold power, whose average value of B_T and n_e are shown at the left top corner.

Hence, for each device, a series of density values indicates where the threshold power is minimum for a given magnetic field value, as shown in figure 4 (a). The length of the segments represents one standard deviation each side of the average value. This figure then shows, for instance, that the minimum threshold power in Alcator C-Mod is obtained when the density is slightly greater than $1.0\times10^{20}m^{-3}$ for magnetic field value of 5T. On the contrary, the minimum threshold power is obtained at a rather low density in JET over the full range of available magnetic field values (1-3T) even if it gently increases with the magnetic field. JT-60U shows similar values at an even higher magnetic field. Smaller devices, ASDEX Upgrade and DIII-D also show a gradual increase of the density at minimum threshold with the magnetic field but the density remains much smaller than in the Alcator C-Mod case. The data for B_T = 2 - 3T appear to indicate that the larger the machine (JET and JT-60U) is the smaller the density for the minimum threshold power is, but ongoing joint ITPA experiments are still trying to assess this point. Next, we examine these density values by normalizing the Greenwald density limit n_{GW} ($10^{20}m^{-3}$) = $I_p/\pi a^2$ (MA/m^2). Figure 4 (b) shows that they lie in the range, $0.2 < n_e/n_{GW} < 0.4$. One might then expect that entering the H-mode at low density in ITER (n_e = $0.5\times10^{20}m^{-3} = 0.42n_{GW}$) is possible even at the full toroidal magnetic field B_T = 5.3T and plasma current I_p = 15MA.

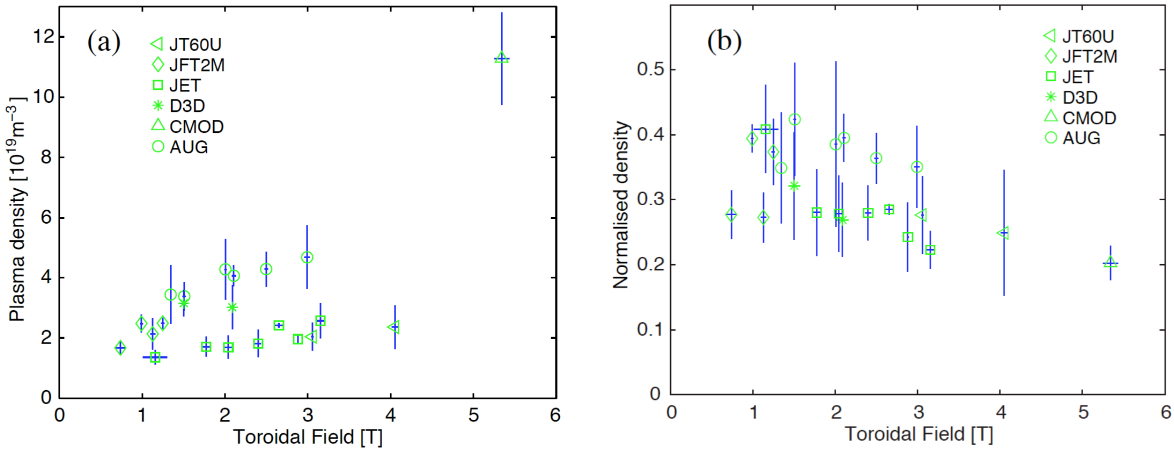

Figure 4. (a) Averaged density n_e and (b) Greenwald density ratio n_e/n_{GW} at which threshold power is minimum as a function of the toroidal magnetic field B_T for a series of tokamaks. The error bars indicate one standard deviation around averaged values along both axis.

6. Access to an H-mode with good confinement properties

The threshold power values predicted for ITER correspond to the power required to enter the H-mode but not necessarily to the power required to obtain a good H-mode in the sense of H-mode having a significantly improved confinement or, equivalently, the H-factor, $H_{IPB98(y2)}$ based on the IPB98(y2) [2] scaling, larger or equal to unity. From the operational point of view, H-modes with $H_{IPB98(y2)} \geq 1$ are often obtained when the power is still increased from the threshold value to leave the type III ELM regime to reach the ELM free regime and then the type I ELM regime [11, 23], for instance, or a grassy ELM regime [24]. Although the threshold database contains data in the H-mode phase, the time slice labelling does not allow us to select time slices at the transition between different H-mode regimes and then analyses similar to the threshold power fitting are excluded. However, the ratio between the actual power and the threshold power, estimated at the same time, can give some indication of the power used to maintain this regime. It then describes the operational range instead of the threshold and, accordingly, can be as high as desired by the operator although limited by the available power. The confinement DB, which contains data from most operational regimes obtained in the contributing devices, is available to study this issue. A result of brief analysis has suggested that good confinement can be obtained in H-mode even for the heating power lower than the threshold power [6]. In the present paper, we expand the analysis by using the most recent version IGDBH4v4 [25].

The distribution of the power ratio for 4 devices considered in previous sections and for the time slices which have been selected for the energy confinement time studies (HMWS05 = 1) in the confinement DB are shown in figure 5. These histograms include time slices with either small or large ELMs (PHASE = HSELM or HGELM). Table 2 indicates the number of time slices for each of these devices, together with the average power ratio.

Table 2. Power ratio (actual input power divided by threshold power estimated at the same time) and number of time slices for different devices.

Tokamak	Number of time slices	Average power ratio
Alcator C-Mod	31	0.88
ASDEX Upgrade	509	1.93
DIII-D	264	2.61
JET	1487	1.68

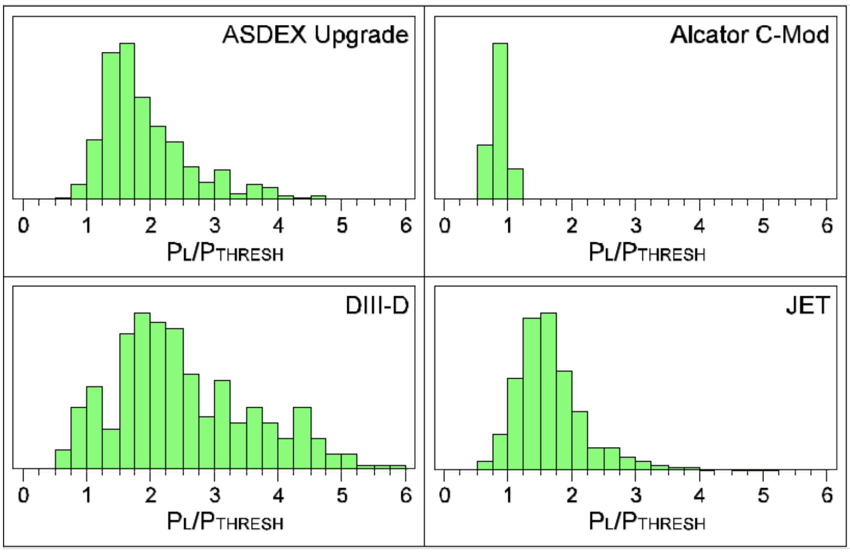

Figure 5. Distribution of power ratio P_L/P_{Thresh} for 4 devices.

Alcator C-Mod clearly benefits from the hysteresis effect, since the average value of the power ratio is smaller than 1. However, the largest population resides between 0.75 and 1.0 and is somewhat larger than the ratio of one half as presented in [4]. In the other devices the average ratio is significantly larger than 1, closer to 1.5 or even 2.5 for DIII-D. Detailed analysis of ASDEX Upgrade data can be found in [26]. In these figures, all ELM types are taken together. As already stated, Type I ELMs are expected to be found at higher power ratio. Unfortunately, ELM types are defined as 'small' or 'large' in the DB. It is not sure but probable there exists correlation between 'small' and Type III on one hand and between 'large' and Type I on the other hand. Anyway, the average power ratio for both ELM classes taken individually does not show significant differences in all devices. This result is confirmed by the relationship between the H-factor, based on the IPB98(y2) [2] scaling, and the power ratio, as shown in figure 6 where green dots correspond to 'large' ELMs and red dots to 'small' ELMs. Indeed, this figure shows that good confinement properties might be obtained at a power ratio close to unity, for both ELM types and on the other hand that increasing the power much over the threshold does not simply guarantee a good confinement. However, most devices currently operate with much more power, compared to the H-mode threshold power than what ITER might be doing. It is therefore mandatory to explore regimes with power closer to the threshold power. On the other hand deeper analysis of the confinement DB might give some results. Such analysis will be presented in a future paper.

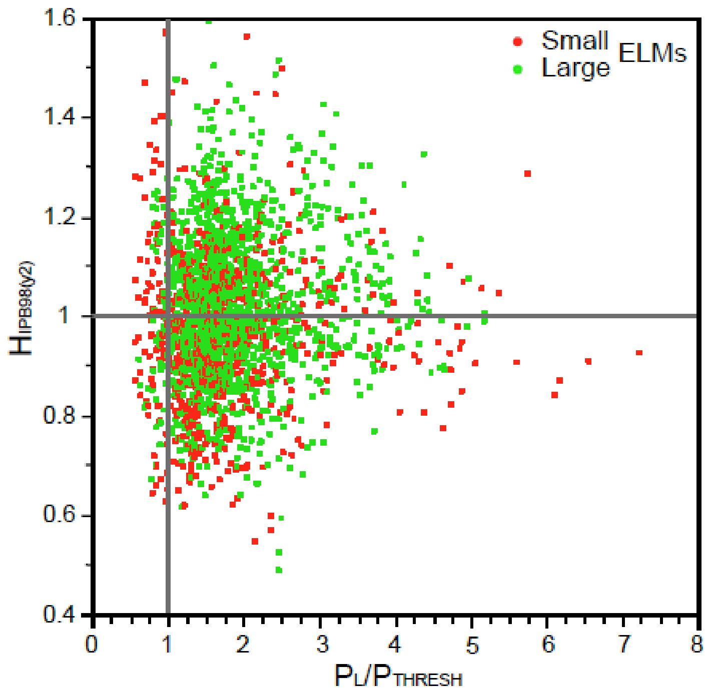

Figure 6. Confinement improvement factor ($H_{IPB98(y2)}$) vs the power ratio P_L/P_{Thresh}. Symbols in the upper left quadrant represent data with good confinement properties obtained at power values below the threshold power of the L-H transition.

7. Conclusion and discussion

New data have been provided to the threshold power database, as well as some modifications to the Alcator C-Mod and ASDEX Upgrade existing data sets. Improvements in the selection criteria have also been made. These changes lead to a new power law scaling expression in which the density dependence is approximately equal to 0.7. With this scaling, the threshold power in low density (n_e = $0.5\times10^{20}m^{-3}$) deuterium plasmas for ITER is estimated at 52MW while at the nominal density of n_e = $1.0\times10^{20}m^{-3}$, it rises to 90MW.

The selection criteria used in these analyses rejected most of small devices in which the threshold power is quite high compared with existing scaling laws [3, 4, 5, 6, 7, 8, 9]. Removing small devices with high threshold power leads to higher predicted values for ITER, through the leverage effect, and, also, to higher uncertainty since the relative extent in the extrapolation is larger. Moreover, the large variety of JET data, issued from different experimental campaigns with different divertor configurations showing significantly different threshold power dependences, causes the uncertainty in determining α_n and α_B. As a result, the 95% confidence interval ranges are rather wide; 30 - 100MW at n_e = $0.5\times10^{20}m^{-3}$ and 50 - 170MW at n_e = $1.0\times10^{20}m^{-3}$. The large threshold power value at high density is increased further when one considers a possible increase in the density exponent α_n with the plasma size and magnetic field. Extrapolating the variation of α_n up to ITER parameters, one finds it might reach 1.3, implying P_{thresh} as high as 135MW at n_e = $1.0\times10^{20}m^{-3}$, though this extrapolation has large error bars. According to this estimation, the access to the H-mode at high density might be very marginal in ITER deuterium plasmas since only 73MW will be available during the deuterium phase. On the other hand, access to H-mode at low density should not present any problem. Indeed, a favourable size effect is found when comparing the density at which the threshold power is minimum.

If one now compares the planned available power to the predicted threshold power during stationary H-mode phases one notices that the power ratio is smaller than unity while, in most present day devices, the ratio is ranging between 1.5 and 2.5. However, analysis of the confinement DB shows that the confinement improvement in H-mode is not directly related to the power ratio P_L/P_{Thrsh}. This is confirmed also by the several experimental reports, such as reference [27] where the good confinement was obtained in JET with a power ratio of 1.2.

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