LIST OF CONTENTS

Synchronisation of L-mode to H-mode transitions on the sawtooth cycle in ohmic TCV plasmas
Y.R. Martin and TCV Team

Control of electron Internal Transport Barriers on TCV

Roles of aspect ratio, absolute B and effective Z for the H-mode power threshold in tokamaks of ITPA database
ITPA H-mode Power Threshold Database Working Group presented by T. Takizuka
Synchronisation of L-mode to H-mode transitions on the sawtooth cycle in ohmic TCV plasmas

Y R Martin and TCV team
Centre de Recherches en Physique des Plasmas, Association Euratom-Confédération Suisse, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

Abstract
L-mode to H-mode transitions (LH transitions) are obtained in wide ranges of plasma parameters in TCV ohmic discharges. LH transitions either occur directly, indicated by a single abrupt drop in Da emission, or present an intermediate 'dithering' phase before the H-mode state is attained, in which the Da emission shows rapid excursions between L-mode and H-mode levels. The type of transition, with or without a dithering phase, depends on the plasma current and plasma triangularity. It is less sensitive to plasma density and divertor geometry. The relative direction of the ion VB drift also plays a role in the characteristics of the LH transition.

The time delay between an LH transition and the preceding sawtooth crash has been measured in every TCV H-mode discharge. Most LH transitions are found to occur in the first 30% of the sawtooth cycle, i.e. in the first 2ms after a sawtooth crash. Moreover, LH transitions often occur soon after the large crash of a 'double sawtooth'. The distribution function of these time delays clearly indicates a synchronisation of these two processes. However, the heat pulse released during a sawtooth crash has a transit time from the q=1 surface to the plasma edge that is much shorter than the time delay between the sawtooth crash and the LH transition.

1. Introduction
LH transitions are generally obtained in diverted plasmas when the additional heating power exceeds a threshold. A power law scaling has been developed to give the minimum power required to obtain a transition in a plasma of a given density and size, in a given magnetic field [1]. This scaling constitutes, up-to-now, the best method to predict the accessibility to the H-mode. However, the uncertainty of the fit is large and its origin is not
yet understood. In order to increase the accuracy of predictions a better understanding of the LH transition physics is necessary.

TCV, with its high shaping capability, is a perfect tool to investigate the effect of other parameters on the accessibility of the H-mode. A large number of LH transitions have been obtained in a wide variety of plasma parameters. Most are obtained in ohmic plasmas when the plasma divertor is formed. A database containing all these LH transitions was compiled and is briefly presented in section 2.

In this paper, two questions are addressed. The first one deals with the type of transition. It is widely recognised that transitions are either direct or in 2 stages with a dithering phase in between. The distribution of the different transition types in the operational domain is discussed in section 3. The second question deals with the influence of the sawtooth cycle on the LH transition physics. Different experiments have already shown that transitions are sometimes synchronised with a sawtooth [2]. Section 4 presents two approaches which lead to the result that most LH transitions are synchronised with sawteeth in TCV. Conclusions are given in section 5.

2. Data Set
All the LH transitions observed in TCV were manually identified on the basis of the Dα emission and the time of their occurrence stored. A database containing these times and the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limiter</th>
<th>Single Null</th>
<th>Single Null</th>
<th>Double Null</th>
<th>Double Null</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>32</td>
<td>382</td>
<td>340</td>
<td>39</td>
<td>146</td>
</tr>
<tr>
<td>Ip [MA]</td>
<td>0.3 - 0.65</td>
<td>0.3 - 0.5</td>
<td>0.23 - 0.45</td>
<td>0.25 - 0.45</td>
<td>0.23 - 0.5</td>
</tr>
<tr>
<td>ne [10^{19}m^{-3}]</td>
<td>5 - 11</td>
<td>3 - 8.5</td>
<td>2.5 - 10</td>
<td>4.5 - 13</td>
<td>4 - 11</td>
</tr>
<tr>
<td>κ</td>
<td>1.3 - 2.2</td>
<td>1.4 - 2.0</td>
<td>1.2 - 2.0</td>
<td>1.4 - 1.7</td>
<td>1.3 - 1.7</td>
</tr>
<tr>
<td>δ</td>
<td>0.2 - 0.55</td>
<td>0.45 - 0.65</td>
<td>0.25 - 0.65</td>
<td>0.55 - 0.75</td>
<td>0.55 - 0.8</td>
</tr>
<tr>
<td>Δin [mm]</td>
<td>0</td>
<td>5 - 40</td>
<td>1 - 50</td>
<td>5 - 25</td>
<td>1 - 30</td>
</tr>
<tr>
<td>R(Xpt) [mm]</td>
<td>0 - 50</td>
<td>10 - 70</td>
<td>0 - 100</td>
<td>0 - 50</td>
<td>0 - 55</td>
</tr>
</tbody>
</table>

Table 1: Operational domain where LH transitions were obtained, for different plasma configurations. Nb, Ip, ne, κ, δ, Δin and R(Xpt) are the number of occurrences, plasma current, density, elongation, triangularity, plasma to inner wall distance and radial distance of the major X-point from the inner wall, respectively.
values of many plasma parameters taken at these times was compiled. Data from about 900 plasma discharges are contained in the database. Table 1 shows how the transitions range in the operational domain for different pairs of plasma configurations and the ion $\nabla B$ drift direction relative to the position of the major X-point. IGRADB=1 is the favourable case, i.e. the ion $\nabla B$ drift is directed towards the X-point.

In order to extract reliable statistics from the database only the 3 most populated classes (column 3, 4 and 6) are studied and are labelled SND-, SND+ and DND+, respectively.

3. LH transition types
One of the signatures of an LH transition is a sudden drop in the $D_\alpha$ emission. However, in some cases a dithering phase may precede the establishment of the H-mode. Figure 1 shows the two different transition types. In the top case, one direct transition occurs, hereafter called 'dLH', and in the bottom case, one indirect transition occurs, in which a first transition from L-mode to Dithering, 'LD', is followed by a Dithering to H-mode transition 'DH'.

In Single Null discharges with the unfavourable ion $\nabla B$ drift (SND-), the transitions are predominantly direct ones (dLH) as shown in Table 2. In the same configuration but with the favourable ion $\nabla B$ drift as many direct as indirect transitions were observed. Finally, in Double Null discharges, most of the transitions exhibit a dithering phase. The type of transition then strongly depends on the plasma configuration. It is worth noting the large number of direct transitions in the first

![Figure 1: Evolution of the $D_\alpha$ emission for two LH transition types. Top: a direct LH transition, indicated by the vertical line and dLH labelling. Bottom: an LH transition with a dithering phase. The beginning and the end of the dithering phase are considered as LD and DH transitions, respectively.](image-url)
<table>
<thead>
<tr>
<th></th>
<th>dLH (direct)</th>
<th>LD-DH (with dithering)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SND -</td>
<td>367</td>
<td>15</td>
</tr>
<tr>
<td>SND +</td>
<td>170</td>
<td>170</td>
</tr>
<tr>
<td>DND +</td>
<td>41</td>
<td>105</td>
</tr>
</tbody>
</table>

Table 2: Number of transitions in both classes for the different TCV configurations

case (SND-). Since LH transitions are obtained in approximately the same operational ranges and since more power is usually required to produce a transition in the unfavourable case, one would naively expect the converse to be true: more dithering transitions in the unfavourable configuration than in the favourable.

The distribution of the transitions types as a function of the plasma current is shown in Fig.2, for the SND+ case. At high plasma current ($I_p > 400\,\text{kA}$) direct transitions are mostly obtained while, around $350\,\text{kA}$, the transitions occur in two steps with an intermediate dithering phase. In this figure both LD and DH transitions have been presented. Their slight misalignment is due to the fact that the plasma current still increases when the transition occurs, the latter usually happening when the divertor is being formed, which is done at the end of the plasma current ramp. Since these transitions are obtained in ohmic plasmas, this figure also shows that direct transitions are obtained when more power is injected into the

![Figure 2](image_url): Distribution of the transition types along the plasma current axis. Grey (or pink): Direct LH transitions; light grey (green): LD transitions; dark grey (blue): DH transitions.
plasma. In the other configurations, similar distributions are observed against the plasma current. In the density domain, the distribution is slightly unbalanced, with more direct transitions occurring at high density. However, this effect is due to the weak correlation between the plasma current and density. The plasma elongation has little effect on the distribution of the transition types. In contrast, the plasma triangularity does have an influence. At low triangularity ($\delta \sim 0.35$) most of the transitions are indirect while at higher triangularity ($\delta \sim 0.55$), more direct transitions are found in the SND+ case.

4. Synchronisation of LH transitions on the sawtooth cycle

It has already been reported that the heat pulse released at a sawtooth crash might help the triggering of an LH transition when arriving at the plasma edge. In order to identify whether sawteeth play a role in the LH transition process in TCV, a search for synchronisation has been undertaken following two approaches. The first one is based on a visual estimation of the synchronisation and is presented in the next subsection (4.1). The second approach (4.2) deals with the measured time delay between the LH transition and the crash of the preceding sawtooth.

In TCV, the sawtooth cycle sometimes shows a reduced crash followed by a ramp with normal slope and duration. The amount of energy released in the following crash is then much larger than average. Figure 3 shows an example of one of these so-called ’double sawtooth’ events as seen on soft-X ray emission from the plasma centre. On the same figure, the $D_\alpha$ emission shows an LH transition occurring less than 1ms after the large sawtooth crash. These ’double sawteeth’ are also identified in the two approaches presented in the next subsections and the synchronisation of the LH transition on the double sawtooth is jointly addressed.

4.1 Synchronisation estimation through visual classification

The effect of sawteeth is visible on the $D_\alpha$ emission in

![Figure 3: Time evolution of the $D_\alpha$ emission and soft-X ray emission from the plasma centre. The soft-X signal exhibits a double sawtooth and the LH transition is synchronised with the large double sawtooth crash. $dt$, $dt2$, A and A2 are used to determine the presence of a double sawtooth.](image)
the form of a small increase in the emission at the time of the sawtooth crash, as shown in Fig.4, where the Soft-X ray emission of the plasma centre is plotted together with the \( \text{D}_\alpha \) emission for three successive discharges. In these discharges, an abrupt drop in the \( \text{D}_\alpha \) emission, indicating a direct LH transition, occurs after the beginning of such a small increase due to a sawtooth. A similar pattern is found in all three discharges even if they are slightly shifted in time, confirming the synchronisation of the two mechanisms. When this behaviour is found in any single discharge, it is considered as synchronised.

Another pattern which clearly indicates a synchronisation between the sawtooth cycle and the LH transition physics is shown in Fig.5. Here, the \( \text{D}_\alpha \) emission pattern changes at each sawtooth crash, going from L-mode to high frequency dithering, then to low frequency dithering and finally to ELM free H-mode. In such a case, both LD and DH transitions are considered as synchronised with sawteeth.

An additional classification has been made for LH transitions occurring after a

\[ \text{Figure 4: Evolution of D}_\alpha \text{ emission (thick line) and soft-X ray emission from the plasma centre (thin line) for three discharges showing the same pattern and same time interval between the sawtooth crash and LH transition, indicating the synchronisation of the two processes.} \]

\[ \text{Figure 5: Evolution of D}_\alpha \text{ emission and soft-X ray emission from the plasma centre for a discharge with a dithering phase. The vertical lines show that a synchronisation exists between the sawtooth and the LH transition process.} \]
double sawtooth. A sawtooth is double when its crash amplitude and its duration exceed by a factor 1.5 the averaged values over the preceding 3 sawteeth, $A_{2}>1.5A_{1}$, $dt_{2}>1.5dt_{1}$ in Fig.3. Moreover a strongly reduced sawtooth crash has to be present approximately at the time where the 1st sawtooth would have occurred.

All LH transitions in the database were tagged with the evaluation of the synchronisation, using these criteria. The distribution function of sawtooth synchronised LH transitions was then analysed for the different types of transitions and with respect to the operational domain.

Table 3 summarises the number of transitions that were non-synchronised, synchronised with a single sawtooth or synchronised with a double sawtooth, for each type of transition and plasma configuration.

This table shows that a large fraction of dLH and LD transitions are synchronised with either a single or a double sawtooth, independent of the plasma configuration. DH transitions are less sensitive to sawteeth, with only half of the transitions showing synchronisation. The ratio of the number of synchronised over non-synchronised dLH transitions slightly varies with the favourable/unfavourable ion VB drift direction. dLH transitions are more often synchronised with double sawteeth than other transitions. In the SND+ configuration almost half of the transitions are triggered by double sawteeth. In the DND+ configuration, a very large fraction of the dLH and LD transitions are synchronised with sawteeth.

In summary, the influence of the sawtooth cycle on the ohmic LH transitions is clearly established. This influence seems even stronger in the favourable ion ṼB drift case, for the dLH transition at least.

<table>
<thead>
<tr>
<th></th>
<th>dLH</th>
<th>LD</th>
<th>DH</th>
</tr>
</thead>
<tbody>
<tr>
<td>SND-</td>
<td>54/252</td>
<td>1/13</td>
<td>5/10</td>
</tr>
<tr>
<td>SND+</td>
<td>16/78</td>
<td>42/120</td>
<td>62/82</td>
</tr>
<tr>
<td>DND+</td>
<td>2/29</td>
<td>3/77</td>
<td>47/43</td>
</tr>
</tbody>
</table>

Table 3: number of non-synchronised / synchronised with a single sawtooth / synchronised with a double sawtooth transitions for different plasma configuration and transition types
The distribution of the non-synchronised / synchronised transitions in the operational domain is quite uniform. The transitions following a double sawtooth are mostly found at the highest value of the plasma current ($I_p$~400kA). In these analyses, it would be interesting to know the statistical distribution of the double sawteeth in the operational domain, independently of the presence of the LH transitions. A more extensive analysis of the sawteeth properties should be performed but this remains beyond the scope of this paper.

4.2 Synchronisation estimation with the time delay statistics

The presence of synchronisation is also tested with the measurement of the time delay between the LH transition and the preceding sawtooth crash, indicated by 'dt' in Fig.3. The LH transition times are identified manually as the last moment before the drop in the $D_{\alpha}$ emission. The times of the sawtooth crashes are calculated from the Soft-X ray emission of the plasma core by a code which determines the beginning and the end of each sawtooth ramp. The time of a sawtooth crash is the average between the end of a ramp and the beginning of the next one. The identification of double sawteeth is also done automatically using the criteria described in the previous subsection.

The phase of the LH transition in the sawtooth cycle is easily calculated from the LH transition time, $t_{\text{LH}}$, and the previous and next sawtooth crash times, $t_{\text{stp}}$ and $t_{\text{stn}}$ respectively, using the expression $f_{\text{st}} = (t_{\text{LH}} - t_{\text{stp}}) / (t_{\text{stn}} - t_{\text{stp}})$ with 0<$f_{\text{st}}$<1. This phase measure is more appropriate for estimating the presence of

![Figure 6: Distribution function of the time delays between the sawtooth and the LH transition for the different plasma configurations. Inserted: phase of the LH transition in the sawtooth cycle for the corresponding configurations.](image)
any synchronisation, since it accounts for the full sawtooth cycle. However, the measure contains an error, smaller than 15%, due to the variation of the sawtooth period caused by the LH transition.

The distribution of the time intervals between the preceding sawtooth crash and the LH transition is shown in Fig.6 for the 3 configurations. All data points are used in this figure. Most LH transitions occur in the first 2ms after the sawtooth crash. The sawtooth period for these discharges ranges from 4 to 8ms. This strongly non-uniform distribution indicates that most LH transitions obtained in TCV are synchronised with sawteeth. Figures of the phase distribution of the LH transition in the sawtooth cycle are inserted in their respective boxes in Fig.6. These figures show that an important fraction of the LH transitions occur in the first 30% of the sawtooth cycle. This confirms the presence of synchronisation and, therefore, the strong influence of the sawteeth on the LH transition physics.

The heat pulse expelled at the sawtooth crash reaches the plasma edge in less than 0.2ms. Therefore the arrival of the heat pulse at the edge does not directly provide the trigger for the LH transition. An intermediate mechanism has to be invoked. This intermediate mechanism needs even more time to take place in the SND+ configuration, as shown by the larger averaged delay in this configuration. The precise nature of the mechanism involved in the synchronisation is not yet known but the plasma current profile could play a role: the change in the pressure profile could lead to a change in the edge current profile and this mechanism needs some time to take place. A threshold value in the edge current could then be reached which leads to an LH transition.

The distribution function of the time delays for the 3 transition types is shown in Fig.7 for the SND+ case. Many direct LH transitions occur less than 0.5ms after the crash of the sawtooth in the plasma centre. The LD transitions occur slightly later on average, however synchronisation is still present. The DH transitions are

![Figure 7: Distribution function of the time delays between the sawtooth and the LH transition for the different LH transition types, in the case of the SND+ configuration.](image-url)
more widely distributed, indicating that this transition requires less influence from the sawtooth cycle.

Since most LH transitions are synchronised with sawteeth, the analysis of their distribution in the TCV operational domain has little interest.

5. Conclusion

All LH transitions obtained in TCV are considered in the search of synchronisation between sawteeth and LH transitions. First, the distribution in the operational domain of the type of transition is analysed. Direct LH transitions are preferentially found at high values of plasma current. The determination of the synchronisation is addressed following two approaches, one manual and one automatic. The manual approach is based on the visual classification of the synchronisation. This revealed that a large fraction of the LH transitions are synchronised with a sawtooth or a double sawtooth. In the SND- case the synchronisation seems slightly less clear. The automatic approach is based on the time delay between the transition and the last preceding sawtooth. The phase of the transition in the sawtooth cycle was estimated as well, and revealed that an even larger fraction of the LH transitions, almost all, are synchronised with a sawtooth crash. The difference in results between the two approaches resides in the fact that the time delay is large in the case of SND-. In the manual approach the synchronisation is not considered, while in the 2nd approach, the calculated time delays shows a peaked distribution indicating the presence of synchronisation. The presence of a delay larger than the heat pulse transit time from the plasma centre to the edge indicates that a change in the plasma edge current, rather than pressure profile, could be responsible for the triggering of the LH transition.

Acknowledgement

The author would like to express its gratitude to the whole TCV team for its highly valuable work on the tokamak and its diagnostics. This work was partly supported by the Swiss National Science Foundation.

References


Control of electron Internal Transport Barriers on TCV

Centre de Recherches en Physique des Plasmas, Association EURATOM - Confédération Suisse, École Polytechnique Fédérale de Lausanne, CRPP - EPFL, 1015 Lausanne, Switzerland

Abstract. Current profile tailoring has been performed with the application of ECH and ECCD leading to improved energy confinement in the plasma core of the TCV tokamak. The improved confinement is characterized by a substantial enhancement (H-factor) of the global electron energy confinement time relative to the prediction of the RLW scaling law [1], which predicts well ohmic and standard ECH discharges on TCV. The improved confinement is attributed to a hollow current density profile producing a reversed shear profile creating an electron internal transport barrier. We relate the strength of the barrier to the depth of the hollow current density profile and the volume enclosed by the radial location of the peak current density. The $\mu_k^2[2]$ criterion is used to evaluate the performance of the barrier relative to changes in the ECH parameters or the addition of ohmic current, which aid in identifying the control parameters available for improving either the strength or volume of the barrier for enhanced performance. A figure of merit for the global scaling factor is used which scales the confinement enhancement as the product of the barrier volume and strength.

PACS numbers: 52.25.Hi, 52.55.Fa, 52.55.Wq, 52.50.Sw

Submitted to: Plasma Phys. Control. Fusion
1. Introduction

Electron internal transport barriers (eITB) have been created on several fusion devices by applying heating off-axis [3, 4, 5]. These eITBs are typically generated during the current ramp up using off-axis deposition which inhibits the ohmic current from penetrating into the plasma center and facilitates the formation of a hollow current profile. This scenario is inherently transitory as the ohmic current eventually penetrates into the center, thus filling the hollow current density profile and destroying the eITB. By contrast, work performed in TCV for the past several years [6] has focused on the generation of eITBs in stationary plasma conditions and maintaining the eITBs for several current redistribution time scales ($\tau_{CRT}$, the time constant associated with the redistribution of the plasma current from the peaked to hollow current density profiles, typically $\sim 150\text{ms}$ for TCV). The eITBs have been formed and maintained with the plasma current driven non-inductively [7, 8] using a combination of electron cyclotron current drive (ECCD) and bootstrap current (BS) or inductively [9] with a non-zero ohmic current contribution ($I_0 \neq 0$). TCV’s flexible high power electron cyclotron heating (ECH) system[10] generates very high central electron temperatures with $T_e >> T_i$, and has been used to study the eITB confinement dependence on the deposition location and current drive effects [11]. The confinement enhancement factors achieved approach $H_{RLW} \approx 6.0$ [12, 13]. The confinement is characterized by normalization to the RLW scaling law [1], i.e. $H_{RLW} = \tau_E/\tau_{RLW}$, which well describes the confinement of L-mode plasmas in TCV[14] (in contrast to the ITER98-L mode scaling [15] which is not really appropriate when $T_e >> T_i$ and typically one-half $\tau_{RLW}$).

This paper discusses the techniques for controlling the confinement enhancement of the eITB by modifying either the ECH or ECCD parameters or the magnitude of the inductive current. The confinement enhancement factor, $H_{RLW}$, is measured in stationary conditions. The second section describes the diagnostic tools which identify the existence of the eITB, and the techniques for controlling the confinement enhancement, which depends on the eITB’s strength and volume. Where, the eITB strength is proportional to the depth of the hollow current density profile and the volume proportional to the radial location of the peak current density. Demonstration of the control of the barrier volume and strength in fully sustained non-inductively driven discharges ($eITB_N$) is presented in the third section. The influence of the ohmic current in inductively driven discharges ($eITB_I$) on the performance is described in section four. A global scaling law, which provides a figure of merit for the confinement enhancement, is proposed in section five followed by conclusions in section six.

2. The eITB basics

At present, there is no direct measurement of the local magnetic field line pitch angle on TCV. The improved confinement of the $eITB_N$ discharges are attributed to a hollow current profile resulting in a reversed shear q-profile [16]. In [11] the strength of the barrier was related to $q_0/q_{min}$ where $q_0$ is the safety factor on axis and $q_{min}$ is the minimum in the safety
factor while the volume is proportional to $\rho_{q_m}^2$ (the radial position of $q_m$). Here $q$, $q_{min}$ and $\rho_{q_m}$ were obtained from simulations of the plasma current density profiles during stationary plasma conditions in eITB$_{N1}$. $I_{BS}$ was derived from the electron pressure profiles, $P_e$ [17] and the ECCD profile from coupled Fokker-Planck ray tracing calculations including cross field transport [16, 18]. The $H_{RHW}$ of the eITB$_{N1}$ was also shown to be linearly dependent on the product of the barrier strength and volume.

It is convenient to characterize the barrier strength as depending on the depth of the hollow current density profile or $(J_{max} - J_0)/J_{max}$, where $J_{max}$ is the maximum plasma current density and $J_0$ is the current density on axis, and by the volume enclosed by the barrier, or $\rho_{J_{max}}$, the radial location of $J_{max}$. Improving the confinement can be accomplished by increasing the depth and/or the width of the hollow current density profile. In contrast, the confinement can be degraded by adding current in the center (decreasing the depth) or narrowing the current density profile (reducing the volume). The hollow current density profile in the eITB$_{N1}$ forms from a large bootstrap current of up to 70% of the total plasma current[7]. Generating more bootstrap current increases the depth of the hollow current density profile, while generating bootstrap current further off-axis increases the width of the hollow current density profile. The bootstrap current depends upon the electron pressure gradient ($\nabla P_e$), which is experimentally seen to be dominated by the temperature rather than the density gradient. This connection motivates an alternative approach for evaluating the performance of the eITBs using the $\rho_T^2$ parameter [2] defined as:

$$\rho_T^2(R, t) = \rho_T(R, t) / L_T(R, t)$$

where $L_T = -T_e / (\partial T_e / \partial R)$ is the local temperature gradient scale length, $T_e$ the electron temperature, $R$ the major radius on the equatorial plane, $\rho_T = e_s / \omega_c$ the ion Larmor radius at the sound speed, $c_s$ the sound speed with $T_e$ and $\omega_c$ the ion cyclotron frequency. The barrier strength and volume is related to $\rho_T^2$ since the bootstrap current, which creates the hollow current density profile, is dominated by $\nabla T_e$. An example of the $T_e$ and $\rho_T^2$ profiles averaged over four phases of a discharge is shown in figure 1. Phase A corresponds to the ohmic target plasma, B the co-ECCD off-axis preheat phase, C same conditions as B but with a weak eITB (no central heating) and D centrally heated eITB. The maximum in $\rho_T^2$ ($\rho_{J_{max}}^2$) can be correlated to the strength of the barrier, with a threshold for eITB existence when $\rho_{J_{max}}^2 > 0.04$. The radial position of $\rho_{J_{max}}^2$ ($\rho_{J_{max}}$) can be correlated to the volume enclosed by the barrier. Both $\rho_{J_{max}}$ and $\rho_T^2$ are obtained from the measured $T_e$ profiles and can quantify the eITB confinement enhancement even in transitory scenarios, in contrast to the cumbersome simulations required for obtaining $q$, $q_{min}$ and $\rho_{q_m}$.

An example of the relationship between the $T_e$ profiles and the eITB$_{N1}$ performance is given in figure 2. In Cycle $S_1$, central heating is added to an eITB which increases the central $T_e$ without broadening the profile. The plasma responds with an increase in $P_e$ and $\nabla P_e$ generating more bootstrap current which increases $J_{max}$ effectively deepening the hollow current density profile, thus strengthening the barrier. This sets up a positive feedback, the
Control of electron Internal Transport Barriers on TCV

Figure 1. $T_e$ (dashed) and $\rho^*$ (solid) profiles averaged during four phases of an eITB discharge. Phase A during the stationary ohmic phase, B during the $P_{\text{ce}}$ pre-eITB, C during the eITB without central heating and D during the centrally heated phase.

stronger barrier increasing the central temperature leading to an even stronger barrier. The cycle continues until the eITB reaches some equilibrium scenario determined by the plasma and heating parameters or the profiles become too peaked resulting in a degradation in performance due to the onset of an ideal MHD mode. The cycle can be reversed, $S_-$ with a decrease in $T_e$ reaching an ultimate equilibrium with a decrease in barrier strength. Note the '+' and '-' subscript on 'S' refers to the forward and reverse direction of the cycle.

In Cycle $V_+$, the central heating is kept constant but the $T_e$ profile is broadened ($\omega_{Te}$). The plasma responds with an increase in the radial position of the pressure gradient, $\rho_{\text{ce}}$, the radial location of the bootstrap current profile. $\rho_{\text{BS}}$ moves outward increasing the width of the hollow current density profile, $2\rho_{\text{max}}$, thus enlargening the barrier volume. Positive feedback occurs with the increase in the volume of the barrier which broadens the $T_e$ profile eventually further increasing the volume until some equilibrium is reached. This cycle can also be reversed, $V_-$ with a narrowing of the temperature profile shrinking the volume of the hollow current profile.

In reality the eITB dynamics are more complicated than portrayed in the above illustrations. For example, mechanisms used to modify the temperature profile can also provide a local current source setting up either of the positive (or negative) feedback cycles starting with direct modifications to the the $I_P$ profile. The mechanisms for modifying the $T_e$ and $I_P$ profiles investigated in this paper include: off-axis co-ECCD power ($P_{\text{co}}$) and deposition location ($\rho_{\text{co}}$), central ECCD
3. Control of the \( \epsilon ITB_{N1} \)

Scans of \( \phi_o \) and \( \rho_{co} \) have been performed on a shot-to-shot basis in \( \epsilon ITB_{N1} \) with \( P_o = 0.5 \text{MW}, P_{co} = 0.9 \text{MW} \) and typical plasma parameters \( I_p \approx 80 \text{kA}, n_e \approx 0.7 \times 10^{19} \text{m}^{-3} \) (line average electron density), \( \kappa \approx 1.5 \) (elongation). While keeping the \( \rho_{co} \approx 0.4 \), \( \phi_o \) was scanned from +5 (co-ECCD) to -5 (cnt-ECCD). A noticeable increase in \( T_e \) and \( \rho_T^* \) is observed as \( \phi_o \) progresses toward cnt-ECCD while the foot of the \( T_e \) profiles remain fairly constant, \( \rho \approx 0.5 \), as shown in figure 3a. The injection of cnt-ECCD on-axis provides a negative current source in the center of the plasma which increases the depth of the hollow current density profile and increases \( H_{RLW} \), see figure 3b. Increasing the depth should strengthen the eITB, i.e., establish a \( S_+ \) cycle characterized by an increase in central \( T_e \), bootstrap current (\( I_{BS} \)) and \( \rho_{max}^* \) while maintaining \( \rho_{co} \) constant. Indeed, \( I_{BS} \) increases, see figure 3b, which results in a net increase in \( I_p \) despite the decrease in the overall EC current drive (\( I_{CD} \)) with \( \phi_o < 0 \). The barrier strength, \( \rho_{max}^* \), increases while the barrier volume, \( \rho_{co} \), increases only slightly, see figure 3c. The slight increase in the barrier volume can be attributed to a second order effect on the increase in \( I_{BS} \). Since the \( I_{CD} \) profile is nearly flat due to current diffusion[16], an increase in \( I_{BS} \) while decreasing \( I_{CD} \) will slightly displace \( J_{max} \) outward setting up a \( V_+ \) cycle increasing the barrier volume.

A scan of the radial location of the off-axis co-ECCD deposition location was performed while maintaining central heating with no toroidal injection (ECII). As the deposition moves outward in \( \rho_{co} \), the \( J_p \) and \( T_e \) profiles broaden, which increases the volume of the barrier, initiating the \( V_+ \) cycle. However, as \( \rho_{co} \) increases, the EC current drive efficiency decreases due to lower electron temperatures off axis resulting in a decrease in \( J_{CD} \). The
Control of electron Internal Transport Barriers on TCV

reduction in $J_{CD}$ decreases both $J_0$ and $J_{max}$ due to diffusion, while the depth of the hollow current density profile ($J_{max} - J_0$) increases, resulting in a stronger barrier, or a $S_+$ cycle. Thus increasing $\rho_{c0}$ should set in motion both $V_+$ and $S_+$ processes, which is evidenced in a wider and higher $T_e$ profile (as shown in figure 4a), and an increase in the bootstrap current (see figure 4b). Also, both the barrier volume, $\rho_{p*}$, and strength, $\rho_{c0}$, increases as shown in figure 4c.

There exists a potential for independent control of either the barrier volume or strength using both $\rho_{c0}$ and $\phi_0$. For example, the eITB strength can be increased while maintaining constant eITB volume by adding cmt-ECCD on axis with only a slight decrease of $\rho_{c0}$. Conversely, the eITB volume can be enlarged while maintaining constant strength by increasing $\rho_{c0}$ and then adding co-ECCD centrally to degrade the eITB strength.

4. Inductive current influence on the eITB

Since the current driven inductively is proportional to $I_R^{3/2}$, any ohmic current induced in an eITB will be predominately deposited in the center of the plasma. The hollow current density profile will be partially filled by a positive loop voltage driving an additional central current source, which weakens the barrier. Also, the current profile will be narrower decreasing $\rho_{jmax}$ and decreasing the volume of the barrier. The eITB performance should degrade with both $S_-$ and $V_-$ cycles as portrayed in figure 2. This process is demonstrated by comparing an eITB$_{N1}$ ($\phi_0 = 0$) used in figure 3b with an eITB$_{HI}$ (equiva-

Figure 4. The eITB$_{N1}$ performance during a scan of the radial deposition, $\rho_{c0}$ as observed on (a) the $T_e$ (dashed) and $\rho_{j1}$ (solid) profiles; (b) $I_P$, $I_{CD}$ and $I_{BS}$; and (c) the barrier strength and radius.

lent EC conditions) with $I_R \neq 0$, but with $I_R < I_{BS}$. As shown in figure 5 the $T_e$ profiles decrease and are narrower with the addition of ohmic current (green curve) relative to the eITB$_{N1}$ (blue curve). Also the barrier strength and volume decrease as expected with the shrinking and filling in the hollow current density profile. If $I_R$ is sufficiently large relative to $I_{CD}$ and $I_{BS}$, the current hole could be filled and the eITB$_{HI}$
Control of electron Internal Transport Barriers on TCV

![Figure 5](image)

The $T_e$ (dashed) and $\rho_T$ (solid) profiles for an eITB$_N$ (blue curves) and equivalent eITB$_3$ with degraded performance due to $I_\Omega \neq 0$ (green curve) with central ECH. The eITB$_3$ is repeated with cnt-ECCD on-axis to negate $I_\Omega$ (red curve).

cn ECCD entirely destroyed.

The additional ohmic current in the center of the plasma can be cancelled out using counter ECCD on axis ($\phi_0 < 0$). The eITB$_3$ discharge described in figure 5 (green curve) was repeated, but with cnt-ECCD on-axis $\phi_0 = -27$ (red curve). The barrier volume and strength improve with cnt-ECCD as seen in the $\rho_T$ profiles, the degradation associated with the addition of $I_\Omega$ is eliminated. However, the same confinement enhancement achieved in the eITB$_N$ (green curve) is not obtained, an increase in $P_b$ beyond 0.5MW would be required. Typically, more counter ECCD is needed on axis for negating the central ohmic current as $[I_p - (I_{HS} + I_{\Omega})]$ increases. For the eITB$_{O3}$ obtained on TCV, $P_b$ ranges from 0.7 to 2.0MW (versus 0.5MW for eITB$_N$ studied). Note that the eITB$_O$ requires less power off-axis, since only broadening of the $T_e$ and current density profiles is required rather than fully sustaining the plasma current as in the case of eITB$_N$. The cnt-ECCD becomes nearly essential for creating the hollow current density profile as $I_{H} > I_{CD} + I_{HS}$.

The cnt-ECCD does not only provide a negative current source, but also heats the plasma. There is a feedback loop on the $dI_{OH}/dt$ to maintain $I_p$ constant. The plasma conductivity increases with the increase in $T_e$, the loop voltage decreases even though $I_{H}$ increases to compensate $I_{out}$ and maintain $I_p$ constant. Small variations in measured central $T_e$ lead to a large range of calculated central ohmic and cnt-ECCD driven current densities and a large variation in the simulated values of $q_{\min}$, $q_0$ and $\rho_{\min}$.

An additional example has been shown in discharge #24913 which was reported in [12, 13]. An eITB is obtained with the plasma current fully sustained noninductively, and then ohmic current is added by a pre-programmed ramp in the ohmic transformer current. The addition of the ohmic current degrades the eITB performance by filling in and decreasing the hollow current density profile resulting in a decrease in barrier strength and volume.

5. global scaling

In reference [11] a general figure of merit for the enhancement confinement was proposed which demonstrated a linear increase in $H_{RLW}$ as a dependence of the product between the eITB volume ($\rho^2_{\Omega_{\min}}$) and the eITB strength ($q_0/q_{\min}$). The inclusion of eITB$_O$ plasmas could not be accomplished due to the inaccuracies in simulating the ohmic and cnt-ECCD current density contributions as described above. The enhancement figure of merit has been reproduced characterizing the eITB's using $\rho_T$, with the eITB volume and strength represented by $\rho_{\max}^-$ and
Control of electron Internal Transport Barriers on TCV

Recently the number of ohmic discharges included in the database has been increased and reveals a potential improved scaling of $\epsilon ITB_\Omega$ (red points) over $\epsilon ITB_{N1}$ (blue points) as shown in figure 6. This seems to be in contrast with the conclusion drawn in the previous section, that the ohmic current fills in the hollow current profile degrading the eITB. The previous comparison was performed with all eITB's formed with $P_{\text{co}} = 0.9\text{MW}$ and $P_\phi = 0.45\text{MW}$. In $\epsilon ITB_\Omega$ the ratio $P_\phi/P_{\text{co}}$ has been increased to at least 3.0 which permits more power to be deposited within the barrier for more effective heating of the eITB, where $P_\phi$ is the sum of both the injected power from cnt-ECCD and the ohmic contribution. Past experiments have demonstrated that when $P_\phi$ increases, $\tau_E$ remains constant or slightly increases resulting in a significant increase in $H_{RLW}$ (in contrast to L-mode discharges where $H_{RLW}$ scales as $P^{-0.5}$).

The power deposited off-axis although required for forming the eITB contributes minimally to heating inside the barrier. Future experiments are planned to test the confinement enhancement factor for different $P_\phi/P_{\text{co}}$ power ratios and search for an optimum relative to the plasma parameters, such as current, density, elongation, etc.

The product $\rho_{\text{max}}^*\rho_{\phi}$ is a simple figure of merit for the enhancement factor of these steady state eITB's and suggests the possibility of even further enhancement as the barriers are extended in volume and strength.

Figure 6. A figure of merit of the $\epsilon ITB_\Omega$ (blue) and $\epsilon ITB_{N1}$ (red) is given as the product of the barrier strength and volume ($\rho_{\text{max}}^*\rho_{\phi}$).

6. Conclusions

The $\rho_T^*$ profiles have been used to characterize the confinement performance of both fully sustained and inductively driven eITBs. The eITB is believed to be associated with a hollow current density profile with the barrier strength related to the depth and barrier volume related to the width of the hollow region. The barrier strength is defined as the maximum in $\rho_T^*$ ($\rho_{\text{max}}^*$), while the barrier volume is dependent on the radial location of this maximum ($\rho_\phi$). The influence of the toroidal injection angle on-axis ($\phi_\tau$) and the off-axis radial position ($\rho_\phi$) on the confinement enhancement has been characterized pointing the way to possible individual control of either the strength or volume.

The influence of additional ohmic current ($I_\Omega$) to the above eITBs has been shown to degrade the confinement by reducing the barrier strength and volume with the use of $\rho_{\text{max}}^*$ and $\rho_\phi$. This degradation can be reversed with additional
Control of electron Internal Transport Barriers on TCV

counter-ECCD in the center. The performance of fully sustained and inductively driven eITBs have been compared in one global figure of merit equal to the product of the barrier strength and volume. Slight variations in the figure of merit may be attributed to different $P_e/P_i$ power ratios, the ratio of power injected centrally versus off-axis. The power on-axis is more efficient in optimizing the performance of the barrier.

7. Acknowledgements

The authors would like to thank the many individuals who operated TCV and diagnostics, which allowed the experiments to occur. Without their participation these results would not have existed, in particular thanks goes to A. Degeling, D. Fasel, P.F. Isoz, A. Perez, R. Pitts, U. Siravo, G. Tonetti and H. Weisen. A special thanks to Xavier Llobet for his continued patience in taming the complexities of our plant control and data acquisition systems on a daily basis.

This work was supported in part by the Swiss National Science Foundation.

References

Roles of aspect ratio, absolute B and effective Z for the H-mode power threshold in tokamaks of ITPA database

ITPA H-mode Power Threshold Database Working Group# presented by T Takizuka

# Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, Naka-marhi, Naka-gun, Ibaraki-ken 311-0193, Japan

Received

Abstract. Analysis of ITPA H-mode power threshold database is advanced to study roles of aspect ratio A, absolute magnetic field and effective charge number $Z_{\text{eff}}$. A new scaling expression for power threshold $P_{\text{th}}$ is presented. Absolute B at the outer surface is used instead of $B_{\text{av}}$ in the scaling, and the $I_{\text{av}}$ dependence of $P_{\text{th}}$ in low-D tokamak is described without the explicit use of $I_{\text{av}}$ variable. Clear and strong dependence on $Z_{\text{eff}}$ is found: $P_{\text{th}} = Z_{\text{eff}}^{-3.2}$. Both the scattering nature in the data fitting and the “low-density anomaly” can be reduced. Nonlinear A dependence is also suggested. The $P_{\text{th}}$ in ITER is predicted on the basis of the present scaling.

1. Introduction

H-mode operation is considered suitable for tokamak fusion reactors, such as ITER [1], because of its high confinement performance. The H-mode state is achieved with the heating power above a certain threshold $P_{\text{th}}$. To evaluate the additional heating power necessary for entering the H-mode state in a future reactor and to find its operation point, a quantitative formula of $P_{\text{th}}$ is required. Since such a theoretical formula has not been developed so far [2], empirical formulas have been proposed among which scaling expressions based on the ITPA (International Tokamak Physics Activity) threshold database are the most reliable [3,4,5].

It has been found that these expressions for $P_{\text{th}}$ include a small number of parameters: toroidal magnetic field $B_t$, line averaged electron density $n_e$, and plasma surface area S (or major radius $R$ and minor radius $a$). The $P_{\text{th}}$ correlates strongly and positively with both $B_t$ and $n_e$. The $R^2$ dependence in an early scaling, $P_{\text{th}} = B_t n_e^{0.7} R^2$ [3], has been modified to the $S$ dependence by the later analysis of the extended database [4]. Several expressions were shown there and they can be approximated as

$$P_{\text{th}} = 0.06 B_t^{0.9} n_e^{0.7} S^{0.9}$$  (1)

with an uncertainty of $G = (B_t/3)^{0.1}(n_e/0.6)^{0.1}(S/60)^{0.1}(3a/R)^{0.2}$. In the present paper, we
employ the units as $P$ in MW, $B$ in T, $n_{95}$ in $10^{09}$ m$^{-3}$, $R$ in m, $a$ in m, and $S$ in m$^2$. One of the recent fitting formulas, $P_{\text{th}} = 0.042 R^1.0 n_{95}^{-0.13} S^{0.34}$ [5], is laid surely within this uncertainty. The above simple fitting formula (1) is used as a normalizing basis in the following analysis.

Recently data from spherical tokamaks (MAST [6] and NSTX [7]) were supplied to the ITPA database and the range in the aspect ratio $A$ (or $R/a$) was significantly extended [5]; $6.2 > A > 2.4$ (standard tokamaks), $A = 1.45$ (MAST) and $A = 1.32$ (NSTX). Now the database includes Alcator C-Mod, ASDEX, ASDEX Upgrade, COMPASS-D, DIII-D, JET, JFT-2M, JT-60U, MAST, NSTX, PBX-M, TCV, and TUMAN-3M. A new analysis has been started to find the cause of large residual scatter in the experimental data when compared to above scaling expressions. It was pointed out in [5] that one of the major causes is the effective charge number $Z_{\text{eff}}$. In this paper, we advance the analysis from the previous works by aiming to study the roles of $A$ and $Z_{\text{eff}}$ on the H-mode power threshold.

2. Data selection

2.1 Phase and heating method

When we analyze the database to develop a scaling, we should be careful how to select the data points. In the present work we treat the data at the LH transition phase. The dithering phase is supposed to be a combined phase of L- and H- modes, and the data points related to this phase are used in the analysis.

As for the heating method, we do not adopt any restriction. We have not observed any significant difference in $P_{\text{th}}$ among NB (neutral beam) heating, IC (ion cyclotron) heating, EC (electron cyclotron) heating, Ohmic heating, and the combined heating with them.

2.2 Configuration

Positions of null points relative to the direction of ion grad-B drift affect the L-H transition. Usually the power threshold is smaller in the single null (SN) configuration for the drift direction towards the null point (IGRADB = 1) than that for the opposite drift direction (IGRADB = -1). In the double-null (DN) configuration (IGRADB = 0), the $P_{\text{th}}$ looks not increasing much compared with that for IGRADB = 1. Therefore, in the following analysis, we use the data of IGRADB = 0 and 1. This evaluation is justified by figure 1 showing the

![Figure 1. Distribution function of $P_{\text{th}}/P_{\text{th}0}$ in JET. Power threshold for IGRADB = -1 is larger than that for IGRADB = 0 and 1.](image-url)
distribution function of $P_{\text{th}}/P_{\text{tot}}$ for different configurations in JET (Criteria described below are imposed).

2.3 Ion mass number

The L-H transition occurs easily at a lower heating power in deuterium discharges than in hydrogen discharges. It has been found from JET data that the threshold power is reduced in tritium discharges. The dependence of $P_{\text{th}}$ on the ion mass number $M$ was roughly given as an inverse proportion, $P_{\text{th}} \propto 1/M$ [8]. In the following analysis, we only use data of $M_{\text{eff}} = 1.5$ and 2 by assuming both data being $M = 2$ data, where $M_{\text{eff}} = (M_{\text{ion}}M_{\text{e}})^{2/3}$ is the effective mass number. The data of $M_{\text{eff}} = 1.5$ correspond to discharges for hydrogen beam into deuterium plasma, and such plasmas at the L-H transition time consist mainly of deuterium.

2.4 Low density and low safety factor

In low-density plasmas, recycling neutral particles from the divertor region penetrate deeply into the core plasma. The penetration length for neutral deuterium with energy of ~10 eV is about $L_{\text{pen}} \sim (0.01n_{\text{th}})$ m. The deep penetration of neutrals can affect the L-H transition. Therefore, we use the data satisfying a condition $L_{\text{pen}}/\rho_{\text{hel}} < 0.1$, i.e., $(n_{\text{th}}/\rho_{\text{hel}}) > 0.1$. By this criterion TUMAN-3M data ($n_{\text{th}}/\rho_{\text{hel}} \sim 0.03$ and $P_{\text{th}}/P_{\text{tot}} \sim 5.5$) and low-density COMPASS-D data ($n_{\text{th}}/\rho_{\text{hel}} \sim 0.02$ and $P_{\text{th}}/P_{\text{tot}} \sim 12$) are omitted, whose $P_{\text{th}}$ values are extremely higher than $P_{\text{th}}$. The selection window for the density is wider than that applied to the previous analyses in [4,5], and the "low-density anomaly" with the relation to $Z_{\text{eff}}$ is investigated in section 4.

Power threshold tends to increase gradually when the safety factor near the plasma surface $q_{98}$ (95% flux surface) decreases below 2.5. This tendency is clearly found in TCV data. Therefore, we use the data of $q_{98} > 2.5$.

The total data selected under the above restrictions (subsections 2.1-2.4) are distributed against the values of $\ln(P_{\text{th}}/P_{\text{tot}})$ almost in a Gaussian form with the standard deviation $\sigma = 0.36$.

3. Power threshold in low-A tokamaks and role of absolute $B$

Power threshold in low-A tokamaks is rather large compared with above scaling expressions derived by using the data of standard tokamaks ($2.4 < A < 6.2$). The ratio $P_{\text{th}}/P_{\text{tot}}$ is observed 1.6 for MAST data ($A = 1.45$) and about 1.7 for NSTX data ($A = 1.32$). It is noted that the MAST data are of Ohmic heating and DN configuration (IGRA DB = 0), while the NSTX data are of NB heating and SN configuration with the favorable drift direction (IGRA DB = 1). It has been emphasized that $P_{\text{th}}$ in NSTX depends strongly and positively on the plasma current $I_p$ [7], contrary to the above $P_{\text{th}}$ scalings with weak $I_p$ dependence.

These different features can be explained in principle by introducing the absolute magnetic field to the analysis. We consider the absolute $B$ at the outer mid-plane of the plasma surface because this region is supposed important for the L-H transition. The absolute $B$ is given as $B_{\text{out}} = (B_{\text{out}}^2 + B_{\text{out}}^2)^{1/2}$, where $B_{\text{out}} = B_r \times A/(A+1)$ and $B_{\text{out}} = (\mu_0 J/2\pi a) < 1.4A^{1/2}$. Several approximations are used to estimate the poloidal field at the outer mid-plane $B_{\text{out}}$, e.g., the poloidal-field asymmetry coefficient $A = 1$. We replace $B_r$ with $kB_{\text{out}}$ and correct the coefficient from 0.06 to 0.072 in equation (1) and obtain a new basis scaling:
\[ P_{\text{thick}} = 0.072 \ \bar{I}_{\text{Beeb}}^{0.7} \ \bar{n}_{30}^{0.7} \ \bar{T}^{0.9} \]  

Figure 2 shows (a) \( P_{\text{thick}}/P_{\text{nor}} \) and (b) \( P_{\text{thick}}/P_{\text{nor}} \) for MAST and NSTX. One can clearly see that the \( I_p \) dependence of the \( P_{\text{thick}}/P_{\text{nor}} \) becomes very weak. The resulting scaling expression subsumes the \( I_p \) dependence at low aspect ratio and is consistent with the full set of data without any explicit \( I_p \) dependence. In addition, the ratio \( P_{\text{thick}}/P_{\text{nor}} \) is remarkably reduced from the value of \( P_{\text{thick}}/P_{\text{nor}} \) to 1.25 for MAST and 2.8 for NSTX, but still stays above unity. We study further the role of \( A \) in section 5.

4. Role of \( Z_{\text{eff}} \)

The store of \( Z_{\text{eff}} \) in the database is rather poor. In the present version (September 2003), \( Z_{\text{eff}} \) data from ASDEX, DIII-D, Alcator C-Mod, JET, JT-60U and NSTX are stored, and those from ASDEX Upgrade were supplied very recently. For ASDEX and Alcator C-Mod, data points with \( Z_{\text{eff}} \) are limited. Measured values of \( Z_{\text{eff}} \) sometimes contain large error bars. Under such situation, the \( Z_{\text{eff}} \) dependence has not been shown in \( P_{\text{thick}} \) scaling expressions.

In order to estimate the accuracy of \( Z_{\text{eff}} \) values, we compare the measured \( Z_{\text{eff}} \) with the calculated values given by \( Z_{\text{eff,cal}} = V_{\text{thr}} S_{\text{cor}} T_{\text{eff}}^{1.5} (2 \pi R L_p) \). We make a data subset within \( Z_{\text{eff}} Z_{\text{eff,cal}} = e^{0.055} \times \langle Z_{\text{eff}} \rangle_{\text{cal}} D_{\text{cal}} \), which is used to develop a \( P_{\text{thick}} \) scaling including \( Z_{\text{eff}} \). Here \( V_{\text{thr}} \) is the one-turn surface voltage, \( S_{\text{cor}} \) is the plasma cross-sectional area (or \( \pi R^2 \)), \( T_{\text{eff}} = W / 3 n V \) is the effective temperature (W: plasma stored energy, V: plasma volume), and \( \langle Z_{\text{eff}} \rangle_{\text{cal}} \) represents the average against a single tokamak. Though the data of Alcator C-Mod with \( Z_{\text{eff}} \) are the data of IGRADB = -1 (see subsection 2.2), these data are used in the analysis here. The data of JET reveal quite large scattering nature especially for IC and combined NBIC heating cases. The reason why \( P_{\text{thick}} \) in JET become sometimes much larger than \( P_{\text{thick}} \) has not been clarified so far. For the simplicity of the analysis here, we use only JET data for NB heating.

Figure 3(a) shows the dependence of \( P_{\text{thick}}/P_{\text{nor}} \) on \( Z_{\text{eff}} \) for JT-60U, where solid circles are the data inside a density window \( (0.19 < n_{30} < 0.26) \). We see the clear \( Z_{\text{eff}} \) dependence of \( P_{\text{thick}}/P_{\text{nor}} \) inside the \( n_t \) window and similarly \( Z_{\text{eff}}^{0.90} \) for all JT-60U data. The \( Z_{\text{eff}} \) generally increases with the decrease of \( n_t \) as shown in figure 3(b). Even though the \( Z_{\text{eff}} \) and \( n_t \) relate with each other, the \( Z_{\text{eff}} \) dependence of \( P_{\text{thick}}/P_{\text{nor}} \) seems unified; \( P_{\text{thick}}/P_{\text{nor}} \approx Z_{\text{eff}}^{\alpha} \), with \( \alpha = 0.7 \). The data other than JT-60U have similar dependence though the scattering is rather large.
Table 1. \(Z_{\text{eff}}\) dependence of \(P_{\text{th}}/P_{\text{th,eff}}\) (\(= Z_{\text{eff}}^2\)) for the data inside \(n_t\) window and for all data.

<table>
<thead>
<tr>
<th>ASDEX</th>
<th>AUG</th>
<th>CMOD</th>
<th>DIII-D</th>
<th>JET</th>
<th>JT-60U</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>number</td>
<td>7</td>
<td>38</td>
<td>40</td>
<td>81</td>
<td>76</td>
<td>62</td>
</tr>
<tr>
<td>(n_t) window</td>
<td>---</td>
<td>0.31/0.43</td>
<td>1.65/2.3</td>
<td>0.29/0.41</td>
<td>0.23/0.40</td>
<td>0.19/0.26</td>
</tr>
<tr>
<td>(\alpha_t) (window)</td>
<td>---</td>
<td>0.66</td>
<td>0.79</td>
<td>0.69</td>
<td>0.69</td>
<td>0.80</td>
</tr>
<tr>
<td>(\alpha_t) (all)</td>
<td>1.51</td>
<td>0.72</td>
<td>0.71</td>
<td>0.66</td>
<td>0.69</td>
<td>0.60</td>
</tr>
<tr>
<td>mean (P_{\text{th}}/P_{\text{th,eff}})</td>
<td>1.78</td>
<td>0.86</td>
<td>1.16</td>
<td>1.37</td>
<td>1.18</td>
<td>1.05</td>
</tr>
<tr>
<td>(\sigma (P_{\text{th}}/P_{\text{th,eff}}))</td>
<td>0.36</td>
<td>0.20</td>
<td>0.30</td>
<td>0.28</td>
<td>0.41</td>
<td>0.13</td>
</tr>
<tr>
<td>mean (P_{\text{th}}/P_{\text{th,eff}})</td>
<td>1.76</td>
<td>0.94</td>
<td>1.34</td>
<td>1.00</td>
<td>1.06</td>
<td>1.14</td>
</tr>
<tr>
<td>(\sigma (P_{\text{th}}/P_{\text{th,eff}}))</td>
<td>0.49</td>
<td>0.24</td>
<td>0.68</td>
<td>0.30</td>
<td>0.44</td>
<td>0.22</td>
</tr>
</tbody>
</table>

compared with JT-60U data. Values of exponent to \(Z_{\text{eff}}\) for the data inside \(n_t\) window (\(\alpha_t\)) and for all data (\(\alpha_t\)) are listed in Table 1. They are all near by \(\alpha = 0.7\). Now we introduce a scaling basis including \(Z_{\text{eff}}\) dependence:

\[
P_{\text{th,eff}} = P_{\text{th}} \times (Z_{\text{eff}}/2)^{0.7}
\]  

Statistical results by the use of this basis are listed in Table 1. We assure that the addition of \(Z_{\text{eff}}\) dependence into the scaling expression works well to reduce the \(\sigma\) value of \((P_{\text{th}}/P_{\text{th,eff}})\) compared with that of \((P_{\text{th}}/P_{\text{th,eff}})\) and to describe principally the rapid increase of \(P_{\text{th}}\) in the low-density regime called "low-density anomaly". We find that the change in exponents to \(B_r, n_{20}\), and \(S\) is not especially necessary.

We examine the effect of \(Z_{\text{eff}}\) on the radiation power, and do not especially find the relation between \(Z_{\text{eff}}\) and \(P_{\text{core}}\) (radiation power from the core plasma) as shown in figure 3(c). As a result, almost the same dependence, \((P_{\text{th}} - P_{\text{core}})/P_{\text{th,eff}} - Z_{\text{eff}}^{2.7}\), is obtained. The store of \(P_{\text{core}}\) in the database is rather poor at present. The analysis considering the effect of \(P_{\text{core}}\) is the future work. It is interesting to note that equation (3) is similar to a theoretical formula given by Minardi [9], \(P_{\text{th}} \sim B_r^{0.3} n_e^{-0.77} Z_{\text{eff}}^{0.57}\). Detailed comparison is also the future work.

5. Role of \(A\)

As described in section 5, \(P_{\text{th}}\) in NSTX is rather large compared with that in standard tokamaks. The \(Z_{\text{eff}} \sim 2\) in NSTX is not the cause of increased \(P_{\text{th}}\). Nonlinear dependence of \(P_{\text{th}}\)
on the aspect ratio $A$ can be true even though the present number of data from low-$A$ tokamaks is not large enough to confirm it. We make bold to propose an example of L-H transition model here. We assume a driving force of the transition is originated by the toroidal effect proportional to the inverse aspect ratio $A^{-1}$. The parallel flow or current of the untrapped particles plays a key role in the transition mechanism. Therefore we assume also the driving force being proportional to the fraction of untrapped particles $f(A) = 1 - (\frac{2}{1+A})^{5.5}$. Transition happens more easily for smaller value of $F(A) = A/[f(A)]$. The threshold power to ensure the critical driving force is then supposed to be $P_{\text{thr}} = -F(A)^{\gamma}$. This correction factor takes its minimum at $A = 2.7$, and increases rapidly when $A$ approaches unity. This model describes well the results of database analysis. The ratio of $P_{\text{thr}}$ to $F(A)^{\gamma}P_{\text{thr, new}}$ for low-$A$ tokamaks now approaches unity ($\sim 1.0$ for MAST and $\sim 2.0$ for NSTX), where $F(A) = 0.1A/[f(A)]$ and $\gamma = 0.5-1.0$. Verification of the model is the future work together with increasing the amount of low-$A$ data.

6. New scaling and prediction for ITER

Following the above analysis, we present a new scaling expression for $P_{\text{thr}}$:

$$P_{\text{thr,new}} = 0.072B_{\text{tok}}^{0.7}n_{\phi}^{0.7}S_{\phi}^{0.7} \left( Z_{\phi}^{0.2} \right) F(A)^{\gamma}$$  \hspace{1cm} (4)

where the nonlinear $A$-dependence term is rather uncertain; $\gamma = 0.5 \pm 0.5$. Figure 4 shows that the new scaling expression (4) fits experimental data better than the $P_{\text{thr}}$ scaling. In figure 4(b), we impose $Z_{\phi} = 2$ to COMPASS-D, JFT-2M, MAST, PBX-M, and TCV data. Scattering in the data points is reduced ($\sigma = 0.35$ for $\ln(P_{\text{thr}}/P_{\text{thr}})$ and $\sigma = 0.31$ for $\ln(P_{\text{thr}}/P_{\text{thr,new}})$), and the low-$A$ data points approach the scaling line for the new scaling.

On the basis of the above results, we predict the power threshold in ITER for the standard operation; $R = 6.2$ m, $a = 2$ m, $B_i = 5.3$ T, $I_p = 15$ MA and $S = 680$ m$^2$ [1]. It is planned to operate the L-H transition at $n_{\phi} = 0.5 \times 10^{19}$ m$^{-2}$. Equation (1) gives $P_{\text{thr}} = 42$ MW, and equation (2) gives $P_{\text{thr,new}} = 43$ MW where $B_{\text{int}} = 4.3$ T is affected only a little by the $\gamma$ value. The correction factor $F(A) = 1.03$ in equation (4) changes little the prediction. If $Z_{\phi}$ will be kept $\sim 2$, $P_{\text{thr}} = 40 - 50$ MW can be reliable. Effort to decrease impurity will be the key to

![Figure 4. Comparison of experimental $P_{\text{thr}}$ data with scaling expression (a) $P_{\text{thr}}$ and (b) $P_{\text{thr,new}}$.](image-url)