ROLE OF THE PEDESTAL POSITION ON THE PEDESTAL PERFORMANCE IN AUG, JET-ILW AND TCV AND IMPLICATIONS FOR ITER

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Abstract

The role of the pedestal position on the pedestal performance has been investigated in AUG, JET-ILW and TCV. When the pedestal is peeling-ballooning limited, the three machines show a similar behaviour. The outward shift of the pedestal density leads to an outward shift of the pedestal pressure which, in turns, reduces the PB stability, degrades the pedestal confinement and reduces the pedestal width. Once the experimental density position is considered, the EPED model is able to correctly predict the pedestal height. An estimate of the impact of the density position on an ITER baseline scenario shows that the maximum reduction in the pedestal height is 10% while the reduction in the fusion power is between 10% and 40% depending on the assumptions for the core transport model used.

When the pedestal is not PB limited, a different behaviour is observed. The outward shift of the density is still empirically correlated with the pedestal degradation but no change in the pressure position is observed and the PB model is not able to correctly predict the pedestal height. On the other hand, the outward shift of the density leads to a significant increase of $\eta_\theta$, where $\eta_\theta$ is the ratio of density to temperature scale lengths, $\eta_\theta = L_{\theta,\text{ne}}/L_{\theta,T_e}$ which leads to the increase of the growth rate of microinstabilities (mainly ETG and ITG) by 50%. This suggests that, when the pedestal is not PB limited, the increase in the turbulent transport due to the outward shift of the density might play an important role in the decrease of the pedestal performance.

1. INTRODUCTION

Differences in the pedestal position of electron density ($n_{e,\text{ped}}$) and temperature ($T_{e,\text{ped}}$) have been experimentally known for many years [1, 2]. Their impact on pedestal performance has started to be investigated in detail only very recently [3,4,5,6]. In particular, AUG [5] has shown that an outward shift of $n_{e,\text{ped}}$ leads to an outward shift of pedestal electron pressure position ($p_{e,\text{ped}}$), which in turn leads to a degradation of the peeling-ballooning (PB) stability and the pedestal pressure height ($p_{\text{ped}}$). The change in $n_{e,\text{ped}}$ was related to a change in gas fuelling and nitrogen seeding rates. Recently, TCV has also shown that $p_{e,\text{ped}}$ can affect the PB stability and hence the pedestal height [7]. Instead, the role of $p_{\text{ped}}$ in JET-ILW has been, so far, elusive and the most recent results are in an apparent contradiction with those presented by AUG and TCV [6]. For example, the degradation of $p_{\text{ped}}$ in a JET-ILW gas scan at constant $\beta$ has been correlated with the increase of distance between $n_{e,\text{ped}}$ and $T_{e,\text{ped}}$ (hereafter called “relative shift”) while no variation in $p_{e,\text{ped}}$ has been observed [6]. To achieve a reliable prediction of the ITER pedestal, it is vital to clarify the roles of the pedestal positions ($n_{e,\text{ped}}$ and $T_{e,\text{ped}}$) in the PB stability and pedestal performance.

From a theoretical point of view, the PB model is the most accepted for a description of the pedestal behavior [8,9]. According to the model, the pedestal pressure increases till the PB modes become unstable and trigger an ELM crash. Indeed, most of the machines, including AUG, TCV, JET-C and some JET-ILW discharges, have shown that the pedestal pressure reaches the PB stability boundary just before the ELM crash. When the pedestal is PB limited, the experimental pedestal pressure height is in good agreement with the expectations from the PB theory.

To predict the pedestal height within the PB framework, the most common approach is to use the EPED model [10]. The most recent version of the EPED model [11] is based on two MHD limits. First, it assumes that the pedestal pressure gradient ($\nabla p_{\text{ped}}$) grows unconstrained till the kinetic ballooning mode (KBM) instability is reached. The KBM boundary defines the value of $\nabla p$. At this stage, the pedestal height increases via a widening of the pedestal pressure width ($w_p$) until the PB boundary is reached and an ELM is triggered. According to the model, the width increases as $w_p \propto D (\beta_p)^{1/2}$, where $\beta_p$ is the poloidal $\beta$ at the pedestal top and D is a constant that depends on the KBM boundary [11]. This expression is often called the “KBM constraint”. The most common version of the model (EPED1 [10]) assumes $D=0.076$ (as determined from an experimental fit of DIII-D low $v^*$ plasmas). In literature, however, the experimental value of D has been observed to vary from $D=0.084$ in C-mod [12], to $D=0.11$ in AUG [13] and in a wide range $D=0.06-0.13$ in JET-ILW [14] and TCV [7]. When the pedestal is PB limited, EPED can correctly predict, within $\pm 20\%$, the pedestal height in a wide range of experimental conditions and in several devices [11]. Recent results from TCV [7] have shown that a more reliable prediction can be achieved if the model uses the empirically estimated D.
However, JET-ILW has shown that the ELMs can be triggered even when the pedestal has not reached the PB boundary [15,16]. For these types of plasmas, hereafter called “non-PB limited”, the EPED predictions significantly overestimate the experimental pedestal height [16]. It is not yet fully clear under which experimental conditions the pedestal is non-PB limited, even if most of the experimental results suggest that this occurs with high gas fueling rate. To date, it is not clear which mechanism triggers the ELMs and which mechanism sets $V_{pped}$ in the non-PB limited plasmas. Recent theoretical studies [17] suggest that the turbulent transport driven by microinstabilities might play an important role in setting $V_{pped}$, however a firm and conclusive experimental evidence is missing.

This work has several goals. (I) To reconcile the JET-ILW results on the pedestal position with those of AUG and TCV, (II) to prove that the impact of $p_{pped}$ on the PB stability is a general phenomenon common to all the three machines when the pedestal is PB limited. These will be discussed in Section 3. (III) To estimate the impact of $p_{pped}$ on ITER performance, Section 4. (IV) To show that, when the pedestal is non-PB limited, $n_{e,pped}$ and the relative shift might still have an impact on $V_{pped}$ by increasing the turbulent transport, Section 5.

**TABLE 1.** List of the eight experimental datasets used in this work. Scans 1-5 and scan 7 are fuelling rate scans at constant power in deuterium plasmas. Scan 6 is a nitrogen seeding scan at constant fuelling rate and power. Scan 8 is a gas scan at constant $\beta_n$. $P$ is total external power, $P = P_{NBHI} + P_{ECRH} + P_{ICRH}$.

<table>
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<th>dataset</th>
<th>machine</th>
<th>description</th>
<th>$P$ (MW)</th>
<th>gas rate (e/s)</th>
<th>$I_p$ (MA)</th>
<th>$B(T)$</th>
<th>$\delta$</th>
<th>$\beta_n$</th>
<th>$H_n$</th>
<th>PB-limited</th>
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<td>0.8-0.9</td>
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<td>(1-2.5) $10^{22}$</td>
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<td>2.2</td>
<td>0.4</td>
<td>1.2-1.4</td>
<td>0.7-0.9</td>
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<td>0.25</td>
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<td>AUG</td>
<td>$\Gamma_4$ scan const. $P$</td>
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<td>1.4</td>
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2. EXPERIMENTAL DATASETS AND TECHNICAL DETAILS OF THE KINETIC PROFILES

The experimental datasets used in the work are from AUG, JET-ILW, and TCV. The datasets are summarized in table 1 and are described in detail in references [6,7,16,18]. These datasets have been selected due to their large variation in the pedestal position.

All datasets consist of NBI heated deuterium plasmas. The AUG datasets have an additional 1MW of ECRH. All plasmas are Type I ELMs M-H modes, as determined via the increase of the ELM frequency in specific NBI power scans [5,6,7,16]. Most of the datasets are a deuterium fuelling rate scan at constant power. Exceptions are scan 6 and scan 8. Scan 6 is a nitrogen seeding scan performed in TCV with constant fuelling rate and constant NBI power [7]. Scan 8 is a gas scan at constant $\beta_n$. $P$ is total external power, $P = P_{NBHI} + P_{ECRH} + P_{ICRH}$.

Scans 1, 3, 4, 7, 8 have been performed in low triangularity plasmas, while scans 2, 5, 6 in high triangularity. As discussed in reference [6], the triangularity does not affect the behavior of the pedestal position in gas scans.

The plasmas of the first six datasets are PB limited, as described in references [5,7,16]. These six datasets are used in Section 3. The plasmas of the last two datasets are non-PB limited at medium and high gas fueling rate [6,16]. They are discussed in Section 6.

The kinetic profiles of electron temperature ($T_e$) and density ($n_e$) are measured with Thomson scattering systems. The profiles have been shifted to have a separatrix temperature ($T_{e,sep}$) consistent with what expected by the two point model for the separatrix power balance, $T_{e,sep}$=100eV in JET-ILW and AUG and $T_{e,sep}$=50eV in TCV. The position of the pedestal is determined as the position of the maximum gradient and is expressed in normalized poloidal flux ($\psi_{p}$) units. The width (w) of the pedestal pressure is determined as $w_{pped} = (w_{Te} + w_{n_e})/2$, in agreement with the EPED definition. All the parameters have been determined with a $\text{mtanh}$ fit considering only the pre-ELM profiles.

3. ROLE OF THE PEDESTAL POSITION IN PEELING-BALLOONING LIMITED PLASMAS

The AUG and TCV results discussed in [5,7] show that the degradation of the pedestal performance with increasing gas rate is due to the reduced PB stability produced by the outward shift of the pedestal pressure. Instead, the JET-ILW results presented in [6] show...
that the decrease in pedestal performance with increasing gas rate is correlated to the increase of the relative shift, with no change in $p_e^{\text{pos}}$. These observations might seem contradictory. However there is a major difference in these three datasets. The AUG and TCV datasets are PB limited, while the JET-ILW dataset is not PB limited at medium and high gas rate.

To have a consistent description of the pedestal behavior among different machines, this section is focused only on datasets that are PB limited. This has been verified by applying the standard PB stability analysis [19] to identify the distance of the pre-ELM pedestal from the PB stability boundary, quantified with the ratio $\alpha_{\text{crit}}/\alpha_{\text{exp}}$. Here, $\alpha_{\text{crit}}$ is the normalized pressure gradient expected by the PB model and $\alpha_{\text{exp}}$ is the experimental one. It is assumed that the pedestal is on the PB boundary when $\alpha_{\text{crit}}/\alpha_{\text{exp}} \approx 1$, within 20%.

The datasets used in this section are the following. For JET-ILW, a gas scan at low power and low triangularity [16] and a gas scan at medium power and high triangularity (scans 1 and 2 in table 1). For AUG, a gas scan at medium power and high triangularity [18] (scans 3 and 4). For TCV, a gas scan and a N seeding scan at constant power and high triangularity [7] (scans 5 and 6).

### 3.1 Experimental Pedestal Structure.

An example of the behavior of the $p_e$ profile in a PB limited JET-ILW gas scan is shown in figure 1. The increase of the deuterium fueling rate ($F_D$) leads to a reduction of $p_e^{\text{ped}}$, a reduction of $V_p$, and an outward shift of $p_e^{\text{pos}}$. This behavior is similar to all the six PB limited datasets, as shown in figure 2.

Figure 2(a) shows the pedestal height of $T_e$ and $n_e$. The increasing $T_e$ leads to a weak increase of $n_e^{\text{ped}}$ and significant reduction of $T_e^{\text{pos}}$ and $p_e^{\text{pos}}$.

An exception is the TCV N seeding scan which produces the decrease of both $T_e$, $n_e$ and $p_e$. This behavior is different from earlier JET-ILW and AUG results [20,5], where an increase of $p_e^{\text{ped}}$ with increasing N seeding was observed, but it is still consistent with the PB model, as discussed in Section 3.3.

Figure 2(b) shows the behavior of the electron pedestal pressure width $w_p$. In all datasets, the increase of the gas rate leads to the reduction of $\beta_n^{\text{ped}}$ and $w_p$. It is interesting to observe that the JET-ILW and the TCV datasets are relatively consistent with the EPED1 assumption, $w_p=D(\beta_n^{\text{ped}})^{1/2}$, with $D$ in the range 0.08-0.10, while the AUG dataset is slightly higher, with $D=0.11-0.13$.

Figure 2(c) shows $T_e^{\text{pos}}$ and $n_e^{\text{pos}}$. The dashed lines are levels curves at constant $p_e^{\text{pos}}$ that have been geometrically determined from artificial scans of $T_e^{\text{pos}}$ and $n_e^{\text{pos}}$. They can be used as a qualitative estimate of the $p_e^{\text{pos}}$ behavior. In all cases, the increasing gas rate leads to an outward shift of $n_e^{\text{pos}}$ and $T_e^{\text{pos}}$. Note that, being $T_e^{\text{pos}}$ fixed, the $T_e$ outward shift is due to the shrinking of the pedestal and the decrease of $T_e^{\text{ped}}$. As a direct consequence of the increase of $n_e^{\text{pos}}$ and $T_e^{\text{pos}}$, the pedestal pressure position moves outward. Note that (1) the relative shift is not zero in most of these discharges ($n_e^{\text{pos}}/T_e^{\text{pos}}$) but that (2) the relative shift is roughly constant because the increase in $n_e^{\text{pos}}$ is compensated by a comparable increase in $T_e^{\text{pos}}$.

### 3.2 Comparison with the EPED Model.

To confirm that the pedestal degradation with increasing gas rate is linked to the outward shift of the pedestal pressure, the EPED1 model is used. The inputs to the standard EPED1 model are $\beta_n$, $n_e^{\text{ped}}$, $Z_{\text{eff}}$, plasma geometry, current and $B_p$. The output is the pedestal pressure height and width. EPED1 assumes that the density position is the same as the temperature, $n_e^{\text{pos}}=T_e^{\text{pos}}$, and that the relative shift is approximately $w_p=D(\beta_n^{\text{ped}})^{1/2}$, with $D=0.076$. More recent versions, for example those implemented in iPED [5] and Europed [21] allow to specify as input $n_e^{\text{pos}}$ and D. In any EPED version, $p_e^{\text{ped}}$ is determined from the predicted pressure profile.

Initially, the experimental pedestal pressure is compared with the standard EPED1 predictive results, i.e. using $D=0.076$ and assuming $T_e^{\text{pos}}$. Then, the EPED1 model is used by imposing the experimental $n_e^{\text{pos}}$. 

![Figure 2](https://via.placeholder.com/150)
Figure 3(a) shows the results for JET-ILW pedestals, scan 1. The standard EPED1 with \( n_{\text{ep}} = T_{\text{ep}} \) (empty squares) qualitatively reproduces the experimental trend with increasing gas rate. The negative trend of the predicted \( p_{\text{ped}} \) with increasing gas rate is due to the reduction of \( \beta_N \). This is because the decrease of \( \beta_N \) has a destabilizing effect on the ballooning modes [8,9]. But, from a quantitative point of view, the standard EPED1 with \( n_{\text{ep}} = T_{\text{ep}} \) overestimates the experimental pedestal pressure by up to \( \approx 30\% \).

On the other hand, the assumption \( n_{\text{ep}} = T_{\text{ep}} \) is not correct. The high gas rate discharge of figure 3(a) has \( T_{\text{ep}} \approx 0.99 \psi_N \) and \( n_{\text{ep}} \approx 1.005 \psi_N \), see figure 2(c). \( n_{\text{ep}} \) is 0.015 \( \psi_N \) more outward than \( T_{\text{ep}} \). Using the experimental \( n_{\text{ep}} \) as input, the predictive EPED results are in much better quantitative agreement with the experimental \( p_{\text{ped}} \), as shown by the full grey squares in figure 3(a). The difference in the predicted \( p_{\text{ped}} \) assuming \( n_{\text{ep}} = T_{\text{ep}} \) and using the experimental \( n_{\text{ep}} \) is \( \approx 20\% \). The outward shift of the density has led to a reduction of the PB stability and hence of the pedestal height. Note that the change in the PB stability is not a direct effect of \( n_{\text{ep}} \) but it is due to the effect of \( n_{\text{ep}} \) on the pressure position and on the bootstrap current \( J_{\text{bs}} \) [5]. \( p_{\text{ped}} \) and the \( J_{\text{bs}} \) peak move outwards and the separatrix \( J_{\text{bs}} \) increases (see Section 5.2). These three effects reduce the PB stability [22].

Figure 3(b) shows the predicted EPED \( p_{\text{ped}} \) versus the experimental \( p_{\text{ped}} \) for four datasets. The empty symbols represent the EPED predictions with the assumption \( n_{\text{ep}} = T_{\text{ep}} \). The overestimation is \( \approx 25-50\% \) for most of the cases but is more than 100\% for the TCV discharge with N seeding. The full symbols represent the EPED predictions using the experimental \( n_{\text{ep}} \). In this case, the agreement between the EPED predictions and the experimental data is within 20\%.

### 3.3 NITROGEN SEEDING in TCV.

As mentioned in Section 3.1, the increase of the N seeding rate in TCV leads to a reduction of the pedestal pressure and to an outward shift of the density and of the pressure, see figures 2(a) and 2(c). This behavior is opposite to what was observed in AUG [5], and JET-ILW [20]. In AUG, the N seeding led to the increase of \( p_{\text{ped}} \) and to an inward shift of \( n_{\text{ep}} \) and \( T_{\text{ep}} \). In JET-ILW the seeding led as well to the increase of \( p_{\text{ped}} \).

Interestingly, the behavior of the pedestal height with N seeding in TCV and AUG are both consistent with the PB model.

In TCV, the pedestal height decreases because of the outward shift of the pressure position with increasing seeding rate. Indeed, once the experimental density position is considered, the EPED model predicts reasonably well the pedestal height, see figure 3(b) and reference [7]. Note that the change in \( n_{\text{ep}} \) causes not only the reduction of \( T_{\text{ep}} \) but also the outward shift of \( T_{\text{ep}} \). The reduced PB stability leads to a decrease in \( \beta_0 \) which leads to a shrinking of the pedestal via the KBM constraint. The shrinking of the pedestal causes the outward shift of the temperature.

In AUG, the behavior is opposite: the N seeding leads to an inward shift of the density, which leads to the inward shift of the pressure which in turn improves the PB stability and increases the pedestal height.

It is not clear yet why, in TCV and AUG, the N seeding has an opposite effect on the pedestal position. This is beyond the scope of the present work but its origin might be correlated to the presence of high-field-side-high-density (HFSHD). The HFSHD is a high density front that in AUG is a major source of fueling for the pedestal [5,23,24]. In AUG, the N seeding reduces the HFSHD, decreasing the pedestal fueling and hence moving the density inward [5,24]. In TCV, due to the open divertor geometry, the HFSHD is likely not present, so the N seeding might simply increase the pedestal fueling.

In conclusion, Section 3 has shown that, when the pedestal is PB limited, the outward shift of \( n_{\text{ep}} \) has similar effects on AUG, JET-ILW and TCV and that the EPED model can reasonably predict the pedestal height once the experimental density position is considered.

### 4. IMPLICATIONS FOR ITER

ITER is supposed to operate at high separatrix density (\( n_{\text{sep}} \)). Separatrix density and \( n_{\text{ep}} \) are correlated since an outward shift of the density leads to an increase of \( n_{\text{sep}} \). See figure 6(a) for a qualitative example.

This section estimates the impact of the density shift, and hence of \( n_{\text{ep}} \), on a standard ITER scenario. This is done using the ELITE code [8] for the PB stability analysis and the Europed code [21] for the prediction of the...
ITER pedestal height. Europed contains the same physics as EPED in the pedestal, but can treat self-consistently the interaction between the core and the pedestal.

The modelling has been done on a ITER baseline scenario, with $I_p=15$MA, $B_T=5.3$T, and assuming constant $\beta_N=2.0$ and $n_{\text{ped}}=8\times10^{19}$m$^{-3}$. Figure 4(a) shows the corresponding PB stability boundary obtained with ELITE. Initially, the PB boundary has been calculated assuming $n_e^{\text{pos}}=T_e^{\text{pos}}$ (red line) and then assuming the density is shifted outwards by 0.018$\psi_N$. The change in the density position leads to the shrinking of both ballooning and peeling boundaries. This is because the change in $n_e^{\text{pos}}$ has two effects on $j_{\text{BS}}$. First, it moves the $j_{\text{BS}}$ peak outwards [5,6,22]destabilizing the ballooning modes and, second, increases the separatrix $j_{\text{BS}}$ destabilizing the peeling modes. The operational points are shown in figure 4(a) with stars. The effect of the density shift is a reduction of the normalized pressure gradient by $\approx15\%$, from $\alpha_{\text{exp}}=6.7$ to $\alpha_{\text{exp}}=5.8$.

A 15\% reduction in the normalized pressure gradient suggests that the impact on ITER pedestal height might be significant. This has been tested using Europed. Initially, Europed has been used considering only the pedestal physics, i.e. without coupling self-consistently core and pedestal, but assuming constant $\beta_N$. Figure 4(b) shows the predicted pressure height (estimated at $\psi_N=0.93$, near the pedestal top) for different values of the density shift. For each density shift, the corresponding value of $n_e^{\text{sep}}/n_{\text{ped}}$ is shown on the top x-axis. The decrease in the predicted pressure with increasing shift is rather rapid, but then saturates for density shifts higher than 0.02$\psi_N$. The maximum reduction of pedestal pressure is $\approx10\%$. The origin of the saturation is due to the fact that, when the density shift is too large, the effect on the pressure position and on the $j_{\text{BS}}$ is minimal, as discussed in details in the next Section.

To estimate the effect of the density shift on the ITER fusion power, $P_{\text{ fus}}$. Europed has then been used considering self-consistently the interaction core-pedestal. From a practical point of view, $\beta_N$ is not used anymore as an external input to determine the core pressure but a simple core transport model has been used. The core transport model assumes (1) low heat diffusivity ($\chi_e=0.1$m$^2$/s) below a critical $R/L_{\text{Te,crit}}$ and (2) a heat diffusivity $\chi_e=0.1$m$^2$/s+(2m$^2$/s)×($R/L_{\text{Te,crit}}$) above.

The model is simple, but it is sufficient to produce a rough estimate of the effect on core pressure and $P_{\text{ fus}}$. We assume 70MW of auxiliary heating located in the core. The heating by fusion $\alpha$’s is taken into account self-consistently. The results are shown in figure 4(c) using different assumptions for the value of the critical $R/L_{\text{Te}}$. $P_{\text{ fus}}$ has been estimated assuming no shift ($n_e^{\text{pos}}=T_e^{\text{pos}}$, red line) and assuming an outward density shift by 0.018$\psi_N$ (blue line). The value of the critical $R/L_{\text{Te}}$ influences significantly $P_{\text{ fus}}$, but the absolute reduction of $P_{\text{ fus}}$ due to the density shift is rather constant $\approx100$MW. In relative terms, the impact of the density shift on $P_{\text{ fus}}$ is from a $\approx40\%$ reduction with low $R/L_{\text{Te}}$ to a $\approx10\%$ reduction with high $R/L_{\text{Te}}$.

5. ROLE OF THE PEDESTAL POSITION IN PLASMAS NOT PEELING-BALLOONING LIMITED.

Non-PB limited pedestals in Type-I ELMy H-mode plasmas have been clearly identified only in JET-ILW. It is not yet clear which physics mechanism triggers the ELMs in this type of plasmas and under which operational conditions they appear. The main experimental evidence is that the pre-ELM pedestal of baseline discharges tends to be far from the PB boundary (in the stable region of \(j-\alpha\) diagram) at “medium”,“high” gas fueling rate and “medium”,“high” power [6,15,16]. Under these conditions, the EPED model significantly overestimates the pedestal pressure [16, 25]. The meaning of “medium” and “high” is arbitrary and can be interpreted only qualitatively within gas scans and power scans. No universal threshold has been identified yet. Good divertor neutral pressure measurements are not always available, complicating the work. Moreover, due to the difficulties in characterizing the wall source in carbon experiments, cross-machine comparisons in terms of fueling and recycling are challenging.
This section investigates the JET-ILW discharges in scans 7 and 8, Table 1. Scan 7 is a gas scan at 15MW. Scan 8 is a gas scan at constant $\beta_N$. In both cases, the pedestal at medium and high $\Gamma_D$ is non-PB limited [6,16].

5.1 PEDESTAL BEHAVIOR IN THE NON-PB LIMITED DATASETS.

The JET-ILW results presented in [6] shows that increases in fueling rate leads to increases in the relative shift ($n_{e,\text{pos}}-T_{e,\text{pos}}$). This has been experimentally correlated with the reduction of $\alpha_{\text{exp}}$ and hence of the pedestal performance. Figure 5(a) shows the correlation of $\alpha_{\text{exp}}$ versus the relative shift. In both datasets, $\alpha_{\text{exp}}$ decreases with increasing relative shift. The empty circles highlight the non-PB limited pedestals.

Figure 5(a) also shows the EPED predicted normalized pressure gradient ($\alpha_{\text{crit}}$), grey squares. As expected, $\alpha_{\text{crit}}$ overestimates $\alpha_{\text{exp}}$ in the non-PB limited plasmas. Note that the model has been used with (i) the assumption $n_{e,\text{pos}}=T_{e,\text{pos}}$ (empty squares) and then with (ii) the experimental $n_{e,\text{pos}}$ (full squares). Interestingly, the two types of assumptions do not affect the result (the full squares cover the empty squares). This is in contrast with Section 3, where a 0.01 $\psi_N$ density shift leads to a 25% difference in the predicted pedestal height. To understand the origin of this contradiction, it is necessary to investigate in detail the behavior of the pedestal structure.

Figure 5(b) shows the pedestal pressure width. In both datasets, a widening of the pedestal with increasing gas rate is observed and the behavior of the width expected in EPED model is not reproduced. The widening of the pedestal with increasing gas rate is fairly common in JET-ILW, as reported in references [14,16,25,26]. Note that this behavior is significantly different from what was observed for the PB limited gas scans discussed of Section 3, where the pedestal shrinking with increasing gas rate was observed.

Figure 5(c) shows the behavior of the pedestal position of density and temperature. In both scans, $T_{e,\text{pos}}$ is roughly constant, while $n_{e,\text{pos}}$ moves outwards with increasing gas rate. This implies an increase in the relative shift. Again, the behavior is different from what was observed in PB limited datasets of Section 3, where $T_{e,\text{pos}}$ was observed to shift outwards with increasing gas rate while the relative shift was roughly constant. The key result of figure 5(c) is that the pedestal positions of scans 7 and 8 move approximately along the level curves of constant $p_{e,\text{pos}}$, suggesting that the position of the pedestal pressure does not change significantly. This is verified in figure 5(d), where $p_{e,\text{pos}}$ versus the relative shift is shown. Despite the increase in relative shift and the outwards shift of the density, $p_{e,\text{pos}}$ is constant. A similar behavior is observed for the $j_{\text{hs}}$ peak, as described in Section 5.2.

This last result explains why the EPED predictions of figure 5(a) do not show any difference using (i) the assumption $n_{e,\text{pos}}=T_{e,\text{pos}}$ and (ii) the experimental $n_{e,\text{pos}}$. The PB stability is in fact affected by the pressure position and not directly by the density position. Moreover, the stability analysis considers the profiles only till $\psi_N=1.0$, so any change outside the LCFS is not expected to influence the PB stability.

5.2 GEOMETRICAL INTERPRETATION.

A geometrical approach is useful to understand why $p_{e,\text{pos}}$ is constant with increasing $n_{e,\text{pos}}$ in the non-PB limited datasets while $p_{e,\text{pos}}$ increases in the PB limited datasets.

The thick lines in figure 6(a) show the $T_e$ and $n_e$ profiles of shot 84600 (JET-ILW low gas, PB limited pedestal of scan 8, with $n_{e,\text{pos}}-T_{e,\text{pos}}=0.01\psi_N$). From the product of $T_e$ and $n_e$ profile it is possible to calculate the $p_{e,\text{pos}}$ profile and the corresponding pedestal position. Then, starting from this reference case, this procedure has been
repeated by shifting outwards and inwards the density profile, as shown by the colored profiles in 6(a). The corresponding $p_{e \text{pos}}$ as function of the relative shift is shown in figure 6(b). The position of the pedestal increases with increasing relative shift till $\eta_e^{\text{pos}}/T_e^{\text{pos}} \approx 0.015 \psi_0$, and then it levels off. This is because, when the relative shift is high, $\eta_e$ is flat inside the separatrix and so $p_{e \text{pos}}/T_e^{\text{pos}}$. The $j_{\text{bs}}$ shows a similar behavior, figures 6(c) and figure 6(d). The position of the $j_{\text{bs}}$ peak increases with increasing relative shift, while the peak value of $j_{\text{bs}}$ decreases. Saturation is observed for $\eta_e^{\text{pos}}/T_e^{\text{pos}} \approx 0.01 \psi_0$.

The vertical dashed lines in figures 6(b) and 6(d) show the range of variation of the relative shift in the PB limited datasets (blue) and in the non-PB limited datasets (red). In the PB limited case, a change in $\eta_e^{\text{pos}}/T_e^{\text{pos}}$ leads to a change in $p_{e \text{pos}}$ and $j_{\text{bs}}^{\text{pos}}$. In the non-PB limited case, $\eta_e^{\text{pos}}/T_e^{\text{pos}}$ is quite large, in a region where $p_{e \text{pos}}$ and the $j_{\text{bs}}$ peak have already leveled off. This description does not consider any possible changes in the $\eta_e$ and $T_e$ pedestal widths, but nonetheless it is sufficient to capture the main mechanism that leads to the different behavior of $p_{e \text{pos}}$ in the PB limited and non-PB limited datasets.

On the other hand, when the relative shift is large, the density shift has a significant impact on $\eta_e$. This parameter is defined as $\eta_e = L_{n_e}/L_{T_e}$ (with $L_{n_e}$ and $L_{T_e}$ the gradient length of $n_e$ and $T_e$, respectively) and it has a significant impact of the growth rate of microinstabilities. The $\eta_e$ profiles corresponding to the profiles of figure 6(a) are shown in figure 6(e). The maximum variation of $\eta_e$ is almost two orders of magnitude. To better quantify this variation, we have taken $\eta_e$ averaged in a region 0.02 $\psi_0$ wide around the position of the $T_e$ pedestal top (where the larger variation occurs). The correlation between $\langle \eta_e \rangle$ and the relative shift is shown in figure 6(f). In the region of the PB limited datasets ($\eta_e^{\text{pos}}/T_e^{\text{pos}} < 0.012 \psi_0$) the variation is minimal, while in the region of the non-PB limited datasets ($\eta_e^{\text{pos}}/T_e^{\text{pos}} > 0.01 \psi_0$) $\langle \eta_e \rangle$ increases significantly.

5.3 POSSIBLE ROLE OF THE TURBULENT TRANSPORT IN THE NON-PB LIMITED DATASETS.

It is well known that strong $\eta_e$ variations in the pedestal have a strong influence on the microinstabilities [27, 28]. The large increase of $\eta_e$ with increasing relative shift is therefore expected to drive increasing levels of temperature gradient driven microturbulence, generating heat transport, inside the pedestal. These microinstabilities might start to have an influence on pedestal transport in these non-PB limited plasmas [17,29].

Figure 7(a) shows the ratio $\alpha_{\text{crit}}/\alpha_{\text{exp}}$ versus $\langle \eta_e \rangle$. The ratio $\alpha_{\text{crit}}/\alpha_{\text{exp}}$ is an estimate of the distance of the pre-ELM pedestal from the PB boundary. $\alpha_{\text{crit}}/\alpha_{\text{exp}}=1$ implies that the pre-ELM pedestal is near the PB boundary, while $\alpha_{\text{crit}}/\alpha_{\text{exp}}>1$ implies that the pre-ELM pedestal is far from the boundary, in the stable region of the $j-\alpha$ stability diagram and that the PB model is not able to predict the experimental pressure gradient. Figure 7(a) shows that all JET-ILW PB limited datasets (full symbols) have $\langle \eta_e \rangle \lesssim 3$, while the non-PB limited data have $\langle \eta_e \rangle \gtrsim 3$. In particular, the gas scan at constant beta (scan 8) shows that $\alpha_{\text{crit}}/\alpha_{\text{exp}}$ increases with $\langle \eta_e \rangle$. Therefore, it is worthwhile investigating if the reduction in $\alpha_{\text{exp}}$ is indeed correlated with the increase of turbulent transport driven by microinstabilities.

To investigate the possible role of microinstabilities, the GS2 code has been used [29] and local linear gyrokinetic analysis at $\psi_0 = 0.95$ (just inside the pedestal top, see figure 6(a)) have been performed for shots 84600 and 84598, see figure 7(a). $T_e = T_\psi$ has been assumed, so $\eta_e$ and $\eta_\ell$ are both equally enhanced in the high relative shift plasmas. Growth rates for the fastest growing modes are given in figure 7(b) as a function of perpendicular wavenumber $k_\perp$, for ballooning angle $\theta_b = 0$. In the high relative shift case, both the ETG modes and the ITG modes are more unstable than in the low relative shift case, with normalized growth rates on average 50% higher. A rough mixing length estimate of the thermal diffusivity suggests an increase of approximately 20% in 84598 (high relative shift, non-PB limited pedestal). No dominant unstable micro-tearing modes have been found at $\theta_b = 0$ on the selected surfaces.
This first linear analysis strongly suggests that the microturbulence driving heat transport increases with increasing relative shift inside the pedestal top. $\eta_p$ are also substantially enhanced in the pedestal, so the increased heat transport is expected to continue into the pedestal itself, which would explain the low pressure gradient observed in these non-PB limited pedestals. More extensive linear and non-linear gyrokinetic simulations are needed to explore the dependence on radius and $\theta_0=0$, and to compute the turbulent fluxes.

6. DISCUSSION AND CONCLUSIONS.

The work has investigated the role of the pedestal position in pedestal performance and has tried to resolve the apparent contradictions in the published results on the topic. A key point has been to distinguish between plasmas with a pedestal that is PB limited and plasma with a pedestal that is not PB limited.

In plasmas that are PB limited, the outward shift of the density leads to the outward shift of the pedestal pressure which in turn destabilizes the PB modes, reducing the pedestal height. This type of behavior, already described in AUG and TCV [5,7] has now been consistently observed also in JET-ILW. In this type of plasmas, the PB model describes the pedestal behavior well and the EPED predictions reproduce the experimental data correctly once the realistic density position is used.

Assuming that the ITER pedestal is PB limited, this work has estimated the impact of the shift of the pedestal density on the ITER baseline scenario. The pedestal is supposed to degrade at most by 10%, while the impact on the fusion power varies between 10% and 40% depending on the critical R/L_Eb.

In plasmas that are not PB limited, the behavior of the pedestal structure with increasing gas rate is quite different. First of all, the pedestal widens instead of shrinking with increasing gas. Then, the density still moves outwards but no significant change has been observed in the pressure position. Therefore, the PB model cannot properly describe the pedestal behavior and the EPED model significantly overestimates the pedestal height.

The work suggests that the lower pressure gradient observed in the non-PB limited plasmas might be explained by an increase of turbulent transport driven by ETG and ITG modes.

The work on the non-PB limited plasmas is just at the beginning and several questions still remain open. Assuming that the lower pressure gradient is due to the increased turbulent transport, it is not yet clear which physical mechanisms trigger the ELMs (hypothesis on possible ELM triggering mechanisms can be found in reference [30]). Moreover, it is not yet clear under which experimental conditions the plasma becomes non-PB limited. The increase of the gas rate seems a key factor, but a universal threshold has not been found yet. Finally, it is not clear why the pedestal widens with increasing gas instead of shrinking like in the PB limited case. Understanding the behavior of the pedestal width is a key factor for understanding why the pedestal position behaves differently in the PB limited and non-PB limited plasmas.

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