Physics and scaling of the H-mode pedestal

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Abstract. The transport barrier which exists at the plasma edge in the high-confinement (H-mode) regime is now recognized as important to global energy confinement. Recently, detailed measurements of the width and height of barriers in electron and ion density and/or temperature have been made on several divertor tokamaks. These results are reviewed, with an emphasis on scalings of the pedestal height and width. Many experiments observe situations in which the limiting pedestal pressure gradient is well described by ideal ballooning stability. In some cases the extreme edge is in the ‘second stable’ regime. Differences between the widths \( \Delta \) of pedestals in electron and ion temperature and densities are noted in several experiments. Some reported scalings are \( \Delta \Delta M_T = 3.3 \sqrt{\Delta \rho_d,ped} \) on JT-60U, and \( \Delta \Delta R/\beta_0 \propto \rho_d,ped \) on DIII-D. \( \Delta \Delta T_e \) is independent of plasma current in many experiments. Theoretical modelling of the fully developed H-mode pedestal is reviewed. Several recent predictions of the pedestal parameters and their scalings are outlined and compared with experiments.

1. Introduction

The defining feature of the high-confinement (H-mode) transport regime, first observed on the ASDEX tokamak [1], is a reduction in transport near the edge of the plasma, typically just inside the scrape-off layer (SOL). This leads to gradients in electron and ion temperature and density which are steeper than those in the low-confinement (L-mode) regime, and those in the core plasma. This steep-gradient region, often referred to as the H-mode ‘pedestal’, can extend anything from a few millimetres to several centimetres inside the separatrix, and sometimes appears to extend slightly into the SOL. Transport in the H-mode pedestal region, which necessarily involves neutrals and interactions with the SOL as well as the local reduction of turbulence, is less well understood than that in the core plasma with transport barriers. Most models of thermal transport in H-mode in fact take the temperature and density inside the top of the barrier (e.g. \( r/a = 0.8 \) or 0.9) as inputs, and then attempt to predict temperature profiles into the plasma centre. This approach works well for modelling actual discharges, but has obvious limitations when attempting to predict parameters on future experiments. It is now recognized that for many transport models, particularly those in which ion temperature gradient (ITG) modes dominate transport, the central temperature can be highly sensitive to the assumed edge \( T_i \) [2]. Such a correlation has been observed experimentally in many, though not all, tokamaks, e.g. [3, 4]. The relation between pedestal parameters and core confinement is a very active area of research, but is outside the scope of this review. Such results do provide strong motivation to understand and be able to predict the plasma parameters in the H-mode pedestal, on the basis of either verified empirical scalings or, preferably, validated physical models.
Measurements of parameters in the pedestal region are extremely challenging. The small spatial scale lengths involved require very high resolution diagnostics, with radial resolution $\delta R$ typically on a centimetre to submillimetre scale. The temperatures and densities found at the edge, typically ranging from SOL values to $\sim 1$ keV and a large fraction of the core density, imply a large dynamic range. Standard core diagnostics are often not well optimized for this regime. In many cases, dedicated pedestal diagnostics are required. Over the past few years increasing attention has been paid to this problem, and most divertor tokamaks now have well resolved measurements of at least some pedestal profiles. A previous review of results was prepared by Loarte [5]. Unfortunately, in many cases different parameters are measured on different devices, making direct comparisons difficult. Furthermore, the presence and type of edge localized modes (ELMs) seem to be important. In the following section the experimental results, primarily from JT-60U, DIII-D, ASDEX Upgrade, C-Mod and JET where groups have been most actively working on this problem in recent years, will be reviewed. In particular, scalings for the pedestal height and width of various plasma parameters will be compared. The limiting gradient, which relates the two, will also be considered. Details of pedestal MHD stability are covered by a separate review [6].

In section 3, theoretical predictions for the pedestal height and width will be reviewed. In contrast to the large number of theories existing for the mechanism and threshold criteria for the L–H transition, which are outside the scope of this paper, relatively few theories give specific predictions for the parameters of a fully developed H-mode pedestal. Transport barrier formation necessarily involves complex nonlinear dynamics and feedback between two or more processes. As has been pointed out by Burrell and others, the dominant terms responsible for suppressing transport in a developed transport barrier may not be the same as those which trigger the transition [7]. Some models, however, do provide either a natural scaling parameter for the pedestal width or a prediction for the barrier width and/or height. In the final section, the experimental results from various devices will be compared with each other and with theoretical predictions. Points of consensus and apparent differences will be summarized and areas for further modelling and experimental tests suggested.

2. Experimental results

2.1. JFT2M and JT-60U

Some of the earliest and most systematic studies of pedestal widths and scaling were performed on the Japanese tokamaks JFT2M and JT-60U. On JFT2M, the scale length $\Delta_{\nu\theta}$ of the $E \times B$ velocity shear layer is obtained using spectroscopic measurements of C VI line emission [8, 9]. This is defined as twice the HWHM of the poloidal rotation velocity profile at the midplane. The measured widths are in the range 2.5–3.5 cm, with a current scan from 170 to 280 kA. These data were compared with the ion poloidal gyroradius $\rho_{i,pol}$, with and without orbit-squeezing effects. While the range of $\rho_{i,pol}$ is not large, the dependence of the width on these quantities, if any, appears less than linear. $\Delta_{\nu\theta}$ is about six times larger than the banana width, and the width of the temperature pedestal is even greater.

Kikuchi et al., in 1992, measured the barrier in $T_e$ [10] on JT-60U. The pedestal full width $\Delta_{T_e}$ is defined in this experiment as the distance from the break in slope of the $T_e$ profile, from edge Thomson scattering (TS), to the separatrix. Widths ranged from 2.4 to 5.6 cm, again about six times the calculated banana width. Later scaling studies using both electron and ion pedestal temperatures showed that the thermal barrier width has a $1/B_T$ scaling, suggesting a $\rho_{i,pol}$ dependence [9, 11]. The measured width is about five times the thermal banana width, or about equal to that of ions having $E = 50$ keV. Since the thermal- and fast-ion widths scale
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Figure 1. Scaling of the $T_i$ pedestal width in JT-60U ELM-free H-modes with $\sqrt{\epsilon \rho_{pi}}$. From Hatae et al [12].

similarly in this experiment, it was not possible to distinguish between these scalings.

Hatae reported very systematic studies of the pedestal width in ELM-free H-modes, in which plasma current was varied from 1 to 4.5 MA and pedestal $T_i$ from 1.3 to 3.9 keV, allowing the $B_p$ and $T_i$ dependences to be independently checked [12]. Ion temperature pedestal widths $\Delta T_i$ measured by charge-exchange recombination spectroscopy (CXRS) were used; $T_e$ widths, where available, are similar. This verified the $1/B_p$ dependence, and also found that $\Delta T_i \propto \sqrt{T_i}$. The widths, which range from 2 to 8 cm, are well fitted by the expression

$$\Delta T_i = 3.3 \sqrt{\epsilon \rho_{pi}} \quad (1)$$

as shown in figure 1. A statistically slightly better fit is $\Delta T_i = 1.75 \epsilon^{0.56} B_p^{1.07}$. These relations hold over wide ranges of triangularity $\delta$, elongation $\kappa$ and safety factor $q_{95}$, indicating that there is not a significant variation of the $T_i$ pedestal width with plasma shaping.

A similar study of the widths of Type I ELMMy H-modes was recently carried out by Kamada et al [13]. At low triangularity, the pedestal width and parameters are typically similar to those before the onset of ELMs. At $\delta > 0.3$, however, the width of the $T_i$ pedestal can increase to 8–15 cm, two to three times larger than in the ELM-free phase and up to 16% of the plasma minor radius. Pedestal $T_i$, shown in figure 2, can increase from 0.5 to 1.6 keV. The width, and also the pressure gradient, increase slowly throughout a discharge after ELMs appear, on a timescale of 2–3 s. This is longer than the energy confinement time and comparable to the skin resistive time. For discharges with $q_{95} > 6$, the ELMs have smaller amplitude and may
disappear altogether. In these cases further increases of the pedestal width and $T_i$ occur. In these ELMy H-modes, the width of the fully developed profile still scales with the pedestal $\rho_{\text{sep}}$, but is three to four times larger. There is a weak $q$ dependence, $\Delta T_i = 5\rho_{\text{sep}} q_{95}^{0.3}$, which was not found in the ELM-free scaling. The width also scales with $\sqrt{\rho_{\text{pol}}}$, which is strongly correlated with $\rho_{\text{sep}}$. Details of these important new results are given in [14, 15]. The slow time evolution during a discharge suggests that there is not a unique value of $\Delta$ for given global plasma parameters, and that MHD stability may play a role, perhaps with a slow feedback loop between the edge magnetic shear and the pedestal stability limit.

The pedestal pressure gradient at the onset of giant ELMs was studied assuming that the full width of the pressure pedestal is $\Delta P = 4\sqrt{\epsilon_{\text{pol}}}$, and computing $\nabla P = P_{\text{edge}}/\Delta P$ [16]. It is found that

$$\nabla P \propto \alpha B_t^2 / \left[ 2 \mu_0 R q_{95}^2 \right].$$

The coefficient $\alpha$ is constant over a wide range of $q$, for fixed shaping. The edge pressure, and therefore $\alpha$, increase with $\delta$, $\kappa$ and the internal inductance $l_i$. These results are consistent with a high-$n$ ideal ballooning mode limiting the gradient. In the high-$\delta$, high-$q$ H-modes for which the pedestal width increased and ELMs disappeared, however, a more detailed assessment of the ballooning limit, including the edge bootstrap current, shows that the plasma edge is in the second stability regime [13]. In these cases, the pressure gradient is observed to increase above the first stability limit, contributing to the rise in pedestal pressure.

2.2. DIII-D

Initial studies of the H-mode pedestal on DIII-D, by Groebner et al, focussed on high time- and spatial-resolution measurements of the radial electric field $E_r$, using active CER [17, 18]. These showed an $E_r$ well with a shear region extending over typically 3–5 cm. $T_i$ and carbon and electron density profiles also steepen, and density fluctuations measured by reflectometry drop,
over approximately the same region, showing that there is a transport barrier in all channels. The peak of $E_r$ is within $\rho_{i,\text{pol}}$ of the separatrix, but does not vary significantly with current. Power scans showed that the $T_i$ and $E_r$ profiles are closely related, with $T_i$ reaching 3 keV within 5 cm of the separatrix, and that the scale length $L_{T_i} \equiv T_i / \nabla T_i \sim 1.5$ cm, comparable to $\rho_{i,\text{pol}}$ [19]. The parametric dependence of the $E_r$ well was examined by Gohil, over a wide range of $I_p$, $B_T$, density and input power [20]. The width of the well, defined by its FWHM, was $1.0 \pm 0.3$ cm in all cases, and showed no systematic variation with any of the parameters studied. The depth of the well did vary.

Recent high-resolution measurements of pedestal profiles on DIII-D use edge TS for $n_e$ and $T_e$ profiles and a CER system measuring the temperature and density of impurity ions. The profiles of the various parameters, shown in figure 3, are generally similar in position and width, but not identical [21]. In particular, at the top of the pedestal, $T_i$ is close to $T_e$, while $T_i$ in the SOL is higher than $T_e$. This leads to gradients in temperature and pressure which are 30–40% larger for electrons than ions. A hyperbolic tangent function is used to fit the various profiles [22]. This gives a good representation to most pedestal data, and reduces the uncertainty which can arise from mapping various diagnostics to flux surfaces. The ion density profile is typically 30–40% wider than that of $n_e$, while the ion pressure width can be twice that of the $P_e$ pedestal.

Scalings of pedestal width have mainly been performed using the more widely available electron pressure derived from $n_e$ and $T_e$ [23–26].
Only the Type I ELM regime has been extensively studied, using the time intervals before the ELM events. Statistical regressions covering a range of plasma currents and fields generally find poor correlation with global parameters and better correlation with local plasma parameters. The widths in the database are narrower than on JT-60U, mainly in the range $\Delta P_e = 0.6$–1.5 cm. The best fits found are $\Delta P_e \propto P_{\text{pol},\text{ped}}^{0.52} / B_{\text{pol}}^{0.94}$ and $\Delta P_e \propto T_{e,\text{ped}}^{0.46} / B_{\text{pol}}^{0.51}$. In terms of dimensionless parameters, the scalings can be expressed as

$$\frac{\Delta P_e}{R} \propto B_{\text{pol},\text{ped}}^{0.4}$$  \hspace{1cm} (3)

or

$$\frac{\Delta P_e}{R} \propto \left( \frac{\rho_{\text{pol},\text{ped}}}{R} \right)^{0.6}. \hspace{1cm} (4)$$

These give similarly good predictions of measured widths, as shown in figure 4. A correlation of $I_p$ and pedestal $n_e$ in the database makes it difficult to distinguish between them. The scaling $\Delta P_e \propto (1 / \nabla n)^{0.5}$ also gives reasonable agreement with the measurements [21]. In order to distinguish between these possibilities, the time behaviour of pedestal widths was examined. In one clear example, cryopumping was used to reduce pedestal $n_e$ and increase $T_e$, at constant pressure. The width remained constant, which favours equation (3) and appears to rule out a strong dependence on $\rho_{\text{pol},\text{ped}}$ [25]. There is thus a clear difference between DIII-D results and those on JT-60U.

The DIII-D team has also made careful studies of the edge pressure gradients and MHD stability in the H-mode pedestal. Gohil et al, using $P_e(R)$ from TS and assuming an equal contribution from ions, found that the total pressure gradient just before a Type I ELM agreed extremely well with the calculated first stable ballooning limit [27, 28]. Both predicted and measured gradients scale linearly with $s / q_{95}$. However, more recent work by Osborne and Groebner, using some of the same discharges as in the pedestal width study, concludes that while $\alpha_{\text{MHD}}$ is approximately constant, as would be expected from ideal MHD, the electron pressure alone can often reach or exceed the first stability limit [24]. Once ion pressures are included, the total $\nabla P$ can exceed the computed limit by a factor of two or more. This surprising result was explained by noting that the standard equilibria used for stability calculations were...
derived from magnetic measurements only. When pressure profiles are constrained to match measured pedestals, larger edge currents are found which can modify the edge shear and produce a region of second stable access [21, 25, 29]. In this case, the gradients should not be limited by infinite-$n$ ballooning modes.

The above results all refer to ‘standard’ DIII-D H-modes, mainly in the Type I ELMy regime. DIII-D has also reported a regime of even higher confinement, the so-called ‘VH mode’ [30]. A notable feature is that the transport barrier widths in an ELM-free H-mode all expand gradually, on a transport timescale. The pressure pedestal can extend to 16% of the minor radius. Confinement is improved over an even larger region, $r/a > 0.6$. This regime was found at high $\delta$, up to 0.8. A region of second stable access at the edge was calculated. Based on measurements of $E_r$ and of increasing core rotation, $\nu_\phi$, as well as decreasing fluctuations, increased penetration of the $E \times B$ velocity shear region of turbulence suppression is suggested as the most likely mechanism for the improved confinement. Some type of positive feedback cycle, perhaps involving $\nu_\phi$, seems to be occurring. These results, and similar ones elsewhere, are significant because they prove that it is possible, under the right conditions, to extend the H-mode transport barrier.

2.3. ASDEX and ASDEX Upgrade

The existence of a transport barrier at the plasma edge was clearly seen in the first H-mode observations on the ASDEX tokamak [1, 31]. Electron temperatures of $\sim 600$ eV were measured a few centimetres inside the separatrix. The main pedestal diagnostics were Thomson scattering, an edge Li beam, a soft x-ray (SXR) array with 2.5 cm resolution and passive charge exchange for $T_e$. It was established that the barrier formed mainly inside the separatrix, although it could extend slightly into the SOL. While well resolved measurements and scalings of pedestal widths were not possible, it was observed that the change in gradients caused by the transport barrier extended up to 8 cm into the plasma, a distance longer than either the shear length or the banana width of thermal particles. SXR profiles appear narrower than this, at least early in the H-mode evolution (see [31], figure 76).

The ASDEX Upgrade tokamak is equipped with a set of higher-resolution diagnostics in the pedestal region, in particular an 18-channel heterodyne ECE system for $T_e(R)$, a Li beam diagnostic for $n_e(R)$ and an edge TS system [32, 33]. These clearly show the steep gradients in temperature ($\sim 16$ keV m$^{-1}$) and pressure, extending typically 2 cm inside the separatrix. Pressure gradients before Type I ELMs scale with $I_p^2$, as expected from ideal ballooning stability, and are in approximate agreement with calculated first stability limits [32–36]. Close examination shows a slightly weaker $B_T$ scaling than would be expected, $p'_e \propto B_T^{-0.3} I_p^2$, or $p'_e \propto B_T^{-1.7} q^2$ [4]. The ASDEX Upgrade pedestal studies mainly concentrate on $n_e$ and $T_e$ near the top of the pedestal in various regimes, and clearly show a strong relation between edge $T_e$ and/or $P_e$ and the core temperature and global confinement. The width of $T_e$ pedestals, determined using a tanh fit, is 2.0–2.6 cm in a controlled $I_p$ scan from 0.6 to 1.2 MA. There is no systematic variation with $I_p$ [37]. The pedestal $T_e$ varies by only $\sim 45\%$ in this scan; thus, in contrast to results on JT-60U, the data do not support a scaling with $\rho_{\text{pol}}$. Recent studies [38], which are described in detail in this conference [39], have focussed on the variation of edge pressure with plasma shaping. The pedestal pressure in the Type I ELMy regime increases up to 50% from low triangularity ($\delta_{\text{av}} \sim 0.15$) to high ($\delta_{\text{av}} \sim 0.36$). This is mainly due to a steeper density gradient; $\nabla T_e$ can even decrease at high $\delta_{\text{av}}$, and the $T_e$ pedestal width remains about 2 cm. The width of the density pedestal is about 5 cm, significantly larger than that of $T_e$, and also shows no systematic variation with plasma current or moderate variations of $\delta_{\text{av}}$. The width of the pressure profile is thus mainly determined by $\Delta_{T_e}$. 
2.4. Alcator C-Mod

H-modes have been observed on Alcator C-Mod over a wide range of currents and toroidal fields ($I_p \sim 0.4–1.4$ MA, $B_T \sim 3–8$ T), and with both ohmic and ICRF heating \cite{40,41}. It was quickly realized that, perhaps due to the compact size of C-Mod ($a = 0.21$ m) or to its high field, pedestals in $n_e$ and $T_e$ are extremely narrow, $\Delta < 1$ cm, and smaller than the resolution of standard ECE and reflectometry diagnostics. Initial studies of edge parameters focussed on the conditions for the H-mode threshold, and identified edge $T_e$ as an important parameter \cite{42,43}. A strong degree of $T_e$ profile stiffness was observed \cite{3}. An unusual feature of C-Mod H-modes is that they do not have regular Type I ELMs. H-modes may have long ELM-free periods, giving very high confinement ($H_{\text{ITER89-P}} < 2.5$), but eventually accumulating impurities. Often, the plasma edge enters a regime of continuously increased particle transport, with high-frequency edge fluctuations, leading to steady-state densities and lower radiation. This regime has been named the enhanced $D_\alpha$ H-mode (EDA) after one of its most apparent features \cite{3,41}. Greenwald has shown that this regime is more likely at $q > 3.5, \delta \sim 0.35–0.55$ and high density or neutral pressure \cite{44,45}. H-mode characteristics in ohmic and RF heated discharges are very similar.

High-resolution diagnostics have been progressively added to C-Mod. A soft x-ray array viewing the midplane \cite{46} shows very steep emissivity profiles, down to the resolution of $\sim 1.5$ mm, typically $\sim 10$ mm inside the separatrix. Details of the $T_e$ profile were enhanced using small $B_T$ ramps to sweep ECE channels across the pedestal. Widths as low as 8 mm were obtained \cite{47}. MHD stability of the edge pedestal was assessed assuming similarly narrow $n_e(R)$. Similarly to the situation on DIII-D, $\nabla P$ exceeds the ideal ballooning boundary calculated without taking into account edge currents. When the pedestal pressure profile is self-consistently included in equilibrium reconstruction, however, an increase in edge current modifies the shear profile and raises the stability boundary, leading to a narrow region of apparently second stable access.

Scaling studies of pedestal parameters have concentrated on the $T_e$ and x-ray pedestals \cite{26,44,48}. The x-ray width $\Delta_x$ shows the clearest variation, consistently becoming narrower at higher $I_p$ (figure 5(a)). Since pedestal T increases with $I_p$, however, $\rho_{i,\text{pol}}$ does not vary much in such a scan. The x-ray pedestal also broadens with higher triangularity (figure 5(b)). Parameters which increase $\Delta_x$ are the same as those which favour the EDA regime; indeed,

![Figure 5. Scalings of the width of the x-ray emissivity profile on C-Mod with plasma current $I_p$ (a) and upper triangularity (b).](image-url)
\( \Delta \xi \) is systematically larger (6–12 mm) in EDA than in ELM-free H-mode (\( \sim 2–6 \) mm). While x-ray emissivity is difficult to interpret in terms of temperatures and densities, the present understanding is that it is dominated by fluorine emission. If impurity transport in the pedestal is neoclassical, a barrier in F is likely to exist near the top of the density pedestal, where \( dn/dR \) increases. Very recently, two new diagnostics, edge Thomson scattering and a visible bremsstrahlung array, have measured the \( n_e \) profile more directly [49]. It is found to be significantly narrower than the \( T_e \) pedestal, with a width of 2–6 mm. While scaling studies are just beginning, preliminary indications are that the density width tends to follow the same qualitative trends as the x-ray pedestals, increasing at low \( I_p \) and high \( \delta \) [50]. In contrast to x-ray and density pedestals, the \( T_e \) pedestal widths, which range between 8 and 20 mm, have shown no systematic variation either with \( I_p \) or with the H-mode regime [26]. This may reflect the fact that energy transport is not much different in EDA and ELM-free plasmas. Both \( T_{e,\text{ped}} \) and \( n_{e,\text{ped}} \) do increase with current as has been observed elsewhere. Generally, higher pedestal temperatures and pressures are correlated with larger \( \Delta T_e \); a scaling with \( \beta_{\text{ped}} \) is therefore possible. In controlled radiation and power scans, the \( T_e \) pedestal width has been observed to increase, along with \( T_{e,\text{ped}} \), at higher net power [49].

2.5. JET

The JET tokamak routinely operates in H-mode, either ELM-free or with Type III or Type I ELMs. The most detailed measurements of the pedestal profiles have been shown by Breger [51, 52]. Profiles of \( T_e \) are obtained from ECE, in the upper part of the pedestal only. \( T_{e,\text{ped}} \), found from bilinear fits, is typically 2.5–3 keV. The width \( \Delta T_e \) is 3–4 cm in ELM-free H-modes and 5–6 cm between ELMs. As was observed on ASDEX Upgrade and C-Mod, \( \Delta T_e \) shows very little dependence on \( I_p \). On JET it is also independent of \( T_e \), meaning that \( \nabla T_e \propto T_{e,\text{ped}} \). Ion temperature profiles, measured by CXRS, show quite different trends. \( \Delta T_i \) varies from 1 to 4 cm and is proportional to \( T_{i,\text{ped}} \), implying a constant \( T_i \) gradient. Density pedestal profiles are measured by an Li-beam diagnostic. The width of the \( n_e \) pedestal, determined from a tanh

Figure 6. Pedestal electron temperature and density profiles measured on JET, showing a narrower barrier width in \( n_e \). The lower trace shows the variation of the density scale length. From Breger et al [52].
fit, is $2 \pm 0.2$ cm, only half that of $\Delta T_e$ on the same discharge, as shown in figure 6. The derived $\nabla P_e$ rises throughout an ELM-free period, reaching half of the ideal ballooning limit, calculated without including edge currents, at the time of the first Type I ELM. Thus, within experimental errors and assuming $P_e = P_i$, the pedestal is consistent with a first stable ideal MHD limit. As in other experiments, however, uncertainties in mapping different diagnostics to the same flux surface lead to relatively large uncertainties in $P(\psi)$.

Later studies on JET have taken a rather different approach to determining the height and width of the pressure pedestal [53, 54]. $T_e$ and $n_e$ are measured at a position a few centimetres inside the top of the pedestal. It is then assumed that for Type I ELMs $\nabla P_e$ is at the ideal ballooning limit, i.e. $\nabla P_e = P_{e,\text{ped}}/\Delta \propto I_p^2 S^2$, where $\gamma$ represents the dependence on edge shear $S$. It is observed experimentally that $P_{e,\text{ped}}$ increases with triangularity, or $S$, for fixed $I_p$ [55]. An empirical fit was used to determine the exponent $\gamma \approx 2$ [53]. Lingerat also noted that pedestal pressure tends to be higher with neutral beam injection (NBI) heating than with RF, which was attributed to a difference in the energy of the fast-ion population at the edge. Isotope scaling experiments showed $P_{e,\text{ped}}$ is higher with T than D, and lowest with H. The best fits to $P_{e,\text{ped}}$ for a range of $I_p$, $B_T$, shear and isotope mass, $m$, for both types of heating, were obtained using $\Delta P_e \propto \rho_{i,\text{pol}}(E_{\text{fast}})$, the poloidal ion Larmor radius calculated using the fast-ion energy rather than the thermal $T_i$ in the pedestal.

Saibene examined $P_{e,\text{ped}}$ for a different set of H, D and T JET discharges, many of which had edge gas puffing [56]. She again found that $P_{e,\text{ped}}$ is proportional to $I_p$, to $S^2$ and to $\sqrt{m}$. However, in this case the data were better fitted by assuming a scaling $\Delta P_e \propto \rho_{i,\text{pol}}(T_{i,\text{ped}})$, the poloidal ion gyroradius of thermal ions, i.e.

$$P_{e,\text{ped}} \propto I_p S^2 \sqrt{m T_{i,\text{ped}}}.$$  \hspace{1cm} (5)

In particular, an NBI power scan gave a strong increase of $T_{e,\text{ped}}$, and $P_{e,\text{ped}}$, while the energy

![Figure 7. Pedestal temperature on JET, plotted as a function of pedestal density normalized to $\sqrt{m T_e,\text{ped}}$. As expected for a thermal Larmor radius scaling, most H, D and T discharges at the same current lie on the same curve, while those with higher $I_p$ have higher edge pressure. From Saibene et al [56].](image-url)
of fast ions was computed to be constant. To resolve this apparent discrepancy, dedicated experiments were recently carried out to distinguish between thermal- and fast-ion dependences [57]. When NBI and ICRF discharges were well matched in edge density, using gas puffing in both cases, temperature pedestals were the same despite an order of magnitude difference in the fast-ion population. Furthermore, NBI experiments with different injected and background species found that $P_{e,\text{ped}}$ is correlated with the mass of the background, rather than the injected, species. Both of these results support a scaling with the Larmor radius of thermal, rather than fast, ions. Figure 7 illustrates that plotting $T_{e,\text{ped}}$ versus $n_{e,\text{ped}}/\sqrt{mT_{i,\text{ped}}}$ brings together most of the H, D and T data. The difference between the 1.7 and 2.6 MA curves illustrates the $B_p$ dependence. $I_p$ and $B_T$ were varied together, so that their dependences cannot be separated. The H discharges at 2.6 MA, however, lie well below the scaling of equation (5), possibly because they were in a Type III ELMy regime.

The different scalings reported for JET serve to illustrate that even in one device, examination of different data sets, or plasma parameters, can yield rather different apparent scalings for the pedestal height and width. These scalings are often not unique. For example, Sugihara et al [58, 59] have shown that, owing to colinearities between $q$ and $S$, the pedestal pressures in the international pedestal database for JET, and also for C-Mod, can be fitted equally well assuming the rather different expressions $Z_{\Delta M}P_e \propto \rho_i,\text{pol}$ or $Z_{\Delta M}P_e \propto \rho_i,\text{tor}S^2$. It is important to consider these uncertainties when comparing results between machines, and with theories, as will be done in the following sections.

3. Theoretical predictions of the transport barrier

Since the first observations of H-mode confinement, many theoretical ideas have been put forward to explain the L–H transition and H-mode evolution. Several good reviews of these theories have been published in recent years [7, 60–63]. In the interests of space, this paper will not attempt to list all available models or describe any of them in detail. Rather, the discussion will be restricted to the specific predictions made for the values and scalings of the height and width of the transport barrier in fully developed H-mode. Some of the earliest ideas on the L–H mode bifurcation were that it is triggered by a bifurcation in the solution of the poloidal momentum balance equation, leading to a sudden change in $E_r$ which suppresses turbulence [64, 65]. In this model, the electric field is mainly due to ion orbit losses at the plasma edge. While no explicit prediction of the pedestal width is given, this loss is expected to be important over roughly one poloidal ion gyroradius from the separatrix. Shaing later modified the theory to take into account ‘squeezing’ of the ion orbits due to the local electric field itself [66]. This ‘squeezing factor’ is given by

$$S_{\text{orbit}} = \left| 1 - \frac{c}{B_p \Omega_p} \frac{dE_r}{dr} \right|. \tag{6}$$

The predicted width of the pedestal is then

$$\Delta = \sqrt{\hat{\rho}_i,\text{pol} \over S_{\text{orbit}}}. \tag{7}$$

For $S_{\text{orbit}} > 1$, there is no longer an explicit dependence of $\Delta$ on the poloidal field $B_p$, giving better agreement with DIII-D and JFT-2M results on the width of the $E_r$ well.

In their review of $E_r$ effects, including these and many other related models, Itoh and Itoh suggest a further modification of the width to include the effects of shear viscosity, $\Delta \sim \sqrt{\hat{\rho}^2 + \mu_\perp / v_i}$, where $\hat{\rho}$ is the squeezed poloidal ion gyroradius, $v_i$ the ion collision frequency and $\mu_\perp$ the shear viscosity [62]. They point out that this can lead to a complicated feedback loop, since steepening the pedestal increases $E_r$ shear, and this in turn can affect the
shear viscosity and the squeezed ion orbit. Even a relatively simple H-mode theory such as the ion orbit loss model, then, does not lead to a scaling for the pedestal width which is either simple or easily testable. For JT-60U ELM-free pedestal scaling experiments, \( S_{\text{orbit}} \) calculated using the measured \( E_r \) is close to one [12]. One would then expect to recover approximately a linear scaling with \( \rho_{i,\text{pol}} \), which is indeed observed in these experiments. The absolute value of \( \Delta_{\Gamma_a} \), however, was three to four times larger than Shaing’s prediction.

An extension of the ion orbit loss model to include the effects of fast particles was recently proposed by Parail et al, in order to explain the apparently larger pedestal width seen in JET with NBI heating as compared with ICRF [67]. This model assumes that turbulence is suppressed by \( E \times B \) shear, and that the pedestal width is set by \( \sqrt{\epsilon_r \rho_{i,\text{pol}}} \) where \( \rho_{i,\text{pol}} \) is calculated using \( T_i \) for thermal ions and the fast beam ions in the case of NBI. They estimate the number of fast ions which would be needed to suppress the turbulence to be \( n_b/n_e \geq \rho_{i,\text{pol}}/R \). For JET, this gives a lower limit of \( \sim 1\% \), which is of the order of fast-particle densities calculated in NBI experiments. However, the recent results in which variations of \( n_b \) did not affect \( P_{\text{e,ped}} \) tend to disagree with this model. Poor agreement of these predictions with the multi-machine data in the ITER pedestal database has also been reported [58].

A rather different physical picture of the L–H mode bifurcation is suggested by Hinton and Staebler [68]. They also consider edge turbulence suppression by \( E \times B \) shear, but assume that this is dominated by the pressure-gradient term; contributions of poloidal and toroidal rotation, which are crucial to the ion orbit loss models, are neglected. The shear is thus proportional to \( (dn_i/dr)(dP_i/dr) \). The same degree of suppression for both particle and heat diffusivities with \( E \times B \) flow shear is assumed. The particle flux \( \Gamma \) is considered to be from edge ionization, and the heat flux \( Q \) from the core, and so nearly constant in the pedestal region. The resulting L–H threshold condition is a minimum product of \( \Gamma Q \); for given \( Q \) there is a minimum local flux \( \Gamma_{\text{min}} \), and vice versa. The width \( \Delta \) of the barrier in steady-state H-mode is then mainly determined by the edge particle source, and the innermost radius at which this \( \Gamma_{\text{min}} \) exists. Assuming power well above the L–H threshold,

\[
\Delta = \frac{n(a)}{n'(a)} \left[ (1 + \xi^2)^{1/2} - 1 \right]
\]

where

\[
\xi \equiv 2 \frac{n'(a)}{n(a)^2} \frac{\nu_0}{\langle \sigma v \rangle} \ln \frac{\Gamma_a}{\Gamma_{\text{min}}}
\]

Approximate solutions for limits of \( \xi \) are:

\[
\Delta \approx \frac{\nu_0}{n(a) \langle \sigma v \rangle} \ln \frac{\Gamma_a}{\Gamma_{\text{min}}} \quad \text{(small } \xi \text{)}
\]

\[
\Delta \approx \left( \frac{2 \nu_0}{n'(a) \langle \sigma v \rangle} \ln \frac{\Gamma_a}{\Gamma_{\text{min}}} \right)^{1/2} \quad \text{(large } \xi \text{)}
\]

\( \Delta \) tends to decrease with increasing edge \( n_e \) or density gradient \( n' \), due to the shorter neutral penetration length. Since \( \Gamma_a/\Gamma_{\text{min}} \) is proportional to \( \Gamma_a Q \), the model predicts a slow increase of the pedestal width with either heat or particle flux. Experimentally, of course, \( \Gamma \) and edge \( n_e \) tend to increase together, and the \( 1/n \) dependence will probably dominate. A narrower pedestal at high edge \( n_e \) is consistent with gas puffing experiments on JET; a quantitative comparison has not been reported. The scaling \( \Delta_{\Gamma_a} \propto (1/\nabla n)^{0.5} \) gave fairly good agreement with the DIII-D data set [21], although it did not reproduce the time variation in a discharge. This model considers only fuelling from the edge. With a significant additional particle flux from the core, as with NBI, one might expect the pedestal to broaden since the L–H criterion
would be satisfied further into the plasma. This might provide an alternative explanation for the higher edge pressures seen in some JET NBI discharges without gas puffing, and seems worth exploring theoretically and experimentally.

The expected scaling of the H-mode pedestal width was examined by Kotschenreuther et al, based on simulations of the gyrokinetic equation [2]. This paper also emphasized the very strong scaling of core temperatures with $T_{\text{ped}}$ which follows from ITG transport. While they do not attempt to predict the height of the pedestal, it is stated that the linear instabilities with the highest growth rate $\gamma_{\text{max}}$ are of drift type, either ITG or trapped-electron modes (TEM). They assume $E \times B$ shear stabilization of this turbulence, and produce a criterion for the scale length of the boundary layer, $L < \rho_{\text{ped}} (G/S)$. $G$ and $S$ are unspecified functions which depend on $v^*$, $\beta$, $q$, $\varepsilon$, $Z_{\text{eff}}$ and possibly other variables, and characterize the dependences of $\gamma_{\text{max}}$ and the shear respectively. They depend on the type of turbulence and the model for the $E \times B$ shear, so that various pedestal scalings are possible. One suggested dependence is $G/S \sim r/q R$, which would give $L \propto \rho_{\text{ped}}$. If $\nabla P$ is limited by ideal MHD, such a scaling results in an unfavourable scaling of $\rho_{\text{ped}}$ and thus of the core $\beta$, with $\rho^*$. Further studies have highlighted the large impact that differences in pedestal width scaling, for example $\Delta \sim \rho_{\text{ped}}$ versus $(Rq\rho_{\text{ped}})^{1/2}$, can have on predictions of performance in future machines [69]. One limitation of these gyrokinetic simulations is that they apparently do not account for electromagnetic instabilities, which Rogers and Drake and others have shown can be very important for transport in the edge region even at relatively low $\beta$ [70].

A more MHD-oriented treatment of the pedestal region by Wilson and Connor [71, 72], points out that conventional ideal ballooning stability limits do not apply since gradient scale lengths are very short. A new analysis of edge drift ballooning modes (EDBM) shows that they have the same growth rates as in more conventional ballooning theory, so that previous estimates for gradient limits still apply. The radial structure, however, is quite different. A Reynolds stress is associated with these edge modes. By assuming that the sheared flow generated by the Reynolds stress will be strong enough to suppress turbulence, they predict an H-mode pedestal width corresponding to the width of the mode,

$$\Delta = \Delta r(EDBM) = L \left( \frac{q^2 \rho^{*2}}{4b} \right)^{1/3}$$

(11)

where $L$ is an equilibrium scale length of order $r$. This leads to a scaling approximately as $\Delta \propto a^{1/3} \rho_{\text{ped}}^{2/3}$. The absolute width of the mode is $\approx 0.05a$, which is about the extent of the pedestal seen on many tokamaks. If $\nabla P$ is at the ideal ballooning limit (equation (2)) the pressure at the top of the pedestal is then

$$P_{\text{ped}} = \frac{B^2 \alpha(S)}{2 \mu_0 R q^2} L \left( \frac{3^{1/4}}{8} \sqrt{\frac{\eta q}{S}} q^2 \rho^{*2} \right)^{1/3}.$$  

(12)

For fixed $q$ and $B$, this leads to a relationship $T_{\text{c,ped}} \propto n_{\text{c,ped}}^{-3/2}$. The model does not address the magnitude of the shear flow generated by the turbulence or the issue of what happens to the pedestal once turbulence is suppressed; these are obvious areas for further work.

Rogers and Drake have also analysed edge ballooning mode stability, using numerical 3D simulations of the full Braginsky equations, as well as some approximate analytic solutions [73]. They find that an important scale length for the problem is $\delta R \approx \rho_{\text{ped}}^{2/3} R^{1/3}$. The stability depends on the pedestal width $\Delta$, which they do not predict in this model. In the limit $\Delta > 2\delta R$, the usual ideal ballooning mode stability relation applies. The pedestal pressure is then given by $\beta \propto (\alpha_c/q^2) \Delta / R$, and depends linearly on the width. This agrees with the analysis of Wilson and Connor. If the pedestal is narrower, $\Delta < 2\delta R$, ideal ballooning modes are found to be largely stabilized by the very localized gradients. $\nabla P$ can then exceed the usual ideal limit.
by a factor $\alpha/\alpha_c \approx 8\delta R/\Delta$, typically up to two to three. This is suggested as an explanation for the high gradients seen on DIII-D. In this regime, the pressure is limited by an ideal, pressure-driven ‘surface’ instability. Because the gradient limit is inversely proportional to the pedestal width, $\Delta$ cancels out of the expression for $\beta$ and the stability limit can be expressed in terms of the pressure drop across the pedestal, $P_{\text{ped}}$. This limit is

$$\beta < \beta_c = \left(\frac{4\alpha_c}{3q^2}\right) \delta R/R \propto \frac{\rho_{\text{pol}}^{2/3}}{q^2}. \quad (13)$$

At fixed $q$, the pedestal $\beta$ does not scale as unfavourably with $\rho^*$ as was implied by the Kotschenreuther scaling. This result can be compared with experimental pedestal pressures, but not with measured widths.

A different pedestal scaling has recently been proposed by Sugihara et al [58, 59]. They also assume turbulence shear suppression, but emphasize the role of magnetic shear in addition to the contribution from $E_r$. This is motivated by the observation that the edge pedestal on many devices coincides approximately with the region of increased shear near the separatrix. Assuming that $E_r$ in the developed pedestal is dominated by the $\nabla P$ term, they derive

$$\gamma E \times B \approx S\rho_{\text{pol}}^2 c_s/\Delta^2. \quad (14)$$

The dependence on shear is reminiscent of the JET scaling (equation (5)), while a scaling $\Delta \propto \rho_{\text{pol}}$ has not been reported by experiments. However, Sugihara points out that increasing $I_p$ tends to reduce $S$, so that one recovers an approximately $\rho_{\text{pol}}$ dependence. If $\nabla P$ is set by the ideal ballooning limit, which also increases with shear, the pressure at the top of the pedestal would be

$$P_{\text{ped}} \propto I_p \sqrt{mT_{\text{ped}}S^3}/q. \quad (15)$$

This scaling reproduces the JET and C-Mod pedestal pressure data in the ITER database, although not the DIII-D data, about as well as the $\rho_{\text{pol}}$ scaling implied by equation (5). A difficulty in comparisons is that $S$ is rarely measured directly; results of routine equilibrium calculations are known to be modified by edge bootstrap currents in the pedestal region. However, the model does provide the possibility to explain the apparent influence of shaping and MHD stability on the pedestal. It would be useful to check the scaling in experiments where the width, and ideally the shear, are directly measured; pedestal pressure measurements alone cannot distinguish between increases in $\Delta$ and $\nabla P$. If $q$ profile shapes remain similar, this model tends to lead to a much stronger dependence of $\Delta$ on machine size than would be predicted by a $\rho_{\text{pol}}$ scaling [59].

Most of the theoretical ideas described above result in a natural scale length for the H-mode pedestal. With the exception of the works of Hinton and Staebler [68], and Rogers and Drake [73], they do not attempt to self-consistently model the transport barrier evolution or the turbulence and profiles in the fully developed state. However, given the important terms in $\omega_{\text{E×B}}$, and the large number of potential feedback loops tending to either expand or contract the turbulence suppression region, the formation of the transport barrier is clearly a very complex process. Since it was first established that $E \times B$ shear of either sign could suppress turbulence [74], the dynamics of transport barrier development has been studied extensively by Diamond, Carreras, Lebedev and others, see, for example [75–77]. They propose that in the early stages of
the H-mode, poloidal rotation driven by Reynolds stress due to the L-mode turbulence provides the dominant $E \times B$ shear. Subsequently, as gradients steepen and turbulence declines, the $\nabla P$ term dominates. Rotation measurements on DIII-D tend to support this picture [7]. A localized ‘seed flow’, for example due to ion orbit loss, may help trigger the transition [76]. This paper describes a model including $\nabla P$ evolution. Expressions for the barrier propagation velocity and width are given in terms of

$$\Delta \varepsilon = \left( \frac{\alpha_3}{\alpha_1} - \frac{\bar{\mu}}{\gamma_0} \right)$$

where $\alpha_1$ and $\alpha_3$ are parameters characterizing turbulence models, $\gamma_0$ is the linear flow rate and $\bar{\mu}$ is the damping due to magnetic pumping. It is noted that $\Delta \varepsilon$ depends on the degree to which the power exceeds the local threshold and that under some conditions a slow broadening of the barrier, as observed in VH-mode, can occur.

Lebedev and Diamond [77] have studied the dynamics of transport barriers in bifurcations in the framework of a simplified model in which the driving flux $\Gamma$ is a nonlinear multivalued function of local gradients, e.g. $n'$, as shown schematically in figure 8. This can apply to either core or edge barriers in various parameters. A different curve will apply at each minor radius. The stationary condition is set by $\Gamma = \Gamma_m(r)$, where $\Gamma_m$ is set by the condition that areas $S1$ and $S2$ in figure 8 are equal. Physically, $\Gamma_m$ is between the L–H and H–L threshold flux of either power or particles. This framework can be applied to many different bifurcation mechanisms, and has been used to estimate the propagation velocity of internal transport barriers. The width of the stationary transport barrier depends on the radial variation of the function $\Gamma_m(r)$.

Diamond recently presented an example of a specific solution for the case of an H-mode barrier in density which is maintained by an edge particle flux [78]. In this case, the flux within the barrier is given by $\Gamma(r) = -D_{neo}(dn/dr)$, where $D_{neo}$ is the residual neoclassical diffusivity. The width for which the barrier is stationary is given by

$$\Delta_n = \left( \frac{2D_{neo}}{v_I(a)} \right)^{1/2} \left( \frac{\Gamma_a - \Gamma_m}{\Gamma_m} \right)^{1/2}$$

in the limit $(\Gamma_a - \Gamma_m)/\Gamma_m < 1$, where $v_I(a)$ is the edge ionization rate and $\Gamma_a$ the edge particle flux. In the limit $\Gamma_a \gg \Gamma_m$, a weaker logarithmic dependence on driving flux is predicted. This solution has several interesting characteristics which agree qualitatively with the experimental results shown in this paper. First, even the relatively simple case solved here produces a width with several different length scales. $\rho_i$, $\rho$ enters through the neoclassical diffusivity and the edge ionization rate through the source term. One would not then expect a simple parameter scaling to apply in all experiments. If the residual $D$ is enhanced, as seems to be the case in C-Mod EDA H-modes, increased $\Delta_n$ would be expected. Second, the width has a dependence on the degree to which the driving flux exceeds the threshold flux and predicts a ‘critical exponent’ of 1/2. C-Mod results show increasing $T_e$ pedestal width with net power.
flux; more careful experiments to determine the critical exponent are in progress. Third, while this result was derived for the density pedestal width, one would in general expect different widths, and probably different scalings, for other parameters such as $T_e$ or $T_i$. The general problem, including temperature as well as density profiles and power as well as particle fluxes, is currently being addressed by Carreras [79]. Preliminary results suggest that if the driving flux originates from the core, as is the case with core heating or fuelling, the pedestal tends to be wider and the critical exponent changes. Further development of this modelling approach and more quantitative comparisons with experimental results from different devices are certainly to be encouraged.

4. Discussion and conclusions

In the previous two sections, a wide variety of experimental observations and theoretical predictions have been presented. At first sight, it seems the range of scalings is so divergent as not to lead to much insight into the physics of the H-mode pedestal. In this section, it seems useful to try to outline the points on which there is experimental or theoretical consensus, as well as the areas of differing results. Areas for further study to clarify the situation are suggested.

The physics which seems the best understood is that of the limiting edge pressure gradient. In all cases where sufficiently detailed measurements exist, $\nabla P_e$ scales as would be expected from ideal MHD stability, and is generally in quantitative agreement within experimental errors (e.g. ASDEX Upgrade, JT-60U, JET). It must be noted, however, that the uncertainties in both $\nabla P$ and the stability limit tend to be quite large ($\sim 50\%$). On all devices the edge pressure increases with $I_p$, at least linearly and sometimes more strongly. $P_{edge}$ also increases strongly with increasing triangularity, $\delta$ (JT-60U, ASDEX Upgrade, DIII-D) or edge shear (JET, equation (5)). There is at most a weak inverse dependence reported on $B_T$ (on ASDEX Upgrade). If one wishes to increase $P_{ped}$, then, higher $I_p$ and strong shaping are clearly favourable. Pedestal temperatures will be higher at lower density, as is universally observed. In some experiments, measured pressure gradients actually seem to exceed the first stability limit (recent DIII-D experiments, C-Mod, JT-60U high-$\delta$ ELMy H-modes). In each of these cases, a detailed MHD analysis has shown that the edge ideal stability limit is increased, or even removed, because of modification of the edge shear due to pedestal bootstrap currents. The pedestal stabilization effect found by Rogers and Drake offers an alternative explanation for the high gradients in the narrow DIII-D pedestal, but seems unlikely to apply in the very wide pedestals on JT-60U. Given that in many cases the edge is near the boundary of first and second stable regimes, ideal ballooning stability codes seem useful for predicting pedestal pressure gradients. Empirical fits to $\nabla P$ on JT-60U lead to strong shaping dependences, e.g. $\partial \beta / \partial r \propto [1 + \kappa^2(1 + 10\delta^2)]/Rq^2$ [69]. However, fits from one machine will not necessarily apply in another with different collisionality, etc, and any such scaling needs to be checked against recent results from ASDEX Upgrade and DIII-D. It remains to be determined just what limits $\nabla P$ in cases where there is not an ideal stability boundary.

The physics determining the pedestal width is less well determined than that setting the gradients. All the models reviewed have the general feature that they rely on stabilization of turbulence by $E \times B$ shear, sometimes in combination with magnetic shear. A very general and approximate condition for this is $\omega_{E \times B} > \gamma_{max}$. The differences lie in the type of turbulence involved (which sets $\gamma_{max}$) and the main contributors to the shear. It is generally considered that after the L–H transition some type of positive feedback loop acts to increase local gradients, therefore further increasing shear. What is less clear is what limits the inward expansion of the barrier. Simply put, why does an H-mode plasma not always evolve into a VH-mode? The
experimental scalings of pedestal width are rather mixed. An important observation is that the steep-gradient regions of different plasma parameters, while generally of a similar location and shape, do not always have the same width. On both C-Mod and JET, the measured barrier in $n_e$ is narrower than that of $T_e$, by a factor of two or more. In ASDEX Upgrade, the density pedestal is wider than that in $T_e$. On DIII-D, the barrier in $T_i$ is wider than that in either $n_e$ or $T_e$. At first sight these differences seem surprising; should not all gradients increase over the same fluctuation suppression region? However, local gradients depend not only on transport but also on the source term, which is generally very different for heat and particles. It is worth noting that on C-Mod, recent measurements show that the edge neutral density profile in H-mode has a scale length of $\sim 3$ mm, comparable with the $n_e$ pedestal width [80, 81]. Different transport channels can respond differently to shear suppression, as has been clearly demonstrated in studies of internal transport barriers [82]. Finally, the SOL boundary conditions for $n_e$, $T_e$ and $T_i$ are quite different. The improved diagnostics of recent years have made it clear that to speak of ‘the pedestal width’, as is done in most theories and inter-machine scalings, is to oversimplify the physical problem.

Table 1. Summary of published scalings for H-mode pedestal width. It should be noted that all these were obtained from single devices; the lack of an explicit $R$ dependence in scalings does not imply that no such dependence exists.

| Parameter | Experiment | Regime | Scaling, notes |
|-----------|------------|--------|---------------|
| $T_i$     | JT-60U     | ELM-free | $\Delta T_i \propto \sqrt{P_{i,ped}}$ |
|           | JT-60U     | Type I ELMs | $\Delta T_i \propto \rho_{i,ped} B_p$ |
|           | JET        | ELM-free | $\Delta T_i \propto T_i$ |
| $T_e$     | ASDEX Upgrade | Type I ELMs | No $I_p$ dependence, increases with $P$ |
|           | C-Mod      | ELM-free, EDA | Wider than ELM-free |
|           | JET        | ELM-free | $\Delta T_e \propto T_e$ |
|           | JT-60U     | ELM-free | $\Delta T_e \propto 1/B_p$ |
| $n_e$     | ASDEX Upgrade | Type I ELMs | No $I_p$ dependence |
| $P_e$     | DIII-D     | Type I ELMs | $\Delta P_e/R \propto \rho_{i,ped} B_p$ |
|           | JET        | Type I ELMs | $\Delta P_e \propto I_p S^2 \sqrt{m T_e \Delta T_i}$ |

If barrier widths are different, their scalings may also differ. It is thus appropriate to examine scalings for each parameter in turn. These are summarized in Table 1. The most extensive scaling studies based on directly measured profiles of ion temperature are those on JT-60U. These showed clearly that in ELM-free H-mode, $\Delta T_i \propto \sqrt{T_i}$ and $\Delta T_i \propto 1/B_p$. The orbit-squeezing effect is small, and the experimental scaling (equation (1)) agrees well with the ion orbit loss scaling (equation (7)) but the absolute width is a few times larger. In this regime the width did not show a significant dependence on shaping, which seems contrary to the scaling with shear proposed by Sugihara (equation (14)). However, the slow increase of $\Delta T_i$ in recent highly shaped ELMy discharges strongly suggests that the width can be increased by effects other than ion orbit losses, perhaps involving edge currents. Equation 1 should perhaps be regarded as a lower bound on $\Delta T_i$. It would be very valuable to explore the barrier expansion phenomenon in more detail; if it can be understood and even controlled this offers the possibility to change the pedestal parameters actively. A more limited study of $T_i$ profiles on JET reports a constant $T_i$ gradient, meaning that $\Delta T_i \propto T_i$, a stronger dependence than would be expected from the JT-60U scaling. However, since both $T_{e,ped}$ and $\Delta T_i$ appear to
increase with \( I_p \), it may be difficult to separate \( B_p \) and \( T_i \) dependences.

Three experiments, ASDEX Upgrade, C-Mod and JET, have reported on scaling of the pedestal in electron temperature and find no systematic dependence of \( \Delta T_e \) on \( I_p \). The widths on ASDEX Upgrade and JET are roughly constant, \( \sim 2 \) cm and \( \sim 3-4 \) cm, respectively, for factors of two in \( I_p \). The variation on C-Mod is larger, \( \sim 8-20 \) mm. One reason for this difference may be that, owing to its high \( B_T \) and \( n_e \), C-Mod tends to operate in a regime where \( P < 2 P_{\text{crit}} \), where \( P_{\text{crit}} \) is the L–H threshold power, rather than \( P \gg P_{\text{crit}} \). This is the regime where, according to Diamond and Carreras, one might expect a strong dependence of pedestal width on the driving flux. Indeed, \( \Delta T_e \) does vary in scans of net power. On JT-60U, \( \Delta T_e \) did appear to scale with \( \rho_{i,\text{ped}} \), although it was less extensively studied than \( T_i \). At present there is not a good understanding of the physics setting \( \Delta T_e \), or its scaling between machines.

No detailed scaling studies have yet been presented for the width of the electron density pedestal. This is unfortunate since it is perhaps the one thing which could be most readily checked against theoretical predictions. In the models of both Hinton and Staebler, and Diamond and Carreras, the edge source of neutrals plays a critical role in setting the barrier width (equations (9), (10) and (16)). The data to make such a comparison appear to exist, for example on DIII-D and ASDEX Upgrade, and this would be a useful test of theories. Scaling studies of \( n_e \) width on C-Mod are just beginning; it appears that widths show trends with \( \delta \) and \( I_p \) similar to those found in x-ray emissivity, and are larger in EDA. A very recent comparison of the widths measured in a limited set of ELM-free discharges with those predicted by equation (16) shows agreement to within a factor of two for a range of plasma current and density [81].

Scaling studies on DIII-D and JET have concentrated on electron pressure, since that is both experimentally accessible and a parameter of direct interest for predicting machine performance. On DIII-D the width \( \Delta P_e \) is directly measured to be \( \sim 0.6-1.5 \) cm. Both \( \Delta P_e/R \propto \rho_{i,\text{ped}}^{0.6} \) and \( \Delta P_e/R \propto \rho_{i,\text{ped}}^{0.4} \) provide an acceptable fit to a wide database. In both cases, the width decreases with increasing \( I_p \). However, since varying \( n_{e,\text{ped}} \) and \( T_{e,\text{ped}} \), at constant \( P_{e,\text{ped}} \), did not affect the width, the scaling with \( \rho_{i,\text{ped}}^{0.4} \) is favoured. This is a difficult correlation to use predictively, since the pedestal pressure enters directly and cause and effect are hard to determine. Studies on JET used pressure measurements at the top of the pedestal and assumed ideal ballooning stability limits to infer a pedestal width. Dependences of \( \nabla P_e \) and \( \Delta P_e \) can thus not be independently checked. They find good agreement by assuming \( \Delta P_e \propto \rho_{i,\text{pol}} \). These experiments are the only ones to determine the influence of atomic mass, \( m \). While there has been debate as to whether \( \rho_{i,\text{ped}} \) is set by thermal or fast ions, recent experiments are more consistent with \( \rho_{i,\text{ped}}(\text{thermal}) \).

Given that no single, simple width scaling has emerged which covers all parameters or all experiments, it seems that theories need to move beyond identifying relevant scale lengths for turbulence suppression. The dynamic framework suggested by Diamond and Carreras may be an important step in this direction. Since the model’s approach is very general, it could be applied to many different transport bifurcations. Experimentally, more work needs to be done to clarify the scaling of pedestal widths in various plasma parameters and confirm (or deny) that there is indeed a difference between them. This could most readily be done by analysing direct measurements of \( n_e, T_e, T_i \) and/or \( n_i \) in one device, for the same set of discharges. Several experiments now have sufficient diagnostics to compare at least two or three of these.

An important issue which has not been addressed in this review is that of an explicit scaling of pedestal width with machine size, \( R \) or \( a \). This obviously cannot be done on a single device. However, until we can be confident that several machines have comparable measurements of the same quantities, and show broadly the same scalings with plasma parameters, indicating they are in the same physical regime, any such scalings will result in very large uncertainties.
It will be important to match as many variables as possible, in particular plasma shaping, in order to look for such size scalings. The comparison between JT-60U and DIII-D, presented at this workshop, is a good example of the type of inter-machine activity required [14]. The international pedestal database developed for ITER is also a useful tool in this regard (e.g. [58]).

It is clear that a great deal of progress has been made in our measurements and understanding of pedestal physics. The majority of the experimental results reviewed here, and much of the theory, have been reported only in the past two to three years. There are several other experiments, on both tokamaks and stellerators, which are now starting to investigate H-mode pedestals (e.g. COMPASS-D, JFT2M, W7-AS, TCV). While space in this review has prevented describing all of these results, they will certainly make useful contributions to the international effort to resolve remaining issues. There is every prospect that the next few years will bring still more advances, and the pedestal will cease to be a ’mystery region’.

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