SCALING OF H-MODE PEDESTAL CHARACTERISTICS IN DIII-D AND C-MOD

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ABSTRACT

Since the H-mode edge pedestal effectively sets the boundary conditions for energy transport throughout the core, a better understanding of the pedestal region is necessary in order to fully predict H-mode performance. Pedestal characteristics in the DIII-D and Alcator C-Mod tokamaks are described, and scalings of the pedestal width with various plasma parameters are shown. The pedestal width in both tokamaks varies in an inverse sense with plasma current, and is independent of toroidal field. Other similarities, as well as differences, are discussed. It is also found that the pedestal widths of the various physical quantities involved (T_e, T_i, n_e, n_i) may be different.

1. INTRODUCTION

The steep edge pedestal region, which is characteristic of H-mode plasmas, is indicative of the formation of a transport barrier (Fig. 1). Even though this transport barrier is localized only to the edge, energy confinement is seen to improve over the entire plasma cross-section [1]. This non-linear behavior can be explained by critical gradient theories of core energy transport. Several of these models [2,3] purport to explain quantitative results from a number of tokamaks, **but require the specification of an edge temperature**. Thus the pedestal region effectively sets the boundary conditions for energy transport throughout the core. Because of the non-linear transport, these boundary conditions strongly affect expected plasma performance, as shown in Figure 2. Furthermore, the large pressure gradient in the pedestal region is thought to drive the ELM instability, which in turn may limit the maximum attainable edge parameters. Therefore, a better understanding of the pedestal region is necessary in order to fully predict H-mode performance. In particular, the physics governing the pedestal width is not well understood. In this paper, H-mode pedestal characteristics in DIII-D and Alcator C-Mod will be presented, and their dependencies on various plasma parameters will be discussed. In addition, the edge pressure gradients measured in DIII-D will be compared to ballooning mode stability limits.

2. DIAGNOSTIC MEASUREMENTS

In both tokamaks, H-mode pedestals have been studied in single-null divertor discharges. The DIII-D data consist primarily of T_e and n_e profiles measured with Thomson scattering, and T_i and n_i profiles deduced from charge exchange recombination spectroscopy of carbon impurities (Fig. 3). Note that the ion temperature pedestal is significantly wider that the T_e pedestal. Nevertheless, the ion and electron pressure profiles ($p = nT$) have approximately the same widths. Most of the DIII-D data presented in this paper were taken in Type-I ELMy [5] discharges, many with the ITER shape. Pedestal widths in Type-III ELMy H-modes are generally twice that of Type-I.

The C-Mod data (Fig. 4) are mostly from ECE, Langmuir probes (in scrape-off layer only), a soft x-ray array ($h\nu > 0.6$ keV), a broadband XUV array (total radiated power profile, $P_{\rm rad}$), and reflectometry (n_e) [6]. The data were taken in both ELM-free and enhanced D_α (EDA) H-modes [7]. The emissivity profile diagnostics are very useful because their radial resolution of 1-2 mm (as compared to ~ 8 mm for the ECE) can better resolve the narrow pedestal width on C-Mod. The soft x-ray emissivity in the edge region is dominated by recombination continuum from low-Z impurities, and has very little temperature dependence after accounting for transmission through the filtering foil (10 μm Be). Therefore the x-ray emissivity profile is primarily a measure of $n_e n_Z$. Note that the C-Mod measurements also seem to show different pedestal widths, and even different radial positions, for the various physical quantities.

For both tokamaks, the measured edge profiles are fit with tanh curves [8] to obtain pedestal widths, heights, and gradients. Scalings of pedestal width in each machine are obtained by either varying I_p, B_ϕ, triangularity, and n_e continuously during a discharge, or by culling from a database of multiple discharges.

3. PRESSURE GRADIENT

One way to characterize the edge pressure (i.e. at the top of the pedestal), is to express it as the product of the pressure gradient, ∇p, times the pressure pedestal width, δ_p (Fig. 5). The motivation behind this approach is that ∇p is presumably limited by the ELM instability, which, in principle, should be calculable from MHD theory. The problem of predicting the top-of-pedestal pressure would then be reduced to understanding the physics that defines the pedestal width. Detailed measurements of ∇p_e in the pedestal of DIII-D just prior to ELM onset have been compared with MHD instability thresholds. Figure 6 shows the calculated stability limits for infinite-n ideal ballooning modes (BALOO code [9]), using only the magnetics measurements, which are fairly insensitive to edge bootstrap currents. The measured pressure gradients apparently surpass the first stable limit, particularly considering that the data values should roughly be doubled to account for the ion pressure. More detailed calculations, in which an edge bootstrap current consistent with the measured ∇p is included, have shown that the DIII-D H-mode edge is commonly in the second stable regime for ballooning modes. Stability calculations done for Alcator C-Mod give similar results [6]. The limit on ∇p may actually be set by edge peeling modes. Therefore, although ∇p is, in principle, calculable from MHD, in practice it may require knowledge of the edge bootstrap current profile, which is not easy to measure.

4. PEDESTAL WIDTH AND SCALING

The determination of the edge boundary conditions, or pedestal height, therefore depends on being able to predict the width of the edge pedestal. Unfortunately, no theory is capable of doing that at the present time. There are, however, a number of physical scale lengths which may be relevant in the edge, and which suggest several scalings to look for. Examples are: banana width ($\propto \rho_p \propto T_i^{0.5}/I_p$), Larmor radius ($\rho_L \propto T_i^{0.5}/B_\phi$), neutral penetration ($\lambda_{\rm mfp} \propto 1/n$), magnetic shear length (q/q', shaping), collision lengths (λ_{ei}), etc.

In DIII-D, the scaling studies have primarily emphasized the electron pressure pedestal, as opposed to n and T individually. Statistical analysis of the data show that only $T_e^{\rm Ped}$, $n_e^{\rm Ped}$, and I_p, and their related quantities ($p^{\rm Ped}$, $\beta_p^{\rm Ped}$, q, $\rho_p^{\rm Ped}$) are correlated with the electron pressure pedestal width, δ_{pe}. (The superscript refers to values at the top of the pedestal.) For most H-mode operations, there is a strong linear co-dependence between $\bar{n}_e$ and I_p, and so there are a number of combinations of n, T, and I_p that can be used for scaling of δ_{pe}, and which fit equally well. In figure 7, the δ_{pe} values from the Type-I ELMy H-mode database (with ITER shape) are plotted against two possible combinations, namely $\rho_p^{\rm Ped}$ and $\beta_p^{\rm Ped}$. A power-law fit gives scalings of $(\rho_p^{\mathrm{Ped}})^{0.6}$ and $(\beta_p^{\mathrm{Ped}})^{0.4}$ respectively, with similar quality of fit. Both exponents are accurate to about ± 0.1. The second scaling law is equivalent to $\delta_{pe} \propto \alpha^{0.8-1.0}$, where α is the normalized ∇p parameter used in ballooning mode stability calculations. The ambiguity between the two scalings can be removed by breaking the co-dependency of $\bar{n}_e$ and I_p in DIII-D H-modes, which has been done in a series of divertor pumping experiments [10] in which the density was varied independently at fixed current. The result is that the β_p scaling remains consistent with the measured pedestal widths, whereas the ρ_p scaling does not.

In Alcator C-Mod, the scaling studies of pedestal widths have emphasized the T_e and x-ray ($\propto n_e n_Z$) data, rather than pressure, since well-resolved measurements of n_e and ion edge profiles are lacking. In figure 8 are shown two x-ray pedestal profiles from a discharge which transitioned from ELMfree to EDA H-mode. The ELMfree H-mode edge has a much narrower x-ray pedestal width ($\delta_{\mathrm{xray}} \lesssim 1.5$ mm) than the EDA edge. The T_e pedestal width, however, does not show any consistent difference between the two types of H-modes. Given the dependence of the x-ray emissivity on $n_e n_Z$, these apparently conflicting results may actually be entirely consistent, since the principal distinction between the EDA and ELMfree H-modes is their particle confinement, not their energy confinement.

Several of the distance scale lengths listed at the beginning of this section depend on I_p. Figure 9 shows a number of diagnostic signals from an EDA H-mode discharge in which the plasma current was scanned dynamically during the shot. The x-ray pedestal width clearly narrows as I_p ramps up, and broadens again when I_p ramps back down. The P_{rad} profile shows the same qualitative behavior. Similar dynamic scans of toroidal field show no effect on the width. In contrast to the x-rays, the T_e pedestal width apparently has little or no consistent dependence on I_p (Fig. 10). Note that the T_e points are culled from a database of different discharges, not from a dynamic scan. The T_e pedestal width is found to correlate strongly with T_e^{Ped}, with little variation in ∇T_e. Thus, in terms of dimensionless parameters, there is a clear positive dependence on β_p^{Ped}.

The x-ray pedestal width also exhibits a dependence on plasma shape. Dynamic scans of both upper and lower plasma triangularity have been done in EDA H-modes, and show a linear variation of δ_{xray} with triangularity, as seen in figure 11. Data from a large number of discharges also suggest that the x-ray pedestal width increases with $\bar{n}_e$ at fixed current in EDA H-modes. Dynamic scans of $\bar{n}_e$ during an H-mode have not been carried out yet.

5. DISCUSSION

Comparing the edge pedestal characteristics and scalings between DIII-D and C-Mod is not straightforward because of the different physical quantities measured (p, T, x-ray) and the different types of H-modes studied (Type-I ELMy, ELMfree, EDA). In fact, there are data from both tokamaks that show that different pedestal quantities do not all have the same profile widths, and perhaps not even the same scalings. The pressure pedestal widths measured in DIII-D tend to scale in an inverse sense with I_p (i.e. I_p^{α}, where $\alpha < 0$), as does the x-ray profile in C-Mod. Neither machine sees any direct dependence on toroidal field. In C-Mod, varying the triangularity changes the x-ray pedestal width, but has little or no effect on the DIII-D profiles. One pedestal feature which is consistent between the two machines is the dependence of width on type of H-mode, i.e. the degraded particle confinement modes (Type-III ELMy in DIII-D and EDA in C-Mod) have wider pedestals than Type-I or ELMfree.

REFERENCES

[1] K.H. BURRELL, *et al.*, Proc. 13th Int. Conf. on Plasma Phys. and Contr. Nucl. Fusion Res., Washington DC, 1990, Vol 1, p. 123.

[2] M. KOTSCHENREUTER, W. DORLAND, Q.P. LIU, G.W. HAMMETT, M.A. BEER, S.A. SMITH, A. BONDESON, S.C. COWLEY, Proc. 16th Int. Conf. on Plasma Phys. and Contr. Nucl. Fusion Res., Montreal, 1996, Vol 2, p. 371.

[3] R.E. WALTZ, R.L. DEWAR, X. GARBET, Phys. Plasmas **5**, 1784 (1998).

[4] J.E. KINSEY, R.E. WALTZ, D.P. SCHISSEL, in Proc. 24th Euro. Conf. on Contr. Fusion and Plasma Phys. (EPS, Berchesgaden 1997) **21A**, Part III, 1081 (1997).

[5] H. ZOHM, Plasma Phys. Contr. Fusion **38** (1996) 105.

[6] A.E. HUBBARD, *et al.*, Phys. Plasmas **5** (1988) 1744.

[7] M.J. GREENWALD, *et al.*, Nucl. Fusion **37** (1997) 793.

[8] R.J. GROEBNER and T.N. CARLSTROM, Plasma Phys. Contr. Fusion **40** (1998).

[9] R.L. MILLER, *et al.*, Phys. Plasmas **4** (1997) 1062.

[10] D.P. SCHISSEL, Nucl. Fusion **34**, (1994) 1401.

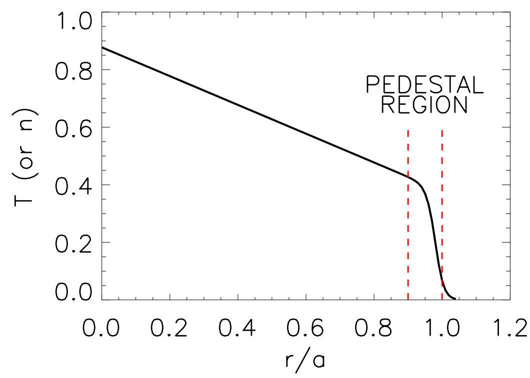

FIG. 1. H-mode plasmas are characterized by a steep pedestal-like shape in temperature, density, etc. in the edge region ($0.9 \lesssim r/a \lesssim 1.0$).

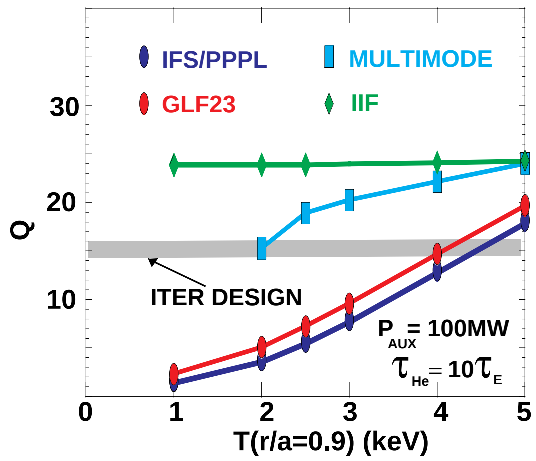

FIG. 2. Stiff turbulent transport models, such as IFS/PPPL [2] and GLF23 [3] predict that projected ITER fusion performance depends strongly on the edge temperature (i.e. top of pedestal). (Reprinted with permission [4].)

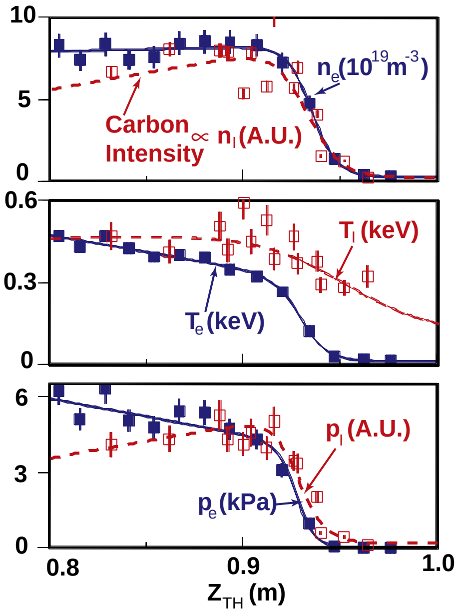

FIG. 3. DIII-D pedestal profiles are measured by Thomson scattering (T_e, n_e) and charge exchange recombination spectroscopy of carbon (T_i, n_i). The pedestal pressure profiles are determined by multiplying the n and T data.

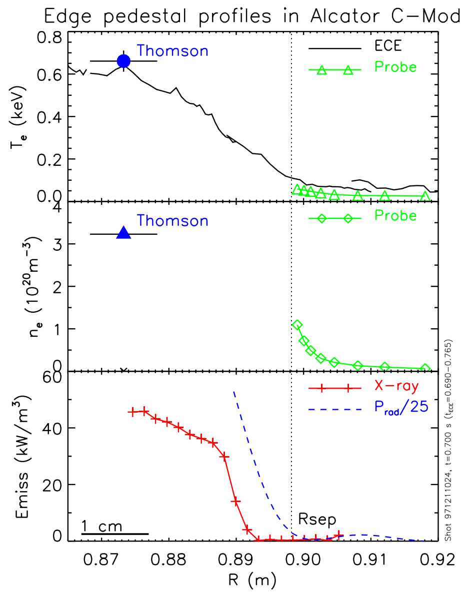

FIG. 4. C-Mod pedestal profiles are measured with 2nd harmonic ECE (T_e), Langmuir probes (T_e and n_e in SOL only), a broadband XUV array ($P_{\rm rad}$), and an x-ray array ($h\nu > 0.6$ keV). In addition, core Thomson scattering provides single point measurements at the top of the pedestal.

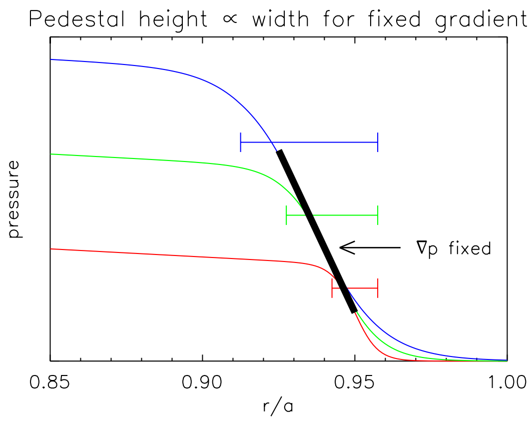

FIG. 5. The pedestal height can be expressed as the product of the pedestal width times the gradient in the pedestal region. For plasma pressure, the gradient is presumably limited by MHD instabilities responsible for ELMs.

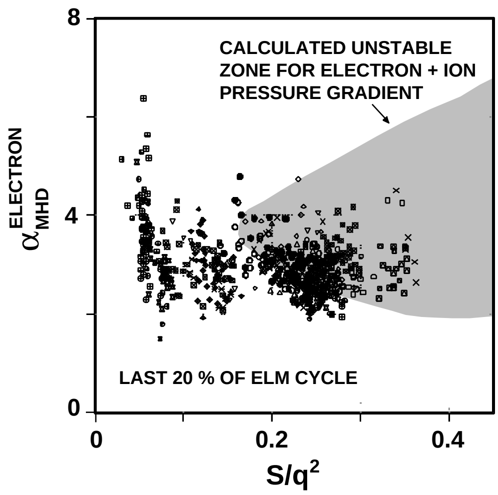

FIG. 6. Comparison of ∇p_e prior to ELM onset in DIII-D with ideal ballooning limits, neglecting edge bootstrap current. Since the total ∇p is $\sim 2\times$ the electron component, the plasma edge is above the first stable boundary.

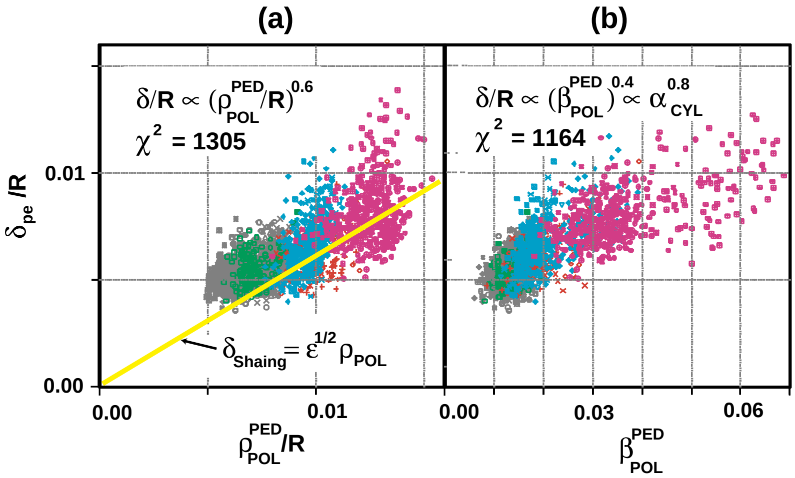

FIG. 7. Electron pressure pedestal widths (δ_{pe}) from the Type-I ELMy H-mode database plotted against ρ_p^{Ped} and β_p^{Ped}. A power-law fit gives scalings of $(\rho_p^{\text{Ped}})^{0.6}$ and $(\beta_p^{\text{Ped}})^{0.4}$ respectively, with similar quality of fit.

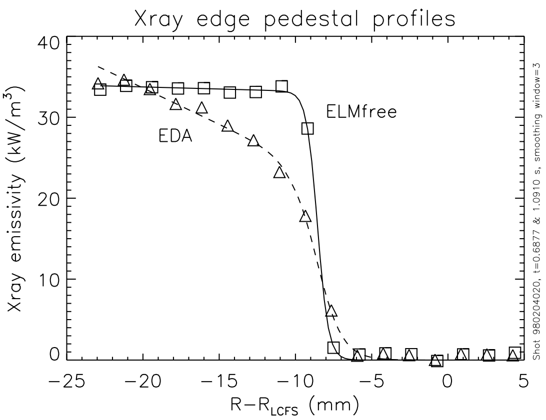

FIG. 8. X-ray pedestal profiles are shown for a C-Mod plasma which transitioned from an ELMfree to an EDA H-mode. The x-ray pedestal width is much narrower in the ELM-free H-mode (1.4 mm) than in the EDA (3.6 mm).

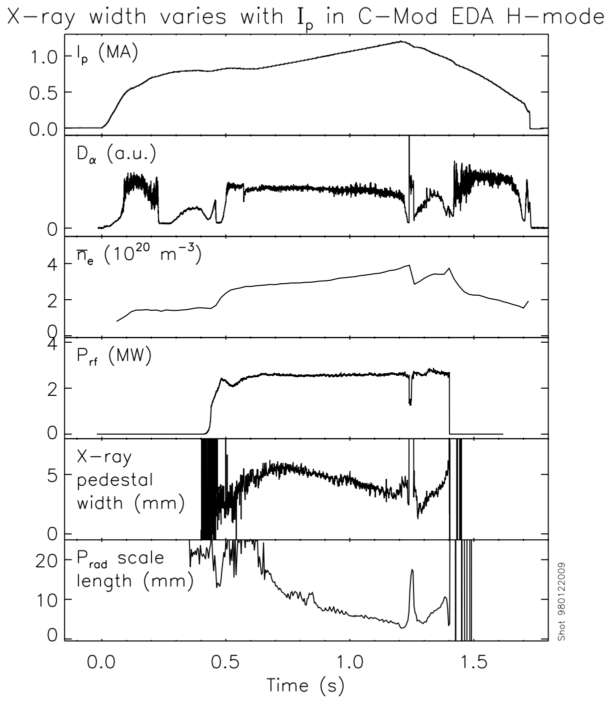

FIG. 9. Evolution of several relevant signals during an EDA H-mode discharge in which the plasma current was ramped dynamically during the shot from 0.8 to 1.2 MA, and then back down again. The x-ray pedestal width clearly narrows as I_p ramps up, and broadens again when I_p ramps back down. The P_{rad} profile shows the same qualitative behavior. (There is a brief transition back to L-mode around $t = 1.25$ s.)

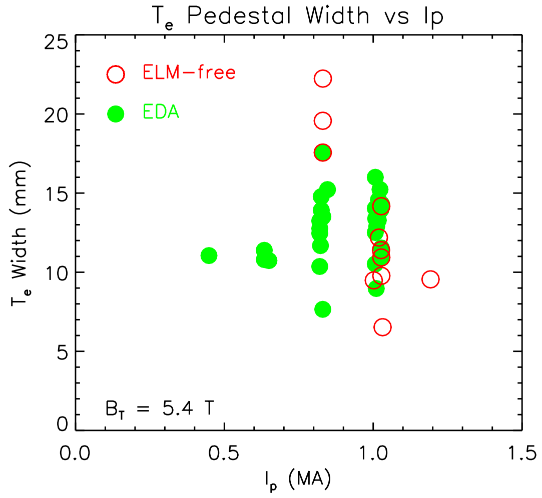

FIG. 10. Plot of T_e pedestal width for various plasma currents. There is apparently little or no consistent variation with I_p.

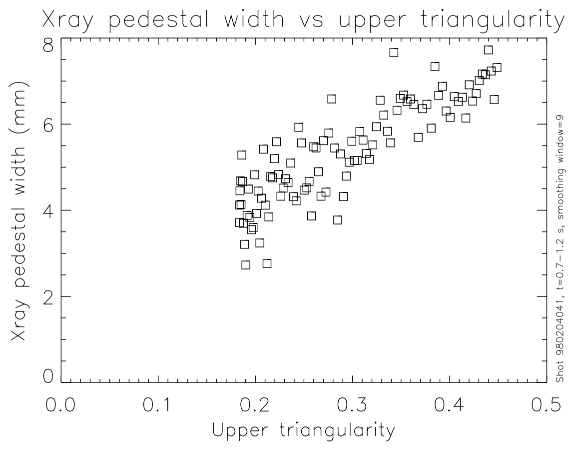

FIG. 11. The x-ray pedestal width varies linearly with plasma triangularity. The data were taken during a dynamic scan of upper triangularity in an EDA H-mode.