H-mode pedestal and L-H transition studies on Alcator C-Mod


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ABSTRACT

H-mode research on Alcator C-Mod is described, with a focus on the edge transport barrier (ETB). ETB pedestals are characterized using several diagnostics, leading to a thorough description of profile structure in H-mode. L-H transition criteria are discussed, along with the fast evolution of the pedestal following the L-H transition. H-mode regimes are described in terms of their edge transport characteristics and the local edge parameters favoring each. Empirical scalings of the pedestal with operational parameters are found, helping to illuminate physics governing the pedestal structure, and the relationship between edge transport and global confinement is discussed. Dimensionless comparisons between discharges on different tokamaks are discussed. Finally, ongoing work and directions for the future are described.
I INTRODUCTION

A characteristic feature of the high confinement (H-mode) regime [1] is the formation of an edge transport barrier (ETB) near the last closed flux surface (LCFS), where steepening of the density and temperature gradients is observed. The importance of ETB physics is underscored by numerous theoretical and experimental works [2] [3] [4] [5] [6] that suggest a strong dependence of the plasma core confinement on edge parameters. Detailed studies of the ETB region are important for understanding the mechanisms of the L-H transition and the subsequent confinement improvement seen in H-mode. As improved edge diagnostics have been deployed on tokamaks, research has focused on the relationships of edge parameters to L-H transition physics, ETB transport and stability, scalings of pedestal parameters and overall global confinement. The Alcator C-Mod tokamak [7] [8] is a compact high-field, high-density device, and it makes a unique contribution to these studies due to the region of parameter space that it occupies. A review of transport studies on C-Mod can be found in a companion paper [9].

Edge studies on C-Mod utilize a number of diagnostics, which are described in Sec. II.A, and in greater detail in a companion paper [10]. Diagnostics with spatial resolution on the order of millimeters are used to characterize the radial structure of edge profiles and collect data across a range of plasma operational parameters [11]. Section II introduces these experimental efforts and describes the behavior of local gradient scale lengths across the edge. By combining simultaneous results from various diagnostics, it is possible to discern distinct radial regions, with generally different transport characteristics, in the vicinity of the LCFS. The ETB, or “pedestal”, region is seen to extend only a few millimeters in midplane radius, with a great deal of variation evident in derived pedestal widths.

L-H transition and pedestal formation studies rely on fast diagnostics, as well as those with high spatial resolution, as seen in Sec. III. Temporally resolved edge measurements of density and temperature have allowed evaluation of local conditions at the L-H transition time [12] [13], which complements the evaluation of global power threshold [14]. Local threshold conditions for transition are found to have less scatter and uncertainty than the threshold in global input power. Two phases of temperature profile evolution are also distinguished with the benefit of these fast measurements, showing sub-millisecond pedestal formation at the transition, followed by a slower phase with a temperature rise time measured in milliseconds [13]. Recent measurements in the scrape-off layer (SOL) reveal an apparent dependence of the L-H transition threshold on the direction and strength of SOL bulk plasma flows, which may help explain large topology-dependent variations in the L-H thresholds [15].

Three regimes of H-mode operation are commonly accessed on C-Mod: edge-localized mode free (ELM-free), enhanced Dα (EDA) and ELMy H-modes. Section IV discusses how these regimes occupy distinct regions of operational space, and exhibit generally different edge fluctuations. Edge transport differs among the three regimes, influencing global plasma confinement. In order to
understand better the physical mechanisms governing edge transport, discharges in the three regimes have been examined for differences in edge parameters [11] [16]. The regions in which each regime predominates are determined by a sophisticated multivariate phase space, in which edge parameters such as collisionality $\nu^*$, safety factor $q$, triangularity $\delta$ and pressure gradient $\nabla p$ appear to play important roles, via their influence on magnetohydrodynamic (MHD) stability. The onset of small ELMs in C-Mod coincides with high edge $\nabla p$ and reduced $\nu^*$, and is well modeled using a coupled peeling/ballooning mode analysis. By contrast, the development of EDA H-mode and its associated quasi-coherent edge fluctuation is not explained within the framework of ideal MHD.

Scaling studies [11] have been performed in EDA H-modes to determine pedestal trends with plasma operational parameters, and the results of this research are reviewed in Sec. V. Discharges at fixed shape yield little systematic variation of pedestal width with plasma parameters, while pedestal heights and gradients show the clearest dependence on plasma control parameters. Among the most significant empirical scalings on C-Mod is a ballooning-like $I_p^2$ scaling for the pressure pedestal, which is observed despite no evidence of large ELMs and calculated stability to ideal MHD ballooning modes. A robust linear scaling of the $n_e$ pedestal with current is also observed, along with a relatively weak scaling with discharge target density. The relation of confinement to the edge pedestal is also characterized, since plasma stored energy $W_P$ scales with pedestal $p_e$. Some progress has been made in examining plasma shaping effects on the pedestal in EDA H-mode, as well.

Complementing the scaling studies on C-Mod are inter-machine dimensionless similarity studies. These have been carried out between C-Mod and DIII-D [17] and between C-Mod and JET [18]. In both cases, reasonable success was had in obtaining matching dimensionless plasma parameters, including collisionality, normalized pressure and normalized gyroradius, at the top of the edge pedestal [19] [20], and both experiments demonstrated similarities in edge fluctuations in dimensionlessly similar discharges on different machines. As discussed in Sec. VI, the joint experiment with DIII-D is particularly notable for having well-matched pedestal profiles, suggesting that matching plasma physics parameters may be sufficient to determine pedestal structure in general, and width specifically.

H-mode and pedestal studies make up a rich field of research that is vital to the international tokamak program, particularly with respect to predicting pedestal parameters, and thereby global confinement, on a future burning plasma experiment such as the International Tokamak Experimental Reactor (ITER). Therefore, this research continues to be actively pursued on Alcator C-Mod. Ongoing efforts to improve experimental diagnosis and modeling of ETBs is summarized in Sec. VII.
Table 1: Some useful diagnostics for edge plasma studies. Detailed discussion of the C-Mod diagnostic set can be found in [10].

## II PLASMA EDGE CHARACTERIZATION

### II.A Edge diagnostics

Since H-mode confinement was first achieved on C-Mod [21], thorough characterization of the edge region has been an experimental priority. In order to study L-H transition physics, pedestal scalings, H-mode transport and stability, it was necessary to develop an extensive set of diagnostics. Those diagnostics especially useful to the current review are listed in Table 1, along with the principal quantities measured by each and the regions of plasma over which each is most relevant. Details on the operation of these and other C-Mod diagnostics are available in a companion paper [10]. The application of each diagnostic to H-mode studies will be discussed in the following sections.

During early H-mode operation, important pedestal measurements were available. Using measured electron cyclotron emission (ECE), scans of the H-mode temperature profile using $B_T$ sweeps placed an upper bound of 8 mm on the $T_e$ pedestal width [22], with measurements limited by the spatial resolution of the ECE grating polychromators [23] [24]. Profiles of edge $n_e$ from reflectometry demonstrated that the density pedestal width was no larger than about 1 cm [25], and reciprocating scanning Langmuir probes [26] showed $n_e, T_e$ gradient scale lengths of millimeters in H-mode near the LCFS [22] [27]. Density and temperature near the top of the pedestal could be diagnosed relatively easily using ECE, interferometry [28] and core TS [29] [30]. However, to obtain details of pedestal structure, new diagnostics with higher spatial resolution were required.
Figure 1: Edge profiles of electron temperature ($T_e$) and density ($n_e$) at the tokamak midplane before and after an L-H transition. The edge transport barrier (ETB) region typically has a width $\Delta$ of a few millimeters. Solid curves represent a fitting function given by Eq. (1). Adapted from [33].

In and around 1998, new measurements became available in the form of soft X-ray arrays viewing the pedestal region [31] and a visible continuum (VC) array [32], giving ETB profiles of impurity density $n_I$ and $n_e\sqrt{Z_{\text{eff}}}$, respectively. Pedestal widths in the range of 2–6 mm were soon routinely observed from both diagnostics.

Since 1999 the study of the H-mode pedestal on C-Mod has been aided by an edge Thomson scattering (ETS) diagnostic [33] with high spatial resolution. The ETS system measures $T_e$ and $n_e$ at the upper edge of the plasma at $R = 69$ cm, obtaining profiles with a nominal radial resolution of 1.3 mm after mapping along flux surfaces to the midplane. The dynamic range of the ETS diagnostic is approximately 20–800 eV, $3 \times 10^{19}$–$5 \times 10^{20}$ m$^{-3}$, which encompasses conditions throughout the H-mode pedestal region in most operational regimes. A dramatic increase in $T_e$ and $n_e$ gradients is observed in the ETB region upon transition from L to H-mode, as demonstrated in Fig. 1. Gradient scale lengths of a few millimeters are typical in C-Mod pedestal profiles.
II.B Radial profile variation

By combining the measurements of multiple diagnostics, extended radial profiles of $n_e$ and $T_e$ have been produced. As an example, Fig. 2 shows a complete profile obtained by simultaneous use of ETS, ECE, the VC array and scanning probes. Here a steady H-mode discharge was maintained, and $B_T$ was swept from 5.4 to 5.6 T and back over a period of 200 ms, giving a radial ECE sweep of approximately 2 cm. The $n_e$ profile from VC is averaged over this time window, as are six ETS time points. Within this time period the scanning probes were driven through the SOL into the vicinity of the LCFS. Radial shifts of a few mm are typically applied in order to account for mapping errors. The profiles in Fig. 2 illustrate the typically good agreement, after correction for errors in radial coordinates, among the C-Mod diagnostics observing the plasma edge, within the experimental uncertainties of each. Profiles from TS (circles) agree with probe data (dot-dashed curves) in the SOL. The profiles of $n_e$ and $T_e$ flatten at the foot of the pedestal and exhibit radial scale lengths $L_n = n_e/|\nabla n_e|$, $L_T = T_e/|\nabla T_e|$ of a few centimeters in the SOL. The large drop in the probe $n_e$ profile approximately 10 mm outside the LCFS happens because the probe is in the shadow of outboard poloidal limiters.

Moving inward radially toward the LCFS, the probe passes from the far SOL into the near SOL, where a strong reduction in gradient scale lengths begins. The narrow region near the LCFS exhibits scale lengths of millimeters. Probes, the VC measurement and ETS all show the steepening of gradients associated with ETBs. The discrepancy between the ECE and TS profiles in the pedestal region is explained by the larger ($\approx8$mm) spatial resolution of the ECE diagnostic. Several millimeters inside the LCFS, gradients relax, and ECE and ETS produce mutually consistent profiles of core plasma $T_e$. There is also good overall agreement between TS and VC. Though the profiles in Fig. 2(a) seem to show small variations in $n_e$ atop the pedestal, these are actually related to measurement uncertainties.

Both profiles exhibit core gradients roughly constant in $R$, usually with gradient scale lengths such that $L_T \ll L_n$. An interesting feature in the $T_e$ profile, observed in a number of steady H-mode discharges, is a region of $T_e$ gradient intermediate between that in the pedestal ($|\nabla T_e| \sim 50-100$ keV/m, typically) and that in the core plasma ($|\nabla T_e| \sim 5-10$ keV/m). This region is located immediately inside the $T_e$ pedestal and is approximately 1 cm in radial extent. The change in $T_e$ gradient in this region has been observed with both ECE and ETS, though the adjacent pedestal seen with ETS is too localized to be measured with ECE. Profile measurements using ECE during $B_T$ sweeps thus lead to wider pedestal measurements, and, prior to deployment of ETS, a reported $T_e$ pedestal width $\Delta T_e \gtrsim 1$ cm [27] [34] [35]. One can infer that similar instrumental differences could also impact the comparison of pedestal data of different machines. The two breaks in slope found in the C-Mod $T_e$ profile indicate that perhaps there are two distinct edge regions with generally different edge transport characteristics. Unfortunately the radial extent of the transition region between pedestal and core is not routinely diagnosed, and not well characterized at this time.
Figure 2: Combined profiles of (a) $n_e$ and (b) $T_e$ near the C-Mod edge from multiple diagnostics during a toroidal field sweep between 5.4 and 5.6 T. Scanning probes are used in the scrape-off layer (SOL), while core profiles are obtained with visible continuum (VC) and electron cyclotron emission (ECE) measurements. Edge Thomson scattering (ETS) resolves the region about the last closed flux surface (LCFS). VC and ETS data are time-averaged over 200 ms. The $T_e$ profile shows a transition region approximately 1 cm in width between the pedestal and core, exhibiting $|\nabla T_e|$ intermediate between pedestal and core gradients. From [11].
The outer ETB profiles, however, are regularly measured with ETS.

II.C Fitting pedestals

The curves underlying the H-mode profiles in Fig. 1 represent fits of a standard parameterized function \([36] [37]\) to the H-mode data. A convenient set of fitting parameters \([b\) (baseline), \(h\) (height), \(R_0\) (position), \(\Delta\) (full width) and \(m\) (interior slope)]\) are obtained from this function, defined on midplane radius \(R\):

\[
f(R) = b + \frac{h}{2} \left[ \tanh \left( \frac{R_0 - R}{d} \right) + 1 \right] + m(R_0 - R - d)H(R_0 - R - d) \tag{1}
\]

where

\[
H(x) = \begin{cases} 
0 & : x < 0 \\
1 & : x \geq 0
\end{cases}
\tag{2}
\]

Figure 3 shows this modified tanh function fit to a measured \(n_e\) profile on C-Mod, with the fitting parameters shown. Here \(d = \Delta/2\) is the pedestal half-width. The Heaviside function, \(H(R_0 - R - d)\), allows one to account for the finite radial slope, \(-m\), that exists inside the pedestal region. At the base of the pedestal \((R = R_0 + d)\), \(f \approx b\); the value of \(f\) atop the pedestal \((R = R_0 - d)\), is approximately \(b + h\). The maximum radial derivative exists at \(R = R_0\): \(\left| \nabla f \right|_0 = h/\Delta\). This notation will subsequently be used to denote the largest gradient of a given pedestal. Also, the subscript \(\text{ped}\) on a given variable will signify the value of that variable near the top of its pedestal (e.g., \(T_e,_{\text{ped}} = b_T + h_T\)). Equation (1) fits most H-mode profiles measured by ETS reasonably well, and is consistent with some models \([38] [39]\) that suggest a tanh-like functional form for the pedestal profile.
Figure 4: Scatter plot illustrating typical range of $T_e$, $n_e$ pedestal widths, with all types of H-mode included. Contours A, B and C enclose 50, 75 and 95% of the 2,809 data points. Dotted lines signify the nominal lower bound of ETS resolution. From [95].

II.D Pedestal parameters

The radial extent of the pedestals shown in Figs. 1, 2 and 3 is typical. Most pedestal widths are in the range of 2–6 mm ($\Delta/a \approx$1–3%), with $\Delta_T$ slightly larger, on average, than $\Delta_n$. This is seen by plotting a large number of individual pedestal measurements in $\Delta_T$-$\Delta_n$ space, as in Fig. 4. Here the density of data is highest in the region where $\Delta_n < \Delta_T$. Examining the distribution of $\Delta_n$, $\Delta_T$ shows that the mean $T_e$ width is larger than the mean $n_e$ width by approximately 0.5 mm, and that the radial position difference $R_{0,n} - R_{0,T}$ is characterized by a similar scale length [11]. Pedestal widths do not respond readily to changes in global plasma parameters, such as toroidal field and current, and thus the spread in $\Delta_T$-$\Delta_n$ space is dominated either by random profile fluctuations or hidden variables. Varying plasma shape has been shown to affect systematically pedestal width and other ETB properties. This is discussed in Sec. V.D. The feet of the $T_e$ and $n_e$ pedestals, where the respective profile values tend toward $b_T$ and $b_n$, both exist near the LCFS, and the baseline values typically measure 15–30 eV and $3\times10^{19}$ m$^{-3}$. This puts the foot of the pedestal in the near SOL, since power balance arguments [40] require $T_e$ between 50 and 100 eV at the LCFS of almost all C-Mod plasmas. Pedestals exhibit a wide range of peak values ($n_e$: $1\sim5\times10^{20}$m$^{-3}$, $T_e$: 200–1000eV) and characteristic gradients, and are sensitive to a number of operational parameters. This is discussed in Sec. V.B.
III L-H TRANSITION STUDIES

H-mode transition thresholds and dynamics have been studied on C-Mod since the first observations of ohmic H-modes in 1994 [41]. While initial studies focused on the global power threshold, increasing attention has been given to analysis of the local conditions in the edge region where the pedestal forms. These exploit the extensive diagnostic set described above. The high time resolution of ECE and VC are particularly valuable for these studies, making it possible to assess conditions at the exact moments of the L-H transition and H-L back-transition and to follow the dynamic evolution of the density and thermal barriers.

III.A Global power threshold

Global threshold trends for the L-H transition were found to be in rough agreement with prior scalings, generally increasing with both density and magnetic field. Absolute power requirements were, however, below expectations based on other tokamaks (e.g. [42]), allowing ohmic H-modes to be obtained at reduced $B_T$. Early data lay in the range $P/S = 0.022–0.044 \times \bar{n}_eB_T$ [5] [21] [43], with the upper values being consistent with prior scalings on ASDEX Upgrade [44]. A low density limit was found below which the power threshold rises sharply, at about $\bar{n}_e = 8 \times 10^{19} \text{ m}^{-3}$ though with some variability in different campaigns. This is significantly higher than the low density limits of $\bar{n}_e \approx 2–3 \times 10^{19} \text{ m}^{-3}$ found on other tokamaks [45] [46]. As has been seen elsewhere, the power threshold is lowest in diverted discharges with ion $\nabla B$ drift toward the active X-point, and is about a factor of two higher with unfavorable drift. A large power hysteresis was found, with the H-L back-transition occurring at $P/n$ up to three times lower than the L-H threshold.

C-Mod data expanded the prior range of data in $P/S$ by nearly an order of magnitude, to 0.6 MW/m$^2$, as shown in Fig. 5. Their contribution to inter-machine databases was important in clarifying the size, density and field scalings of the power threshold, leading to improved scalings, such as [14]

$$P_{\text{thresh}} = P_m - \frac{dW}{dt} = 0.054 \times \bar{n}_e^{0.49} B_T^{0.85} S^{0.84}$$

(3)

which are used to predict the power threshold for future devices such as ITER. However, in both C-Mod and global datasets, it is recognized that there is a large degree of scatter in the power threshold, up to a factor of two for similar conditions. This persists even for well controlled, well conditioned experiments and is well outside the experimental errors in the various scaling quantities. Such variability leads to large uncertainties in threshold extrapolations, and indicates that global scalings cannot capture the physics of transition thresholds. This has motivated intensive study of the local parameters in the edge region where the transport barrier and fluctuation suppression first occur.
Figure 5: A recent H-mode threshold scaling [14] showing how C-Mod data (circles) extend the range of density and toroidal field with respect to other tokamaks in the international database (crosses).

III.B Local threshold conditions

The likely importance of edge temperature was inferred from the earliest H-modes on ASDEX, where it was noted that transitions tended to occur following a sawtooth heat pulse [1]. This was confirmed on C-Mod; high resolution ECE measurements clearly showed the transient increase in edge $T_e$ following sawtooth crashes and that L-H transitions often occur in such phases. C-Mod was among the first to study systematically the edge $T_e$ values just before L-H and H-L transitions. It was quickly noted that, for given $I_P$ and $B_T$, threshold $T_{e,95}$ lay in a narrow range at the L-H transition. (In this paper, the subscript “95” will signify that the quantity is evaluated at the surface enclosing 95% of poloidal flux.) In contrast to the power threshold, temperature values at the H-L back-transition were similar [43]. Density and power scans revealed a tight threshold in $T_{e,95}$ over a wide range of density, having much less scatter than the power threshold, as illustrated in Fig. 6 [12], strongly suggesting that temperature or a closely related quantity such as its gradient is involved in the transition. The edge $T_e$ threshold increased with $B_T$ and, significantly, was seen to be about a factor of two higher with unfavorable drift direction, contradicting theories which suggested the difference might be simply due to different transport in these configurations.

An advantage of local threshold measurements is that they allow more direct comparison with transition theories. C-Mod measurements were compared with a model developed by Rogers and Drake based on 3D simulations of drift-ballooning turbulence, which predicted thresholds in a
Figure 6: Total input power (top) and edge temperature (bottom), for a series of discharges in which power was ramped at different densities. Solid triangles represent the threshold condition just prior to the L-H transition, showing that a critical $T_e$ is needed [12].

space determined by an MHD ballooning parameter $\alpha_{\text{MHD}}$ and an ion diamagnetic parameter $\alpha_{d,i}$ which is inversely related to collisionality [47]. Good agreement was found, as shown in Fig. 7 [12]. The data did not support a threshold in collisionality as might be expected in neoclassical models. More recent comparisons with an analytic expression for generation of zonal flows by Guzdar [48], which was stimulated by the above simulation results, also show quite good agreement with the $B_T$ scaling [13], as discussed in Sec. III.D.

Local data on C-Mod have also enabled direct experimental measurement of the flux-gradient relationship through the L-H-L cycle, an important prediction of H-Mode theories. Power flux vs. edge gradients were mapped out by slowly ramping input power up through the threshold and back down [49] [50]. A typical example showing the classic “S-curve” is shown in Fig. 8. A clear bifurcation is seen, with H-mode $T_e$ gradients about five times those in L-mode, at the same normalized power flux $Q/n_e$. Curves represent predictions of a dynamic fluctuation flow model by Carreras [49] (solid), and of an expression by Hinton (dashed) assuming strong suppression of $\chi$ with $\nabla T_e$ [51]. Both show reasonable agreement, while other models predicting weaker or stronger dependences do not fit the data.

### III.C Dynamic evolution of the pedestal

Transient evolution of the edge transport barrier following the L-H transition has been studied exploiting fast density and temperature measurements. It was found that all edge $T_e$ channels respond simultaneously, within the 0.5 ms precision of the break-in-slope determination; there is no evidence of barrier propagation. Rates of rise in $n_e$ and $T_e$ are approximately $2 \times 10^{21} \text{ m}^{-3}/\text{s}$ and
Figure 7: Experimental values of ballooning parameter $\alpha_{\text{MHD}}$ and diamagnetic parameter $\alpha_{d,i}$, for C-Mod datasets at two different fields. The values at the L-H transition (triangles) lie close to the model predictions of Rogers [47]. Adapted from [12].

Figure 8: Relationship of normalized heat flux $Q/(2kA_n)$ versus pedestal temperature gradient, through the L-H-L cycle. Diamonds represent transient phases through the transition. “S-curves” predicted by two different models are shown for comparison. (Fig. 2b from [50])
20 keV/s respectively [49]. Somewhat surprisingly, the rate of rise of $T_e$ did not vary as the power ramp rate was scanned. The evolution of the pedestal pressure in the barrier formation phase (first tens of ms after L-H transition) is consistent with that expected from an instantaneous reduction in $\chi_{\text{eff}}$ within the barrier from an L-mode value of about 0.5 m$^2$/s to less than 0.1 m$^2$/s in H-mode. However, the relative contributions of the density and temperature rise vary depending on the target conditions. At typical L-mode target densities, $n_{e,L} \approx 2 \times 10^{20}$ m$^{-3}$, the $T_e$ and $n_e$ contributions to the pressure rise are comparable, whereas at lower target densities ($\approx 1.2 \times 10^{20}$ m$^{-3}$), the density rise becomes weak, reflecting a lower particle source measured by Lyman-$\alpha$, and the $T_e$ rise dominates. For even lower densities, approaching the low density limit, there is essentially no $n_e$ increase and the transition is not sustained, while at very high source rates there is often little $T_e$ pedestal development.

Closer examination of the initial transients, using faster ECE diagnostics [52], revealed that the edge $T_e$ increase within the barrier occurs in two phases, a fast “jump” lasting about 500 $\mu$s, followed by the slower diffusive response described above [13] (Fig. 9a). At radii inboard of the pedestal, only the slower response is seen. Again, the duration of the jump did not depend on the input RF power flux. At powers just above the transition, the fast rise was often followed by a slight decrease at some radii, while with marginal power “dithering” L-H-L cycles of a few ms duration often occurred, as illustrated in Fig. 9(b); these phenomena appear related. The transition dynamics were modeled numerically by a spatially non-local fluctuation-flow model based on work by Diamond et al. [53] which evolves the poloidal flow shear, the pressure and the fluctuations. Diamagnetic contributions were found to be important. Several of the observed features, including the “dithering” oscillations but not the two-phase evolution, were reproduced. More accurate modeling would need to evolve separately the temperature and density pedestals and include particle sources.

### III.D Role of SOL flows and plasma configuration

Recent experiments on L-H thresholds have focused on the role of plasma configuration on H-mode thresholds. As mentioned above, and illustrated in Fig. 10, L-H power thresholds can vary dramatically with configuration [54]. New measurements of SOL flows [15] [55] have revealed strong flows in the high-field side which reverse direction depending on X-point location. In the usual field direction, with ion-$\nabla B$ drift down, they are co-current in lower single null (LSN), counter-current in upper null (USN), and near-zero with double null (DN). Modeling suggests that these are due to strong ballooning-like transport on the low-field side, combined with weak cross-field transport on the high-field side, causing plasma to flow along field lines toward the inner SOL. Changes in L-mode core toroidal rotation are also seen which respond similarly to these edge flows, suggesting the momentum source comes from the edge [56] [57]. In all configurations, core and edge rotation become more co-current with increasing input power and stored energy. A striking result, illustrated in Fig. 11, is that the L-H transition in all three cases occurs when the net rotation is near a constant
Figure 9: Examples of transient evolution at the L-H transition, illustrating the high time and spatial resolution of C-Mod pedestal measurements. Of note are the two-phase evolution shown in (a), and the “dithering” cycles seen before the sustained transition in (b). From [13]
Figure 10: Global power threshold on Alcator C-Mod in five magnetic configurations: upper single null (USN), double null (DN), lower single null (LSN), inner wall (IW) limited and limited on the divertor nose (lower limited). Adapted from [54].

Figure 11: Time histories of three discharges exhibiting L-H transitions, near power threshold, in upper null, double null and lower null. Note that the core rotation (e) is near constant at the transition, while $T_e$ and $\nabla p_e/n_e$ are higher in USN. Adapted from [15].
Figure 12: Comparison of predicted and measured values of a threshold parameter proposed by Guzdar [48]. Note that predictions (circles) lie midway between values for LSN and USN configurations; the model does not include configuration effects. From [58].

value. The edge temperature, pressure and gradients, in contrast, are higher in USN as previously reported. This suggests that the mean edge flows, perhaps through their influence on $E_r$, which is not directly measured, set up a boundary condition which either favors or hinders the transition. Larger or smaller edge gradients are then needed. While we do not suggest that edge flows are themselves responsible for the L-H transition, they may well cause the differences in threshold with configuration. Present transition models do not take into account such flows. For example, the predicted threshold of Guzdar lies midway between the experimental result for LSN and USN, as shown in Fig. 12 [58]. Understanding these effects, and the fundamental physical threshold conditions, will be the focus of future C-Mod experiments and diagnostic improvements. It will be of interest to investigate whether differences in flows and rotation could also explain some of the shot to shot variation in thresholds which is seen on all experiments.

IV H-MODE REGIMES AND EDGE STABILITY

H-mode operation in general can exhibit varying levels of confinement, depending on the H-mode regime that is obtained, and the regime of operation can be related to the quality of transport through the ETB. Common categories of H-mode on C-Mod can be characterized primarily on this basis. The three main regimes considered in this review are referred to as the edge-localized-mode free (ELM-free), enhanced $D_\alpha$ (EDA) and high-power ELMy H-modes. These regimes occur in discharges of standard shape, and the differences in plasma parameters in either regime can
be quite subtle in some cases. Considerable effort has been undertaken to resolve distinguishing features of these regimes, both in terms of global plasma parameters and local edge conditions. These H-mode types are described below, and additional detail can be found in [9].

IV.A Regime description

Discharges without ELMs [59] or other significant edge fluctuations are termed ELM-free, and are characterized by low levels of edge particle transport, leading to high confinement. They exhibit increasing core density and impurity concentration, leading to termination of the H-mode by radiative collapse. This behavior can be seen clearly in Fig. 13a–e, which shows the uncontrolled density and radiation rise in multiple ELM-free H-modes, triggered in this case by modest amounts of auxiliary ICRF power. When the radiated power $P_{\text{rad}}$ approaches the value of total input power, the H-mode can no longer be sustained. As a result of increased particle confinement, particle recycling drops, and reduced levels of $D_\alpha$ are measured at the edge (Fig. 13c). Yet another signature of H-mode onset is the reduced level of broadband turbulence at the edge. This can be shown by plotting the auto-power spectrum of signal from an edge reflectometer, as in Fig. 13d.

A common operating regime on C-Mod is the enhanced $D_\alpha$ H-mode [49] [60] [61] [62] [63], so named because measured $D_\alpha$ intensity can be much larger than that in ELM-free operation. Energy confinement in EDA H-mode is near that of ELM-free, but particle confinement is reduced, allowing a steady H-mode to be maintained with constant density and stored energy, and with no accumulation of impurities. Temporal behavior of a typical EDA H-mode is shown in Fig. 13f–j. After the L-H transition, a period of approximately 20 ms follows in which the H-mode bears all the characteristic signatures of ELM-free H-mode, including abrupt density rise (Fig. 13f), increasing radiated power (Fig. 13g), depressed $D_\alpha$ (Fig. 13h) and suppressed broadband fluctuations (Fig. 13i). However, within about 100–200 ms, the density and radiated power reach roughly steady values, and the $D_\alpha$ brightness becomes much higher. These signatures indicate high particle recycling at the edge and enhanced particle transport.

Strong experimental evidence was presented [49] [61] [64] that suggests the enhanced particle transport of EDA is driven by a strong fluctuation localized to the pedestal region. The most easily identified component of this quasi-coherent mode (QCM) is that of density, as seen using the phase contrast imaging (PCI) diagnostic [65], or edge reflectometry [66] (e.g. Fig. 13i). Within 100–200 ms, EDA H-modes typically reach steady state and can be maintained for times $t \gg \tau_E$ with the application of steady ICRF heating (Fig. 13j). Measurements have localized the QCM to the pedestal region [67], and large radial ion fluxes have been inferred from measured fluctuations (on the order of 50%) of density and electric potential [49]. The QCM has a variable amplitude, which correlates well with signatures of enhanced particle transport through the ETB. Figure 14 shows that as density is raised at fixed $I_P$ and $B_T$, $n_e$ fluctuations from PCI increase, as do edge $D_\alpha$ (deuterium recycling) and the width of the soft x-ray pedestal (impurity transport). (Further
Figure 13: Characteristic time-behavior of H-mode types on C-Mod. Periods of H-mode are denoted by light gray shading. Rows of plots show line-integrated density, core radiated power, edge $D_\alpha$, edge reflectometer spectrograms and the ICRF input power used to trigger and sustain the H-modes. Edge-localized-mode-free (ELM-free) H-modes (left) show a continual rise in both core density (a) and radiated power (b), while $D_\alpha$ (c) drops considerably from L-mode levels, indicating lower levels of particle recycling. Enhanced $D_\alpha$ (EDA) onset (center) results in a rollover in particle inventory and radiation, and is characterized by elevated levels of $D_\alpha$, all symptoms of increased edge particle transport (f–h). Edge reflectometry reveals the existence of a quasi-coherent mode (QCM) present in EDA H-mode (i) but absent in ELM-free (d). In high power ELMy H-modes (right), density and radiation can rise slowly, and the $D_\alpha$ trace shows high-frequency bursts (k–m). The QCM drops in frequency and becomes swamped by increased broadband fluctuations (n).
Figure 14: Fluctuations and indicators of particle transport in a series of 5.3 T, 0.8 MA H-modes with varying target density at the L-H transition. H-mode times are taken 80 ms after the transitions. (a) $dn_e/dt$, which drops as steady state is approached. (b) $D_\alpha$ emission (squares, in mW/cm²/Sr) and width of the x-ray pedestal (diamonds, in mm), which depends on impurity diffusivity. (c) Amplitude of quasi-coherent mode (QCM) in phase-contrast imaging (PCI) fluctuations. From [49].
details on impurity transport in H-modes can be found in [68], in this issue.) Global density rise is reduced as the QCM grows in strength. In addition, estimates of effective diffusivity at the LCFS were found to increase with the measured amplitude of the QCM [9].

The QCM thus provides a mechanism for reducing buildup of core density and impurity accumulation, leading to steady state H-mode operation. This contrasts with the confinement relaxation mechanisms on most other tokamaks. Often in these devices, the presence of large ELMs is seen to reduce confinement in bursts by expelling edge plasma into the SOL [69] [70] [71] [72]. Though large Type I ELMs are not observed on C-Mod, a regime of smaller ELMs is observed in high power discharges, typically with $\beta_N \gtrsim 1.3$. Figure 13k–o shows traces from a sample ELMy discharge. The rise of density and radiation (Fig. 13k–l) is smaller than in ELM-free H-mode, though not as well controlled as it is in the EDA regime. Fluctuations in D$_\alpha$ signal (Fig. 13m) are well correlated with peaks of the divertor probe saturation current and magnetic coil signals, and thus represent bursts of particle transport across the LCFS and into the SOL. Reflectometry (Fig. 13n) shows increased broadband fluctuations, relative to EDA, with the QCM in evidence at a lower frequency. For higher edge pressures, the QCM may be replaced entirely by ELMs. No significant degradation of the pedestal is observed. These ELMs are of similar quality to high frequency, small ELMs at high edge pressure (variously termed “grassy” or Type II) observed on other machines [73] [74]. These ELMs differ from Type III ELMs, also reported on C-Mod [21]. Type III ELMs occur when $T_{e,95} < 200$eV [22], with a frequency that decreases with increasing input power. This low-power ELMy regime is not extensively studied on C-Mod, and only the high-power, grassy ELM regime will be considered below.

IV.B EDA and ELMy access

Though Type I ELMs allow for sustainable high-pressure H-modes, the high intermittent heat fluxes present a challenge to divertor design in any tokamak of reactor scale. Because EDA is steady and absent of large ELMs, it has drawn interest as a possible reactor regime and has been examined extensively. Of particular interest are the conditions favoring EDA and how these conditions give rise to the QCM. The general operational conditions favoring EDA have been determined for some time. Experiments show [16] [61] that EDA is favored by both high edge safety factor ($q_{95} \gtrsim 3.7$) and higher values of triangularity. ($\delta \gtrsim 0.3$). Factors other than magnetic geometry are important too. Discharges at fixed shape and magnetic configuration show a threshold also in the target density $\bar{n}_{e,L}$, which is the line-averaged density prior to the L-H transition, below which H-modes are ELM-free and do not exhibit the QCM [75] [76]. Figure 14 shows that the amplitude of the mode is seen to increase as $\bar{n}_{e,L}$ is raised above the threshold value (about $1.3 \times 10^{20}$ m$^{-3}$ in 5.3T, 0.8MA plasmas) [49]. Because continuous variation of the QCM amplitude is obtained when passing between EDA and ELM-free regimes, the operational boundary between the two modes of operation is often described as “soft”.
Figure 15: Operational space of EDA (diamonds) and ELM-free H-modes (circles). Here $\alpha_{\text{PED}}$ is proportional to $(q_{95}^2 R) / B_T^2 \times |\nabla p_e|_0$. Larger values of each quantity favor EDA operation. From [11].

Because the QCM exists in the pedestal region, the characteristics of the ETB in both EDA and ELM-free H-modes were examined [11], in order to understand the QCM existence criteria and illuminate the physics governing the mode. ETS pedestal data from discharges of roughly fixed shape ($0.35 < \delta_{AV} < 0.45$) were categorized according to either the presence or the absence of the QCM, as observed using either reflectometry or PCI diagnostics, then sorted by $q_{95}$ (ranging from 3.2 to 6.5). For $q \lesssim 3.7$, H-modes are predominately ELM-free. However, the QCM exists even at these $q$ values, provided mid-pedestal $n_e$ is above $1.3\times10^{20} \text{ m}^{-3}$. There is no such density threshold for $q \gtrsim 3.7$ operation, where EDA predominates. For mid-pedestal $T_e \gtrsim 200\text{ eV}$, the QCM disappears at high $q$, leading to ELM-free operation.

Taken altogether, the tendency for EDA operation at higher $q_{95}$ and pedestal $n_e$ and lower pedestal $T_e$ suggests that edge collisionality $\nu^*$ plays an important role in determining the existence of the QCM. At fixed shape, $\nu^*$ scales as $qn_e/T_e^2$. In addition, low-$q$ data suggest a role for pressure gradient in determining the EDA/ELM-free boundary, showing that, at low collisionality, EDA operation is possible with sufficient $\nabla p_e$. A boundary between EDA and ELM-free operation was observed in these discharges in terms of $\nu^*$ and the normalized pressure gradient $\alpha_{\text{MHD}}$, as shown in Fig. 15. Here $\nu^*$ and $q$ are evaluated at the 95% flux surface, and the maximum pedestal $p_e$ gradient is used to compute $\alpha_{\text{PED}}$. Roughly speaking, the data show the QCM pedestals experimentally satisfy the condition $\alpha_{\text{PED}}\nu^*_{95} \gtrsim 8–10$. It is important to note that these data are from discharges at fixed shape, and that in general the boundary can change with variations in plasma shaping. In fact, the
Figure 16: Small ELMs appear in discharges with high pedestal pressure gradient and temperature. Note similar edge pressure gradient range for EDA and ELM-free H-modes. Adapted from [76].

boundary between ELM-free and EDA operation appears to be dictated by a multivariate phase space involving magnetic geometry and edge plasma parameters, and currently is determined in a rather approximate way.

Access to ELMy H-mode can be expressed in terms of pedestal parameters as well. Figure 16 illustrates how both sufficient $T_{e,\text{PED}}$ and $\nabla p_e$ are required before ELMs are obtained. For $T_{e,\text{PED}} \lesssim 400\text{eV}$ and $2 dp_e/d\Psi \lesssim 1 \times 10^7 \text{Pa}/(\text{Wb}/\text{rad})$, a mixture of EDA and ELM-free H-modes is obtained. A range of $q$-values is included in Fig. 16, causing a substantial overlap in the EDA and ELM-free data. In general, for $q \gtrsim 4$, the QCM subsides for $T_{e,\text{PED}} \gtrsim 400\text{eV}$ and the plasma makes a transition either to ELM-free (low to moderate $\nabla p$) or to ELMy (high $\nabla p$).

**IV.C MHD stability**

In order to understand better the physical mechanisms underlying transitions between H-mode regimes, ideal MHD stability analysis was undertaken, using ELM-free, EDA and ELMy discharges [76]. Initial modeling of edge stability using the BALOO code [77] demonstrated that, while the pressure pedestals would otherwise be above the critical gradient for infinite-$n$ ballooning modes given by ideal MHD, they are stable if a collisionally damped bootstrap current [78] is included, allowing a moderate parallel current to modify magnetic shear in the high-gradient region. The opening of the plasma edge to a second-stability regime is illustrated with BALOO results in Fig. 17.
The result is similar to the stability analysis results from other tokamaks [73] [74] [79], and leads to the conclusion that the observed QCM and ELMs could not be explained in the context of pure ideal ballooning theory.

Next, discharges were analyzed for stability to coupled peeling/ballooning modes [80] [81], intermediate-$n$ modes driven by combination of edge pressure gradient and current density. The proposed mechanism of these instabilities involves an external kink mode, destabilized by increasing edge current density, coupled with an unstable ballooning mode driven by pressure gradient. Instability manifests itself in this model by an ELM, the amplitude of which is determined by radial extent of the unstable modes. Stability to these modes was analyzed with the general-geometry linear MHD stability code ELITE [82], using real C-Mod equilibria, just as in the earlier ballooning analysis. Modes with $10 < n < 50$ were shown to be destabilized by edge bootstrap current $j_b$, with increased collisional damping of the current resulting in smaller growth rates [76]. In the case of a collisionally damped but finite $j_b$, modes were completely stabilized at low mode number ($n < 15$). In ELMing discharges with high $\nabla p$ and relatively low collisionality, higher-$n$ modes were calcu-
lated to have finite growth rate and to possess a radial mode structure extensive enough to drive an ELM-like radial transport event. Higher-$n$ modes were found increasingly stable in discharges with decreasing $\nabla p$ and $T_e$, consistent with the experimentally observed disappearance of ELMs and emergence of EDA operation. EDA and ELM-free discharges generally either were found stable to all intermediate-$n$ modes or showed a very narrow radial eigenmode structure thought to be incapable of producing an ELM. ELITE runs on several discharges spanning a wide range in $\alpha_{MHD}$-$T_{e,\text{PED}}$ space demonstrate a stability boundary that is consistent with the experimentally observed transition between EDA and ELMing. This is shown in Fig 18. The peeling/ballooning model has been used to explain ELM behavior on other machines as well \[83\] \[84\].

The above results indicate that EDA discharges are stable to both ideal ballooning and coupled peeling/ballooning modes, since the calculations typically found no instabilities for equilibria with the QCM in evidence. The physical mechanism underlying the QCM thus appears to lie outside the framework of ideal MHD. Due to prevalence of the QCM at higher values of $q$ and collisionality, a drive due to resistive ballooning modes \[85\] has been suggested. Efforts to model the C-Mod edge using fully electromagnetic 3-D fluid turbulence codes \[86\] \[87\] have exhibited coherent modes with characteristics similar to those of the measured QCM, including approximate frequency and wave number \[88\], large radial particle transport drive \[89\] and mode instability scaling with $q$ \[90\]. However, there are still questions surrounding the mode. We have yet to understand the
saturation mechanism of the QCM, or why it is relatively ineffective at transporting heat across field lines. Further work can be done to address these and other questions. Modeling the dependence of mode character on local edge parameters, in order to make a connection to the empirical boundaries determined in Sec. IV.B, should yield more understanding of the onset physics of the QCM.

V EMPIRICAL PEDESTAL SCALINGS

The next step in pedestal characterization is studying the scaling of pedestal parameters with tokamak operational parameters, as well as the correlation with global confinement. In doing so, one hopes to learn more about the physics setting the widths and heights of the pedestal on C-Mod, thus allowing comparison to modeling and experimental results on other tokamaks, and perhaps extrapolation to unbuilt burning plasma experiments. As seen in Sec. II.D, a large amount of scatter exists in the pedestal width derived from ETS profiles. In order to reduce experimental scatter in widths and other parameters for the purposes of scaling studies, TS and other plasma measurements were time-averaged over steady EDA H-modes only. Dedicated experiments were conducted with a standard C-Mod equilibrium, having $R = 68$ cm, $a = 22$ cm, elongation $\kappa \approx 1.7$, and average triangularity $\delta_{AV} \approx 0.4$. A range of plasma current ($0.6 < I_P [\text{MA}] < 1.2$), magnetic field ($4.5 < B_T [\text{T}] < 6.0$), and target density ($1.3 \times 10^{20} < \bar{n}_{e,L} [m^{-3}] < 2.6 \times 10^{20}$) was obtained. Here $\bar{n}_{e,L}$ is defined as the line averaged density immediately prior to transition from L- to H-mode. H-modes were triggered and maintained with steady $P_{RF}$, which ranged from 1 to 3MW.

V.A Width scaling

Of particular interest is the manner in which pedestal widths $\Delta$ scale with plasma parameters, since physical mechanisms exist which limit pedestal gradients (e.g. MHD activity, turbulence), and for a given pedestal gradient, $\Delta$ determines the pedestal height. On C-Mod, at a fixed shape, there is no clear systematic variation in the electron temperature and pressure pedestal widths $\Delta_T$ and $\Delta_p$. This contrasts with results from other tokamaks [91] [92] in which width variation with $I_P$ and edge $T_e$ was demonstrated. C-Mod pedestals show no evidence of a scaling with poloidal ion gyroradius $\rho_{i,\text{pol}}$ predicted by some theories [93], though the measured pedestal widths are of the same order as $\rho_{i,\text{pol}}$. The apparent lack of correlation is illustrated in Fig. 19 for the widths of the $T_e$, $n_e$ and $p_e$ pedestals. The invariance of $T_e$ and $p_e$ pedestal width is similar to results on ASDEX Upgrade at low triangularity, in which $\Delta_p$ is invariant as $I_P$ is scanned and global confinement correlates equally well with either $p_{e,\text{PED}}$ or pedestal $\nabla p_e$ [94]. Evidence of systematic variation in density pedestal width was seen in scaling studies [11]. In the normal operating range for EDA H-mode (4.5–6.0T, 0.6–1.0MA), $\Delta_{n_e}$ was seen to trend roughly both with $n_{e,\text{PED}}$ and $1/q_{95}$, given a fixed L-mode target density. These trends, shown in Fig. 20, demonstrate similar amounts of uncertainty due to scatter, and seem to be correlated
Figure 19: C-Mod pedestal widths $\Delta_T$, $\Delta_n$ and $\Delta_p$ vs. poloidal ion gyroradius $\rho_{i,\text{pol}}$, in a variety of EDA H-modes. No significant correlation is observed. From [95].
Figure 20: Density pedestal width (a) vs. \(n_e\) pedestal in EDA H-modes at 5.4 T and (b) vs. inverse edge safety factor \(1/q_{95}\). Data in both plots are from EDA H-modes at fixed L-mode target density, \(\bar{n}_{e,L} \sim 1.6 \times 10^{20} \text{ m}^{-3}\). Adapted from [11].

largely through a linear dependence of \(n_{e,\text{PED}}\) with \(I_P\), shown in Sec. V.B.1. More recent results have shown that at \(I_P < 600\text{kA}\), \(\Delta n_e\) becomes considerably wider [95], substantially reversing the trends in Fig. 20. Thus, over the full range of accessible parameter space on C-Mod, the scaling of the density pedestal width shows a complicated behavior that cannot be encapsulated by a single power law scaling. At all currents, the mean pedestal width is invariant to changes in the edge fueling source. That is, the variation of \(\Delta n_e\) with \(n_{e,\text{PED}}\) can be attributed mainly to changes in \(I_P\) and associated plasma transport changes, rather than to changes in neutral source rate. This specifically contrasts with DIII-D results showing \(\Delta n\) scaling with \(1/n_{e,\text{PED}}\) [96]. This suggests that on C-Mod \(\Delta n\) is not set primarily by the neutral penetration length at the edge, as predicted by simple neutral fueling modeling [39]. Understanding the contribution of neutrals to setting pedestal width is a high priority on C-Mod, and the subject of ongoing work. Important implications could exist for burning plasma devices, which will have values of neutral opacity (that is, the number of collisions experienced by a fueling neutral as it traverses the edge region) closer to that of C-Mod than to that of lower-field, lower-density tokamaks.

V.B Heights and gradients

In contrast to the widths, pedestal heights and gradients in EDA H-mode show clear scalings with control parameters. As an example, \(T_e\) profiles from ETS and ECE, obtained in identical discharges
Figure 21: Profiles of $T_e$ obtained from ECE (thick curves) and edge TS (diamonds) in 5.4T, 0.8MA discharges with varying levels of input ICRF power $P_{\text{RF}}$: 1.6MW (profile A), 2.1MW (profile B) and 2.7MW (profile C). Both $T_{e,\text{PED}}$ and $|\nabla T_e|_0$ increase with $P_{\text{RF}}$. From [11].

with varied levels of ICRF power, are shown in Fig. 21. As $P_{\text{RF}}$ is raised, the $T_e$ pedestal rises, both in height and gradient, while the width remains constant. The $n_e$ pedestals are unchanged in these three discharges. Examination of many discharges revealed that both pedestal $T_e$ and $|\nabla T_e|_0$ can be scaled in terms of the power passing into the scrape-off layer $P_{\text{SOL}}$ given by the power balance relation,

$$P_{\text{SOL}} = P_{\text{OH}} + \eta_{\text{RF}} P_{\text{RF}} - P_{\text{RAD}} - \frac{dW_P}{dt}$$  \hspace{1cm} (4)$$

where both the rate of change in plasma stored energy $dW_P/dt$ and the core radiated power measured from bolometry $P_{\text{RAD}}$ are subtracted from the ohmic power $P_{\text{OH}}$ and auxiliary heating power $\eta_{\text{RF}} P_{\text{RF}}$. (ICRF heating efficiency $\eta_{\text{RF}}$ is assumed to be 0.8.) Here it is worth noting that the radial extent of the transition region between pedestal and core (see Sec. II.B) is not as well fixed as $\Delta T$; impurity puffing experiments that varied edge temperature dramatically showed evidence of the transition region expanding farther into the core plasma at higher values of $P_{\text{SOL}}$ [35]. The width of the transition region as indicated in Fig. 21 is an approximation only.

Because of its correlation with the $T_e$ pedestal, $P_{\text{SOL}}$ was chosen as a “control” parameter in the empirical scaling studies, rather than $P_{\text{ICRF}}$. Global plasma controls considered were $I_P$ and $B_T$. Fueling control was represented by the L-mode target density $\bar{n}_{e,L}$, which was the main knob available for changing the H-mode fueling source, since the discharges under study were not puffed or pumped following the L-H transition. Essentially, the core $n_e$ during H-mode is a “natural” density that is well correlated with the pedestal density: $n_{e,\text{PED}} \approx 0.8 \times \bar{n}_{e,H}$. Power law functions given
by $C_0(I_P)^{\alpha_1}(\bar{n}_{e,L})^{\alpha_2}(B_T)^{\alpha_3}(P_{SOL})^{\alpha_4}$ were fit to measured pedestal parameters, using the method detailed in [11]. This choice of functional representation is mostly for convenience, and is almost certainly too simple to capture all the relevant physics setting the ETB parameters. Nonetheless, useful predictive scalings were developed for the pedestal in EDA H-modes:

\begin{align*}
    p_{e,PED} &= 9.4 \times I_P^{(1.98 \pm 0.11)} (\bar{n}_{e,L}^{-0.56 \pm 0.13}) P_{SOL}^{(0.48 \pm 0.06)} \quad (5) \\
    n_{e,PED} &= 4.6 \times I_P^{(0.95 \pm 0.06)} (\bar{n}_{e,L}^{0.39 \pm 0.06}) B_T^{(-0.46 \pm 0.14)} \quad (6) \\
    T_{e,PED} &= 83 \times I_P^{(0.95 \pm 0.10)} (\bar{n}_{e,L}^{-0.78 \pm 0.11}) B_T^{(0.80 \pm 0.19)} P_{SOL}^{(0.64 \pm 0.06)} \quad (7)
\end{align*}

Here, the respective units of $I_P$, $\bar{n}_{e,L}$, $B_T$ and $P_{SOL}$ are MA, $10^{20}$m$^{-3}$, T and MW; $T_{e,PED}$, $n_{e,PED}$ and $p_{e,PED}$ are in eV, $10^{20}$m$^{-3}$ and kPa. The goodness of these fits to the experimental data is illustrated in Fig. 22, which plots the measured values of $T_e$, $n_e$ and $p_e$ pedestals to the values obtained from Eqs. (5–7).

**V.B.1 The influence of plasma current on the pedestal**

What is immediately striking about the above scaling laws is the dominant dependence on current in each pedestal quantity. The $p_e$ pedestal trends especially strongly, having an $I_P^2$ dependence. Both $n_{e,PED}$ and $T_{e,PED}$ have a nearly linear dependence on $I_P$, evenly “sharing” the pressure scaling between them. Due to the invariance of $\Delta p_e$, the pressure gradient in the pedestal has exactly the same functional dependence as $p_{e,PED}$, and thus the leading scaling for $\nabla p$ is also $I_P^2$. Such a
dependence would be expected in a pedestal limited by ideal ballooning modes, as in Type I ELM-ing discharges on a number of other tokamaks [6] [69] [70]. However, as discussed in Sec. IV.C, EDA pedestals are computed stable to ideal high-n ballooning modes as well as to intermediate-n peeling-ballooning modes. The results indicate that it is possible to have a critical α_{MHD} in the pedestal brought on by mechanisms other than ideal MHD instabilities.

Data taken with scanning Langmuir probes in the near SOL also show a I_P^2 dependence on local pressure gradient in ohmic L-mode plasmas, which have no obvious transport barrier [97]. A minimum gradient scale length for p_e is located approximately 2 mm outside the LCFS, at which point local α_{MHD} exhibits a value dependent on the diamagnetic parameter α_d previously mentioned in Sec. III.B. The indication from these data is that the edge transport is regulated by critical-gradient phenomena near the LCFS, and the results are cited as evidence for electromagnetic fluid drift turbulence (EMFDT) setting the edge plasma state. Connections were found between these experimental results and edge simulations [86] performed within the framework of EMFDT. What connection exists between these L-mode results and the H-mode pedestal scalings is not completely determined, but one can speculate that, since the near SOL evolves into the pedestal foot in H-mode, EMFDT physics could play a role in setting the H-mode ∇p as well. That the pedestal gradient might be set largely by turbulence is reasonable, considering that electron transport is highly anomalous in the ETB.

Just as L-mode SOL data show that α_{MHD} can vary with plasma collisionality (represented in [97] by α_d), the H-mode ∇p does not hit a hard limit dictated by I_P alone. Equation (5) shows that the gradient can be increased at a given current by increasing the power flux at the LCFS or decreasing target density, actions that lead to a decrease in edge ν*. To illustrate the “softness” of the I_P-limit, pressure gradient data from a current scan at constant target density are plotted in Fig. 23 vs. P_{SOL}, and have been grouped according to I_P.

The n_{e,PED} ∝ I_P scaling is illustrated in Fig. 24, along with the weaker trend with target density (∝ n_{e,L}^{0.4}). The relation suggests a strong connection between particle confinement in the pedestal and a quantity related to current, such as edge poloidal field, or safety factor. As noted in Sec. IV.B, the particle transport associated with the QCM in EDA H-mode is generally enhanced as edge q is increased. Finally, there is a linear dependence of T_{e,PED} on I_P for a given P_{SOL}. This additional I_P dependence implies that the effect of plasma current on the T_e pedestal cannot be explained simply as a contribution of ohmic power. This could correspond to reduced thermal transport in the pedestal at higher I_P, or could simply result from the algebraic cancellation of the density and pressure pedestal scalings: T_{e,PED} ≈ p_{e,PED}/n_{e,PED} ∝ I_P.

V.B.2 Scaling with other control parameters

The weak scaling of n_{e,PED} with n_{e,L} demonstrated in Eq. (6) and Fig. 24b suggests that the available neutral source plays a role in determining H-mode plasma density. However, the dominance of the
Figure 23: Pedestal electron pressure gradient in EDA pedestals vs. $P_{\text{SOL}}$ at four distinct values of $I_P$: 0.6 (squares), 0.8 (circles), 1.0 (diamonds), and 1.2 MA (triangles). Dashed curves represent the empirical scaling law, $|\nabla p_e|_0 \propto I_P^2 P_{\text{SOL}}^{1/2}$, evaluated at the four noted values of $I_P$. From [11].

Figure 24: Pedestal $n_e$, at top (diamonds) and base (squares) of pedestal, vs.: (a) plasma current $I_P$, with fixed toroidal field, $B_T = 5.4T$ and fixed L-mode target density, $\bar{n}_{e,L} \approx 1.5 \times 10^{20}\text{m}^{-3}$; (b) $\bar{n}_{e,L}$, with fixed $B_T = 5.4T$, $I_P = 0.8\text{MA}$. Dotted line is the estimated lower limit of the ETS dynamic range. Adapted from [11].
$I_P$ scaling in determining the density pedestal indicates that neutral source variation on C-Mod does not yield substantial pedestal control. Ongoing work seeks to understand this behavior better by modeling coupled plasma and neutral transport processes in the edge pedestal, and is producing promising results [98]. While increasing the neutral source slightly increases the attained pedestal density, Eqs. (7) and (5) show that $T_{e,\text{PED}}$ and $p_{e,\text{PED}}$ both decrease with increased $\bar{n}_{e,L}$. As mentioned above, both edge temperature and pressure increase with $P_{\text{SOL}}$, while Eq. (6) shows no impact of power on the density pedestal. The $T_e$ pedestal also trends with $B_T$, while there is a corresponding inverse trend in the density pedestal, such that $p_{e,\text{PED}}$ shows no scaling with $B_T$ at all. The trends with field are unexplained at this time, though one may speculate that they are brought on by changes in the efficiency or deposition profile of ICRF power as $B_T$ is scanned, moving the ICRF resonance location over a wide range in radial coordinates.

V.C The pedestal and confinement

A strong correlation of core confinement with edge conditions has been observed on multiple machines [4] [6] [70] [99] [100]. Transport and confinement studies on C-Mod indicate a positive dependence of the core temperature gradient on edge temperature [4], indicative of a critical gradient scale length for ion temperature brought on by marginal stability to ion thermal gradient modes [2]. As discussed in [9], stiff core temperature profiles result from this marginal stability. In the absence of internal transport barriers [101], core density profiles tend to be flat, so volume-integrated core pressure, or stored energy, is found to trend almost linearly with edge pressure. The correlation of $W_P$ with $p_{e,\text{PED}}$ is shown in Fig. 25.

An implication of this result is that scaling laws for energy confinement time $\tau_E$ should be closely linked to scalings of the pressure pedestal with control parameters. In fact, a power law similar to (5) is obtained for $W_P$ [95]:

$$W_P[kJ] = 94 \times I_P^{(2.08\pm0.07)} \bar{n}_{e,L}^{(-0.43\pm0.08)} P_{\text{SOL}}^{(0.75\pm0.04)} \quad (8)$$

The confinement time $\tau_E$ can also be determined from the multi-variable regression, giving

$$\tau_E[\text{ms}] = 19 \times I_P^{(1.31\pm0.01)} \bar{n}_{e,L}^{(-0.37\pm0.09)} B_T^{(0.54\pm0.14)} P_{\text{SOL}}^{(0.09\pm0.03)} \quad (9)$$

The scatter in the power law fit to $\tau_E$ is large relative to the $W_P$ fit, and there does not seem to be a simple relationship between the expressions in (8) and (9). This is because $\tau_E = W_P/P_{\text{LOSS}}$ in steady state, where $P_{\text{LOSS}} = P_{\text{SOL}} + P_{\text{RAD}}$. Because the functional dependence of $P_{\text{RAD}}$ is not simply expressed in terms of the other parameters, and because the radiated power fraction can be considerable (up to 60% in the discharges considered, and strongly dependent on density), attempts to determine scalings of confinement time meet with less clear results than for scaling $W_P$ alone.

Furthermore, it is not entirely straightforward to compare these results to commonly used cross-machine confinement scalings, due to differing choices of fitting parameters. Power laws
Figure 25: Relation of global plasma energy $W_P$ to the electron pressure pedestal $p_{e,PED}$ in EDA H-modes. The best power law fit to the data gives $W_P \propto (p_{e,PED})^{0.88\pm0.03}$. From [11].

determined from analysis of the ITER confinement database [102] have as a dependent parameter the line averaged H-mode density $\bar{n}_{e,H}$ rather than $\bar{n}_{e,L}$, and use total power loss $P_{\text{LOSS}}$ instead of $P_{\text{SOL}}$. Because there is an almost perfect correlation between H-mode density and plasma current on C-Mod, $\bar{n}_{e,H}$ can be excluded from the fitting procedure [95], leading to the result

$$\tau_E[\text{ms}] = 70 \times I_P^{(1.66\pm0.10)} P_{\text{LOSS}}^{(-0.38\pm0.06)} \quad (10)$$

where the $B_T$ scaling has been found statistically insignificant. This can be compared to the multi-machine ELMy H-mode scaling law in [102], having proportionality

$$\tau_E \propto I_P^{(0.97)} \bar{n}_{e,H}^{(0.41)} P_{\text{LOSS}}^{(-0.63)} \quad (11)$$

Setting density proportional to current causes expressions (10) and (11) to have similar exponential dependences.

V.D Plasma triangularity variation

Whereas the preceding portion of this section was concerned with the standard C-Mod shape, there is an effect of triangularity on the pedestal, as mentioned in Sec. II.D. For fixed $B_T$ and $I_P$, the measured $n_e$ gradient is seen to relax with increasing $\delta$, with pedestal height falling and width increasing [11] [95]. A particularly dramatic increase in $\Delta n_e$ is observed when triangularity is increased dynamically during a discharge, as shown in Fig. 26. This trend is still present, though
Figure 26: Variation of $n_e$ pedestal width on the average of upper and lower triangularity ($\delta_u$, $\delta_l$) observed during shaping scans. Data from plasmas with lower single null geometry (circles) and upper single null geometry with reversed $B_T$ (squares) are included. Points shown are in the range: $5.0 < B_T[T] < 5.6$, $0.7 < I_P[MA] < 1.3$, $3 < q_{95} < 5$, $1.55 < \kappa < 1.70$. Inset shows two sample pedestal profiles at low and high $\delta_{av}$. Adapted from [11].
weaker, when triangularity is fixed for the duration of an individual discharge and varied from shot to shot [95]. As edge density falls, the $T_e$ pedestal rises, such that variation in the pressure pedestal is not large. This is illustrated in Fig. 27, which shows $n_{e,PED}$, $T_{e,PED}$ and $p_{e,PED}$ for $I_P$ near 1MA, plotted against $\delta_{av}$. In this limited data set, $p_{e,PED}$ has no systematic variation with triangularity. The data show no significant trend in the $T_e$ and $p_e$ widths with $\delta$.

Trends across a range of $I_P$ emerge if appropriate normalizations to current are introduced. The first is a significant drop in the value of $n_{e,PED}/I_P$, shown in Fig. 28a. Dividing by $I_P$ aims to remove the natural scaling determined for EDA H-modes in Sec. V.B. Likewise, the $I_P^2$ scaling in pressure gradient can be divided out, resulting in an overall downward trend in the maximum obtained $|\nabla p_e|$ as $\delta$ is increased. This result, shown in Fig. 28b, is rather interesting. It contrasts with results on other machines which show the attainable normalized pressure gradient (characterized by $\alpha_{MHD}$) increasing with stronger shaping [103] [104] [105]. In these other tokamaks, however,
pedestals were limited by Type I ELM activity, and such ELMs become less frequent at higher $\delta$ due to increased stability to high-$n$ ballooning modes. In the case of the EDA H-mode pedestal on C-Mod, which is stable to ideal MHD modes in the first place, increased triangularity seems by contrast to destabilize the QCM, inducing additional particle transport in a given discharge. This is consistent with the EDA regime being favored by higher $\delta$ [16] [61]. It should be noted, though, that the changes in the pedestal with plasma shaping could result from a mixture of physics, including both changes in QCM stability and variations in the neutral fueling as the equilibrium configuration changes.

VI CROSS-MACHINE PEDESTAL COMPARISONS

One potentially useful approach for improving understanding of pedestal physics is to apply techniques of dimensionless identity, which have traditionally been used in studies of core plasmas [106] [107], to study the physics of the pedestal region. These techniques are based on the fact that the governing equations of plasma physics can be made dimensionless by introducing three characteristic parameters (collisionality $\nu^*$, normalized plasma pressure $\beta$ and normalized gyroradius $\rho^*$) [108]. Holding these parameters fixed, along with shaping and magnetic parameters, should give invariance of plasma physics, and, in principle, matched pedestal profiles. However, the presence of sources and sinks in the edge region are not accounted for in the dimensionless formulation, and could result in deviation from matched pedestal profiles.

Experiments were carried out to study the similarity of H-mode physics on Alcator C-Mod.
Table 2: Scaling of plasma parameters required for dimensionless similarity. Typical C-Mod parameters are shown together with target DIII-D parameters [19].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>C-Mod value</th>
<th>DIII-D value</th>
<th>Size scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>0.69m</td>
<td>1.75m</td>
<td>$a^1$</td>
</tr>
<tr>
<td>a</td>
<td>0.22m</td>
<td>0.55m</td>
<td>$a^1$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>0.28</td>
<td>0.28</td>
<td>$a^0$</td>
</tr>
<tr>
<td>$B_T$</td>
<td>5.4T</td>
<td>1.7T</td>
<td>$a^{-5/4}$</td>
</tr>
<tr>
<td>$I_P$</td>
<td>1MA</td>
<td>0.8MA</td>
<td>$a^{-1/4}$</td>
</tr>
<tr>
<td>$n_{e,PED}$</td>
<td>$3 \times 10^{20}$ m$^{-3}$</td>
<td>$5\times 10^{19}$ m$^{-3}$</td>
<td>$a^{-2}$</td>
</tr>
<tr>
<td>$T_{e,PED}$</td>
<td>600eV</td>
<td>380eV</td>
<td>$a^{-1/2}$</td>
</tr>
</tbody>
</table>

and DIII-D [19], comparing plasmas with matched local edge dimensionless parameters ($\beta$, $\rho^*$, $\nu^*$, $q_{95}$) and shape ($\epsilon$, $\kappa$, $\delta$). A match was accomplished first by obtaining equilibria on DIII-D with shape parameters that matched a suitable C-Mod discharge, then adjusting $B_T$, $I_P$, $n$ and $T$ according to the size scalings listed in Table 2, such that the dimensionless transport-relevant quantities matched atop the pedestal. Upon establishing dimensionless similarity at the edge, it was seen that appropriately scaled global confinement parameters $W_P$, $\langle \beta_n \rangle$ and $\tau_E$ matched between the two machines, further illustration of the correlation of edge conditions to tokamak confinement.

A mixture of discharges with and without grassy ELMs was achieved on each machine in the course of the similarity experiment. Scatter in pedestal width measurements in DIII-D discharges were similar to those described for C-Mod in Sec. II.D, apparently due to edge fluctuations and small ELMs. Time-averaging of the profiles was thus required, and yielded profiles like those shown in Fig. 29. A high degree of similarity was demonstrated for both discharges with and without ELMs, and the profile matches indicate that pedestal width scales as $\Delta_n \propto a$. Since neutral mean free paths are expected to scale as $\sqrt{T/n} \propto a^{7/4}$, these results suggested a strong role for plasma transport physics in setting the density pedestal width, rather than characteristic neutral penetration length, as expected from simple modeling of pedestal fueling [39]. It is important to note, however, that the poloidal distribution of neutral fueling, a factor that should affect the width scaling in $\Psi$-coordinates, has not been rigorously addressed in this similarity study.

In H-modes with matched pedestals, similar edge fluctuations were observed. Discharges in DIII-D with scaled pedestal parameters similar to those of the C-Mod EDA H-mode showed a mode localized to the outer half of the pedestal, similar in character to the QCM. For example, the poloidal wave number $k_\theta$ of the mode exhibits a poloidal variation consistent with a field-aligned perturbation, as does the QCM [64], and the ratio of $k_\theta$ on C-Mod and DIII-D is approximately
equal to the machine size ratio of 2.5. The ELMy regime on either machine occurred in discharges with correspondingly higher pedestal temperatures and pressures, as expected from the C-Mod results of Sec. IV.B. Examples of these discharges are shown in Fig. 30.

Dimensionless pedestal matching of C-Mod and JET was also attempted, using the same general method [20]. In between bursts of ELMs, coherent edge fluctuations were observed, just as on the matching C-Mod discharges. However, unlike the QCM, the JET edge fluctuation did not appear to drive sufficient particle transport to keep particle inventory and recycling steady. Due to insufficient radial resolution of the edge pedestal on JET, it is not clear in this study how close a profile match was obtained. More recently, a joint experiment between C-Mod and JFT-2M [109] was conducted in order to compare edge parameters and fluctuations in EDA H-mode and the high-recycling steady (HRS) regime [110] exhibited on the latter device. A detailed discussion of this experiment can be found in [111]. Shaping parameters were well matched between the machines, with the exception of inverse aspect ratio ($\epsilon_{\text{JFT-2M}}/\epsilon_{\text{C-Mod}} \approx 0.6$). As a result of the poor match in $\epsilon$, true dimensionless identity discharges could not be obtained between the two machines. Differences in edge coherent fluctuations were found in EDA and HRS, with C-Mod measuring lower frequencies and higher mode numbers than JFT-2M. Nonetheless, EDA and HRS regimes were found to have similar access conditions in $q_{95}-\nu^*$ space, being favored by $\nu^*_{\text{PED}} \gtrsim 1$. Furthermore, in both tokamaks an attractive regime with small ELMs was obtained at moderate $\nu^*$ and higher pressure. Further
Figure 30: Pedestal $n_e$ and $T_e$, and edge $D_\alpha$ traces from dimensionlessly similar discharges in C-Mod (black) and DIII-D (gray). DIII-D data have been scaled appropriately by machine size. In either case, an early EDA-like portion of the H-mode is replaced by ELMing H-mode when $T_{e,PED}$ reaches a critical value.
cross-machine pedestal comparisons are possible and desirable, especially those that can utilize the technique of dimensionless identity, and these should be pursued in the future as the community readies for ITER.

VII ONGOING WORK

At Alcator C-Mod the study of H-mode pedestals moves forward on several fronts. Experiments are continually being developed to test models for pedestal scalings, particularly those for width. In parallel, we seek models for plasma and neutral transport that can help explain empirical edge behavior.

We are currently extending the parameter range of empirical pedestal scaling studies from 2.7 to 8.0T and from 0.4 to 2.0MA, and at the same time extending the study of pedestal scalings to the ELMy and ELM-free regimes [112]. In particular, we seek to examine the transient pedestal behavior of evolving H-modes, in the initial 50ms following an L-H transition. A systematic comparison of pedestals in normal and reversed field is also being considered. Extensive experimental mapping of the SOL phase-space is being undertaken [113], exploring the effects that changing edge flows have on SOL plasma profiles in ohmic plasmas, including ohmic H-modes. Resolving the connections between the critical gradient phenomena evident in the near SOL and empirical scalings of the H-mode pedestal is an important topic for future research.

Continued ELM studies are also of interest on C-Mod. The JFT-2M joint experiment mentioned in Sec. VI resulted in discharge shaping that favors ELMs on C-Mod. In fact, the experiment led to the discovery of an H-mode regime at high triangularity and low collisionality which exhibits larger ELMs, though not obviously of the familiar Type I variety [114]. Calculation of MHD stability of these discharges using the ELITE code is planned in the near future, in order to characterize the observed ELMs.

Modeling is being pursued to help understand the relative contributions of plasma transport and neutral fueling in determining the structure of the edge pedestal. To this end a kinetic treatment of the neutral transport is being explored. Initial efforts in this direction were shown in [115] and developed further in [95], and recent work has made progress coupling a solution of the kinetic equation for neutrals with a model for plasma transport in the pedestal [98]. This allows us to study the effect of neutral source perturbations on the density pedestal.

It is hoped that continued collaboration with other experiments and with the edge modeling community can provide further insight into pedestal transport mechanisms. C-Mod data are being added to the International Tokamak Physics Activity pedestal databases (both scalar and profile data) to enable comparison with other models, and additional inter-machine experiments are planned. By proceeding along these fronts, we hope to to sharpen our understanding of the ETB across a wide range of parameter space and allowing more certain predictions for the pedestal and global confinement on ITER.
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