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Access to pedestal pressure relevant to burning plasmas on the high magnetic field tokamak Alcator C-Mod

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Abstract

Experiments on the Alcator C-Mod tokamak have utilized reactor-relevant magnetic fields to sustain substantially higher pedestal pressure than in other devices and allow close approach to the ITER H-mode baseline target pedestal pressure of 90 kPa. The EPED model, which couples the physics of transport driven by kinetic ballooning modes and MHD instabilities arising from peeling-ballooning modes, predicts the pressure profile at the onset of edge-localized modes (ELMs), and yields to lowest order a critical-\(\beta_N\) like behavior for the pedestal: \(p \propto B_t^2 B_p^2\) (\(\propto B_t^2\) for fixed edge \(q\)). C-Mod routinely accesses edge plasma pressure in excess of 30 kPa, often by using a high-density (\(\bar{n}_e > 3 \times 10^{20} m^{-3}\)) approach to high confinement, taking advantage of a regime known as enhanced D-alpha (EDA) H-mode. In the EDA H-mode, plasma transport regulates both the pedestal profiles and the core impurity content, thus holding the pedestal stationary at just below the peeling-ballooning stability boundary. This stationary ELM-suppressed regime has approached the maximum pedestal predicted by EPED at these densities: 60 kPa. This in turn gives rise to volume-averaged core plasma pressure in excess of 0.2MPa, a world record value for a magnetic fusion device. Another approach to achieving high pressure utilizes a pedestal limited by current-driven modes at low collisionality, in which pressure increases with density and which allows access to a higher EPED solution, termed “super-H”. C-Mod experiments at reduced density (\(\bar{n}_e < 2 \times 10^{20} m^{-3}\)) and strong plasma shaping (\(\delta > 0.5\)) accessed this regime, producing pedestals with pressures up to 80kPa (approximately 90\% of the ITER target) and temperatures of nearly 2 keV. In a number of these hot H-modes, we observe strong edge instabilities at low toroidal mode number (\(n=1\)) when pedestal pressure approaches predicted values from EPED, showing that current-driven MHD modes can serve as a limit on the pedestal in a metal-walled tokamak at high pressure and low collisionality.

I. On the influence of magnetic field on plasma pressure in a tokamak

The reaction rate in a fusion plasma is well known to scale with the square of confined plasma pressure. The historic successes of magnetic fusion energy concepts, such as the tokamak, are largely thanks to the ability to support high plasma pressure using large values of magnetic pressure. Generally, limits are placed on pressure \(p\) through magnetohydrodynamics (MHD), which sets limits on the plasma normalized pressure
\[ \beta = p/(B^2/2\mu_0), \] or on beta renormalized according to Troyon: \( \beta_N = \beta \times (Ba/I_p) \) with \( \beta \) in per cent, \( I_p \) the plasma current in MA, \( B \) the field in T, and \( a \) the minor radius in m. For a given \( \beta \), one sees readily that the fusion power in a magnetic fusion device will scale as \( P_fus \propto p^2 \propto B^4 \). This was recognized in DD experiments performed on TFTR in the 1990s, and played a role in the extension of that machine’s DT operation up to toroidal field \( B_t=5.6 \)T, and the subsequent achievement of 10MW of fusion power [1, 2]. The promise of high magnetic field has over time led the fusion community to propose experiments in the range of 9—13T with the goal of making compact high fusion gain devices [3, 4, 5, 6, 7] and modest sized fusion pilot plants [8].

In contemporary tokamaks, the high-confinement mode (H-mode) provides a powerful demonstration of the impact of magnetic field strength on plasma confinement. H-modes yield higher confinement primarily through the formation of an edge transport barrier, which typically introduces a pedestal into the profiles near the last closed flux surface (LCFS). The core substantially amplifies the pedestal on which it sits, via resilient profile gradient scale lengths, set by so-called stiff transport. Simulations of core transport for D-T machines consistently show a large sensitivity of fusion gain on pedestal pressure [9]. While the physics processes setting the structure of the density and temperature in the pedestal region are manifold and potentially complex, the pressure profiles can be modeled and predicted successfully using arguments based on MHD and gradient limiting micro-instabilities, such as in the EPED model [10]. EPED, discussed below, calculates that pedestal pressure \( p_{ped} \) should generally increase with both toroidal and poloidal field, such that a given tokamak should reach a similar maximum value of normalized pedestal beta \( \beta_{N,ped} \) across a wide range of operating space. This naturally suggests that increasing \( B_T \) and \( B_p \) provides great potential for raising \( p_{ped} \), and thus overall fusion gain.

A. EPED predictions and pedestal scaling with field

EPED combines two predictive elements for the pressure profile in the plasma edge. First it adopts the ansatz that, while many mechanisms drive transport across the edge region, the pressure gradient in high power, low-to-moderate collisionality H-modes is ultimately limited by kinetic ballooning modes (KBMs). These are relatively localized modes, capable of driving both heat and particle transport, and are unstable above a critical gradient in poloidal beta. Because they are not well stabilized by strongly sheared \( ExB \) flows, they can remain a dominant instability in the steep gradient region associated with the H-mode pedestal. As a proxy for the full non-local kinetic ballooning stability calculation, EPED typically uses a criterion of unstable infinite-\( n \) ideal ballooning modes across some fraction of the pedestal width, using a functional form that takes into account non-local effects. EPED couples the KBM limit with a calculation of global peeling-balloonong mode (PBM) instabilities, which are widely shown to limit the extent and height of the pressure pedestal. These MHD limits are very robust and calculable from model or experimental equilibria.

The physics of the KBM and the PBM combine to yield a limit on the pedestal pressure, which scales approximately with the product of toroidal and poloidal field: \( p_{ped} \sim B_t \times B_p \).
This is by no means an exact equation, as the physics of the combined KBM/PBM constraint is complex, and varies significantly between primarily pressure- and current-driven PBMs, but is a good guideline for H-mode pedestals that are limited by medium-\( n \) PBMs (\( n \approx 10 \)). Pedestal pressure is expected to scale more strongly with \( B_t \) for lower-\( n \), “peeling-like” modes, and more strongly with \( B_p \) for higher-\( n \) “ballooning-like” modes. In general, raising toroidal field and/or plasma current are fundamental pathways to increasing the maximum pressure pedestal in a tokamak. Previously EPED has been tested across a wide range of \( p_{\text{ped}} \), up to values within a factor of 2—3 of the value predicted for ITER, through the inclusion of the compact high magnetic field tokamak, Alcator C-Mod \([10, 12, 13]\). Alcator C-Mod H-modes having pedestals limited by edge-localized modes (ELMs) were modeled by EPED in discharges reaching \( B_t \times B_p \sim 5 \, \text{T}^2 \), demonstrating pressure pedestals of 40kPa. The predictive capability of EPED has been successfully tested on tokamaks with lower fields as well, covering nearly two orders of magnitude in H-mode pedestal pressure \([10]\).

Strong D-like shaping of the poloidal cross section, obtained primarily by increasing the triangularity parameter of the tokamak equilibrium, creates an additional opportunity for accessing high pressure. EPED can produce multi-valued solutions over an intermediate range of density. The lower solution for pressure corresponds to the situation that is typically realized experimentally, the H-mode. However the higher pressure solutions are equally valid, and dictate a theoretically predicted range of pedestal pressure above the H-mode solution: hence the name “super H”. The prediction of the super H solutions has been validated experimentally on the DIII-D tokamak \([11, 14]\).

Extensions of super H to high magnetic field devices become particularly interesting as we attempt to optimize performance on ITER and future burning plasmas. Under ITER baseline conditions, a super H solution is obtained in EPED by increasing density, allowing \( p_{\text{ped}} \) to exceed the baseline value of 90kPa by a significant margin \([11]\). This has strong implications for confinement and fusion gain, and motivates tests of the EPED model in ITER-relevant conditions, including similar values of toroidal and poloidal field, density and collisionality.

**B. High pressure pedestal on Alcator C-Mod**

Alcator C-Mod \([15, 16, 17]\) is a compact high-field diverted tokamak that produced fusion plasmas from 1993 until 2016. While capable of attaining \( B_t \) on axis of 8T, most operation occurred near the more modest ITER baseline field of 5.3T. C-Mod also accessed \( B_p \) up to 1.3T, surpassing the maximum poloidal field of ITER: 1.2T. High poloidal field leads naturally to high intrinsic Greenwald density limit, \( n_G = I_p / \pi a^2 \) \([18]\) and high parallel heat fluxes \([19]\), so it is natural that C-Mod routinely featured plasma particle densities and power fluxes representative of ITER specifically, and burning plasma devices in general.

As noted above, pressure pedestal parameters measured on C-Mod were compared previously to EPED predictions, focusing exclusively on Type I ELMy H-mode, in which the PBM stability boundary is approached, and for which EPED is expected to be valid.
The typical magnetic equilibrium used for ELMy H-mode on C-Mod is shown for reference in Figure 1(a). Experiment and modeling showed mutual agreement, and the C-Mod contributions extended the $p_{ped}$ in the EPED database to ~40kPa, roughly a factor of 2 above the maximum from lower-field devices. Most discharges considered in that study were at $B_t$ of 3.5—5.4 T. Recently we extended the database of C-Mod contributions to EPED with additional ELMy H-modes at up to 7.8T [20].

The current article will focus on the application of predictive EPED to H-modes (including super H) without ELMs, at more typical C-Mod $B_t$ (5—6T), where the machine’s standard heating schemes are optimized, thus allowing us to take H-modes to their highest performance and probe the upper limits of pedestal pressure. Several specific discharges are discussed in this paper. Table 1 provides summary information for these discharges. These plasmas were run in majority D, and span the range 5.3—5.7T and 0.8—1.4MA. They were heated near-axis with ion cyclotron range of frequencies (ICRF) heating at 80MHz, absorbing on minority H. This results in a mix of main ion and electron heating, with zero external torque and no core particle source. We will consider separately the H-mode behavior at high density and low density. Calculations of pressure pedestal are performed with the version of the model known as EPED1, with a model for diamagnetic stabilization that was updated to account for the strong stabilization term present in the narrow C-Mod pedestal.

In discharges with no ELMs, we do not necessarily expect agreement between measured $p_{ped}$ and EPED prediction. However, it is useful in these cases to relate the pressure realized in experiment to the theoretical limits determined computationally. In addition, theoretical predictions can provide guidance to experimental design, allowing one to increase device performance, as in the case of predicting the super H operational space. In Section II we will show that in high collisionality discharges a stationary pedestal can be obtained, which avoids PBM instabilities and remains systematically below the EPED prediction. Section III will discuss the development of low collisionality H-modes with the potential for much higher pressure pedestals, limited by low-n PBMs. Section IV demonstrates that the pedestal may be limited by the onset of a low-n edge mode, then shows examples of quiescent low collisionality pedestals at increased $I_p$, which achieve pressures in excess of the standard H-mode solution from EPED, and consistent with super H access. Implications of these findings for high field tokamaks are discussed in Section V.

II. High density path to high pressure

C-Mod has typically accessed high performance H-modes via high density operation, giving rise to a naturally ELM-suppressed regime called enhanced D-alpha (EDA) H-mode [21, 22, 23]. EDA H-modes can operate close to PBM stability boundaries [13, 24], however mechanisms other than ELMs are generally responsible for regulating the pedestal. A prominent quasi-coherent mode (QCM) [25, 26] is usually evident in EDA H-mode, and appears to play a strong role in inducing continuous particle and impurity removal from the core plasma [27, 28, 29]. The existence of the QCM in the H-mode
pedestal has been linked to particular ranges in edge safety factor \( q_{95} \), pedestal collisionality \( \nu^*_{95} \), and normalized pressure gradient \( \alpha_{MHD} \) [30]. For a given \( q_{95} \), the resultant \( \nu^* \) and \( \alpha_{MHD} \) of the pedestal are largely controlled by the edge neutral fueling and the absorbed auxiliary power. This translates into a “rule of thumb” for EDA access on C-Mod: the density in the preceding L-mode should be controlled to be above \( 0.2 \times n_G \) [20]. Attempting to access L-H transitions at lower programmed density typically results in weaker QCM amplitude, and a transition to transient ELM-free H-modes with unmitigated impurity accumulation [22]. ELM-free H-modes can demonstrate very high energy confinement immediately following their formation, but without an edge relaxation mechanism to remove impurities from the core plasma, they typically transition to L-mode via a radiative collapse. Some exceptionally long-lived ELM-free H-modes have been observed and will be discussed in Section III.

Once EDA H-mode is accessed at high density, PBMs can become unstable and drive small ELMs, assuming sufficient power is supplied to the core plasma [24]. (It is noteworthy that this tends to occur above a critical \( \beta_N \) of approximately 1.3.) However, it is possible to achieve excellent pedestal and core confinement in EDA H-modes, even while remaining below the pressure limit for ELMs. Discharges with extrinsically seeded low-Z impurities have proved very effective at allowing robust ICRF heating and reduced high-Z impurity generation, allowing for significant improvements in confinement [31, 32, 33]. These improvements were tightly correlated with both power flow through the pedestal and the resultant pedestal temperature. [33] Additionally, EDA H-modes benefit from a low relative separatrix density, with \( n_{e,sep}/\bar{n}_e < 0.5 \) being necessary at fixed power flow to achieve acceptable normalized H-mode confinement \( H_{98} \sim 1 \) [33], similar to a broader set of observations in ELMy H-modes [34]. These prior observations point to the need for improved models for pedestal structure that separately account for the thermal and particle transport channels. While EPED currently is not designed to do this, it is worthwhile to compare the model’s predictions for pressure with those realized in experiment, as shown below.

A. Developing high power, high density discharges at high \( I_p \).

The EDA H-modes studied in [33] had \( B_t=5.4 \)T and \( I_p=0.9 \)MA. Further extension of performance in these discharges could be expected by increasing one or both of these parameters, in part due to their leverage on the maximum attainable pedestal pressure. However, because of the EDA access conditions outlined above, significant increases in \( I_p \) required concurrent increases in density, which has implications for both ICRF coupling and pedestal performance.

Several experiments on C-Mod sought to take advantage of the EDA H-mode to study pedestal formation and behavior with large plasma densities, in which the penetration of neutral D into the pedestal is reduced, and in which ionization sources are weak inside the LCFS. The technique for maximizing density involved a combination of large auxiliary power and low-Z seeding in order to keep plasma confinement high (\( H_{98} \sim 1 \)), increased current to allow high absolute density at modest Greenwald fraction \( (\bar{f}_G=n/n_G<0.7) \), and supplemental fueling supplied preferentially from the high field side of the tokamak.
Figure 1(b) shows a poloidal section of C-Mod with a typical equilibrium from these EDA H-mode experiments. The discharges were close to double null, though with one primary X-point and strike points on the vertical plate divertor. Field direction was oriented such that $B \times \nabla B$ was directed toward the lower divertor and the active X-point. Figure 2 provides an overlay of three example discharges, each of which accesses the stationary EDA regime in a shot-to-shot current scan ($I_p$ of 1.0, 1.3 and 1.4MA). In each case, the H-mode is sustained with 3.5—4.5MW of auxiliary heating, and the pedestal exhibits the continuous QCM, rather than ELMs. Parameters of these three H-modes are summarized in the first three columns of Table 1.

The high density H-modes that resulted demonstrated pressure pedestals in excess of 30kPa, which increased substantially with $I_p$. Figure 3 shows examples of edge density and temperature profiles measured in a shot-to-shot current scan in EDA H-mode ($I_p$ of 1.0, 1.3 and 1.4MA). The smooth curves represent fits to the data of a modified hyperbolic tangent function, which will serve as the standard technique for extracting pedestal heights (e.g. $n_{e,ped}$, $T_{e,ped}$, $p_{ped}$) in this article. As was seen in prior EDA H-mode explorations [30, 35], $I_p$ is a robust controller of the pedestal electron density $n_{e,ped}$. Higher electron temperature pedestal $T_{e,ped}$ is also facilitated by increased $I_p$, but as in [30, 33] additional variability is introduced by changes in the amount of power flowing through the pedestal $P_{net}$. In a stationary plasma $P_{net}$ is given by the difference between the heating power and the core radiated power $P_{heat} - P_{rad,core}$.

**B. Comparisons of EDA pedestal with EPED**

Figure 4 shows profiles of total pressure fitted from experimental data in the current scan described above. Ion temperature ($T_i$) measurements are not available for these discharges, but prior experimental investigations have shown equivalent pedestal $T_i$ and $T_e$ across a range of pedestal $\nu^*$ values [36, 37, 38]. Whereas in/out asymmetries are deduced for the impurity temperature pedestal [38], the main ion temperature profile is expected to exhibit less variation [37]. Here and later in this article we therefore assume $T_i=T_e$, where $T_e$ is measured by Thomson scattering (TS) and by electron cyclotron emission (ECE), when available. We estimate ion dilution fraction $f=n_i/n_e$ using available measurements of effective charge $Z_{eff}$, and an assumed mix of boron and heavier impurities, resulting in an average impurity charge $Z_f=10—15$. The total pressure is then assumed to be $p_{tot} = n_eT_e + n_iT_i = n_e(1+f)T_e$. Pressure from non-thermal minority H, induced by ICRF heating, is expected to be negligible in the pedestal region.

EPED simulations of the pedestal height and width are indicated by the open symbols in Figure 4. The EPED prediction of pressure pedestal increases with $I_p$, although more weakly than would be expected in a pure $I_p$ scan. Because other quantities in these three discharges are changing, the EPED predictions should not be interpreted as a pure current scan. Rather, they are included in order to test the proximity of the experimental measurements to theoretical pressure limits. The overlay shows that the experimental values of both height and width are systematically below the model prediction. A $p_{ped}$ well below the predicted value is unsurprising if mechanisms other than PBM instabilities were limiting the pedestal. This is completely consistent with the ELM-suppressed
character of the EDA H-mode. The closest approach of experiment to EPED prediction occurs in a high stored energy discharge at 5.7T, 1.4MA. Both the EPED prediction and the experimental data give a pedestal pressure of approximately 60kPa, significantly above the maximum values previously obtained on C-Mod in ELMy H-mode [13]. We note that diamagnetic stabilization of PBMs is an important consideration in EDA H-mode, due to the sharp profile scale lengths in the pedestal region. The EPED calculations for these EDA H-modes were performed using a weak assumption for diamagnetic stabilization. If the diamagnetic effect on the stability of PBMs were assumed to be stronger, then the predicted $p_{ped}$ in these three cases could be significantly larger.

The high pedestals realized in this EDA H-mode scan led to some of the highest values of stored energy realized over the entire operation of Alcator C-Mod. Using the stored energy $W_p$ and plasma volume $V$ computed from EFIT equilibrium reconstructions, we can derive a volume-averaged pressure $<p>=2/3 W_p/V$ for any given C-Mod discharge. Figure 5 plots the maximum value of $<p>$ realized in this set of EDA H-modes against the product $B_t x I_P$, the operational metric used to attempt increases in pedestal and core performance. We find that the successful discharges in this experiment all have maximum $<p>$ values falling within the upper 10% of all C-Mod discharges. The uppermost data point on the graph corresponds to the blue profile in Figure 4, having $p_{ped}=60kPa$. This exceptional pressure pedestal allows the core plasma to attain a central pressure of 0.45MPa, with a resulting volume-averaged pressure of 0.21MPa. We assert that this is the highest value of $<p>$ ever observed in a magnetic confinement fusion device.

III. Higher pressures possible at lower density

In the EDA H-modes discussed in Section II, pedestal collisionality is in the range of $1<\nu^*_g<4$, and the pedestal tends to exist near a region of PBM stability space in which the ultimate pedestal limit is dictated by medium to high-$n$ modes. However, at lower pedestal $\nu^*$, and with moderately strong shaping of equilibria, improved global stability properties are found when high-$n$ PBM growth rates are reduced relative to low-$n$ modes. Significant gains in $p_{ped}$ can result from this shift to reduced collisionality. Calculations for ITER suggest that its pedestal could exist in this more favorable stability regime, and project a $p_{ped}$ of 90kPa using standard assumptions about pedestal density and $Z_{eff}$ and perhaps higher values, subject to assumptions on pedestal density and impurity content [11]. EPED predictions for C-Mod can also be used to seek higher performance at low collisionality. We begin with an ELMy H-mode case, which reveals the potential for C-Mod to access a region of low-$n$ PB instability.

Type I ELMy H-modes are not readily accessed on C-Mod, and typically are explored using an equilibrium with deliberately weakened shaping, i.e. elongation $\kappa<1.6$ and upper triangularity $\delta_u<0.3$. [12, 13, 39]. Figure 1(a) shows an example of this plasma shape. This low shaping is compatible with EDA H-mode, if the pedestal is sufficiently collisional [40]. However, when combined with a low-collisionality pedestal, the weakly shaped equilibrium favors destabilization of peeling-ballooning modes, with fairly
modest application of auxiliary power. The EPED $p_{ped}$ solutions for such a case are shown in Figure 6, along with the experimental point in green. This plot, and others to follow, will use $n_{e,ped} Z_{eff}^{1/2}$ for the x-axis, since this is a useful metric determining the magnitude of the pedestal bootstrap current. High values of $n_{e,ped} Z_{eff}^{1/2}$ will lead to reduced pedestal current, and to PBM instabilities at high $n$ that are dominated by pressure drive. Low values of this metric lead to enhanced pedestal current, and to PBM instabilities at low $n$, dominated by peeling terms. The black curve in Figure 6 represents EPED solutions governed by high-$n$ ballooning-like instabilities. The maximum achievable $p_{ped}$ decreases as density and/or $Z_{eff}$ increases. Therefore one cannot arbitrarily obtain higher pressure by supplying greater fueling and power. Increased shaping and higher toroidal and poloidal field provide the only clear path to increasing $p_{ped}$ at high $n^*$. This was the approach successfully demonstrated in Section II, in EDA H-mode.

The experimental point indicated in green in Figure 6 is typical of ELMy H-modes on C-Mod, in that the pedestal is limited by higher-$n$ modes [13]. According to EPED, if sufficient reductions in H-mode density could be achieved, the pedestal would exist in a region of low $n^*$ pedestal operation, with dominant low-$n$ instabilities, as indicated by the blue curve. In this regime, increases in density and/or $Z_{eff}$ will actually increase $p_{ped}$. Then it would be possible to increase density at nearly constant $T_{ped}$. As density increases from this point, EPED also predicts access to a stable region well above the conventional H-mode solution, between the two red contours. This is the region dubbed super H and recently explored on DIII-D [11, 14]. Prediction of these high pressure solutions motivated considerable thought about how such a reduction in density could be realized.

A. Challenges in accessing L-H at low density

Several challenges hinder the formation of H-modes at low density. First, there is the existence of the low-density branch for H-mode access [41, 42, 43, 44], in which input power required for an L-H transition, $P_{th}$, increases dramatically. Almost all tokamaks that have studied H-mode power thresholds have observed this phenomenon at the low end of their operating density ranges and have reported optimum densities, above which $P_{th}$ increases with density, consistent with multi-machine scaling laws [45], and below which $P_{th}$ decreases with increasing density. The optimum L-mode density for accessing H-mode is approximately $1 \times 10^{20} \text{m}^{-3}$ on C-Mod [42]. Obtaining H-modes at similar density requires even lower L-mode target densities, substantially increasing power demands.

Tokamaks with high-Z walls face a second challenge when accessing low density H-modes. Higher temperatures at PFCs increase impurity sources, and divertor compression is insufficient to control impurity contamination in the core plasma. This reduces the net power flowing through the pedestal region, which generally leads to marginally reduced pedestal conditions. Reduced pedestal quality can in turn lead to weaker ELMs or other edge relaxation mechanisms, compounding the problem of impurity removal. The edge relaxation and impurity pump-out happen naturally at high density on C-Mod, via the QCM onset. ELMs serve the role of impurity control in weakly shaped discharges [13], but have not been accessed robustly in more strongly shaped discharges with good energy
confinement properties. As a result, attempts on C-Mod to access low collisionality H-modes in ITER-like shapes have historically resulted in highly radiative, transient H-modes, which degrade in confinement well before reaching intrinsic limits to $p_{\text{ped}}$.

**B. A favorable I-H transition discovered**

A fortuitous discovery of a long-lived high confinement H-mode at low density provided an opportunity to mitigate the above challenges. This H-mode arises through a transition from the I-mode confinement regime [36, 46, 47]. I-mode is a distinct confinement regime with energy confinement comparable to H-mode and particle transport characteristic of L-mode. Typically I-mode is associated with a single null divertor configuration with $B \times \nabla B$ directed away from the active X-point [46], while H-mode access is facilitated with $B \times \nabla B$ directed toward the X-point [48, 49]. For discharges operated in nearly double null magnetic equilibrium [47], I-H transitions are readily obtained. The transition can even be sought at a desired time, using a programmed scan in the magnetic balance.

The technique for initiating the desired I-H transition utilizes a near double null equilibrium like that shown in Figure 1(c). A low density I-mode plasma is triggered using ample RF heating and with $B \times \nabla B$ directed away from the active X-point. This magnetic configuration maximizes the H-mode power threshold, and allows for high confinement I-mode. Upon reducing the separation between the primary and secondary separatrices, the plasma moves to a near double null configuration with two active X-points, and closer to the magnetic balance associated with easier H-mode access. The subsequent H-mode pedestal arises from an I-mode with high $T_{\text{ped}}$ and low $n_e$, and as a result the H-mode can initiate at very low $v^*$. Pedestal electron temperatures $T_e$ exceeding 1.5keV are routinely observed following this I-H transition, and the pedestal densities are among the lowest ever observed on C-Mod, as low as $0.7 \times 10^{20}$ m$^{-3}$. H-modes triggered in this manner, following I-H transitions, can be relatively long-lived when compared to ELM-free H-modes made at similar density and in single null configuration, although repeatability was below that of EDA H-modes. Since particle and impurity accumulation in the low $v^*$ H-modes is largely unregulated by ELMs or other fluctuations, efforts were made to run these discharges with a recent boronization, thus reducing high-Z sources. Extrinsic seeding of N$_2$ was also applied in many examples.

Figure 7 contrasts the pedestal parameters in one such low $v^*$ H-mode with those of an EDA H-mode. Both discharges have $B_t=5.4T$, $I_p=0.8MA$ and $P_{\text{aux}}=2.5MW$, and they have closely matched equilibrium shapes. The $T_e$ and $n_e$ at the 90% flux surface is indicated in Figure 7, sampled from the initial 200ms of the two representative H-modes. The hot H-modes can maintain their pedestals without impurity collapse, meeting or exceeding the pedestal pressures obtained in the high density regime. Discharge 116089014 in Figure 7 is summarized further in Table 1. The normalized performance of this discharge is remarkable: $\beta_N \sim 1.6$, and normalized confinement $H_{98} \sim 1.8$. H-modes of this type were typically 0.15—0.2s in duration (a few confinement times), and generally were terminated in one of two ways: pedestal collapse correlated with a low-$n$ MHD instability in the pedestal (discussed in Section IV) or via enhanced radiation, with impurity
dynamics familiar from ELM-free H-mode operation. Why some of the I-H transitions featured suppressed impurity build-up relative to ELM-free H-modes is not known. In H-mode with strong edge turbulence suppression, the expectation is that impurity transport in the pedestal would be dominated by neoclassical transport, and comparisons between experiment and theory have largely supported this [50, 51] Historically, observations have shown the self-organized pedestal density and temperature profiles result in strong inward neoclassical impurity flux, leading a need for some particle regulation mechanism. In the standard paradigm [52], ion density gradients lead to inward impurity convection while ion temperature gradients result in outward convection. Recent scoping work for ITER [53] suggests that the standard experimental observation of net inward directed impurity flux in H-modes need not always be the case, provided high temperature pedestals can be maintained along with high separatrix densities. Dedicated experiments are under analysis to determine if the low-collisionality H-modes described here transiently accessed this regime, mitigating early intrinsic high-Z impurity contamination by establishing strong ion temperature gradients in the I-mode prior to the H-mode transition [54].

These high $T_{\text{ped}}$ H-modes provided a new opportunity to test EPED predictions at low collisionality in a high field device. EPED model simulations suggested the pedestal exists near the peeling-limited region of operating space, where pressure can increase with increasing density. This would make for a promising starting point for exploring the super H channel, since it would require only density increases, and not reductions, while in H-mode, and could be done with standard equilibrium shapes.

**IV. Exploring the low collisionality pedestal with modeling guidance**

**A. Experimental evidence of hot pedestals limited by peeling mode instabilities**

The low-collisionality high pressure pedestal discussed in Section III appeared from EPED modeling to be susceptible to instabilities from low-$n$ current driven PBMs. We sought experimental confirmation of this in one set of 5.4T, 0.8MA discharges by deliberately weakening the shaping of the equilibrium. Figure 8 demonstrates the method through time traces of key plasma parameters in the H-mode, which is entered by an I-H transition triggered via magnetic balance shift as explained above. This H-mode is therefore in a nearly double null configuration with $B \times \nabla B$ directed toward the upper divertor. Figure 8(a—d) shows that with relatively steady ICRF input power, the H-mode exhibits steadily increasing line-averaged density, $T_e$ just inside the pedestal region, and core pressure. The discharge is quite similar to the low-collisionality H-mode discussed in Figure 7, but with a significant difference. We weakened the equilibrium shape through a programmed decrease in lower triangularity, as shown in Figure 8(e). As the plasma triangularity is reduced, peeling-balloonning instabilities should become increasingly unstable, leading to an operational pedestal limit.

The H-mode is fairly quiescent for most of its duration, with no strong fluctuations measured by instruments observing the pedestal region. However, at t=0.79s, we observe
the onset of a substantial fluctuation near 10kHz in frequency, which can be localized to the pedestal region using soft X-ray and O-mode reflectometry measurements. Figure 9(a,b) shows these signatures in spectrograms calculated over the same time window used in Figure 8. Figure 9(c) shows that the mode can also be observed using fast magnetics. The high pedestal H-mode persists for 30ms following the onset of this mode, possibly with a reduction in the rate of rise of density and temperature. Figure 8(f) shows that radiated power continues to rise at the same rate after 0.79s, and does not exceed the heating power. Coherent edge fluctuations persist until nearly the end of the collapse of the highest confinement phase of the discharge, at t=0.82s when the temperature pedestal is seen to drop abruptly. This sequence of observations suggests that the pedestal collapse originates from an MHD event, originating in the pedestal region, and not from a sudden reduction in net power.

Localization of the fluctuations with reflectometry and soft X-rays indicates the density fluctuation is strongly peaked in the pedestal region, and mode analysis of magnetics indicates a dominant $n=1$ component. These experimental signatures suggest the destabilization of a low-$n$ peeling mode leading to a continuous fluctuation, rather than a rapidly growing ELM. Similar low-$n$ modes have been observed in QH-modes on DIII-D, usually manifested as edge harmonic oscillations [55]. QH-modes with EHO activity have not previously been reported on a tokamak with metal walls, and with zero external torque.

Figure 10 shows the calculated $p_{ped}$ from EPED simulations, starting from inputs taken at the time of maximum $p_{ped}$ in this discharge, $t=0.79s$, also corresponding to the onset of $n=1$ fluctuations. Qualitatively the EPED contours resemble those in Figure 6, which was based on ELMy H-mode. However, we see access to higher pressures at low collisionality (blue), which we attribute to the improved shaping of the discharge relative to the ELMy H-mode case. The super H channel is predicted to be accessible at higher density and pressure (red). Experimental measurements of pedestal parameters are plotted for various times during the H-mode phase. The pedestal is not obviously constrained in the early part of the H-mode, and therefore the points generally trend upward in pressure with time, until the final point, taken at peak $p_{ped}$. At the time of the $n=1$ mode onset, $t=0.79$, the experimental point closely approaches the EPED calculation of pressure, based on inputs taken from the same time in the discharge. We have not calculated $p_{ped}$ solutions for times prior to $t=0.79$, although we anticipate the curves would be qualitatively similar. This comparison of experiment with model predictions further supports the conclusion that this pedestal reached a low-$n$ PBM limit, and therefore the maximum $p_{ped}$ it could attain at its given operational parameters. The ramp-down in triangularity that was introduced is likely essential to inducing this limitation on pedestal growth, since the companion shot with uniformly high triangularity was not limited by edge MHD, and reached higher pedestal pressure (compare discharges 1160809014 and 1160922020 in Table 1).

B. Access to super H mode
EPED predictions of even higher pressure at increased plasma current encouraged further experimental exploration of the peeling-limited pedestal on C-Mod, with increases in poloidal field. The technique of accessing low density H-mode from an I-H transition proved robust even at higher $I_p$, although there was increased impurity accumulation and higher $Z_{eff}$ realized in the higher current, low collisionality experiments. Previous experimental studies have indicated correlations of impurity confinement times with $I_p$ in C-Mod high confinement regimes [56]. Increased wall sources could also be playing a role in the latest experiments. Despite the higher impurity levels, operation in the peeling-limited range was possible, allowing the pressure pedestal to exceed substantially the values that would be realized in the ballooning-limited range. In order to facilitate the highest possible $p_{ped}$, triangularity ramp-downs were eliminated, thereby enhancing PBM stability. Steady auxiliary power at the maximum available level of 4MW was applied. The resulting discharges do not exhibit obvious signs of edge MHD and have no ELMs; rather, their collapse out of high confinement is more likely related to a rising core radiated power fraction.

The last two columns in Table 1 summarize two of these discharges with increased $I_p$, and in which the triangularity is held constant at a high value, and Figure 11 plots the pedestal data. Figure 11(a) shows the result from a 1.0MA case, and Fig. 11(b) shows a 1.4MA case. Also plotted are curves representing the EPED solutions, again based on inputs taken from the times of maximum pressure: $t=0.93\text{s}$ for the 1,0MA case and $t=0.90\text{s}$ for the 1.4MA case. We found that a modest increase in plasma current, from 0.8 to 1.0MA, allowed extension of pedestal pressure to approximately 70kPa. Figure 11(a) shows that this measurement is consistent with values allowed theoretically, based on EPED calculations for the time in the H-mode with maximum pedestal performance. The experimental endpoint of this H-mode is consistent with operation near calculated super H solutions (red).

In Figure 11(b) we see the companion results from a 5.7T, 1.4MA low collisionality H-mode, the final point in our scan of $I_p$ (from the second to last plasma shot attempted on Alcator C-Mod). The discharge realizes a $p_{ped}$ value of approximately 80kPa, which is significantly higher than the conventional H-mode EPED solution (black), and which is consistent, within error bars, with operating near one of the higher solutions (red), calculated at the time of maximum pressure. It is also the highest pressure pedestal ever observed in a magnetic fusion device.

V. Discussion

The above results demonstrate two distinct paths to increasing the pedestal pressure, and thus the overall performance of the Alcator C-Mod device. The conventional path for the C-Mod program, involving high density EDA H-modes, relies on a pedestal that generally avoids PBM instabilities, and is regulated by intrinsic plasma transport and the benign QCM. As seen above, this path achieved a record volume-averaged pressure, in a stationary ELM-suppressed state. Lower density H-modes with low pedestal collisionality represent a second path for extending performance. This path has allowed the realization of higher $p_{ped}$, at least transiently. In the low $\nu^*$ regime, we have not
obtained a stationary H-mode, presumably because either there is insufficient transport to flush out main ion and impurity particles or the perturbation caused by the low-\(n\) mode is too severe. Repetitive Type I ELMs also have not been observed in ITER-like shapes (though the \(n=1\) event shown in Figure 9 is in some respects similar to an EHO or Type I ELM). Very weakly shaped equilibria can give rise to Type I ELMs, as seen in prior work [12, 13, 39].

When accessing H-mode in both the high and low density cases (i.e. L-H and I-H), the diagnosed pedestal has never exceeded EPED predictions. In cases where the EPED prediction for \(p_{\text{ped}}\) is reached at low \(v^*\), we sometimes observe MHD activity consistent with a low-\(n\) PBM instability. These results demonstrate a powerful capability of EPED; it can predict the maximum pressure pedestal attainable in a high performance tokamak pedestal, across a wide range of density. A major step forward has been the application of the model to discharges at and beyond the ITER value of magnetic field, which are unique to C-Mod. While other work [12, 20] performed this validation on ELMy H-modes at relatively weak plasma shaping and modest confinement, the present comparison has successfully explored ITER-like shapes, and greatly expanded the range in poloidal field.

Comparing the maximum pressure obtained in a given discharge to the EPED prediction allows the extension of the EPED data set to 80kPA, or 90% of the value EPED predicts for the ITER baseline scenario. It is no accident that the discharge in which this \(p_{\text{ped}}\) was obtained had a product of \(B_t \times B_p = 5.4T^2\), compared to the ITER value of \(~6T^2\). Because C-Mod and ITER have very similar equilibrium shaping and aspect ratio, they are expected to have a similar characteristic value of pedestal \(\beta_N\). Figure 12 compares a number of pedestal measurements to EPED predictions, both from the present work and from prior model validation exercises in ELMy H-mode [13]. The four C-Mod cases at highest pressure have no ELMs, and include (1) the 1.4MA EDA H-mode having the highest volume-averaged pressure, discussed in Section II, (2) the low-collisionality H-mode having an \(n=1\) edge mode discussed in Section IV.A, and (3) the discharges that access the super H regime discussed in Section IV.B. The level of agreement between experimental and predicted pressure for these cases is similar to that of previous studies, i.e. within 20%. The range of \(p_{\text{ped}}\) values from other present and past devices is shown for context in the lower left corner of the plot, and the ITER baseline prediction is indicated at top right. C-Mod validation of EPED bridges a gap between ITER and the world’s other tokamaks. EPED has now been tested over a range of \(~70x\) in pressure, and its ability to project the maximum H-mode pressure across nearly 2 orders of magnitude, and on such a range of devices, is remarkable. While extended physics models are needed in order to separately predict the density and temperature pedestals in H-mode, the EPED validation effort greatly increases confidence in projections of the ITER pressure pedestal, and provides a pathway to modeling the pedestal in even higher pressure fusion devices.

As an example, take the concept for ARC [8], an affordable robust compact fusion reactor designed to serve as a pilot plant for fusion. ARC is a tokamak approximately the size of the JET device (\(R=3.3\) m), but with \(B_t=9.2T\) on axis and \(I_p=7.8\)MA, for a product
of $B_t \times B_p = 11 T^2$. A guiding design consideration for ARC was to minimize size based on the maximum toroidal field allowed by technology and engineering considerations, taking advantage of the high-field approach to sustain high pressure, and thus high fusion gain. This device, operating at a similar $\beta_{N,ped}$ as C-Mod, would have a pressure pedestal of 0.10—0.14 MPa, well in excess of ITER.

As is well known, pedestal pressure has an enormous impact on the performance of a fusion device, as shown in both experiment and modeling. The discharges at high $p_{ped}$ studied in this work exemplify this fact, since they have among the highest values of stored energy ever observed on C-Mod. The scatterplot in Figure 13 illustrates how these values of $<p>$ appear in the context of the historical C-Mod data base. The maximum $<p>$ in every C-Mod discharge is plotted against $(B_T I_p)/a$. The product of field and current is chosen in order to illustrate the strong leverage of this figure of merit in determining the total pressure in the magnetic confinement device. The normalization to minor radius (almost universally 21—22cm on C-Mod) is included to facilitate comparison to other devices of dissimilar size. These data are compared with noteworthy high performance discharges discussed in the literature: discharge 80539 from TFTR [1], discharge 87977 from DIII-D [57] and discharge 42976 from JET [58]. C-Mod routinely exceeded the $<p>$ from these discharges by operating at higher fields and at modest beta. The EDA H-mode in C-Mod discharge 1160930033, discussed in Section III, builds upon its 60kPa pedestal to achieve $<p>=0.21$MPa, the highest value of core-averaged pressure ever achieved in a magnetic fusion device, and approximately 2/3 of the ITER $<p>$.

The pedestal is the focus of the present work, but naturally core transport and stability may play additional roles in determining the overall global confinement of a given discharge. Though high pedestals clearly lead to high core pressure, varying impacts on core performance can be seen, even when discharges are produced with similar $p_{ped}$. By way of example, Figure 14 compares full profiles of the EDA H-mode having record $<p>$ with the super H attempt having record $p_{ped}$. Fits to data are shown for both $n_e$ and $T_e$, along with the consequent profiles of $p_e$ and the inferred total pressure. Both discharges are at $B_t=5.7T$, $I_p=1.4$MA, with similar equilibrium shapes. Despite having a somewhat lower pressure pedestal, the discharge with higher collisionality reaches a higher central pressure. The pressure peaking $p_0/p_{ped}$ is higher in EDA H-mode than in low collisionality H-modes, in the plasmas investigated so far. The causes for this are under examination. We expect that a full picture of the integrated pedestal and core confinement at varied densities will have to account for a number of physics elements, including auxiliary power absorption, radiation losses, and heat flux in ion vs. electron channels. Future work will examine the core plasma characteristics in these high pressure discharges.

VI. Conclusions

Pedestal research on Alcator C-Mod clearly demonstrates the benefits of high field operation on performance. Large values of $B_t$ and $B_p$ are expected from theory to enable a high pressure pedestal, due to the $\beta_N$-like constraint on $p_{ped}$. C-Mod has confirmed this at the highest values of both $B_t$ and $B_p$ ever obtained on a diverted tokamak. We have made
comparisons of C-Mod experimental pedestal pressure to EPED predictions, in a range spanning 10—80kPa. The pedestal in ELMy H-modes with poor pedestal stability was previously predicted by EPED to within 20% [13]. We have extended EPED to higher pressure pedestals in discharges without Type I ELMs, using more ITER-relevant shapes. The $p_{\text{ped}}$ values in discharges without ELMs approach, but have not exceeded the EPED simulation values, in accordance with expectations. Pedestal performance was maximized along two paths: high density and high temperature.

The first path involved maximizing the particle inventory and net power in higher-$I_P$ EDA H-modes. Based on the comparison with EPED, we conclude that the discharges at the highest pressures exist in a region of stability space close to pressure-dominated PBM instabilities. However we do not see evidence that these EDA H-modes exceed peeling-balloonning stability thresholds. The pedestal remains nearly stationary and free of ELMs for multiple confinement times, a significant achievement. The endpoint for this experiment was a 5.7T, 1.4MA H-mode with a 60kPa pressure pedestal, and core $<p>=0.21\text{MPa}$, the highest $<p>$ ever obtained in a magnetic fusion experiment.

A direct outgrowth of predictive modeling using EPED, the high temperature path takes advantage of low pedestal $v^*$ and strong shaping to operate more closely to current-dominated PBM instabilities, and to achieve higher $p_{\text{ped}}$. The low-collisionality regime at strong shaping, with high $B_t$ and $B_p$, is very similar to the conditions assumed for ITER, and for which EPED predictions have been made (see Figure 12). In this regime we performed deliberate experiments on C-Mod intended to destabilize pedestal MHD, and observed in these cases an $n=1$ pedestal-localized instability which is likely limiting the pedestal. At the time of the onset of this mode, EPED predictions for the pedestal height are in reasonable agreement with the experimental value, suggesting that the mode is indeed a manifestation of a peeling instability.

In a sequence of discharges with strong shaping and increasing $I_P$, we increased the low-$v^*$ pressure pedestal from 40 to 80kPa, and evidently began to access the region of elevated $p_{\text{ped}}$ predicted by EPED, called super H. Although pedestal-limiting MHD was not observed in these super H attempts, the pressures obtained are close to EPED predictions of super H and significantly above the conventional H-mode solution. The pressure pedestal of 80kPa is the highest $p_{\text{ped}}$ ever obtained in a magnetic fusion experiment, and is approximately 90% of the value predicted for ITER in conventional H-mode.

Taken altogether, the results from Alcator C-Mod make a clear case that favorable pedestal performance is enabled by high magnetic fields. In addition, we have vastly increased confidence in our ability to predict the limits on pedestal pressure in a tokamak. We envision that these successes will provide a foundation for exploring advanced models constructed to predict the pedestal density and temperature separately, both in current and future devices. This includes ITER, which operates at $B_t$ and $B_p$ values spanned by C-Mod, but also potentially higher-field devices which could lead to more compact net-energy fusion reactors [8].
Acknowledgments

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References


[2] Michael Bell, private communication, from records of TFTR internal discussions in 1994


Figure 1. Poloidal section of Alcator C-Mod with typical magnetic equilibria referenced in the text: (a) a Type I ELMy H-mode, (b) a high pressure EDA H-mode without ELMs, (c) a low-collisionality H-mode without ELMs
Figure 2. Time behavior of three plasmas accessing EDA H-mode at $I_p=1.0\,\text{MA}$ (black short dashes), 1.3MA (red long dashes) and 1.4MA (blue solid). (a) Plasma current, and duration of ICRF auxiliary heating. (b) Line-averaged electron density, with duration of H-modes marked (c) Volume averaged plasma pressure.
Figure 3. Electron density ($n_e$) and temperature ($T_e$) data from Thomson scattering (TS), plotted against normalized poloidal flux, in EDA H-modes with $I_p=1.0$MA (black downward triangles), 1.3MA (red diamonds) and 1.4MA (blue upward triangles). Curves are fits to the data using a modified tanh function.
Figure 4. Modified tanh fits to experimental total pressure vs. normalized poloidal flux, for the I_p scan shown in Figure 3. Circles indicate the top of the experimental pressure pedestal. The other symbols represent the location and height of the pressure pedestal top predicted by EPED in each of the three discharges.
Figure 5. Maximum value of volume-averaged pressure $<p>$ vs. the product of toroidal field and plasma current, from experimental scans designed to maximize EDA H-mode density. The uppermost data point represents a world record $<p>$, obtained on 30 September 2016, the last day that C-Mod made plasmas. The marks at right indicate the percentiles into which these pressure values fall, when considered in the context of the entire C-Mod data base of discharges.
Figure 6. EPED predictions of pedestal pressure based on perturbations around model inputs from a C-Mod ELMy H-mode at 5.4T, 0.9MA (green square). EPED solutions governed both by high-n PBMs (black) and low-n PBMs (blue) are seen to occupy different density ranges. Additional solutions at higher pressure – the super H solutions – are indicated in red.
Figure 7: Electron temperature vs. density at the 90% flux surface, for a low collisionality H-mode originating from an I-H transition (purple squares), and for an EDA H-mode originating from an L-H transition (black triangles). Solid symbols indicate data 40ms following the H-mode formation. Open symbols indicate data taken at subsequent intervals of 30ms as the H-mode evolves, out to 190ms following H-mode formation. Dotted curves represent contours of constant collisionality, with $Z_{\text{eff}}$ taken equal to 2. Dashed curves represent contours of constant electron pressure. Higher $p_e$ is realized following the I-H transition. Discharges have matched $B_T$, $I_p$, shape and auxiliary power.
Figure 8: Time traces from a high $T_{\text{ped}}$ H-mode at 5.4T, 0.8MA that was designed to reach a pedestal instability. Vertical dashed lines indicate the onset time of a $n=1$ edge fluctuation. Shown are (a) relatively steady ICRF input power, (b) steadily increasing density, (c) plasma volume averaged pressure, (d) $T_{e,90}$, (e) the programmed decrease in lower triangularity. Here the dashed line indicates the baseline level of triangularity that would have been realized without the programmed ramp-down. (f) Radiated power.
Figure 9: Spectrograms of fluctuating signals during the H-mode shown in Fig. 8, with the pedestal $T_e$ trace overlaid in red for reference: (a) soft X-rays, from a chord sampling the pedestal region. (b) O-mode reflectometry, with a reflection layer in the steep gradient region of the pedestal, (c) a Mirnov coil embedded on the LFS.
Figure 10: Experimental approach to increased density and pressure in low ν* H-mode, with programmed triangularity ramp-down. Measurements are plotted as purple squares, and contours represent EPED predictions based upon the final time point in the H-mode evolution (filled square). The blue curve represents the enhanced pressure regime enabled by strong shaping and low collisionality. The red contours represent super H solutions existing above the conventional H-mode solution. The final experimental point in the sequence coincides with the onset of the n=1 mode in the plasma edge.
Figure 11: Experimental approach to increased density and pressure in low $v^*$ H-mode, with shape held fixed. (a) 5.4T, 1.0MA H-mode arising out of I-mode. (b) 5.7T, 1.4MA H-mode arising out of I-mode. Measurements are in purple, and contours represent EPED predictions based upon the final time point in each H-mode (filled squares), using the same color scheme as in Figure 10.
Figure 12: A comparison of measured pedestal pressure height vs. EPED simulated values for discharges highlighted in this article. Single-valued EPED predictions are compared in the case of EDA H-mode 1160930033 and peeling-limited H-mode 1160922020. Triple-valued predictions, including super H bands, are shown for the highest $p_{\text{ped}}$ cases, 1160922032 and 1160930042. The dashed line represents exact agreement between EPED and experiment, and the dotted lines are +/-20% bands. ELMy H-modes compared in [13] are included for comparison (diamonds). The gray pie slice indicates the extent of the EPED database on existing devices other than C-Mod, and the nominal ITER baseline prediction is the blue open circle.
Figure 13: Maximum pressure obtained in 49,110 discharges spanning the lifetime of the C-Mod experiment (+), vs. $B_T I_p / a$, which is the effective denominator of normalized beta. All confinement regimes are included. The record pressure is denoted by the dashed horizontal line. The ITER target parameters are indicated, as well as some noteworthy high performance discharges (HPD) from the literature for TFTR [1], DIII-D [57] and JET [58].
Figure 14: Profiles of (a) \(n_e\) from TS and (b) \(T_e\) from TS and ECE for discharges with high pressure pedestal. The EDA H-mode (blue, triangles) was previously shown in Figures 3, 4. The low-collisionality super H discharge (red, squares) was illustrated in Figure 11(b). Profiles of (c) electron pressure (dashed) and total inferred pressure (solid) are also shown.
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<td>2.5</td>
</tr>
<tr>
<td>Line-averaged density $\left( 10^{20} m^{-3} \right)$</td>
<td>3.3</td>
<td>4.7</td>
<td>5.0</td>
<td>1.6</td>
<td>1.4</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Pedestal density $\left( 10^{20} m^{-3} \right)$</td>
<td>2.5</td>
<td>3.2</td>
<td>3.6</td>
<td>1.2</td>
<td>1.0</td>
<td>1.1</td>
<td>1.5</td>
</tr>
<tr>
<td>$\beta_n$</td>
<td>1.09</td>
<td>1.32</td>
<td>1.43</td>
<td>1.57</td>
<td>1.30</td>
<td>1.53</td>
<td>1.18</td>
</tr>
<tr>
<td>Pressure pedestal (kPa)</td>
<td>30</td>
<td>25</td>
<td>59</td>
<td>52</td>
<td>41</td>
<td>69</td>
<td>81</td>
</tr>
<tr>
<td>Stored energy (MJ)</td>
<td>0.15</td>
<td>0.23</td>
<td>0.29</td>
<td>0.18</td>
<td>0.14</td>
<td>0.21</td>
<td>0.23</td>
</tr>
<tr>
<td>$&lt;p&gt;$ (MPa)</td>
<td>0.11</td>
<td>0.16</td>
<td>0.21</td>
<td>0.13</td>
<td>0.11</td>
<td>0.15</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau$ (s)</td>
<td>0.034</td>
<td>0.048</td>
<td>0.054</td>
<td>0.079</td>
<td>0.057</td>
<td>0.048</td>
<td>0.054</td>
</tr>
<tr>
<td>Time after L-H transition (s)</td>
<td>0.37</td>
<td>0.17</td>
<td>0.23</td>
<td>0.19</td>
<td>0.14</td>
<td>0.20</td>
<td>0.12</td>
</tr>
<tr>
<td>$H_{tot}$</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>1.8</td>
<td>1.5</td>
<td>1.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 1: Parameters for key H-modes discussed in this article. All discharges have $R=0.67 m$, $a=0.22 m$. To assist the reader, descriptions of the H-modes are provided in the second row, and cross references to the Figures are given in the third row.