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Abstract. Mechanisms determining the structure of edge temperature and density pedestals, which are associated with edge transport barrier (ETB) formation in tokamaks, are investigated on Alcator C-Mod. Experiments suggest a strong role for critical gradient behavior in setting profile characteristics of edge plasma. The maximum pressure gradient scales as the square of plasma current in both H-modes without edge-localized modes, and in the near scrape-off layer in Ohmic discharges. In either case, the pressure gradient obtained, normalized to the square of plasma current, is a function of local collisionality, hinting that common physics may contribute to setting profile gradients in both confinement regimes. Varying the neutral fueling source has little effect on density gradient scale lengths in the ETB and a relatively weak impact on the height of the density pedestal, even during aggressive deuterium puffing. Strong screening of neutrals in the ETB are observed, creating a challenge for fueling H-modes in C-Mod beyond their "natural" density. A simple pedestal fueling model does not reproduce the typically clamped density gradients seen in experiment during H-mode puffing. These results suggest that a simple diffusive model for plasma transport is deficient, and that a critical gradient assumption for transport may be essential for pedestal modeling.

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1. Introduction

The edge plasma plays a key role in regulating the confinement properties of tokamak discharges, due to the strong sensitivity of core transport to edge boundary conditions, as suggested by both experimental and computational results [1, 2]. In particular, the high-confinement-mode (H-mode) regime [3] is the result of a strong edge transport barrier (ETB), evinced by localized regions of increased density and temperature gradients, forming a "pedestal" in the edge profiles and producing greater energy confinement than low-confinement-mode (L-mode). H-mode is the baseline operational regime for ITER [4]. However, the height of the pedestal in ITER is highly uncertain, largely because the physical mechanisms determining ETB radial widths and gradients are not understood fully.

Experiments on the Alcator C-Mod tokamak have provided insight to the underlying mechanisms through a combination of studies [5, 6, 7]. Experimental evidence suggests a strong role for plasma transport in setting the gradient scale lengths of the edge profiles under most circumstances, including both H-mode and L-mode regimes. In addition to transport, an important consideration for pedestal modeling is the role of the ionization source in determining ETB structure, since the inclusion of atomic physics removes the ability to extrapolate simply to ITER using dimensionless scalings based on plasma physics [8]. The role of neutrals in setting the density pedestal has been investigated on C-Mod through both experiment and modeling, and indications are that the fueling characteristics play a weak role, relative to plasma transport, in determining profile structure.

This paper expands on existing work, introducing H-mode profile studies in a recently extended operating space on Alcator C-Mod, and discussing potential links to edge pressure gradient behavior in L-mode. Recent experiments are described which test the effect of neutral fueling perturbations on both pedestal structure and core fueling during H-mode discharges. We find that the presence of a strong ETB inhibits core fueling, and that ETBs are generally "stiff", exhibiting invariant gradients during application of supplemental fueling. These experiments were conducted at absolute pedestal densities at or above the ITER design value, with a similar value for neutral opacity in the scrape-off-layer (SOL), and thus provide potentially useful information about plasma fueling in an ITER-relevant regime.

2. Edge pressure profile behavior in H-mode and Ohmic plasmas

Experiments on C-Mod continue to uncover evidence that critical gradient phenomena largely determine the profile characteristics of the edge plasma. Empirical scaling studies in H-modes have been used to determine the dependence of pedestal structure on plasma operational parameters, first over the typical range of operation [5], and more recently over an extended parameter space [7]. These combined studies explored a wide range of toroidal field ($2.7 < B_T[\mathrm{T}] < 8$) and plasma current ($0.4 < I_P[\mathrm{MA}] < 1.7$) and took advantage of millimeter resolution Thomson scattering (TS) profiles of electron density (n_e) and temperature (T_e) for pedestal characterization. The first main finding of these studies was that the pedestal width shows little systematic variation with operational parameters such as field, current and programmed density, remaining in the range of 2–6mm over the typical range of operational space. Increases in pedestal width beyond the typical range are observed in both low-current and strongly shaped plasmas, and are the subject of ongoing study. Second, it was seen that significant variation of the pedestal heights and gradients could be obtained by changing global operational parameters.

Predictive scaling laws were developed initially for H-mode pedestal heights and gradients, using operational parameters such as field, current, density and power as dependent variables. These scaling studies utilized the steady state enhanced D_α (EDA) [9] regime, commonly accessed on C-Mod, in which edge particle transport is regulated continuously, and discharges do not exhibit edge localized modes (ELMs). A significant result of the EDA scaling studies was that the maximum ETB pressure gradient scales as the square of plasma current ($\nabla p \propto I_P^2$), such that the normalized pressure gradient

$$\alpha_{\mathrm{MHD}} = \frac{2\mu_0 q^2 R}{B^2} \nabla p \tag{1}$$

remains roughly constant as I_P and B_T are varied. Since this scaling is obtained from discharges without ELMs, and analysis of EDA discharges without ELMs shows that the pedestal is linearly stable to coupled peeling-ballooning modes [10], this scaling does not appear to represent a limitation arising within the framework of ideal MHD.

The current-squared scaling of the pedestal pressure in EDA H-modes was also observed to be a soft limit [5], insofar as the critical α_{MHD} obtained can be increased with the addition of auxiliary heating, which increases the edge T_e. It was shown [6] that normalized edge pressure gradient increased somewhat with decreasing edge collisionality $\nu^\star$, defined as

$$\nu^\star = \frac{\nu_{\mathrm{eff}}}{\nu_b} = \frac{qR\nu_{ei}}{\epsilon^{3/2} v_{\mathrm{th},e}} \tag{2}$$

where ϵ is inverse aspect ratio and $v_{\mathrm{th},e}$ is the electron thermal speed. This was demonstrated readily for EDA H-modes, having fairly collisional edges ($\nu^\star_{\mathrm{PED}} > 1$). Recent extensions of C-Mod operating space to lower values of edge $\nu^\star$ have shown a continuation of this trend, reflected in both EDA and ELM-free H-modes. Figure 1 shows the normalized pressure gradient in the pedestal plotted against the local collisionality at the point of maximum ∇p_e. Here and throughout this paper, we assume $T_i = T_e$ over the entire pedestal region when calculating α_{MHD}. Over 800 TS data points are included, spanning the large range in current and field called out above, and preliminary identification of EDA and ELM-free points has been made on the basis of edge fluctuation data. No temporal averaging is used, which results in considerable scatter. However, the tendency for higher pressure gradient at lower collisionality is clear, providing a confirmation of the trend reported for high $\nu^\star$ in [6]. Also noteworthy is that EDA H-modes, albeit some with fairly weak levels of particle transport, are observed even at the lowest values of $\nu^\star$. For a given value of $\nu^\star$, ELM-free H-modes tend to exhibit lower values of α_{MHD} than EDA H-modes; this confirms and extends the higher collisionality results of [5].

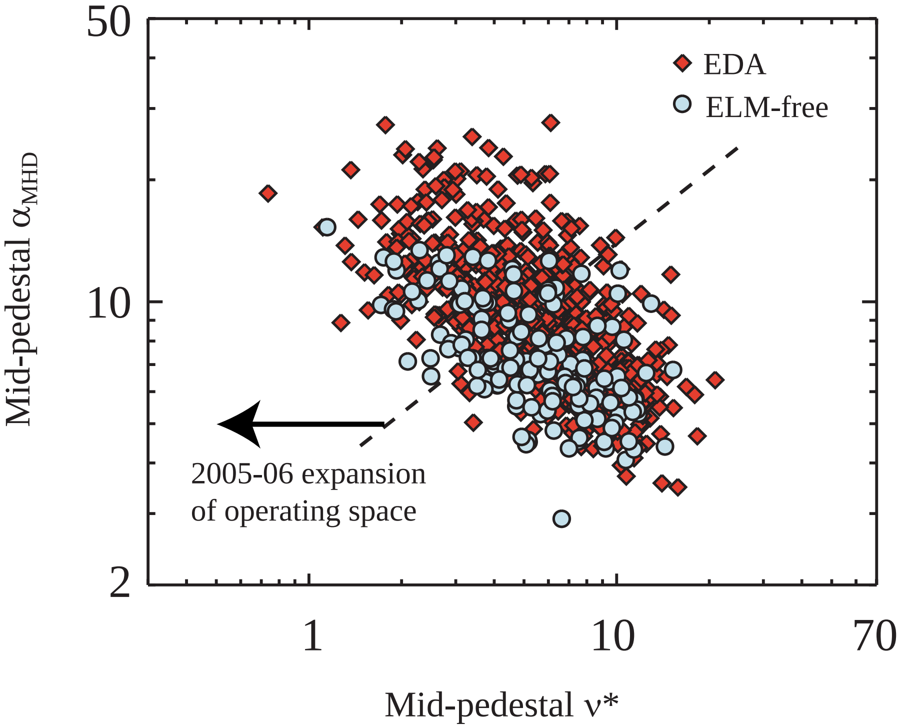

Figure 1. Normalized pressure gradient α_{MHD} *vs.* collisionality $\nu^\star$ at the midpoint of the pressure pedestal. Data are from single Thomson scattering (TS) times across a wide range of plasma operational parameters. Data taken within 40ms of the L-H transition are excluded. Below and to the right of the dashed line, the data overlap roughly with older data analyzed in the original C-Mod pedestal scaling study [5].

An extensive study of edge profiles obtained with reciprocating Langmuir probes in the near scrape-off layer (SOL) has uncovered a similar pressure gradient scaling in low-confinement-mode (L-mode) discharges [11]. The near SOL, a region of unconfined plasma within a few millimeters of the last closed flux surface (LCFS), exhibits a local minimum in gradient scale length, leading to a weak pedestal-like feature even in Ohmic discharges. This is demonstrated in Figure 2, which compares composite profiles generated using probes and TS in characteristic Ohmic L-mode and H-mode plasmas. The value of the p_e gradient in the near SOL is also seen to increase as I_P^2, for a given value of edge collisionality. Figure 3 compares these near SOL data to H-mode pedestal results, plotted in terms of dimensionless parameters determined from the theory of electromagnetic fluid drift turbulence (EMFDT) [12, 13]: α_{MHD} and α_d, where α_d is a diamagnetic parameter defined in [13]. Higher values of α_d correspond to lower values of collisionality. In the case of both Ohmic and H-mode plasmas, the edge plasma state appears restricted to a band in this dimensionless parameter space, in spite of large variation in the plasma operational parameters like current, field and density.

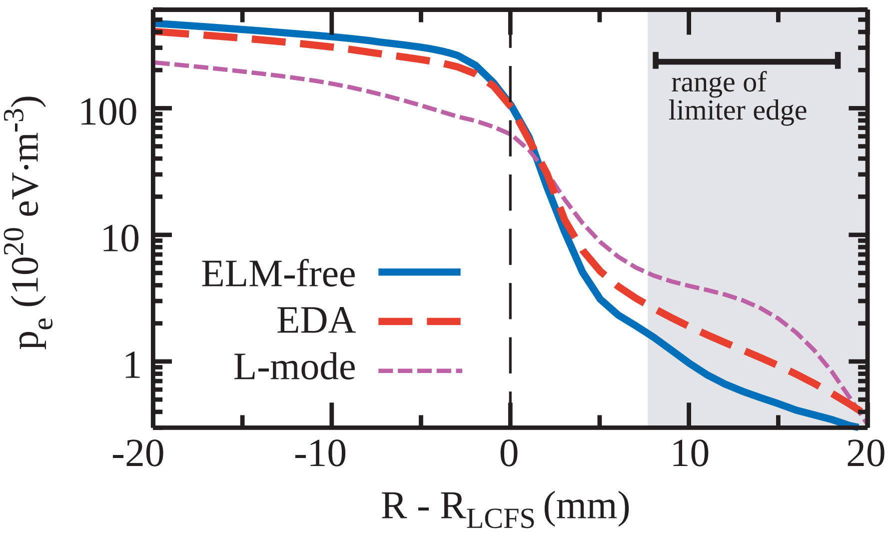

Figure 2. Composite profiles of electron pressure assembled from TS and probes in Ohmic L-mode and H-mode plasmas. A local steepening of gradient is observed in the near SOL even in L-mode.

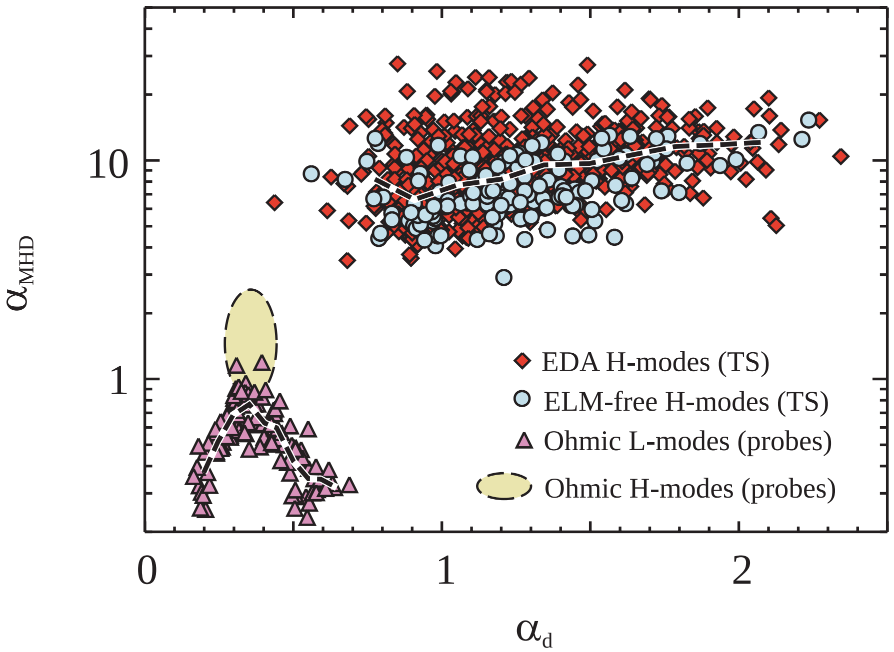

Figure 3. Near SOL (probe) and H-mode pedestal (TS) data cast into a dimensionless phase space suggested by electromagnetic fluid drift turbulence theory. SOL data are taken at the point of minimum pressure gradient scale length in the edge of Ohmic discharges with I_P ranging from 0.5 to 1.0MA. H-mode points are from the same data set shown in Figure 1. The dashed lines represent the median value of measured $\alpha_{\rm MHD}$ as a function of α_d.

The allowable states in the Ohmic case are, in fact, qualitatively consistent with first-principles numerical simulations of EMFDT [12, 13]. This result suggests that plasma transport regulates itself in a manner that yields such an allowable state, and that edge profiles achieve a critical gradient characteristic of local conditions.

For $\alpha_d > 0.4$, the edge plasma seems to occupy one of two states, the first having a relatively low pressure gradient and corresponding to a L-mode plasma, and the second exhibiting a substantially larger ∇p associated with the H-mode ETB. Further work is planned to examine the connections between edge profile scalings in L-mode and H-mode, two very different transport regimes, and also to understand the factors determining transitions between the two transport states. A promising direction for this work will be the further exploration of Ohmic H-modes, which were shown in [11] to occupy an intermediate region in phase space (diagrammed with a dashed ellipse in Figure 3). which can be simultaneously diagnosed with probes and TS. For now, existing results indicate features common to both regimes, and they demonstrate that a nearly constant α_{MHD} scaling, typically associated with ballooning limits, exists near the LCFS in pedestals without ELMs, and even without an H-mode pedestal.

3. Factors determining the H-mode density pedestal

Externally controlled plasma parameters are seen to regulate particle transport in the pedestal, consequently setting the height of the density pedestal. Scaling experiments show a robust linear dependence of electron density pedestal $n_{e,\text{PED}}$ on I_P, while inferred values of cross-field particle diffusivity are seen to decrease markedly with increasing current [6]. Typical H-mode operation on C-Mod results in a natural steady state density, which the pedestal obtains with no external puffing or pumping after the L-H transition. Fixing I_P and varying the programmed target density $\bar{n}_{e,L}$ (defined as the line-averaged density prior to the L-H transition) provides relatively weak control of the overall density pedestal, further suggesting a dominant role for plasma transport characteristics in determining pedestal structure. Experimentally, this resultant density is found to scale as $n_{e,\text{PED}} \propto \bar{n}_{e,L}^{0.4}$ at fixed I_P and B_T. As shown in [6], this density pedestal scaling is qualitatively reproduced by a simple model of pedestal response to variations in neutral source amplitude. This modeling of pedestal response to variations neutral fluxes was undertaken by coupling a kinetic model for the neutral transport [14] to a simple diffusive model for plasma transport in slab geometry.

Despite several highly simplifying assumptions, the coupled model reproduced key experimental observations [6]. First, neutral penetration through the pedestal is very small, with an effective penetration length of neutrals L_D such that $L_D < L_n < \lambda_{\text{ion}}, \lambda_{\text{cx}}$, where L_n is the gradient scale length of the density profile and λ_{ion}, λ_{cx} are simple estimates of the neutral mean free path to ionization and charge exchange. Second, as neutral and plasma density increase, the local peak in the ionization profile shifts

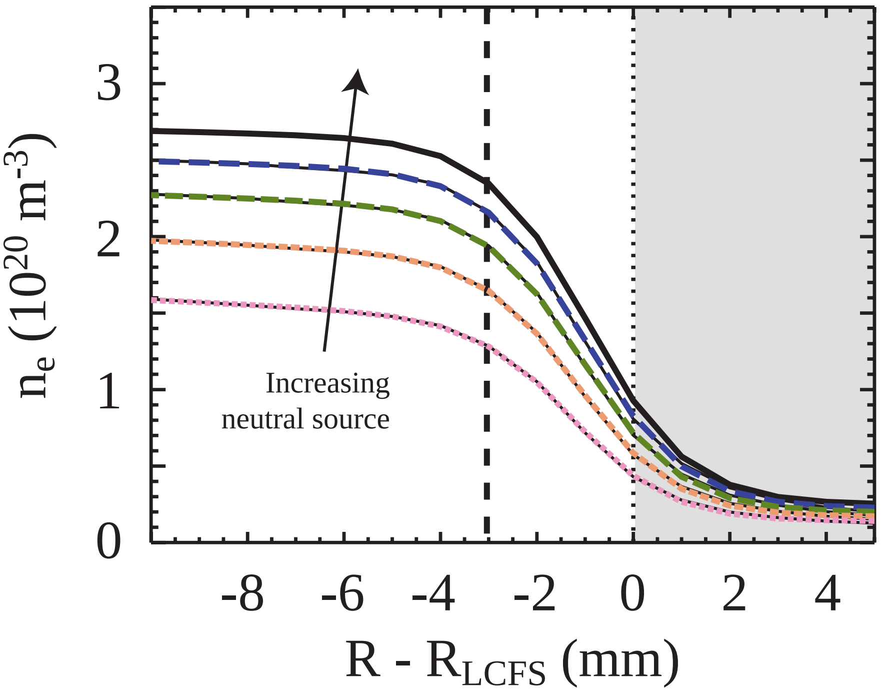

Figure 4. Modeled density pedestal response to varying neutral source, with plasma tranport assumed diffusive and fixed. Pedestal self-screening results in a largely self-similar set of profiles, which resemble experimentally measured H-mode profiles at varied L-mode target density. The thick dashed vertical line represents the approximate position of the pedestal top.

radially outward, toward the foot of the pedestal. The perturbed pedestals exhibit a degree of self-screening to the increased neutral fueling, such that L_n remains essentially fixed within the pedestal, leading to self-similar n_e profiles. An example of this density profile response is shown in Figure 4 for a modeled 1MA H-mode discharge. The roughly fixed pedestal width and the height that increases in proportion to the square root of the overall neutral source are both in good qualitative agreement with experimentally determined pedestal profile response, when target density alone is varied. The dependence of pedestal height with neutral source in these model profiles also approximates the empirical scaling of density pedestal with respect to the neutral source in L-mode.

It is expected that this modeling should only be applicable to small changes in the fueling source, since arbitrarily large perturbations are likely to change the edge state considerably and to violate the assumption of fixed plasma transport. In addition, the pedestal fueling model used here is quite simple, particularly in its treatment of geometry and plasma transport. In particular it has not yet been modified to account for alternative descriptions of plasma transport that incorporate non-diffusive terms. Based on observations of effectively clamped pressure gradients in steady H-mode pedestals, as described in Section 2 and discussed further in Section 4, it is probable that a critical-gradient model for plasma transport is a more appropriate choice than the traditional use of constant transport coefficients. Nonetheless, the modeling provides physical insight into the effects of neutral fueling changes on the density pedestal, the structure of which is regulated mainly by I_P-sensitive plasma transport.

4. Gas puffing into H-mode

The above results were based on steady state wall-fueled H-modes with no active puffing, which are typical for C-Mod operation. When, on the other hand, additional deuterium is puffed into an established H-mode discharge, it becomes possible to assess the level of screening evinced by an existing ETB. Figure 5 compares time traces from one H-mode and two Ohmic discharges, all steady state at 5.4T and 800kA, and all fueled without any external puffing prior to the time marked by the dashed vertical line. Additional D_2 is inserted through puffing capillaries starting at a predetermined time. The total amount of additional D_2 inserted is shown in Figure 5(a), and is identical for each discharge. In the Ohmic discharges, an increase in core particle inventory is observed within about 50ms, as indicated by increased TS measurements of central and edge n_e in Figures 5(d,e). The core inventory of the H-mode remains flat, however, suggesting a high level of neutral screening associated with the presence of the ETB. (The increase of H-mode line-averaged density in Figure 5(c) is due to a substantial increase in SOL density.)

Since neutral transport modeling suggests an importance of neutral screening in the C-Mod ETB [6], we sought to examine the effects of puffing on ETBs of differing strength. In order to obtain a significant variation in n_e pedestal, diverted discharges were run over a wide range of current (I_P = 0.4, 0.6, 0.8 and 1.0MA) and at fixed toroidal field ($B_T = 5.3$T). Programmed $\bar{n}_{e,L}$ was adjusted in order to maintain constant normalized density in the L-mode phases: $\bar{n}_e/n_G \approx 0.3$, where n_G is the Greenwald density limit. ICRF heating in the range of 2–2.5MW was used to trigger and sustain H-modes in these target discharges. The significant variation in I_P allowed density pedestals to be obtained over the range of 0.8–2.5$\times 10^{20}$ m^{-3}.

Supplemental edge D_2 puffs were delivered into these plasmas to examine the pedestal response and changes in core particle inventory. Generally, the increase in observed edge density has a positive dependence on the total amount of D_2 inserted and a negative dependence on the overall pedestal density. This is shown in Figure 6, which plots density and temperature values at the 95% flux surface ($n_{e,95}$, $T_{e,95}$) as a function of puff quantity in H-mode plasmas at varying currents. Figure 6 demonstrates a resilience of the density pedestal to fueling when the ETB is very strong (*e.g.*, at $I_P = 1$MA), whereas fueling with external puffing is more efficient in weak ETBs (*e.g.*,

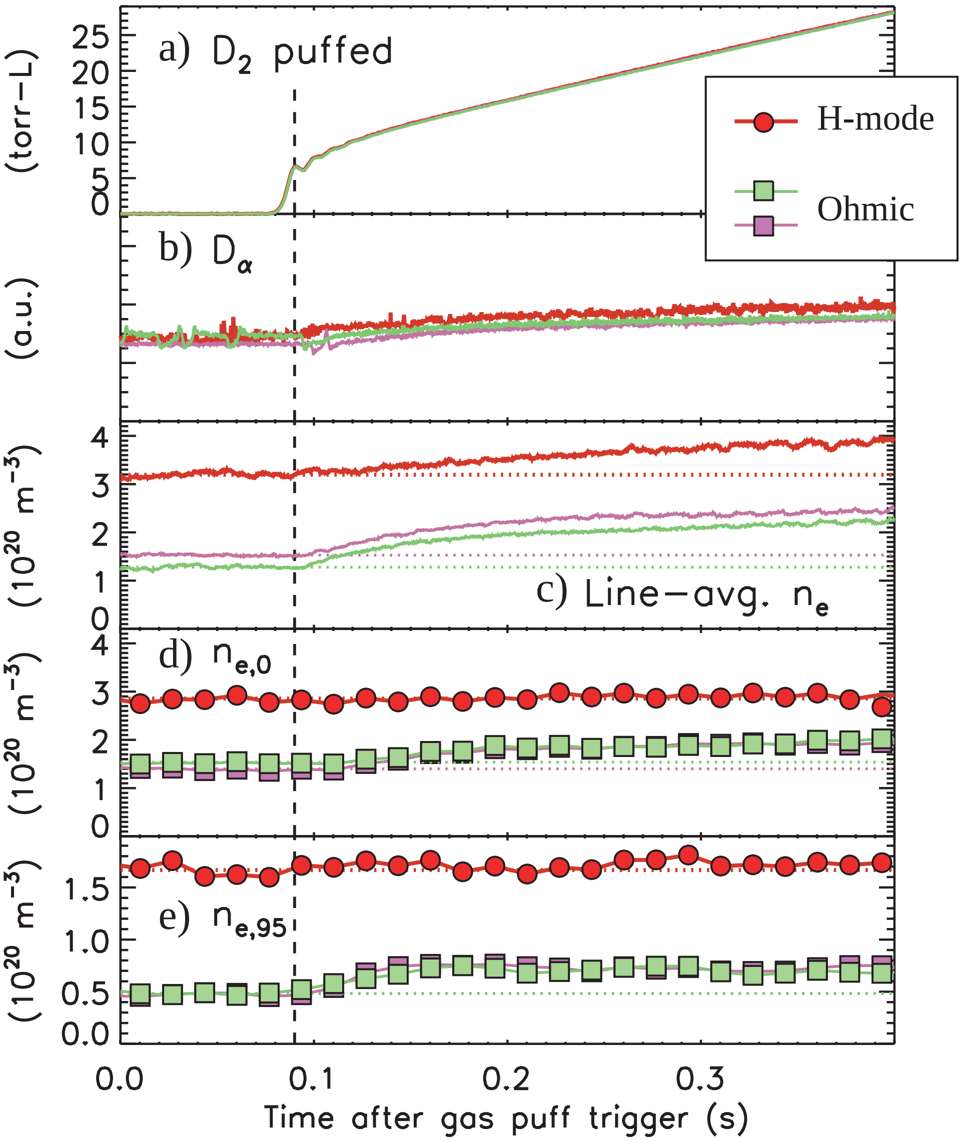

Figure 5. Examples of external gas puffing on steady state Ohmic and H-mode plasmas at 0.8MA, 5.4T. For a given amount of puffed D_2, the core plasma fuels less efficiently in H-mode than in L-mode.

at I_P = 0.4MA). By way of comparison, the overall edge density increase in puffed 400kA H-modes is comparable to that in puffed 1MA Ohmic discharges, while $n_{e,\text{PED}}$ in the puffed 1MA H-modes does not respond at all. Changes in core particle inventory generally track the edge density response, leading to poor overall core fueling in the higher-I_P discharges.

The detailed response of pedestal profiles to gas puffing changes as the plasma current is varied, as seen in Figure 7. Unlike the results of the modeling described in Section 3 and visualized in Figure 4, it is not universally the case that the density

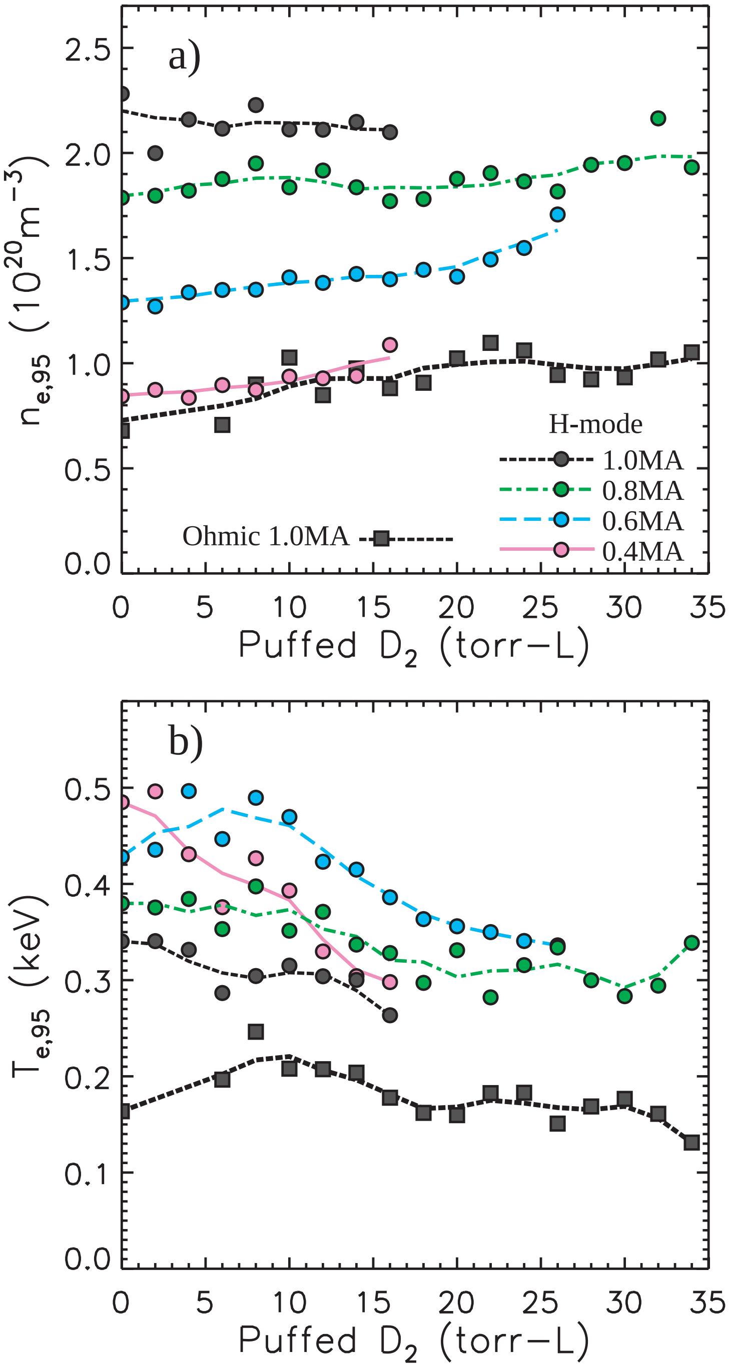

Figure 6. Effect of D_2 puffing on H-mode discharges at four distinct plasma currents and fixed toroidal field. (a) Electron density and (b) temperature at the 95% flux surface are shown vs. total puffed deuterium. Ohmic fueling at 1MA is included for comparison.

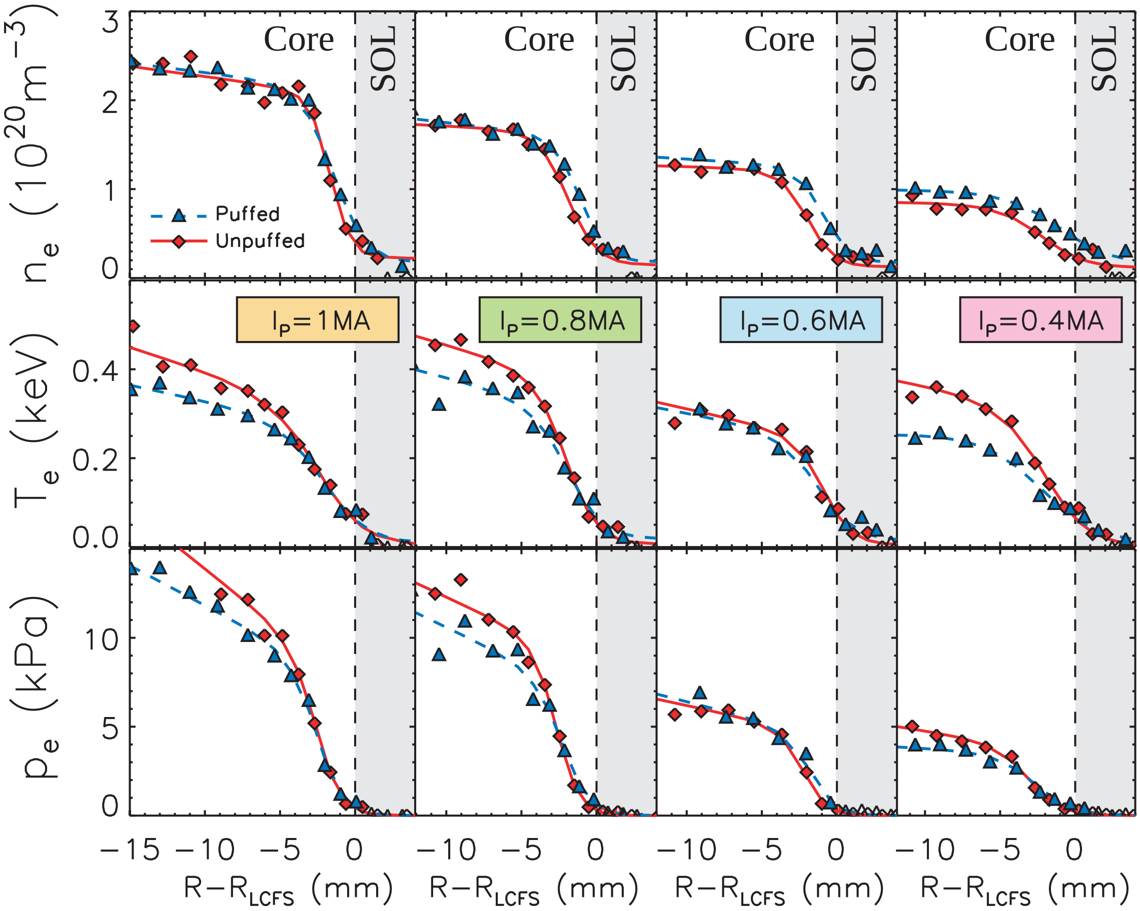

Figure 7. The effect of supplemental gas puffing on H-mode profiles of n_e, T_e, and p_e at four values of I_P with $B_T = 5.4$T. The puffed cases correspond to about 15 torr•L of supplemental fueling.

pedestal responds to a fueling perturbation. In the 1.0MA discharge, the n_e pedestal is not significantly affected, although density increases near the foot are perhaps observed, and a clear effect is seen on the T_e pedestal. Lowering I_P to 0.8MA and applying a similar amount of puffing results in an elevated density at the pedestal foot, and a constant density gradient, effectively shifting the n_e pedestal outboard of the T_e pedestal. The slight increase in the value of $n_{e,\mathrm{PED}}$ in response to increased neutral source is only observed at the discharges with relatively low I_P, which in turn have low particle confinement and a density pedestal more like that in L-mode.

The measured pedestal profiles of puffed H-modes illustrate the variation in neutral screening across a range of pedestal densities. The pedestal appears to be largely self-screening, much as suggested by the above modeling. However, for $n_{e,\mathrm{PED}}$ larger than approximately $10^{20}\mathrm{m}^{-3}$, the resilience of the density pedestal height to supplemental puffing and the consequent core screening are not reproduced by the simple model. A

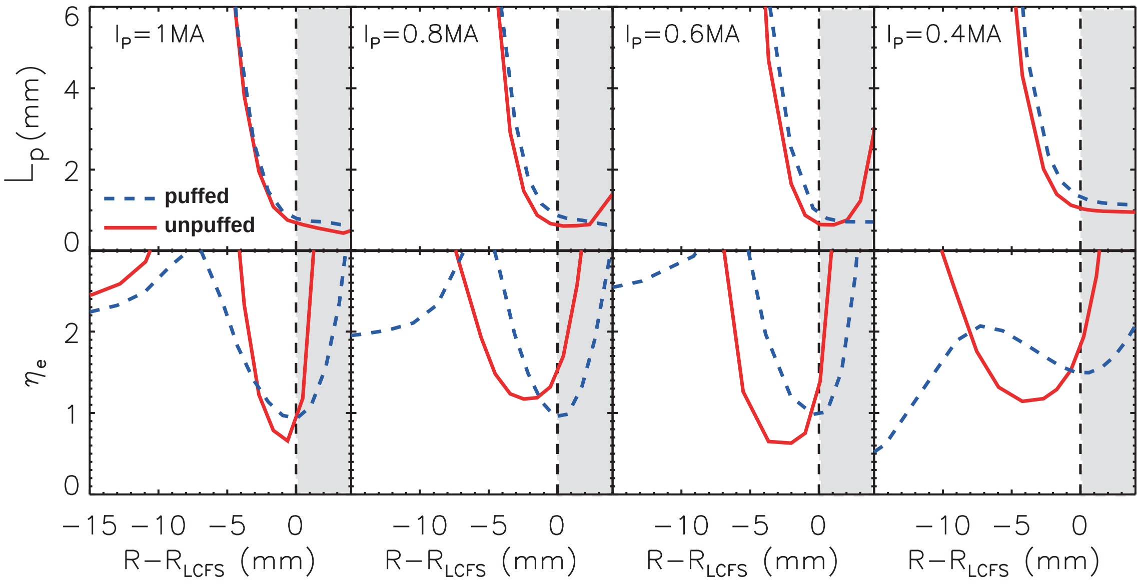

Figure 8. Pressure gradient scale length L_p and $\eta_e = L_n/L_T$ for the baseline (solid curves) and puffed (dashed) discharges shown in Figure 7. L_p is largely invariant, while η_e changes considerably.

probable explanation for this deficiency is that the pedestal profiles respond to external fueling in a way that maintains the gradient, within a narrow boundary layer, consistent with sustainable plasma states, much as is suggested in Section 2 for the near SOL of Ohmic plasmas. If plasma transport adjusts dynamically to maintain a kind of critical gradient, experimental results much like those in Figure 7 would be expected: little change in the experimental n_e and p_e gradients before and during the puff. A direct comparison of p_e gradient scale length $L_p = |p_e/\nabla p_e|$ shows very little change in response to puffing at all values of I_P, as seen in Figure 8. This provides additional evidence for stiff edge pressure profiles in the ETB. By comparison, profiles of the stability parameter $\eta_e = d(\log T_e)/d(\log n_e)$ appear very different before and during puffing, and also differ between discharges at varied I_P. Thus, there appears to be no significant η_e constraint on these profiles, unlike in pedestals obtained in ELMy H-mode on ASDEX Upgrade [15].

5. Discussion

The above results highlight some important considerations for edge profile structure and H-mode fueling. First, a body of evidence has been assembled, indicating that a critical gradient paradigm for plasma transport may be an appropriate description for use in modeling both the L-mode and H-mode edge. In particular, evidence of a collisionality-dependent critical α_{MHD} in the H-mode pedestal has been seen for even the lowest values of $\nu^\star$ yet obtained on C-Mod. A firm upper bound for normalized ∇p at low collisionality so far has not been demonstrated, though it is possible that as $\nu^\star$ is pushed lower, discrete ELMy regimes will arise, leading to pressure gradient saturation through associated stability limits.

A critical gradient description contrasts with the frequently used diffusive model for plasma transport and should produce different results when used to predict the shape and magnitude of edge pedestal profiles. Nonetheless, a diffusive model for plasma transport, when coupled with a numerical kinetic treatment for neutral transport, models well the self-screening of the density pedestal in response to increases in available neutral source. Limitations are evident in the results of the modeling, since large model perturbations generally do not reproduce the effectively clamped n_e gradients seen during H-mode gas puffs. A critical gradient model provides a potential means of both reconciling this apparent discrepancy and improving pedestal modeling for C-Mod, and for ITER as well.

In addition to the stiffness of edge profiles, C-Mod demonstrates strong neutral shielding associated with edge transport barriers. This effect occurs along with fueling inefficiencies that result from having an SOL that is opaque to wall-source neutrals. As the ITER edge is expected to be similarly opaque to neutrals as that of C-Mod, an improved understanding of these issues could be vital for correct modeling of pedestal fueling on the future device. Indeed, the ineffectiveness of gas fueling on C-Mod underscores recent modeling work (e.g. [16]) predicting very low efficiencies for edge fueling for ITER.

Acknowledgments

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