Edge Profile Stiffness and Insensitivity of the Density Pedestal to Neutral Fueling in Alcator C-Mod Edge Transport Barriers

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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. Techniques include empirical scaling studies and experimental diagnosis and modeling of neutral fueling effects on the density pedestal. Experiments suggest a strong role for critical gradient behavior in setting profile characteristics of edge plasma. 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 (SOL) in ohmic discharges. In either case, the obtained pressure gradient, 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. The near SOL findings connect well with first-principles numerical results that suggest an underlying physical explanation based on electromagnetic fluid drift turbulence. The electron density pedestal in H-mode shows a linear dependence on plasma current, and inferred effective cross-field transport coefficients increase markedly as current is lowered. Varying the neutral fueling source alone 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. Altogether, these data indicate a substantial role for plasma transport in determining the density pedestal and gradient, with details of the neutral fueling source being less important. A modeled response of the density pedestal to perturbations to the edge neutral source couples a kinetic neutral treatment with a diffusive model for the plasma transport. The modeled response to small source perturbations is qualitatively consistent with experimental measurements, though the response to large perturbations does not reproduce the typically clamped density gradients seen in experiment during H-mode puffing. Together 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.

1. Introduction

Edge plasma plays a key role in regulating the confinement properties of tokamak discharges, due to the strong sensitivity of core transport on 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 resolved fully.

Experiments on the Alcator C-Mod tokamak have provided insight on the underlying mechanisms through a combination of studies: empirical scalings and diagnosis of particle transport, an examination of the effect of neutrals on the density pedestal and experiments with strong external gas fueling. As will be shown, 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. 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 [5]. The role of neutrals in setting the density pedestal is investigated on C-Mod through both experiment and modeling, and indications are that the fueling characteristics play a relatively weak role in determining profile structure.

2. Edge pressure gradient invariance in H-mode and ohmic plasmas

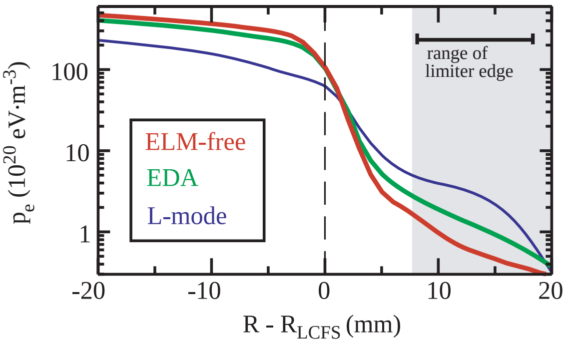

FIG 1: Composite profiles of electron pressure assembled from Thomson scattering and probes in ohmic L-mode (blue) and H-mode plasmas (red, green). A local steepening of gradient is observed in the near SOL even in L-mode.

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 determined the dependence of pedestal structure on plasma operational parameters [6]. These studies explored the range of toroidal field ($4.5 < B_T$[T] < 6.0) and plasma current ($0.6 < I_P$[MA] < 1.2) obtained in typical C-Mod operation and took advantage of millimeter resolution Thomson scattering profiles of electron density (n_e) and temperature (T_e) for pedestal characterization. The main findings of these studies were, first, that pedestal width showed little systematic variation, remaining in the range of 2—6mm over the typical range of operational space, and second, that significant variation of the pedestal heights and gradients could be obtained by changing global operational parameters. Scaling laws were developed for H-mode pedestal heights and gradients in the enhanced D_α (EDA) [7] regime. A significant result of these studies was that the maximum ETB pressure gradient scales as the square of plasma current ($\nabla p_e \propto I_P^2$) in these steady-state H-modes, such that the normalized pressure gradient $\alpha_{MHD} = (2\mu_0 qR/B^2)\cdot\nabla p$ remains roughly constant as I_P and B_T are varied. Since this scaling is obtained from discharges without edge-localized modes (ELMs), and analysis of EDA discharges without ELMs shows that the pedestal is linearly stable to coupled peeling-ballooning modes [8], this scaling does not appear to represent a limitation arising within the framework of ideal MHD.

A recent 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 [9]. The near SOL, the region of unconfined plasma within a few mm 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 Fig. 1, which compares composite profiles generated using probes and TS in characteristic ohmic L-mode and H-mode plasmas. The value of p_e gradient in the near SOL is also seen to increase as I_P^2, for a given value of edge collisionality. Fig. 2 shows these near SOL data plotted in terms of dimensionless parameters determined from the theory of electromagnetic fluid drift turbulence (EMFDT) [10,11]: α_{MHD} and α_d, where α_d is a diamagnetic parameter defined in

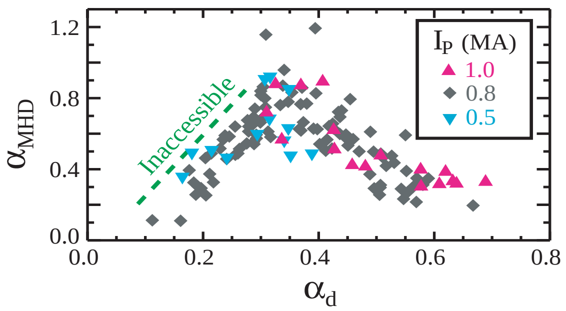

FIG 2: Normalized pedestal pressure gradient α_{MHD} vs. inverse collisionality parameter α_d, 2mm into the SOL of ohmic discharges. The data trace out a boundary of allowable plasma states.

Ref. 11. Higher values of α_d correspond to lower values of collisionality. In spite of large variation in the plasma operational parameters like current, field and density, the edge plasma state appears to be restricted to a narrow band in this dimensionless parameter space, which is qualitatively consistent with first-principles numerical simulations of EMFDT [10,11]. 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.

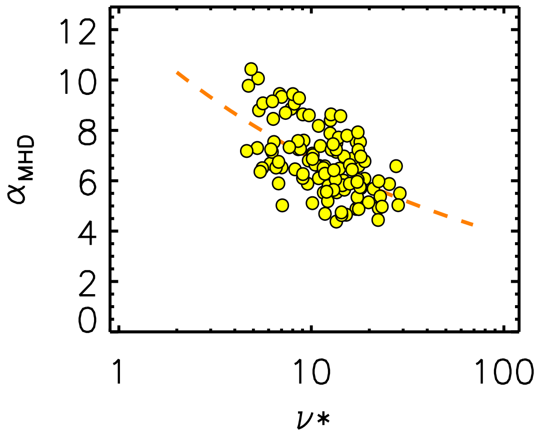

FIG 3: Normalized pedestal pressure gradient α_{MHD} vs. pedestal collisionality ν in EDA H-modes on Alcator C-Mod.*

The current-squared scaling of the pedestal pressure in EDA H-modes is also observed to be a soft limit [6], insofar as the critical α_{MHD} obtained can be increased with the addition of auxiliary heating, which increases the edge T_e. Casting the dimensionless pedestal pressure gradient in terms of collisionality, one finds that higher ν^* correlates with lower α_{MHD}, as shown in Fig. 3. Understanding the link between edge profile scalings in L-mode and H-mode, two very different transport regimes, is a remaining challenge. However, the existing results indicate features common to both regimes, and they demonstrate that a constant α_{MHD} scaling, typically associated with ballooning limits, exists near the LCFS in pedestals without ELMs, and even without an H-mode pedestal. Ongoing work is exploring the extension of this and other empirical scalings to a wider range in parameter space ($2.7 < B_T$[T] < 8, $0.4 < I_P$[MA] < 1.7).

3. Determination of 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. Experiments show a robust linear dependence of electron density pedestal $n_{e,\mathrm{PED}}$ on I_p, as demonstrated in Fig. 4 over an extensive range. In order to evaluate particle transport quantitatively, effective cross-field transport coefficients D_{eff} were inferred, assuming ion and neutral radial flux balance and using high resolution measurements of n_e, T_e and D_α emissivity to evaluate neutral density ionization rate profiles [12]. Resultant D_{eff} profiles are shown in Fig. 5 for three distinct values of I_p at B_T=5.4T. Particle diffusivity increases markedly as current is lowered.

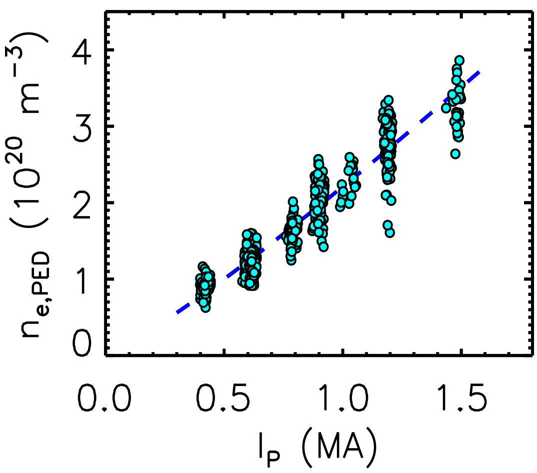

FIG 4: Density pedestal scaling with plasma current across nearly a 4x variation.

Fixing I_P and varying the programmed target density provides relatively weak control of the overall density pedestal, further suggesting a dominant role for plasma transport characteristics in determining pedestal structure. The n_e pedestal heights and widths obtained in such a scan are summarized in

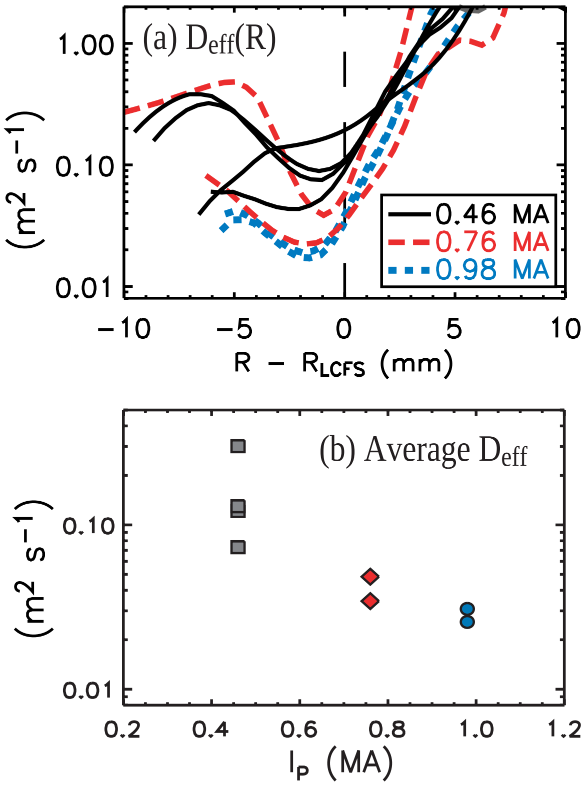

FIG 5: Effective diffusivity in the pedestal at varying I_P, fixed B_T (a) Spatially resolved profiles determined from n_e, T_e and inferred ionization rate. (b) D_{eff} averaged over the pedestal region

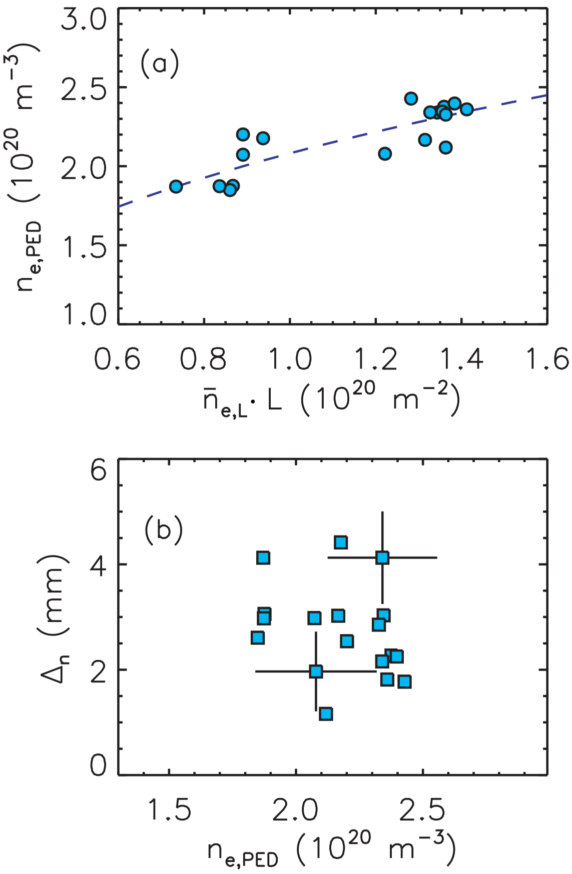

FIG 6: Results of a density scan in 0.8MA, 5.4T plasmas. (a) H-mode pedestal density as a function of line-integrated L-mode starting density. (b) Pedestal width in the same discharges vs. pedestal density, with typical error bars

Fig. 6, where the line-averaged density prior to the L-H transition $\bar{n}_{e,L}$ is chosen as an actuator. The values of $n_{e,\mathrm{PED}}$ shown in Fig. 6(a) represent a natural steady state density, which the pedestal obtains in an H-mode with no external puffing or pumping after the L-H transition. Experimentally, this resultant density is found to scale as $n_{e,PED} \propto \bar{n}_{e,L}^{\,0.4}$ at fixed I_P and B_T. Once a steady state H-mode is established, pedestals can be perturbed by additional gas puffing, and the results of such efforts are discussed in Section 4.

Figure 6(b) shows the lack of a systematic dependence of pedestal width on overall pedestal density in the target density scan. Measured profiles suggest little or no change in the gradient scale length of the n_e pedestal when neutral source alone is varied, contrary to both a simple theoretical scaling of pedestal width determined by ion-neutral flux balance and empirical results on the DIII-D tokamak [13]. This difference in behavior, along with the observation that, in C-Mod, characteristic gradient scale lengths of plasma profiles are smaller than estimates of mean free paths for neutral interaction, prompted an analysis of pedestal fueling using a kinetic transport model for incoming neutrals [14]. Modeling of pedestal response to variations in the amplitude of the neutral flux was undertaken by coupling the kinetic neutral model to a simple diffusive model for plasma transport in slab geometry. The D_{eff} profile was assumed to remain unchanged, while the incoming neutral flux from the wall was varied. The background plasma temperature profiles (T_i=T_e) were also assumed to be unperturbed by the

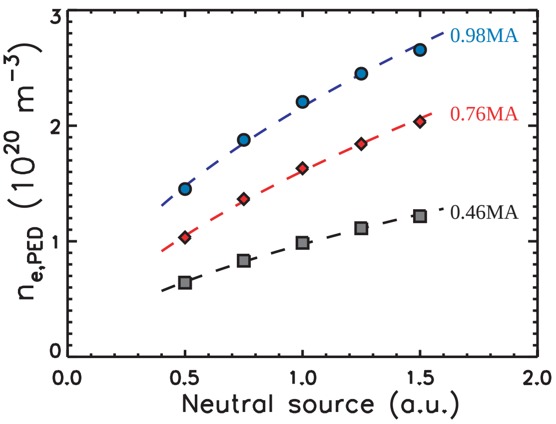

FIG 7: Computed density pedestal response to neutral source perturbations, at three distinct plasma currents. In each case, $n_{e,PED}$ scales roughly as the square root of neutral source.

changes in neutral source. Despite these highly simplifying assumptions, the coupled model reproduced key experimental observations [12]. First, neutral penetration through the pedestal is very small, with an effective penetration length of neutrals L_D such that $L_D < L_n < \lambda_{ion},\lambda_{cx}$, 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 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. Finally, the overall scaling of density pedestal with respect to the neutral source in L-mode is approximately reproduced, as shown in Fig. 7. When the same technique is used to model pedestals more typical of DIII-D, which are several times wider and less dense than those in C-Mod, an increase in L_n is observed at the lowest densities, leading to a wider pedestal, also as observed in experiment [13].

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, 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.

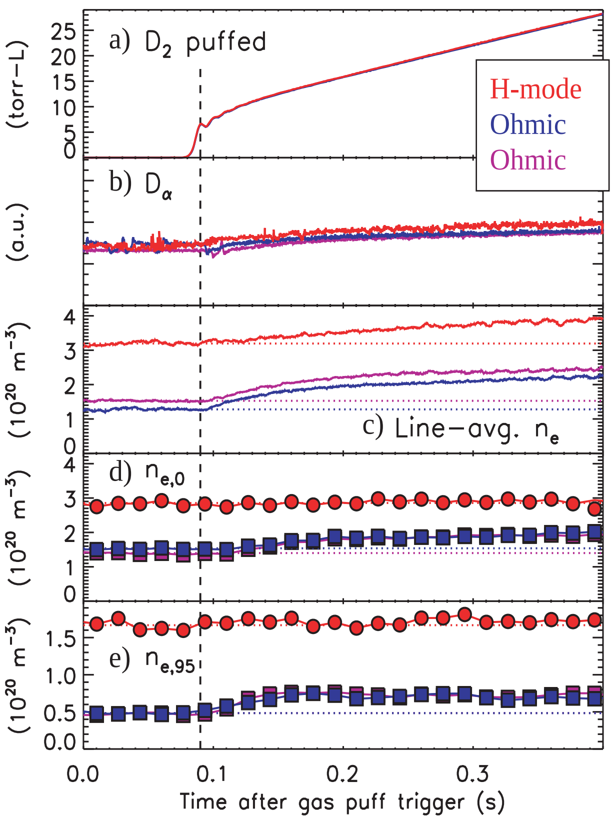

FIG 8: Examples of external gas puffing on steady state ohmic (blue, violet) and H-mode (red) plasmas at 0.8MA, 5.4T. For a given amount of puffed D_2, the core plasma fuels less efficiently in H-mode than in L-mode

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 systematically diagnose the level of pedestal screening. Figure 8 compares time traces from one H-mode and two ohmic discharges, all steady state and fueled without any external puffing prior to the time marked by the dashed vertical line. The total amount of additional D_2 inserted into the vessel is shown in Fig. 8(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 Figs. 8(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 Fig. 8(c) is due to a substantial increase in SOL density.) Gas puffing experiments for a range of currents demonstrate that, in general, the increase in observed $n_{e,95}$ 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 Fig 9, which plots $n_{e,95}$ and $T_{e,95}$ as a function of puff quantity in ohmic and H-mode plasmas at varying currents.

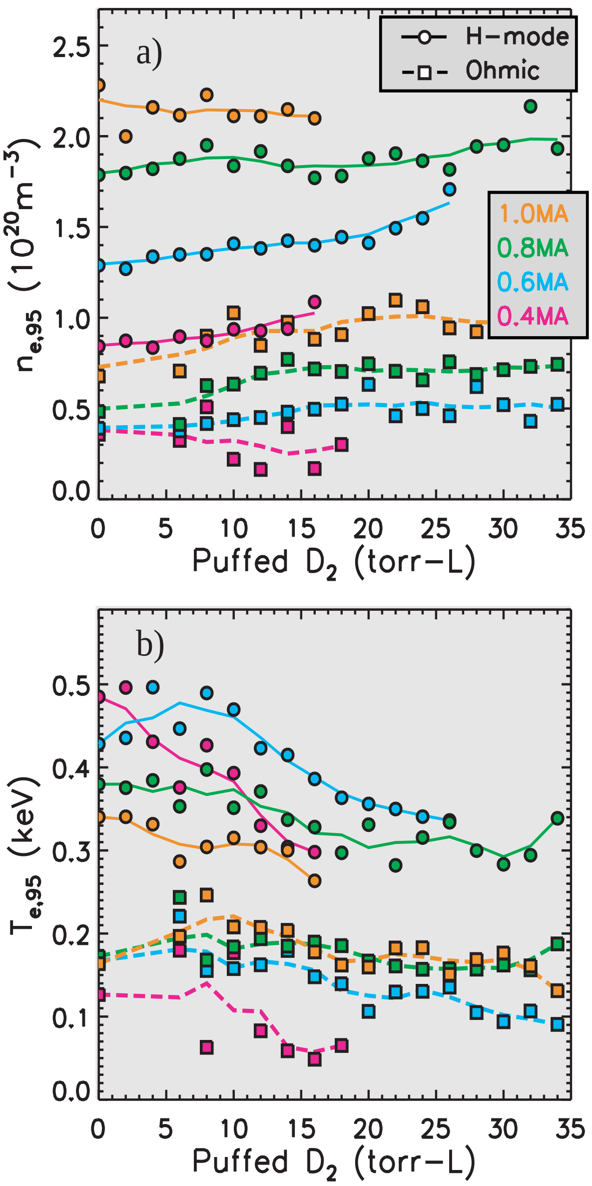

FIG 9: Effect of D_2 puffing on ohmic and H-mode discharges at four distinct plasma currents and fixed toroidal field. Electron density and temperature at the 95% flux surface are shown vs. total puffed deuterium

The response of pedestal profiles to gas puffing changes as the plasma current is varied from 1.0 to 0.4MA. Sample profiles are shown in Fig. 10. Unlike the results of the modeling described in Section 3, it is not universally the case that the density 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 $n_{e,,PED}$ 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.

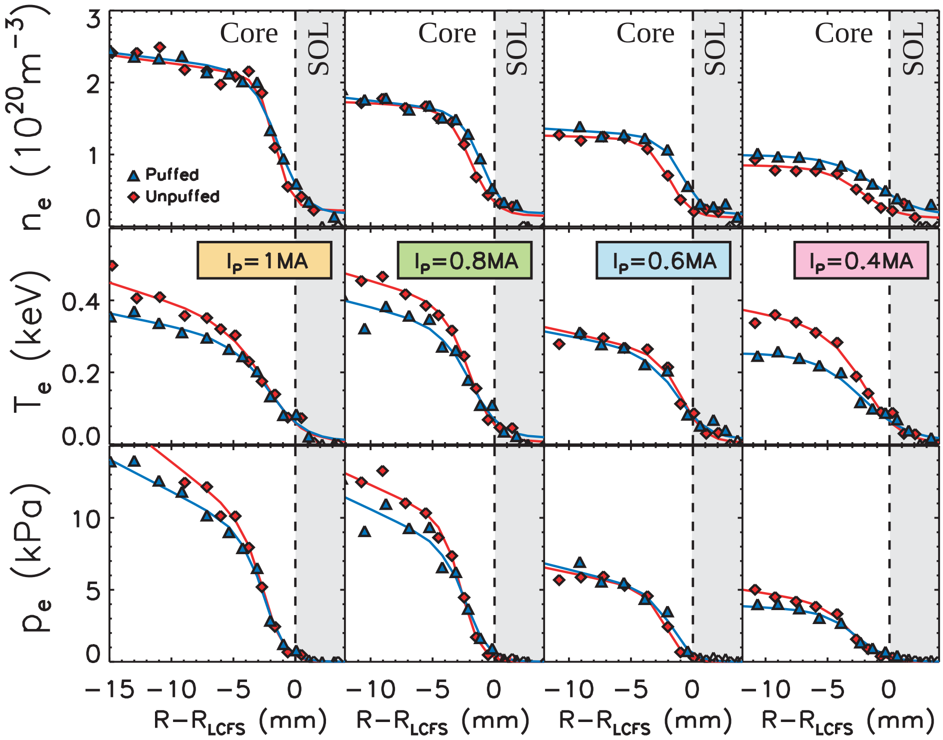

FIG 10: The effect of supplemental gas puffing on H-mode profiles of n_e, T_e, and p_e at four values of I_P with B_T=5.4T. The puffed cases correspond to about 15 torr·L of supplemental fueling.

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}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 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 Fig. 10 would be expected. It is noteworthy that there is little change in the experimental n_e,and p_e gradients before and during the puff.

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. Such a 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 density pedestal response to small perturbations to the neutral source. Derived gradient scale lengths, ionization profiles and diffusivity profiles are quite consistent with measurements, and perturbations to the fueling yield a growth in $n_{e,\mathrm{PED}}$ which agrees qualitatively with an experimental scaling of the pedestal height *versus* L-mode target density. The empirical result of constant pedestal width is also reproduced by the C-Mod pedestal model. Using the same modeling technique on pedestals characteristic of larger, less dense tokamak plasmas, density pedestal width is seen to increases with decreasing $n_{e,\mathrm{PED}}$, a result that makes contact with prior experimental and theoretical work on DIII-D [13]. Limitations are evident in the results of the modeling, since large 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.* [15]) predicting very low efficiencies for edge fueling for ITER.

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