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# H-mode pedestal and core plasma response to gas fueling on the Alcator C-Mod tokamak

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A pedestal in edge pressure is critical in setting global confinement in H-mode tokamak plasmas with edge transport barriers (ETBs), the base case for operation of the ITER device [1]. Profiles of temperature and density in the plasma edge are likely determined by the interplay of plasma physics processes and neutral fueling, the details of which may significantly impact the attainable H-mode pedestal. Recent experiments on the Alcator C-Mod tokamak have explored the effect of neutral fueling perturbations on both pedestal structure and core fueling during H-mode. We find that the presence of a strong ETB inhibits core fueling, and that ETB 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 may provide potentially useful information about plasma fueling in an ITER-relevant regime.

Prior work on C-Mod has established a body of evidence that critical gradient phenomena largely determine the profile characteristics of the edge plasma. Notably, the ETB pressure gradient scales as the square of plasma current $I_P$ in steady-state H-modes [2], such that the normalized pressure gradient $\alpha_{\mathrm{MHD}}$ remains roughly constant. In addition, a recent extensive study of ohmic profiles in the near SOL has uncovered a similar pressure gradient scaling in low-confinement-mode (L-mode) discharges, and a connection has been drawn to first-principles numerical simulations of electromagnetic fluid drift turbulence, suggesting an underlying physical mechanism [3]. In both cases, the edge profiles do not appear limited by ideal MHD. These results together demonstrate that a ballooning-like scaling for edge pressure ($\nabla p \propto I_P^2$) exists without edge-localized modes (ELMs), or even without an H-mode pedestal.

The roles of plasma and neutral transport in setting density pedestal structure have also been examined. Experiments show a robust linear dependence of electron density pedestal $n_{e,\mathrm{PED}}$ on $I_P$, along with a weaker scaling with the density, $\bar{n}_{e,L}$, of the L-mode (pre H-mode) target plasma. Effective cross-field diffusivity $D_{\mathrm{eff}}$, inferred from pedestal measurements, increases markedly as $I_P$ is lowered [4]. Little or no change is seen in the gradient scale length of the $n_e$ pedestal ($L_n$) when neutral source alone is varied. Altogether, these data indicate a substantial role for $I_P$-sensitive plasma transport in determining the pedestal height and gradient, while details of the neutral fueling source are less important. A dramatic illustration of this behavior has been seen in edge density profiles measured before and during aggressive $D_2$ gas puffs into H-mode, as shown in Ref. 4. Below we expand the discussion of these experimental results.

Significant puffing of $D_2$, a generally effective knob for raising L-mode densities, is rather ineffective at fueling the core plasma in normal C-Mod H-mode operation. The response of a steady H-mode at 0.8MA and 5.4T to a substantial insertion of gas is shown in Fig. 1. Here, ICRF power is used to maintain a steady wall-fueled H-mode discharge, into which a $D_2$ injection is administered from the inner wall. Effects of hard gas puffing usually include an increase in line-averaged density $\bar{n}_e$, accompanied by an edge $T_e$ depression and a drop in the bulk radiated power. Despite the increase in the overall particle inventory during the puff and an increase in SOL density measured by probes, the $n_e$ pedestal measured by Thomson scattering (TS) shows little or no change.

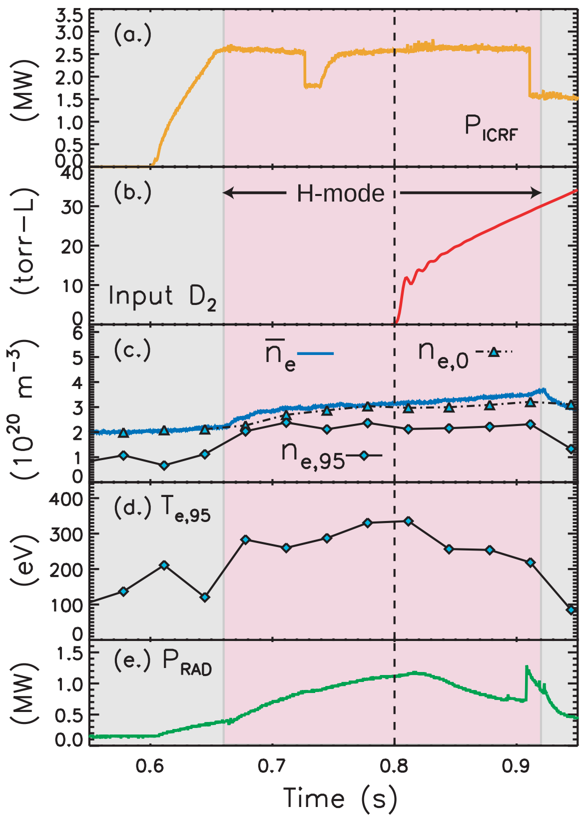


Figure 1: $D_2$ puffing into established H-mode at 0.8MA, 5.3T. (a) ICRF power used to initiate and sustain H-mode. (b) Total supplemental $D_2$ injection. (c) Comparison of global, central and edge $n_e$ (taken at $\psi = 0.95$). (d) Edge $T_e$. (e) Radiated power.

Since neutral transport modeling suggests an importance of neutral screening in the C-Mod ETB [4], we sought to examine the effects of puffing on ETBs of differing character. 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 1.05MA) 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 $n/n_G \approx 0.3$, 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 $0.8\text{–}2.5\times10^{20}$ m$^{-3}$.

Figure 2 summarizes the effects on the discharges due to supplemental gas puffing. In all cases, interferometry [Fig. 2(a)] shows an increase in vessel inventory as the puff is increased. However, varying degrees of core and pedestal fueling are demonstrated by TS measurements of central and edge $n_e$ [Fig. 2(b,c)]. The increase in central density obtained for a given amount of gas is generally higher for Ohmic discharges than for H-modes. Fueling an Ohmic discharge generally increases $n_{e,95}$, except at the lowest $I_P$, where the increased fueling quickly drives the plasma toward a detached radiative state. The impact of puffing on the H-mode edge $n_e$ is minimal for typical C-Mod currents of 0.8 and 1.0MA, but a more significant increase in H-mode $n_{e,95}$ is observed as $I_P$ is lowered, producing a weaker ETB. An enhancement of $2 \times 10^{19}$ m$^{-3}$ in $n_e$ pedestal is obtained at 0.4MA with roughly half the supplemental fueling that is required for the same density enhancement at 0.8MA.

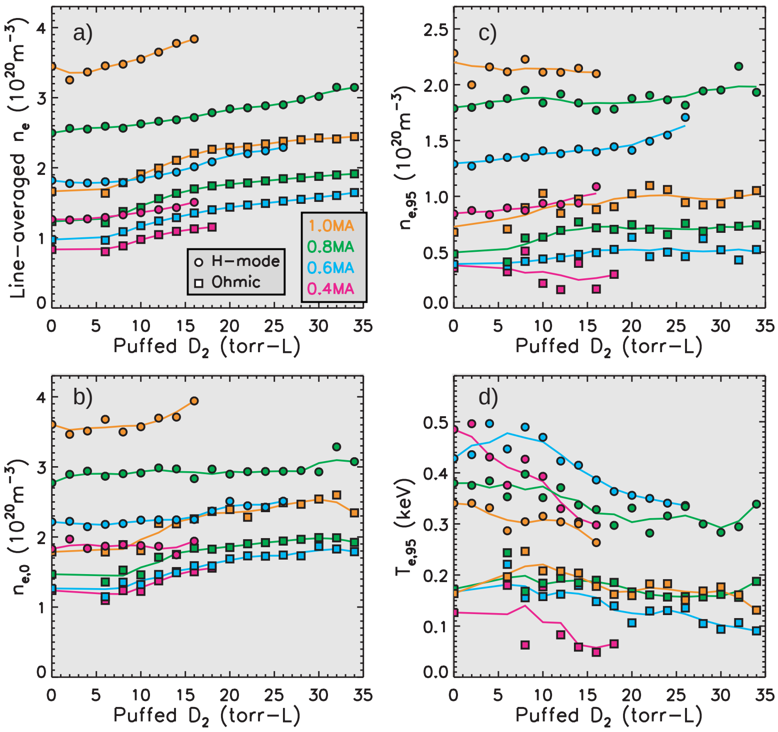


Figure 2: Effect of $D_2$ puffing on Ohmic and H-mode discharges at four distinct plasma currents. (a) Line-averaged density $\overline{n}_e$ (b) Central $n_e$. (c,d) $n_e$, $T_e$ at the 95% flux surface. Symbols represent binned and averaged clusters of data.

The impact of a given gas puff on the pedestal varies considerably when going from high to low current, as shown in Fig. 3. At the highest value of $I_P$, $n_{e,\mathrm{PED}}$ is large, and the only effect seen on the ETB is a reduction in $T_{e,\mathrm{PED}}$. As current is lowered, $n_{e,\mathrm{PED}}$ drops, and the puff begins to have a larger effect. At $I_P = 0.8$MA, the absolute value of $n_{e,\mathrm{PED}}$ remains almost fixed during the puff, but an outward shift of the $n_e$ pedestal relative to the $T_e$ pedestal is observed. This fueling-induced radial shift persists at lower $I_P$, and the $n_e$ pedestal increase noted above begins to show, becoming substantial at the lowest current. In all cases, the characteristic $\nabla n_e$ stays roughly fixed (as does, indeed, $\nabla p_e$), even as the pedestal shifts outward. Neutral density profiles inferred using the technique described in Ref. 4 indicate substantial screening of the supplemental neutrals inboard of the $n_e$ pedestal.

The edge profile behavior in response to extra fueling during the H-mode differs somewhat from the variation of $n_e$ pedestal in response to changes in the source rate determined by the L-mode target density. When varying $\overline{n}_{e,L}$ at fixed $I_P$, $n_e$ gradient scale lengths tend to remain fixed, resulting in a self-similar density profile, the height and gradient of which both increase with supplied neutral source. These trends were observed also in modeling of edge fueling using typical C-Mod H-mode pedestal profiles as inputs [4]. When a purely diffusive model for plasma transport is used, and the $D_{\text{eff}}$ profile is assumed fixed while neutral source is increased, modeled $n_e$ at the LCFS rises, just as in most puffed H-modes (see Fig. 3). However, modeled $L_n$ tend to remain fixed, resulting in a self-similar density profile, the height and gradient of which both increase with supplied neutral source. This contrasts with results from direct H-mode puffing (Fig. 3), which show both invariant $n_e$ gradients and an effect on pedestal height that varies with the quality of the transport barrier, as regulated by $I_P$.

That experimental H-mode profiles demonstrate fixed density gradients in response to aggressive attempts to change neutral source provides additional evidence that edge plasma transport is regulated by critical gradient phenomena, and that such a 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 significantly different results when used to predict the shape and magnitude of edge pedestal profiles. Attempts will be made to incorporate such a plasma transport description into pedestal modeling on C-Mod.

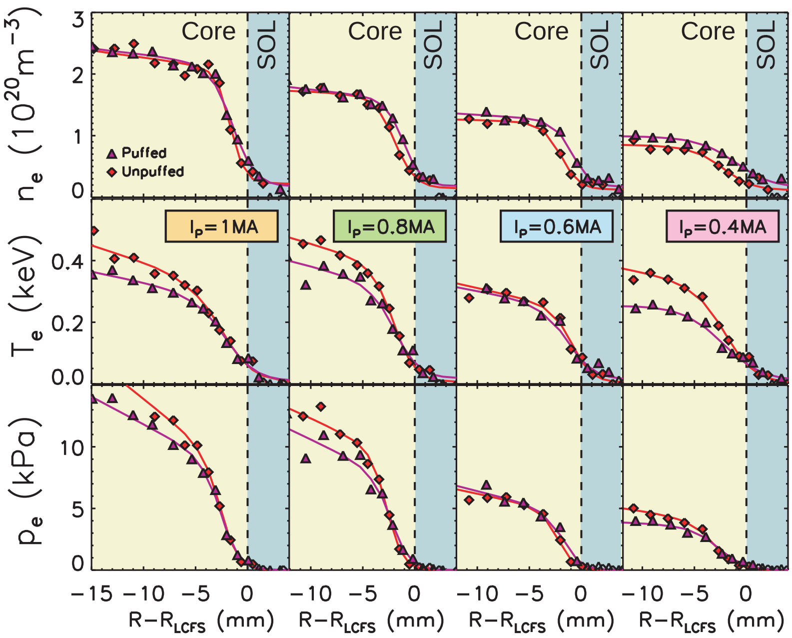


Figure 3: The effect of supplemental gas puffing on H-mode profiles of $n_e$ and $T_e$ at four values of $I_P$. The puffed cases correspond to about 15 torr-L of supplemental fueling.

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## References

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