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H-mode experiments at reduced collisionality on Alcator C-Mod*

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Introduction

The height of the H-mode pedestal, on Alcator C-Mod as many other tokamaks, is strongly correlated with the total stored energy and global confinement, through 'stiffness' in the temperature profile[1,2,3]. This makes the understanding and scaling of the transport barrier, under a wide range of regimes and plasma parameters, crucial. On C-Mod, which has high field, compact size (R=0.67 m, a=0.21 m) and all metal walls, H-mode regimes have differed from those on most other tokamaks. The most common regime is 'Enhanced D_α' or EDA, which is characterized by a continuous edge 'quasicoherent' (QC) mode[4]. At sufficient amplitude, this provides steady density without heat pulses from large ELMs. At sufficiently high pressure, small ELMs can occur[5]. A disadvantage is that the steady n_e regime has, to date, been seen primarily at moderately high edge collisionality, $\nu^*_{ped} > 2$. At lower ν^*, and/or low q_{95} (< 3.5), ELM free H-modes predominate[3]. These have high confinement but are generally transient, with density and radiation increasing until a back-transition occurs.

Pedestal scalings have been well documented on C-Mod[6]. Until recent campaigns, studies focussed on the EDA regime, primarily with B_T ~5.4 T, and for discharges with a single null near the closed lower divertor, in the direction of $B\times\nabla B$ drifts. The pedestal width is insensitive to I_p and other bulk plasma parameters, and is very narrow, typically 2-5 mm. The height of the density pedestal is strongly correlated with I_p and varies weakly with target density or neutral pressure[7]. Fuelling efficiency is low, especially in high I_p plasmas, reflecting both large pedestal screening of neutrals and the high SOL opacity[8]. We note that ITER is expected to have even higher n_0L. We report here on H-mode studies over an extended parameter range, with B_T =2.6-7.9 T and I_p= 0.4-1.7 MA, and unfavourable magnetic configurations. Both high field and unfavourable drifts tend to lead to lower ν^*_{ped}. The configuration has been varied dynamically to separate threshold and pedestal effects.

H-mode experiments over B_T of 2.6-8T

Operation at a wide range of magnetic fields has been achieved by varying the ICRF heating frequency from 50-80 MHz. D(He^3) minority heating has been used in addition to

D(H) and has successfully heated discharges up to 7.9 T. Plasma currents from 0.4-1.7 MA gave q_{95} =2.6-9.5. Over nearly all of this parameter range, pedestal widths remain relatively constant, and show no clear correlation with poloidal or toroidal gyroradius[9]. At the lowest I_p, which also gives relative low n_{ped} (10^{20} m^{-3}), density widths tend to increase, up to 8 mm. Pedestal pressures are independent of B_T for fixed I_p, scaling roughly as I_p^2. n_{ped} scales linearly with I_p and, up to ~5 T, appears insensitive to field. At higher B_T, (6-8 T), however, the pedestal parameters for fixed I_p tend to shift towards lower n_{ped} and higher T_{ped}, as illustrated in Figure 1.

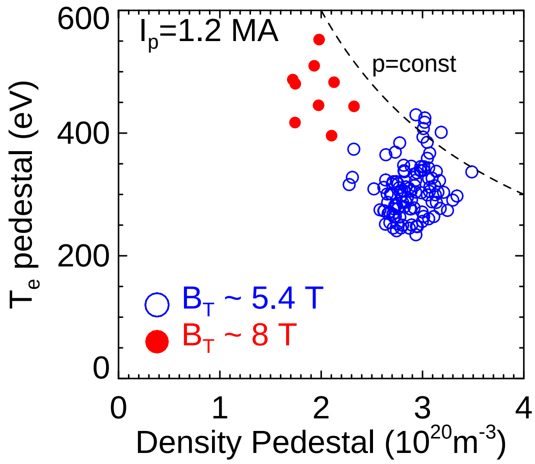

Figure 1. Pedestal T_e vs n_e for a set of 1.2 MA discharges at 5.4 T (blue) vs 7.9 T (red)

We note that, as found in prior experiments on C-Mod and elsewhere, L-H thresholds also scale with B_T; up to 4 MW of total (ohmic plus ICRF) input power is required at 7.9 T. Edge temperatures are also significantly higher at the transition, typically 300-400 eV at ψ=0.95 at 7.9 T vs 100-200 eV at 5.4 T. It is possible that these higher threshold temperatures contribute to the higher pedestal T_e at high field. Whatever the reason, the shift toward higher T_{ped} leads to significantly lower ν^*_{ped}, since $\nu_e^* = 6.921\times10^{18} q_{95} R n_e Z_{eff} \ln\Lambda / (T_e^2\, \varepsilon^{3/2})$. ν^*_{ped} in the higher B discharges, computed assuming Z_{eff}=1, a lower bound, is typically 0.4-2. Likely as a result, these H-modes tended to be transient. Most were ELM-free, although some discharges at q_{95}> 6 did exhibit weak QC modes. Because the L-H threshold power was near the available heating power during these experiments, only a limited range of density could be explored. Increases in ICRF and lower hybrid heating power are planned in future experiments.

H-mode experiments with unfavourable B×∇B drift direction

H-mode experiments have also been conducted with varied magnetic configuration, including discharges with the B×∇B drift away from the active x-point. This can be achieved in the usual B_T and Ip direction by switching from lower to upper single null. For comparison without changes in geometry, B_T and I_p were reversed for a set of experiments so that lower null became unfavourable. These were done at B_T=5.4 T and 800 kA. As expected, this gave much higher L-H power thresholds than in the same conditions with 'normal' B, 2.7-3.7 MW vs 1.1-1.7 MW. Edge temperatures at the threshold were also much higher, ~400 eV at $\bar{n}_e$ ~1.5-2x10^{20} m^{-3}, and increasing to >700 eV at lower $\bar{n}_e$. Interesting transient behaviour was seen leading up to these transitions, suggesting slow changes in edge thermal confinement[9]. The changes in threshold were consistent with prior C-Mod results indicating a role for SOL flows in the differences in threshold[10,11]. High field side flows were found to be *independent* of B_T direction, but switched from co to counter current when I_p and B_T were reversed.

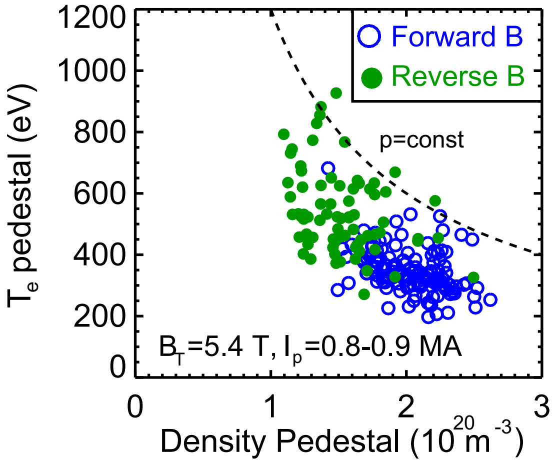

Figure 2: Pedestal T_e vs n_e for a set of 5.4 LSN discharges with forward B_T, 0.9 MA (blue) vs reversed B_T, 0.8 MA (green).

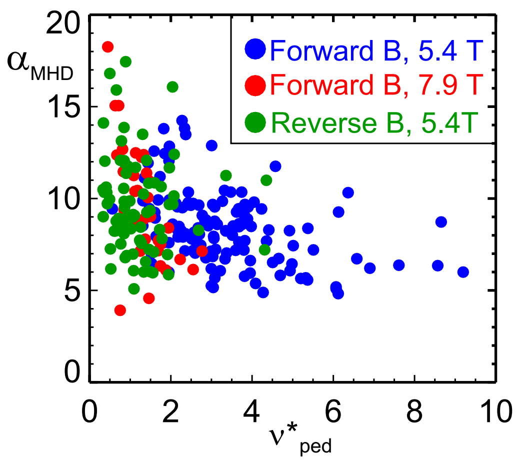

Figure 3: α_{MHD} at the pedestal midpoint vs ν^*_{ped} for forward field (blue 5.4 T, red 7.9 T) vs reversed field 5.4 T (green).

More unexpected were the changes in H-mode pedestal parameters with unfavourable drift. Pedestal pressures remained constant to first order, but as illustrated in Figure 2 the pedestals shifted towards lower density and higher T_e, up to 900 eV. The corresponding ν^*_{ped} are also lower. Figure 3 compares ν^*_{ped}, and the normalized pressure gradient α_{MHD} for the forward and reversed B_T pedestals at 5.4 T, 0.8-0.9 MA, and the forward B_T pedestals at 7.9 T, 0.9-1.7 MA. The reversed B_T points are strikingly similar to the high B_T points, both extending to ν^* ~0.5, and to high α_{MHD}. The increase of α_{MHD} with decreasing ν^*_{ped} is consistent with a trend previously observed at $\nu^* > 2$[7]. Likely due to the reduced collisionality, these H-modes again tend to be transient, with or without a weak QC mode.

An obvious commonality between the reversed B and high B H-modes is their high thresholds – both require ~ 3 MW of heating power and have edge T_e ~ 300-400 eV at the transition, comparable to pedestal T_e in many EDA H-modes. It is thus possible that conditions at the threshold are contributing to higher T_{ped} in the subsequent H-mode. Since the pressure is fixed by plasma current, even in the absence of evident ideal MHD instabilities, this would lead to lower n_{ped} and ν^*. To separate the effects of threshold conditions from the intrinsic effects of magnetic configuration, recent experiments have varied the configuration dynamically. With normal magnetic field, the separatrix was kept slightly lower null (favourable drift) until an L-H transition, then shifted to slightly upper null. This has a clear effect on n_{ped}, with density reducing in upper null and sensitive to the magnetic balance. These discharges had relatively low collisionality, ν^*_{95}~1-2 but, interestingly, had fairly steady pedestals and an edge QC mode. This contrasts with the transient H-modes typically produced in unfavourable configurations, and suggests that both threshold conditions and the configuration during H-mode play a role in setting pedestal conditions.

Conclusions and future directions

H-mode experiments on Alcator C-Mod have been extended over a wide range of plasma parameters, up to 1.7 MA and 7.9 T. These generally confirm prior trends, with widths showing little variation, and pedestal densities strongly correlated with I_p and insensitive to fuelling. At the highest fields, which also have high L-H thresholds, pedestals tend to have lower collisionality and H-modes to be transient in nature. The effects of plasma configuration, specifically $B\times\nabla B$ drift toward or away from the active x-point, have also been explored. In the unfavourable configuration, H-mode pedestals again tend to have lower n_e and collisionality, suggesting a link to threshold conditions. Recent experiments in which the configuration is varied dynamically indicate that the magnetic balance also has a direct effect on pedestal density; this technique appears promising to produce lower collisionality, but steadier, H-modes. Density control will also be aided by a new cryopump in the upper vacuum vessel. These experiments will be continued in the 2007 and future campaigns.

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