

Pedestals and confinement in Alcator C-Mod H-modes

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1. Introduction

The study of H-mode regimes, pedestal conditions and confinement is a focus of research on the Alcator C-Mod tokamak. In addition to the usual ELM-free regime, a new regime has been observed on C-Mod which has good energy confinement but lower particle and impurity confinement, named the "Enhanced D-alpha (EDA) H-mode" for one of its signatures [1]. This mode can be steady-state and usually has no discrete ELMs, making it potentially attractive for a reactor. Since the main changes in H-mode are in the plasma edge region, measurements of the pedestal are critical to this study. New, high resolution diagnostics and profiles are described below.

A good correlation is found on C-Mod between pedestal temperature and both core T_e gradients and global confinement times, across all L- and H-mode regimes. There is concern for future reactors that the injection of impurity gases to enhance radiation, in order to achieve the dissipative divertor operation required for handling high heat fluxes, will reduce the pedestal temperature and thus the confinement. Controlled scans of radiation and RF power have been used to explore these issues; results are given in section 3.

2. Pedestal Measurements

Several high resolution diagnostics have recently been added to measure plasma parameters in the very narrow pedestal of Alcator C-Mod. An edge Thomson scattering system viewing the top of the plasma provides T_e and n_e measurements with 2 mm radial resolution, mapped to the outside midplane. T_e is also measured using ECE, with small sweeps of B_T used to improve the detail in the profiles [2]. Electron density profiles and fluctuations are measured by reflectometry, with 5 channels having critical n_e up to $1.5 \times 10^{20} \text{ m}^{-3}$. This is usually in the outer part of the pedestal, as edge densities on C-Mod can be as high as $4 \times 10^{20} \text{ m}^{-3}$. A tangential CCD array measures bremsstrahlung emissivity with 0.8 mm spatial resolution and can be used to follow the fast time evolution of the pedestal. Two soft x-ray arrays with 1.5 mm resolution view the outer midplane and the top of the plasma, while an AXUV diode array measures the edge radiated power emissivity with 2 mm resolution. T_e and n_e profiles in the SOL are measured by two scanning Langmuir probes. In addition, a spectrometer viewing a helium gas puff measures T_e and n_e profiles across the separatrix and into the pedestal region.

Profiles from several of these diagnostics are shown in Fig. 1, for an ELM-free ohmic H-mode with $I_p = 1.2 \text{ MA}$ and $B_T = 5.2 \text{ T}$. The top panel shows the T_e pedestal, measured by ECE, Thomson scattering, and a scanning Langmuir probe. The present spectrometers in the

edge Thomson system are able to measure reliably temperatures only up to about 180 eV. The two profiles agree well in this outer region, giving confidence in the reliability of ECE measurements in C-Mod pedestals. Probe temperature and density data also agree well with Thomson scattering in the SOL. The T_e pedestal width, derived from hyperbolic tangent fits to the ECE profiles, is 11 mm based on raw data, and 6.6 mm after deconvolution of the instrument function. The n_e profile (middle panel), is much narrower, with a width of 3 mm.

This difference in width is found for all the H-modes observed, whether ELM-free or EDA. Density pedestal widths range from 2 to 6 mm, while T_e widths range from 8 to 25 mm. Similarly narrow density profiles can be deduced from bremsstrahlung emissivity, if one assumes that Z_{eff} does not vary rapidly across the pedestal. The narrowest profiles, with widths of 2-3 mm in this discharge, are found in soft x-ray emissivity (bottom panel of Fig. 1). The x-ray widths have been found to be consistently wider in EDA than in ELM-free H-modes, and to increase at lower current and increasing triangularity [3]. The same trends are seen in AXUV radiation profiles. High q (>3.5) and medium δ (0.35-0.55) have also been found to favour the EDA regime in C-Mod [1], suggesting that the widths reflect changes in the particle confinement. The T_e pedestal widths, in contrast, do not show a consistent scaling with any of these parameters. This may reflect the fact that energy confinement is only slightly different in EDA H-mode. All pedestal parameters are very similar in ohmic and RF heated H-modes.

3. Effect of Pedestal on Core Confinement

A general result found on C-Mod plasmas is that, as temperatures near the plasma edge are raised, the temperature gradient in the plasma core confinement region increases [4]. This correlation holds across all transport regimes, including L-mode, ELM-free and ELMy or EDA H-modes. Similar trends were also seen on ASDEX Upgrade [5]. For plasmas of similar density, the global energy confinement time τ_E and H-factor thus also correlate with edge T_e . This is suggestive of a 'stiff' type of transport regime, in which core transport depends strongly on boundary conditions and temperature profiles tend to exhibit a self-similar behaviour. For example, recent modelling of some C-Mod discharges using the IFS-PPPL model [6] predicts that core T_i increases with boundary temperature. However, the model tends to seriously underestimate the experimentally observed gradients in T_i profiles, which are close to T_e profiles, and to overestimate the central T_e [7].

The correlation between edge and core parameters does not in itself prove a causal relationship; it could be that some change in turbulence is affecting both the edge and core transport. In order to study the relationship in a more controlled way, an experiment was carried out in which impurity gases were puffed into steady-state EDA H-mode discharges. This increased the radiation, primarily in the outer half of the plasma, and thus lowered the pedestal temperature by a variable degree. The discharges used for this experiment had $I_p = 1$ MA, $B_T = 5.4$ T, a line averaged density of $3.5 \times 10^{20} \text{ m}^{-3}$ and 1.6 MW of centrally absorbed ICRF heating. A short puff of neon or krypton increased the radiation by up to 2.1 MW, with only a slight effect on the edge or average density (up to 14%). For both gases, the incremental emissivity peaks at $r/a \sim 0.85$, just inside the pedestal. 80% of the integrated power is outside r/a of 0.7. Fig. 2 shows measurements of the temperature pedestal for three shots in the series. As might be expected, the discharges with impurity puffing have lower pedestal temperatures, as measured either at a fixed location (eg $\psi = 0.85$) or by tanh fits to the profile. More surprisingly, the T_e pedestal *width* also decreases from 16 to 9 mm, giving a nearly

constant pedestal T_e gradient of 28.5 ± 3.5 keV/m. This might indicate that the power flux can, under some conditions, affect the pedestal width. Such a dependence on the driving flux was suggested by Lebedev, who considered the case of density pedestals and particle fluxes [8].

The core confinement in the radiative discharges also drops as $T_{e,ped}$ is lowered, as shown in Fig. 3. There is a 35% decrease in dT/dR at $\psi=0.5$, despite the fact that the net power flux across this surface varies by only 430 kW, or $\sim 17\%$. τ_E and the $H_{ITER-89P}$ factor decrease similarly, to near L-mode levels. Any further increase in radiation causes an H-L transition. It thus appears that an independently imposed change in pedestal temperature and pressure does indeed cause a change in global transport, strengthening the argument that core confinement is sensitive to the plasma boundary conditions.

In a separate experiment, absorbed RF power was varied from 0.63 to 2.75 MW in a series of EDA H-modes at constant average n_e of $3.2 \times 10^{20} \text{ m}^{-3}$. Fig. 4 shows that T_e ($\psi=0.85$) and stored energy, W_{MHD} , each exhibit the same dependence on total power. Although in this case it is the centrally deposited input power which varies, a correlation between edge T_e and both the core T_e gradient and H factor was observed which mirrors that in the impurity scan. At these power levels we have not observed a clear saturation in any of these quantities with P_{total} , though the trends are non-linear. It will be interesting to see the behaviour as RF power is doubled in the near future. Dynamic experiments to test the dependence of the pedestal widths on input power are also planned.

Conclusions

Detailed measurements of H-mode pedestal parameters have shown that density pedestals are significantly narrower than T_e pedestals, and can be as small as 2 mm. Pedestal profiles in ohmic and RF heated H-modes are similar. The influence of edge temperature on core confinement has been tested using puffing of neon and krypton. These experiments show that cooling the edge does lower the core gradients and confinement. This may be a concern for dissipative divertor experiments. On C-Mod, better confinement was obtained by puffing nitrogen, which radiates closer to the separatrix than neon or krypton [8]. We plan to explore further the effects of this and other gases on the pedestal, the divertor and core confinement, using radiation localized within the pedestal as well as at smaller minor radii.

Acknowledgements

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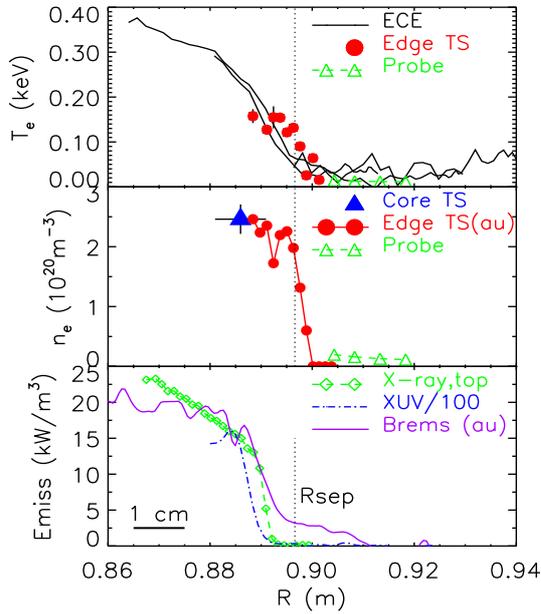


Figure 1. Pedestal profiles for an ELM-free H-mode. The T_e pedestal (top) is significantly wider than the n_e pedestal (middle) and the x-ray, XUV and bremsstrahlung emissivity pedestals (bottom).

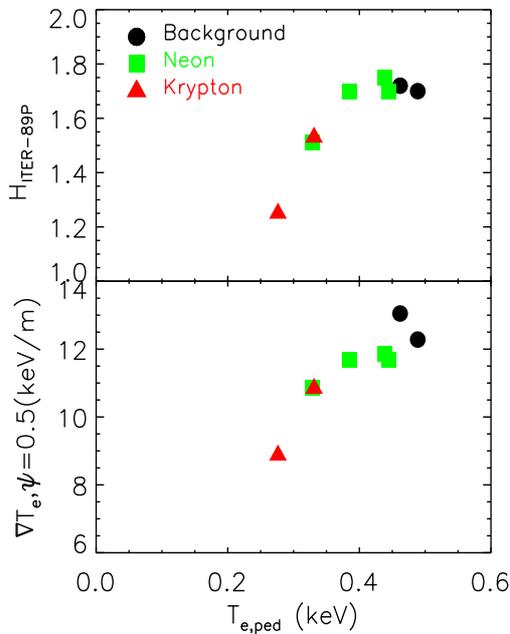


Figure 3. $H_{ITER-89P}$ (top) and core T_e gradient (bottom) vs pedestal T_e , obtained from tanh fits to ECE profiles, for some of the discharges in the radiation scan.

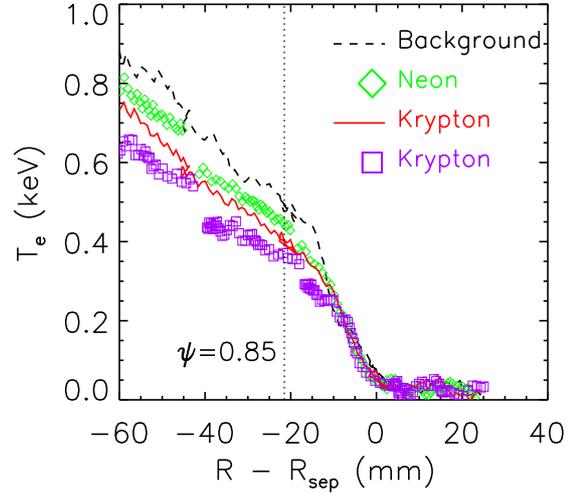


Figure 2. T_e pedestal profiles for four EDA H-mode time slices in the impurity radiation scan. The pedestal width as well as height decreases with increasing radiation.

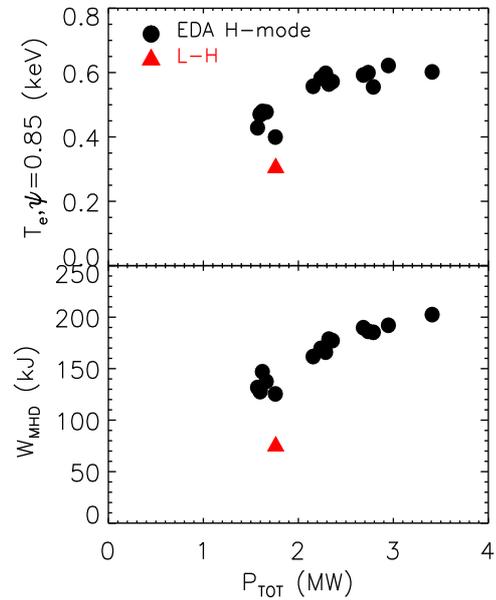


Figure 4. Edge temperature (top) and stored energy (bottom) vs total power for an RF power scan in steady EDA H-mode discharges. T_e ($\psi=0.85$) and W remain nearly proportional.