Local variables affecting H-mode threshold on Alcator C-Mod

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Abstract. An edge temperature threshold for the L–H transition is found on the Alcator C-Mod tokamak. The critical temperature depends weakly on density and increases with \( B_T \) and with unfavourable drift direction. \( T_e \) at the H–L transition can be greater than or equal to the L–H threshold. Magnetic fluctuations are observed at some H–L transitions. Measured parameters are compared with H-mode theories, including nonlinear drift-ballooning code simulations.

1. Introduction

Recent exploration of the H-mode threshold on Alcator C-Mod, at fields up to 8 T, has concentrated on the characterization of local threshold conditions. In particular, we have been studying electron density and temperature in the region just inside the separatrix, where the H-mode pedestals form. As reported in [1], the global power threshold on C-Mod is relatively low, but as on other machines and indeed in the multi-machine ITER database [2] it shows considerable scatter. At the last H-mode workshop, it was noted that a critical edge temperature is associated with the L–H transition [3, 4]. Local conditions at the transition have now been documented much more fully. The edge diagnostic set and parameters at L–H and H–L thresholds are described below. Connection is made with recent theoretical modelling.

2. Local conditions at L–H and H–L transition

The primary electron temperature diagnostic used for local threshold studies is a nine-channel ECE grating polychromator, which has \( \sim 2 \) cm channel spacing and 9 mm radial resolution. The time resolution for these measurements was 70 \( \mu \)s. Profiles are interpolated onto a desired location, usually the 95% poloidal flux surface. While edge \( T_i \) profiles are not yet measured, the electron–ion equilibration time at the edge is a few milliseconds, so it is reasonable to assume that \( T_i \approx T_e \).

The main density profile diagnostic is an interferometer with 10 vertical chords [5]. Since the chords are located well inside the separatrix, assumptions must be made about the scrape-off layer density in the inversion process. Derived edge densities have relatively large uncertainties and tend to reflect the average density in the discharge.

The clearest demonstration of a local threshold condition for the L–H transition on C-Mod comes from a density and power scan in which ICRF power was stepped up in small
increments to find the minimum threshold power. This was repeated for fixed magnetic configuration ($I_p = 0.8 \text{ MA}$ and $B_T = 5.3 \text{ T}$) at different densities. Figure 1 shows that the threshold power varies nonlinearly, increasing both at higher densities and near the low-density limit, and is not well described by any simple scaling. The edge $T_e$, in contrast, is always close to 120 eV at the L–H transition, independently of density. This strongly suggests a necessary condition in $T_e$ or a closely related parameter (e.g. $T_i$ or $\nabla T$) for obtaining H-mode.

Local conditions prior to L–H or H–L transitions have been monitored for many other discharges in a broad range of plasma parameters. Figure 2 shows the edge parameter space for plasmas with $B_T = 8 \text{ T}$. The edge temperature is again in a fairly narrow range (200–250 eV) for most of the L–H transitions, and is clearly higher than at 5.3 T. A few discharges at the lowest densities show somewhat higher threshold temperatures. A similar tendency is seen in the complete 5.3 T data set. Statistical regressions give $T_e,\text{crit} \propto B_T^{1.6\pm0.15} n_e^{-0.57\pm0.1} I_p^{-0.17\pm0.2}$.

**Figure 1.** Total power (top) and $T_e(\psi = 0.95)$ (bottom) at L–H transition (triangles) during a density and power scan with $B_T = 5.3 \text{ T}$ and $I_p = 800 \text{ kA}$, showing an edge $T_e$ threshold.

**Figure 2.** Temperature and density at $\psi = 0.95$ for L-modes, H-modes and transitions in discharges with $B_T = 8 \text{ T}$ and $I_p = 1.0–1.25 \text{ MA}$. A higher L–H threshold is seen. $T_e$ varies at H–L transitions, but is always $\geq T_e(\text{L–H})$. 
A few experiments were carried out with the field and current direction reversed, giving the ion $\nabla B$ drift direction away from the active divertor rather than towards it. As observed on other tokamaks, roughly twice as much input power was required to obtain H-mode in this case. We found that the edge threshold temperature is also doubled. This means that the local threshold condition changes, and may imply that flows in the SOL, which are known to depend on drift direction [6], are playing a role.

Conditions at the H–L transition show more variation. In cases where the back transition is clearly due to insufficient power, for example with reduced RF power or increased radiation, the H–L transition temperature is essentially the same as the L–H threshold, showing little or no hysteresis. This was the typical situation prior to the use of boronization on C-Mod [3]. At some H–L transitions the $T_e$ pedestal drops within a few milliseconds, simultaneous with the rise in $D_\alpha$. The temperature immediately prior to such rapid back transitions shows large scatter, as reflected in figure 2, and is often greater than at the L–H threshold. In some rapid transitions a burst of fast magnetic fluctuations accompanies the pedestal crash, suggesting a role of MHD instabilities. Magnetic precursors at $>100$ kHz have been seen 100 $\mu s$ before $D_\alpha$ emission starts to rise, followed by a larger-amplitude, lower-frequency burst. The cause of the MHD activity is still being investigated.

3. Comparison with theory

The availability of local parameters at the H-mode transition, on C-Mod as well as on other machines [7–10], makes possible more direct comparisons with theory than could be done on the basis of global power thresholds. All current theories involve edge parameters, either in the SOL or in the pedestal region. Probably the most prevalent idea is that $E \times B$ velocity shear leads to turbulence suppression [11, 12]. The existence of a threshold in $\nabla T$, which is closely related to $\nabla P/n$, is certainly consistent with such a picture. However, the theories as presently developed do not lead to easily testable predictions for an H-mode threshold. Edge toroidal and poloidal rotations, for which we do not yet have data on C-Mod, can be important variables in this model. The planned addition of a diagnostic neutral beam will permit measurements of rotations as well as of $T_i(R)$ and $j(R)$.

In a different approach, 3D numerical simulations of drift-ballooning turbulence near the plasma edge have been carried out [13]. The transport in these simulations depends critically on two dimensionless parameters: the ideal MHD ballooning parameter $\alpha = -Rq^2\partial \beta/\partial r$, and an ion diamagnetic parameter $\alpha_{di} = v_{di0}t_0/L_0$, where $v_{di0} = \rho sc_s/L_{pi}$ is the equilibrium ion diamagnetic velocity, $t_0$ is the ideal ballooning time and $L_0$ is a characteristic turbulence scale length. These variables are as defined in [13], except that we have used the shorter ion pressure scale length $L_{pi}$ in place of $L_n$. The simulations indicate that a transport barrier forms spontaneously due to self-generated, sheared poloidal flows when these parameters both exceed certain order-unity thresholds: $\alpha \gtrsim \alpha_{crit}$, $\alpha_{di} \gtrsim \alpha_{di,crit}$, where, for the case of $T_i \sim T_e$, $\hat{s} \sim 1$, and $\eta_i \lesssim 1$, $\alpha_{crit} \sim 0.5$ and $\alpha_{di,crit} \sim 0.6$.

Figure 3 shows a plot of $\alpha$ and $\alpha_{di}$ values, computed at the $\psi = 0.95$ surface, for the 8 T points from figure 2. The L–H transitions, represented by solid triangles, do exhibit thresholds in these parameters which are close to the critical values $\alpha_{crit}$ and $\alpha_{di,crit}$ predicted by the simulations. L–H transitions at 5.3 T, while displaying greater scatter as in the raw data, overlap the 8 T points in this dimensionless space despite having quite different global and local threshold parameters. It should be noted that the scale lengths $L_{pi}$ and $L_n$ vary in space and have significant experimental uncertainties. They are likely to be overestimated in the H-mode pedestal [14], so that the circles represent a lower bound on $\alpha$ and on $\alpha_{di}$. Inside the separatrix $\eta_i > 1$ for C-Mod, unlike in the simulations to date. We thus find the
Figure 3. Dimensionless ballooning parameter $\alpha$ versus the ion diamagnetic parameter $\alpha_{di}$ at $\psi = 0.95$ for the 8 T points from figure 2. Solid triangles indicate L-H transitions, and are near predicted critical values (solid curve). H-mode points (circles) extend to $\alpha = 1.2$ and $\alpha_{di} = 1.7$.

level of agreement of predicted and measured thresholds very encouraging, and will pursue further comparisons.

There is not yet a single H-mode theory which can be definitively validated by local threshold parameters. However, much progress is being made by such comparisons on several tokamaks. It is, for example, evident that theories requiring a threshold temperature which increases with density (e.g. constant collisionality) are inconsistent with our measured data. On a single device, correlations between parameters such as $T$, $\nabla T$, $\nabla P/n_e$ and $\beta$ make it difficult to distinguish between possible thresholds. We hope to make further progress by comparing data between machines. Measurements and modelling to assess the possible role of neutrals on the H-mode transition are also in progress.

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