

PFC/JA-96-42

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October 1996

To be published in the Proceedings of the 16th IAEA Fusion Energy Conference.

This work was supported by the U. S. Department of Energy Contract No. DE-AC02-78ET51013. Reproduction, translation, publication, use and disposal, in whole or in part by or for the United States government is permitted.

LOCAL PLASMA PARAMETERS AND H-MODE THRESHOLD IN ALCATOR C-MOD

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Abstract

Local plasma conditions in the outer region of the Alcator C-Mod tokamak are studied at the transition between L and H mode. Both controlled parameter scans and a database of H-mode discharges are examined. It is found that a minimum edge temperature, as measured by electron cyclotron emission diagnostics, must be exceeded in order to enter and remain in H-mode. This condition is not always sufficient, however. Density, and therefore pressure, appear to play a less important role. Comparison of 5.3 T and 8 T discharges shows that the threshold temperature increases with B_T . The ion larmor radius thus remains in a narrow range at the transition, while beta and collisionality show a very wide variation. Discharges with the ion grad-B drift away from the x-point have L-mode temperatures similar to those with the usual direction toward the divertor. Both the global power threshold and local edge temperature at the L-H transition are approximately doubled.

1. INTRODUCTION

The role of the local temperature and density in the transport barrier region in determining the transitions between the L-mode and H-mode confinement regimes has been examined on the Alcator C-Mod tokamak. C-Mod is a high field, compact device, with $R=0.67$ m and $a=0.21$ m. H-mode is routinely obtained with ICRF heating, at toroidal fields up to 8 T. Ohmic and RF H-modes have also been seen at B_T as low as 2.6 T. These parameters are quite different from those of other divertor tokamaks, making C-Mod an interesting device for H-mode threshold studies. Most operation has been with molybdenum walls, but improved H-modes have been obtained in 1996 experiments following boronization [1].

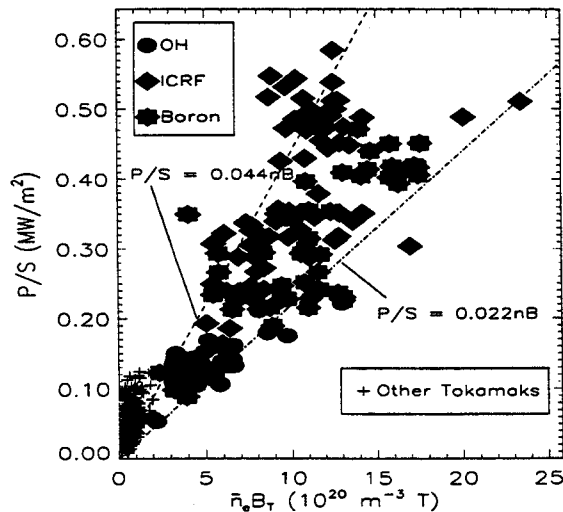


Fig. 1. Global H-mode power threshold for C-Mod, showing scaling with the product of density and magnetic field.

Scalings for the H-mode power threshold on C-Mod in terms of global quantities show that the power required to obtain an L-H transition is $P_{\text{thresh}}(\text{MW}) = 0.02\text{-}0.04 n_e B_T S$, where n_e is the line averaged density (10^{20} m^{-3}) and S the surface area (m^2) [2]. Wall conditions appear to play a role and after boronization thresholds tend to lie at the lower end of this range (Fig. 1). Below a density of $\sim 0.9 \times 10^{20} \text{ m}^{-3}$, the threshold power increases sharply, giving a low density limit which is relatively high. Such global parameter scalings, which include C-Mod data, are used to predict power requirements for ITER [3]. However, with any present scaling, there is typically variation of a factor of two or more in the threshold power on a given machine, and nearly an order of magnitude when comparing different machines. A lower threshold is generally found for the H-L transition, and the scaling of this hysteresis is even less well established. A further limitation of global power scalings is that they provide little insight into the physical mechanisms responsible for the transitions in confinement.

The limitations in our understanding and predictive capability motivate the search for more local threshold conditions. It has been observed since the earliest H-modes on ASDEX [4,5] that edge parameters appear to play a role. In particular, the transition was often correlated with a sawtooth heat pulse, and H-mode could be delayed by cooling the edge. Recent experiments on DIII-D [6] also point to a role for edge electron or ion temperature.

2. DIAGNOSTICS

The study of local parameters on C-Mod concentrates on the region just inside the separatrix. Since this is where temperature and density gradients are observed to steepen and fluctuation levels to drop in H-mode, it is likely that this is an important region for the threshold. The primary edge diagnostics are electron cyclotron emission (ECE) for $T_e(R)$ and reflectometry for $n_e(R)$. ECE diagnostics consist of a Michelson interferometer, which is absolutely calibrated, and a nine channel grating polychromator, which gives higher time and radial resolution and is cross-calibrated against the Michelson. Estimated systematic errors are $\pm 10\%$ on T_e , with radial resolutions approximately 1 cm. The random noise level is typically ~ 20 eV. Density profiles are measured by an interferometer with 10 vertical chords. For some discharges, these are supplemented by edge profiles from a 5-channel o-mode amplitude-modulated reflectometer. A scanning Langmuir probe is used to measure profiles outside the separatrix, where the ECE becomes optically thin. Probably the biggest source of uncertainty for all of these measurements, given the steep gradients characteristic of the edge region, is the mapping of data to a given surface of normalized poloidal magnetic flux, ψ . The mapping is done using the EFIT magnetic reconstruction package [7] and its estimated accuracy is 3 mm at the horizontal midplane. The effects of these uncertainties can be minimized by keeping magnetic equilibria similar while doing controlled threshold scans.

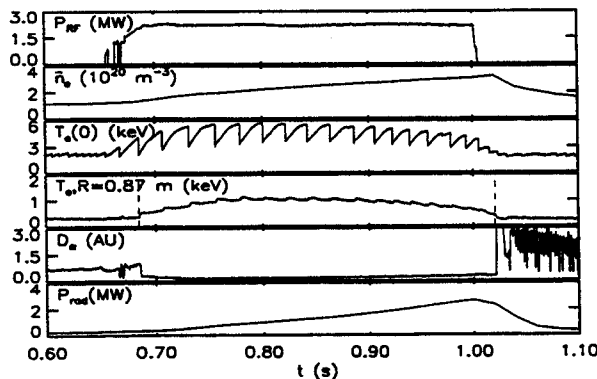


Fig. 2. Time evolution of plasma parameters during an ELM-free H-mode with $I_p = 1.0$ MA and $B_T = 5.3$ T. The vertical lines show the L-H and H-L transitions..

The time behaviour of plasma parameters during a typical ELM-free H-mode with boronized wall conditions is shown in Fig. 2. In the RF-heated L-mode, electron temperature increases throughout the plasma cross-section while the density is unaffected. Once the H-mode transition occurs, as evidenced by a drop in D_{α} , there is a rapid formation of an edge pedestal in both density and temperature. The central T_e and n_e also increase, as does the radiated power due to an improvement in impurity confinement. This gradually erodes the edge T_e pedestal, and an H-L transition occurs at 1.02 seconds. ELMy and enhanced D_{α} H-modes are also observed on C-Mod. For threshold studies, it is the conditions just before the L-H and H-L transition, rather than the details of H-mode behaviour, which are of interest.

3. RESULTS

The most striking result to date is that for a given magnetic configuration, ie. constant I_p , B_T and grad-B drift direction, the L-H transition occurs at a nearly constant edge T_e over a wide range of plasma densities and input powers. This is most clearly evident in a controlled parameter scan such as that summarized in Fig. 3, which shows results at 0.8 MA and 5.3 T. For each discharge, the power was stepped up and the temperature at the $\psi=0.95$ surface increased correspondingly. In each case the L-H transition (solid symbols) occurred when $T_e(\psi=0.95)$ reached 0.12 keV. At the lowest densities in this scan, the optical depth of the ECE at this radius is becoming marginal. However, the same trend is observed further in the plasma ($\psi=0.85$), where T_e and n_e are higher. The power required to reach the threshold temperature generally increases with density, consistent with the global power scaling. The exception is near the low density limit, when the edge is much cooler and where more power is required to reach H-mode. In other low n_e discharges of this scan, the edge remained below 0.1 keV even at maximum available power and H-mode was not achieved.

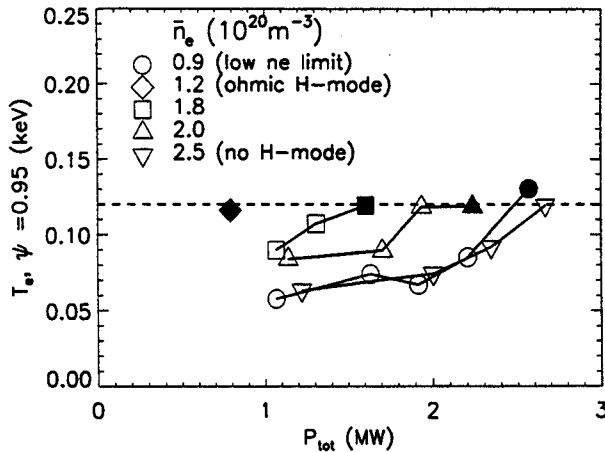


Fig. 3. Dependence of T_e at $\psi=0.95$ on total input power in L-mode, for a series of discharges with different densities. The solid symbols indicate conditions just prior to the L-H transition.

The trend of a minimum edge temperature for achieving H-mode is also seen in the wider database of C-Mod shots. Figure 4 shows a number of discharges from the post-boronization run period, with $I_p=1.0-1.2$ MA and $B_T=5.3$ T. While, not unexpectedly, there is more scatter in the data, all the L-H transitions (solid triangles) occur at $T_e > 100$ eV and most are at $T_e < 150$ eV, independent of density. A few discharges are found to have higher temperature at the transition, in particular those with n_e approaching the low density limit. This implies that the edge temperature threshold may be a necessary but not always sufficient condition for entering H-mode. Similar trends were found in the 1995 data [2]. The lower threshold T_e quoted here is a result of more accurate calculation of the location of ECE channels with respect to flux surfaces; there is not a systematic change due to boronization.

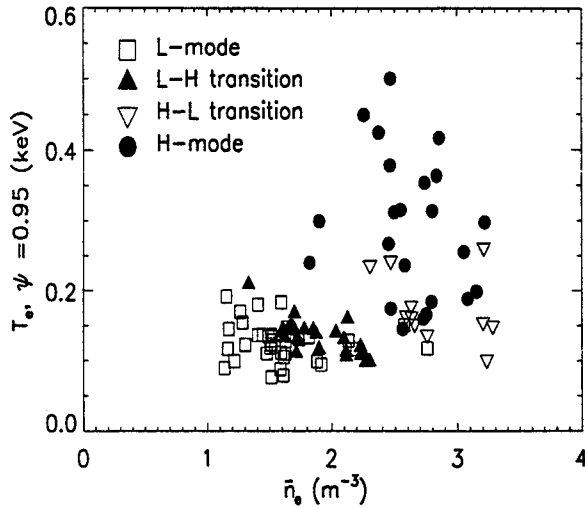


Fig. 4. Edge T_e vs line averaged density for discharges with $I_p = 1.0-1.2$ MA and $B_T = 5.3$ T. Note the large increase in T_e during H-Mode, and the clustering of values at the L-H transition.

Scalings of local discharge parameters with global parameters show that the strongest dependence is on toroidal field. The L-H transition temperature increases with B_T (Fig. 5), with a power between 1.2 and 1.5, depending on the dataset used and the other parameters included in regression fits. This is consistent with a global power threshold which increases with B_T , as seen on C-Mod and in multi-machine databases. No significant dependence on I_p is seen. There is a weak dependence of the average threshold temperature on n_e , due mainly to the increased scatter at low density. The minimum T_e at which H-modes have been seen is, however, nearly independent of density.

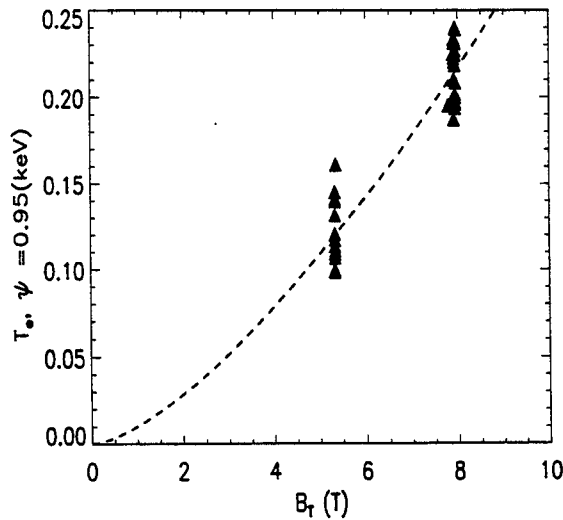


Fig. 5. Dependence of T_e threshold on toroidal field, for a group of 1996 discharges with $I_p = 1.0-1.1$ MA and density well above the low density limit. Dashed line is best fit, proportional to $B_T^{1.46}$.

The behaviour at the H-L transition is more complicated, and depends on the type of H-mode and radiation conditions. After the H-mode edge temperature pedestal is formed, it tends to decrease as density and P_{rad} increase due to improved particle confinement, especially in ELM-free H-modes. If the edge temperature is reduced below the L-H threshold temperature, the plasma reverts to L-mode. This was the typical behaviour in pre-boronization experiments, and leads to a relatively slow loss of confinement. On many boronized discharges, particularly ELMy H-modes, the edge T_e remains well above the L-H threshold throughout a long H-mode. When the H-L transition occurs, there is a rapid collapse of the edge pedestal. At least some of these discharges, which typically have very steep edge pressure

gradients, are computed to be unstable to ballooning and low n ideal modes. MHD activity is sometimes seen prior to such H-L transitions. It again appears that the edge temperature threshold is a necessary but insufficient condition for remaining in H-mode, and that this local condition, unlike global power thresholds, does not show hysteresis. In this context, the lower H-L power threshold may be seen as a result of the improved confinement in H-mode, ie. for a given P/n_e , an H-mode plasma will have a hotter edge. Given the wide variation in H factors which is seen under various conditions and on different experiments, it is not surprising that the H-L global power threshold shows a wide variation [3]. The added requirement for MHD stability further complicates this power threshold.

An interesting and often-observed feature of the H-mode is that approximately twice as much power is required when the ion grad-B drift direction is away from instead of towards the active divertor. In the context of a local threshold, it is thus of interest to compare the edge plasma conditions in the two configurations. While most C-Mod operation, including all of the results quoted above, has been with the favourable drift direction, a few days were devoted to operation with 'reverse' B_T and I_p . It was found that in L mode, edge temperatures follow the same scaling with total power per particle as in discharges with 'normal' field direction (Fig. 6). The main difference is that they remained in L-mode with much more power, and correspondingly higher edge temperatures. In the few discharges which did briefly enter H-mode, the temperatures at the L-H transitions were in the range 260-320 eV, approximately twice the threshold values with the more favourable drift direction. A similar observation has been mentioned on ASDEX Upgrade [8]. This shows that the reason for higher global thresholds with reverse field is *not* that the edge is cooler. Whatever the mechanism for the H-mode transport improvement, it clearly is affected by field direction, either via drift or other flows.

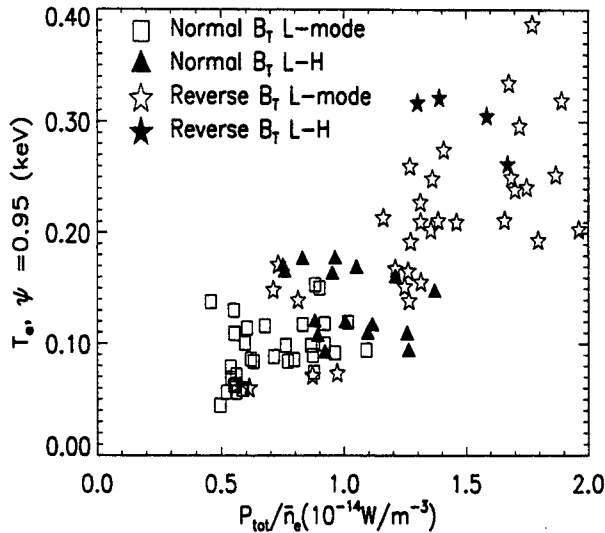


Fig. 6. Comparison of T_e ($\psi=0.95$) vs P_{tot}/n_e for similar groups of discharges with ion grad-B drift towards and away from the divertor. Parameters are $B_T=5.3-5.6$ T, $I_p=0.8-1.0$ MA, $n_e=1.8-3.0 \times 10^{20} \text{ m}^{-3}$, and RF power 0-3.1 MW.

4. DISCUSSION

Thresholds based on local parameters offer a basis for comparison with H-mode transition theories. Most prevalent theories involve stabilization of turbulence via ExB shear, though there is debate as to the mechanism for the shear [9]. It should be noted that the measured ECE temperatures inside the separatrix are indicative of the temperature gradient in the transport barrier region. Measured gradient scale lengths are typically 1 cm or less, limited by diagnostic resolution. At the high densities on C-Mod we expect $T_i \sim T_e$, but are presently lacking spatially resolved measurements of T_i in the edge region. It will thus be difficult to distinguish a threshold in T_e from one in T_i or dT/dR . Similar thresholds and scalings to those

shown are found plotting dT_e/dR , or T_e at the 85% or 90% flux surface, so $\psi=0.95$ is not necessarily the critical location for H-mode transitions. However, since up-down asymmetries mainly affect the region outside or just inside the separatrix, the results of reverse field experiments imply that the extreme edge region plays an important role in H-mode physics.

The threshold scalings can be used to help identify which dimensionless variables may be important for H-mode transitions. The observed temperature threshold is not strongly dependent on n_e . This implies either that η^* and β are not important variables, or that their functional dependences are such as to cancel out the density dependence. Given the positive dependence of threshold T_e with field, the ion gyroradius ρ emerges as a possibly important parameter. Figure 7 shows ρ vs β at the 95% flux surface, calculated using B_T at the outer midplane and assuming that $T_i=T_e$, for all L-H transitions in the database for the spring 1996 campaign. While there is scatter in both parameters, it is clear that the ion gyroradius shows less variation at the transition than does β and is nearly independent of B_T . The calculated $\rho \sim 0.4$ mm is to be compared with gradient scale lengths of 1-2 mm typical of the C-Mod SOL near the separatrix. The normalized ion collisionality η_i^* at $\psi=0.95$ varies from 2.1 to 32 at the L-H transition, making it an unlikely candidate for a dimensionless threshold.

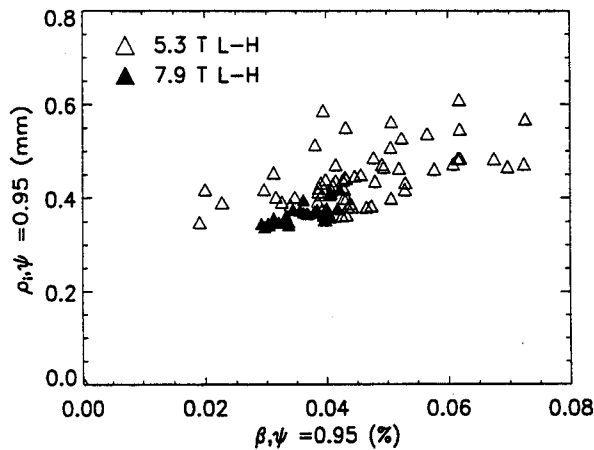


Fig. 7. Variation of β and ion gyroradius at $\psi=0.95$ for L-H transitions with a wide range of plasma parameters.

Comparing the observed local and dimensionless parameters on machines of different sizes and global parameters, as is proposed in a new version of the ITER threshold database, may provide further opportunities for scalings and tests of theory. Planned experiments on C-Mod include extending the density range of H-modes at 8 T and more systematic study of the H-L transition and low density limit.

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