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The regime of high particle and energy confinement known as H-mode [Phys. Rev. Lett. **49**, 1408 (1982)] has been extended to a unique range of operation for divertor tokamaks up to toroidal fields of nearly 8 T, line averaged electron densities of 3 x 10^{20} m^{-3}, and surface power densities of nearly 0.6 MW/m^2 in the compact high field tokamak Alcator C-Mod [Phys. Plasmas **1**, 1511 (1994)]. H-modes are achieved in Alcator C-Mod with Ion Cyclotron Resonant Frequency (ICRF) heating and with ohmic heating alone without boronization of the all molybdenum tiled first wall. Large increases in charge exchange flux are observed during H-mode over the entire range of energies from 2 to 10 keV. There appears to be an upper limit to the midplane neutral pressure, of about 0.08 Pascal, above which no H-modes have been observed. The plasmas with the best energy confinement have the lowest midplane neutral pressures, below 0.01 Pascal. There is an edge electron temperature threshold such that $T_e \geq 280$ eV ± 40 eV for sustaining the H-mode, which is equal at L-H and H-L transitions. The hysteresis in the threshold power between L-H and H-L transitions is less than 25% on the average. Both core and edge particle confinement improve by a factor of two to four from L-mode to H-mode. Energy confinement also improves by up to a factor of two over L-mode.

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I. Introduction

A regime of plasma operation in which both the particle and energy confinement spontaneously improve accompanied by steep gradients in the edge temperature and density and reduced H_α emission is known as a high confinement mode of operation, or H-mode.[1] This mode of operation was first discovered on the Asymmetric Divertor Experiment, ASDEX, [1,2] and later observed on many different tokamaks.[3,4,5] The H-mode regime is extended on the compact, high field divertor tokamak, Alcator C-Mod,[6] up to toroidal fields of nearly 8 T and average surface power densities of nearly 0.6 MW/m^2. Previous H-mode results on the Japanese Tokamak Upgrade, JT60-U,[7] and the Tokamak Fusion Test Reactor, TFTR,[8] had toroidal fields up to 4.2 and 5.2 T, surface power densities up to 0.16 and 0.3 MW/ m^2, and line averaged densities up to 0.3 and 0.25 x 10^{20} m^{-3}, respectively. The results presented here extend the toroidal field by 50%, the power density by a factor of two, and the electron density by an order of magnitude, into the range expected for the International Thermonuclear Experimental Reactor, ITER.[9] Unlike most other tokamaks, which have a first wall made of graphite, Alcator C-Mod has a molybdenum first wall and all of these results have been obtained without boronization.[10]

H-mode operation on C-Mod can be achieved with Ion Cyclotron Resonant Frequency, ICRF, heating or with ohmic heating alone. Ohmic H-modes have occurred with plasma currents of $0.6 < I_p < 0.9$ MA and toroidal fields from $2.9 < B_T < 5.3$ T. The ohmic input power required to reach H-mode has varied from 0.75 MW to 1.5 MW. ICRF heated H-modes have been achieved at toroidal fields of 5.3 and 7.9 T, which correspond to the cyclotron resonances for H and He^3 minorities at the 80 MHz fixed frequency of the ICRF transmitters. The total input power for ICRF H-modes has varied from 0.9 to 4.2 MW. The H-modes at 7.9 T occurred shortly after a lithium pellet was injected into the plasma at line averaged electron densities of 3 x 10^{20} m^{-3}, before the density returned to the pre-pellet level.[11] The pellet produces highly peaked density profiles which, together with strong ICRF heating, produce enhanced neutron rates characteristic of Pellet mode, P mode,[12] or Pellet Enhanced Performance mode, PEP mode.[13] The presence of H-mode at such high density and toroidal field suggests that either the lithium has transiently improved wall conditions or that pellet fueling may be favorable for achieving H-mode at high density.

All of the H-modes on C-Mod have occurred with the ion ∇B drift in the favorable direction[2] toward a single null X point. An attempt was made to achieve H-modes with the ion ∇B drift direction away from the single null X point by reversing both the plasma current and the toroidal field, but no clear H-modes were observed with more than twice the input power required to achieve H-mode under similar conditions with the favorable ion ∇B drift direction. All of the results presented here are with deuterium plasmas. No attempt to test the isotope scaling of the H-mode threshold has been made on C-Mod. The confinement measurements presented here all use the magnetohydrodynamic, MHD, calculated stored energy from the EFIT code.[14]

This paper will concentrate on some of the more important characteristics of H-modes in Alcator C-Mod including the behavior of neutral particles, the hysteresis in the power threshold, and the measured improvement in both particle and energy confinement.

II. Neutral Particle Behavior in H-mode

At the Low-High, L-H, transition, the midplane neutral pressure drops and the charge exchange flux often increases across the entire range from 2 to at least 10 keV. There is a tendency for the H-mode power threshold to be lower at lower midplane neutral pressure and there appears to be an upper limit to the midplane neutral pressure above which H-modes no longer occur. In addition, the H-mode plasmas with the best energy confinement have the lowest midplane neutral pressures.

The drop in the midplane neutral pressure when the plasma enters H-mode leads to the highest divertor neutral compression ratios $(\frac{P^0_{\mathrm{divertor}}}{P^0_{\mathrm{midplane}}})$ of all regimes of operation in C-Mod. The neutral pressure measurements are made with standard ion gauges about 1.5 meters from the plasma through a horizontal port (midplane) and a vertical port (divertor). While the divertor pressure also drops slightly in H-mode, the ratio of the divertor to midplane pressure increases to peak values of about 140 in some H-mode discharges. This is to be compared with the highest values of the neutral compression ratio in the high density, high recycling regime of about 75.[15] Maintaining a high divertor neutral compression ratio is thought to be good for a future reactor because it reflects the efficiency of the divertor in diverting particles away from the main plasma and because higher divertor neutral pressures lead to lower heat flux on the target plates. Thus, combining the high recycling divertor and H-mode regimes provides the most efficient divertor operation.

Figure 1 shows time traces of the hydrogen and deuterium charge exchange flux in the 3.5 keV energy range for an ICRF heated, hydrogen minority discharge with several H-mode phases. Both the hydrogen and deuterium fluxes increase by at least a factor of two indicating that either the ion temperature or the neutral density in the main plasma increased substantially. The charge exchange flux increases in H-mode throughout the energy range from 2 keV to at least 10 keV (Fig. 2), indicating that the particles affected have a broad energy spectrum. The change in the slope of the energy spectrum suggests that the ion temperature increased, but an increase in the neutral density cannot be ruled out. By contrast, previous results on the Poloidal Divertor Experiment, PDX, indicated that the fast neutral particle flux decreased by 30 - 50% from the plasma core.[3] Since the temperature and density profiles both drop outside the last closed flux surface (LCFS) in H-mode,[16] neutral particles are less effectively screened by the scrape off layer and so more neutrals should penetrate inside the last closed flux surface. Such enhanced neutral penetration might explain the increased charge exchange flux as well as the drop in neutral pressure in H-mode.

Lower midplane neutral pressure in H-mode is also correlated with the highest energy confinement. Figure 3 shows that all discharges with energy confinement times above about 1.5 times the ITER89-P L-mode scaling[17] have midplane neutral pressures below 0.01 Pascal. There may be other factors at work since the discharges with the lowest neutral pressure are all ohmic, but the fact remains that good energy confinement is correlated with low midplane neutral pressure. A similar result was also found on PDX.[3] Thus, high midplane neutral pressure may make it difficult to set up the steep gradients, electric fields, or high temperatures necessary to sustain the H-mode confinement barrier at the edge.

III. H-mode Power Threshold

The total input power required to enter the H-mode depends on a number of global plasma parameters and machine conditions such as the magnetic configuration, wall conditions, electron density, and the toroidal field. The scaling, $P/S = 0.044\ \bar{n}_e\ B_T$, where P is the total input power and S is the total plasma surface area at the last closed flux surface, was proposed to describe ASDEX-Upgrade.[18] A similar scaling was previously found on DIII-D.[19] The Alcator C-Mod H-mode power threshold also increases with density and toroidal field, though the coefficient usually lies between 0.02 and 0.044,[16] indicating a rather low power threshold even without boronization, which tends to lower the threshold in graphite first wall machines. Note that the lowest thresholds in C-Mod occur with and without lithium pellets. While some other tokamaks find low density limits of $\bar{n}_e \approx 2 - 3 \times 10^{19}\ m^{-3}$ below which no H-modes are observed,[20,21] a low density limit of $\bar{n}_e \approx 8 \times 10^{19}\ m^{-3}$ is found on C-Mod.[16]

In addition to the dependence of the H-mode power threshold on global parameters, there is also a strong dependence on the edge electron temperature.[16,19,22] Figure 4 shows the electron temperature at the 95% flux surface measured by a nine channel Electron Cyclotron Emission (ECE) grating polychromator[23] versus the H-mode power threshold scaling parameter $P / (\bar{n}_e B_T S)$ for a number of discharges with $I_p = 1$ MA and $B_T = 5.3$ T. There are nine ECE channels in the midplane with 1 - 2 cm radial spatial resolution. The temperature at the 95% flux surface is determined by mapping these channels to flux surfaces calculated with EFIT. The edge electron temperature has approximately the same threshold value, 280 ± 40 eV, at both the L-H and the H-L transitions. This indicates that the edge temperature must be greater than this threshold value to remain in H-mode. The threshold edge temperature increases with plasma current and, although the data are limited at other toroidal fields, it also appears to increase with toroidal field.

One question of importance to ITER is to what extent there is hysteresis in the H-mode threshold. That is, how much power is required to maintain the H-mode once the plasma is in H-mode. The hysteresis in the threshold can be defined for a given scaling as the ratio of the threshold values at the L-H transition to the values at the H-L transition. Then, a hysteresis of 2 would mean that the H-mode could be constantly maintained with half of the threshold power. Figure 5 shows the ratio of $[P/(nBS)]_{L\text{-}H}$ just before the L-H transition to $[P/(nBS)]_{H\text{-}L}$ just before the H-L transition versus $[P/(nBS)]_{L\text{-}H}$ for ohmic H-mode discharges and ICRF H-mode discharges in which the power was not switched off before the H-L transition. The hysteresis varies from 0.8 to about 1.8 with an average value of 1.24. So, on the average, the density could increase 24% and the plasma would remain in H-mode with constant input power. Or, equivalently, the H-mode could be maintained at constant density with only about 80% of the L-H threshold input power. The hysteresis is unaffected by lithium pellets. Note that in the edge electron temperature threshold figure (Fig. 4), many of the H-L transition data points were taken just after the ICRF power was switched off, so the H-L threshold power is underestimated and the hysteresis is not well determined.

IV. Particle Confinement

One of the fundamental characteristics of H-modes is a large, rapid increase in particle confinement at the L-H transition that lasts for the duration of the H-mode. The edge particle confinement in C-Mod is estimated from the ratio of the total number of ions in the plasma to an average of the H_α emission. The core particle confinement is measured directly from the decay of non-intrinsic, non-recycling impurities injected into the core with laser ablation. Both of these methods show a factor of two to four improvement in particle confinement between L and H-mode.

Taking the ratio of the total number of ions in the plasma, N, to the outflux of ions, Γ, times the area of the plasma, A, minus $\frac{dN}{dt}$, the edge particle confinement time can be written as:

$$\tau_p = \frac{N}{\Gamma A - \frac{dN}{dt}} \propto \frac{N}{\langle \sum H_\alpha \rangle} \quad . \tag{1}$$

The last proportionality is made by assuming that the ion outflux is equal to the ion influx, the H_α emission is proportional to the ion influx, and by using the fact that the measured $\frac{dN}{dt}$ term is negligible. Figure 6 shows the ratio of the total number of particles to the average H_α emission versus line averaged density. The H-mode values are clearly higher than those in L-mode by factors of 2 to 4. The characteristic increase in particle confinement at low density then decrease at high density can also be seen.[24]

The core particle confinement time can also be inferred directly from the decay of the emission from a non-recycling impurity injected into the plasma core. Figure 7 shows a comparison of Zr^{+29} emission following laser ablation of zirconium into two similar discharges, one in L-mode and the other in H-mode. The emission decays with a characteristic timescale of about 20 msec in L-mode and about 40 msec in H-mode. In this case, the core particle confinement time in H-mode is approximately twice the L-mode value.

V. Energy Confinement

In addition to the improved particle confinement in H-mode, the energy confinement also improves by up to a factor of 2 over L-mode. The highest energy confinement in C-Mod has been obtained in ohmic H-mode plasmas at a relatively low toroidal field of 3.5 T. Figure 8 shows time histories of the total energy confinement time, the line averaged density, and the H_α emission from the X point for such an ohmic H-mode discharge. Peak values of τ_E up to about 80 msec have been observed. The energy confinement time depends on a number of parameters including the total input power, the electron density, the plasma current, and the midplane neutral pressure. Figure 9 shows the total energy confinement time versus total input power for both H-mode and L-mode discharges. The energy confinement clearly degrades with input power with something like a $P^{-0.5}$ dependence.

Since there are covariances in the parameters on which the energy confinement depends, no attempt has been made to determine a confinement scaling with the C-Mod data alone. Instead, the C-Mod results can be compared with the published confinement scaling laws for

ITER. Figure 10 shows the comparison of both L and H-mode discharges with a) the ITER89-P L-mode scaling,[17] b) the ITER93 (Edge Localized Mode) ELMy H-mode scaling,[25] and c) the ITER93 ELM-free H-mode scaling.[25] Define three H factors, H_L , H_E , and H_{EF} as the ratio of the measured τ_E to the τ_E calculated from the ITER89-P, ITER93 ELMy, and ITER93 ELM-free scaling laws.

The ohmic H-modes in C-Mod often have better confinement than the ICRF H-modes for line averaged densities below about 1.5 x 10^{20} m^{-3} (Fig. 10a). In comparison with ITER89-P, the ohmic H_L factors reach 2, while the ICRF H_L factors reach only 1.5. The ICRF L-mode data and most of the elongated ohmic data that are not in H-mode generally follow the ITER89-P L-mode scaling.[26] So, except for some of the ohmic data at moderate density that lie between 1.3 and 1.5 x L-mode (Fig. 10a), it is reasonable to call the ohmic data that are not in H-mode ohmic L-mode.

In comparison with the ITER93 ELMy H-mode scaling, the H_E factors in C-Mod are generally greater than 1, indicating that the confinement is as good or better than expected for an ELMy H-mode, even for much of the L-mode data. Taking the ratio of the ITER93 ELMy H-mode scaling to the ITER89-P L-mode scaling and inserting typical C-Mod parameters, one finds values of about 1, effectively predicting L-mode confinement for ELMy H-modes. This brings into question the validity of the ITER93 ELMy H-mode scaling law for C-Mod. The very strong size dependence of the ELMy H-mode scaling law ($R^{2.52}$) predicts rather poor ELMy H-mode confinement for a small machines like C-Mod, Compass-D, and the Tokamak a Configuration Variable, TCV, and exceptionally good confinement for a large device like ITER.

Finally, comparing the C-Mod data to the ITER93 ELM-free H-mode scaling, the H_{EF} factors are generally less than 1 with only a few of the best ohmic H-modes reaching as high as 1.2. Since only a few of the ELM-free H-modes reach H_L factors of order 2, it makes sense that only those H-modes should have H_{EF} factors of order 1. The H_{EF} factors of the L-mode data cluster around 0.5 to 0.6 and since ELM-free H-modes are generally expected to have about twice L-mode confinement, it makes sense that the L-mode data have H_{EF} factors of about 0.5. If one takes the ratio of the ITER93 ELM-free H-mode scaling to the ITER89-P L-mode scaling and inserts typical C-Mod parameters, one finds values of about 2, which is what is expected for good ELM-free H-modes. Thus, the ITER93 ELM-free scaling law agrees reasonably well with C-Mod data.

VI. Conclusions

Neutral particles appear to play an important role in the H-mode. The charge exchange flux increases substantially over the energy range from 2 to at least 10 keV when the plasma is in H-mode. The H-mode threshold tends to be lower for lower midplane neutral pressure and there appears to be an upper limit of about 0.08 Pascal above which no H-modes occur. The best energy confinement occurs when the midplane neutral pressure is below about 0.01 Pascal. The highest divertor neutral compression ratios in C-Mod occur in H-mode with values up to 140.

The H-mode power threshold is lower in C-Mod than in many other tokamaks assuming a $P/S \propto nB$ scaling. The hysteresis in the H-mode power threshold, however, is not particularly large in C-Mod, allowing a density increase, on the average, of less than 25% at constant input power before the plasma will return to L-mode. The L-H and H-L transitions occur at approximately the same edge electron temperature, indicating that local edge quantities may provide a better measure of the H-mode power threshold scaling than global parameters.

Both particle and energy confinement show considerable increases from L to H-mode. Core and edge particle confinement times increase by a factor of 2 to 4. Total energy confinement times increase by up to a factor of 2. The L-mode data fit the ITER89-P L-mode scaling reasonably well and the best H-modes have H factors of 2. The ELMy H-mode data fall between 1 and 2 times the ITER93 ELMy H-mode scaling, indicating that this scaling law underestimates the measured ELMy H-mode confinement in C-Mod, suggesting that the size scaling is too strong. The ELM-free H-mode data fall between 0.5 and 1.2 times the ITER93 ELM-free H-mode scaling, indicating reasonable agreement.

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Figure Captions

Fig. 1. Charge exchange flux signals for hydrogen and deuterium at 3.4 keV and 3.5 keV, respectively, together with a midplane H_α emission signal versus time showing large increases in the charge exchange flux during ELM-free H-modes and corresponding decreases during ELMy H-modes. The deuterium flux has been normalized to the hydrogen flux for comparison.

Fig. 2. Energy spectrum of the hydrogen and deuterium charge exchange flux in L and H-mode showing the increase in flux in H-mode across the energy range.

Fig. 3. The total energy confinement time normalized to the ITER89-P L-mode scaling versus midplane neutral pressure for L and H-mode discharges. Note that the discharges with the best confinement have the lowest midplane neutral pressures.

Fig. 4. Edge electron temperature at the 95% flux surface versus the H-mode threshold scaling parameter P/(nBS) showing that L-H and H-L transitions occur at approximately the same edge temperature. One discharge is followed from L-mode through the L-H transition to H-mode, back through the H-L transition to its return to L-mode.

Fig. 5. The H-mode power threshold hysteresis versus the threshold scaling parameter P/(nBS) at the L-H transition for ohmic and ICRF heated H-modes.

Fig. 6. Ratio of the total number of ions in the plasma to an average of the H_α emission versus the line averaged density for L and H-mode discharges. This ratio is assumed to be proportional to the edge particle confinement time.

Fig. 7. Emission from Zr^{+29} after laser ablation of zirconium into two similar discharges, one in L-mode and the other in H-mode. Exponential fits to the decay of the impurity emission shows that the core particle confinement time in H-mode is about twice the L-mode value.

Fig. 8. Time history of an ohmic H-mode discharge with $B_T = 3.5$ T, $I_p = 0.6$ MA showing the total energy confinement time compared to the ITER89-P L-mode scaling and the ITER93 ELM-free H-mode scaling, the line averaged density, and the H_α emission from the X point. One short ELMy H-mode is visible as well as three ELM-free H-modes interspersed with L-mode phases.

Fig. 9. The total energy confinement time versus total input power for both L and H-mode discharges. The filled symbols are H-mode and the open symbols are L-mode. The data exhibit a degradation with input power roughly proportional to $P^{-0.5}$.

Fig. 10. Comparison of the measured total energy confinement time with the ITER scaling laws: a) L-mode and all H-modes compared with the ITER89-P L-mode scaling, b) L-mode and ELMy H-modes compared with the ITER93 ELMy H- mode scaling, and c) L-mode and ELM-free H-modes compared with the ITER93 ELM-free H-mode scaling.