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ABSTRACT. Ohmic H-modes have been achieved in Alcator C-Mod with toroidal fields up to $B_T \approx 5.25$ T and line averaged densities up to $\bar{n}_e \approx 1.4 \times 10^{20}$ m^{-3} with less than 1 MW of input power. In ELM-free cases at lower toroidal field, the energy confinement increases by at least 60% and the particle confinement increases by more than a factor of two. The ELM-free H-modes appear to fit the threshold power scaling observed on other tokamaks, P/S (MW/m^2) $= 4.4 \times 10^{-3}$ $\bar{n}_e B_T$ (10^{19} m^{-3} T), up to power densities of about 0.15 MW/m^2. At higher toroidal field, ELMy H-modes were observed after the injection of lithium pellets at about half of the scaled threshold power density. All of these results were obtained with molybdenum plasma facing components and the ELM-free H-modes were obtained without boronization or other wall coating.

Particle and energy confinement in a tokamak plasma have been observed to improve spontaneously in a large number of experiments throughout the world when certain edge conditions are achieved and a threshold input power is exceeded. Such an improved or high confinement regime, known as an H-mode, was first observed on ASDEX [1] when sufficient neutral beam power was injected into a well conditioned diverted discharge. With high neutral beam power ($P_{NB} > 18$ MW) and substantial wall conditioning, H-modes have been achieved on JT-60U up to $B_T = 4.2$ T with $\bar{n}_e \leq 3 \times 10^{19}$ m^{-3} [2]. On several tokamaks, through extensive wall conditioning techniques to reduce impurity influxes, H-modes have also been achieved with ohmic power alone up to $B_T \leq 2.1$ T and $\bar{n}_e \leq 8 \times 10^{19}$ m^{-3} [3-5]. The threshold input power necessary to achieve H-mode was found to increase with increasing toroidal field [2-6] and electron density [4,5], which led to the conclusion that high field, high density tokamaks would find it difficult or impossible to operate in the H-mode [7]. The initial results from Alcator C-Mod [8] show that ohmic H-modes can be achieved at toroidal fields at least as high as $B_T = 5.25$ T and line averaged densities up to 1.4×10^{20} m^{-3} with all molybdenum plasma facing components.

The first indications of ohmic H-modes on Alcator C-Mod ($R = 0.67$ m, $a = 0.21$ m, $\kappa = 1.6$) were observed on the first day of operation with the ion ∇B drift direction toward the lower divertor in a lower single null X point magnetic configuration (Fig. 1). This field configuration was chosen because it was found to have a lower H-mode power threshold on other tokamaks. The toroidal field was ramped down at a rate of about 2 T/s with the plasma current held constant at $I_p \approx 0.65$ MA. Typically, ELMy H-mode transitions were observed as the toroidal

field passed below $B_T \approx 3.3$ T at a line averaged density of $\bar{n}_e \approx 1 \times 10^{20}$ m^{-3}. The ELMy H-mode continued for as long as 350 ms through the beginning of the plasma current ramp down, then returned to ohmic L mode as the plasma current dropped below 0.6 MA. The toroidal field dropped below about 3 T at the time of the H-L transition. There were modest density rises of less than 10% and little change in the stored energy.

These early indications of ohmic H-mode then led to a series of discharges with the toroidal field ramp starting earlier in the discharge and $I_p \approx 0.7$ MA. Transitions to ELM-free ohmic H-modes occurred with $2.9 < B_T < 3.2$ T and $0.75 < \bar{n}_e < 1.1 \times 10^{20}$ m^{-3}. The ELM-free phase was preceded by a short "dithering" or ELMy H-mode phase that lasted typically 100 ms. Increases of at least 60% in the plasma stored energy and electron density were observed in the ELM-free phase, which lasted typically 50 ms, often ending in a low q disruption as q_{95} passed through 2. Figure 2 shows an example of a discharge with a series of ELM-free ohmic H-modes. The main characteristics of H-modes[1], which include a distinctive drop in the $H_\alpha(D_\alpha)$ emission, sharp rise in the central electron density, increased particle and energy confinement, and steepening of edge gradients, are also observed on C-Mod. Estimates of the particle confinement time from $H_\alpha(D_\alpha)$ emission and electron density show a sudden increase of at least a factor of two at the L-H transition that remains for the duration of the H-mode. The neutral pressure, measured with a neutral pressure gauge in the divertor, drops substantially when the plasma goes into an ELM-free H-mode. Note that no wall conditioning was required to achieve these ELM-free H-modes except for standard Electron Cyclotron Discharge Cleaning (ECDC), which is normally on for several hours before tokamak operation, indicating that the molybdenum first wall of C-Mod can support sufficient power density at the plasma boundary to obtain H-modes without excessive cooling from impurity radiation.

Calculations of the energy confinement time during the ELM-free H-modes indicate at least a 60% increase in τ_E before any corrections for the changing stored energy, dW/dt. Typical values of τ_E before the H-mode are around 30 - 35 ms, reaching more than 60 ms before the H-L transition. These values can be compared with the regression fit power law expression for τ_E under ELM-free H-mode conditions from the combined ASDEX, DIII-D, JET, and PBX-M database [9],

$$\tau_{th} = 0.066 \ I_P^{1.11} \ P_L^{-0.51} \ R^{1.75} \ a^{-0.3} \ \kappa^{0.18} \ B_T^{0.15},$$

where I_p is the plasma current in MA, $P_L = P_T - dW/dt$, where P_T is the total input power in MW, R and a are the major and minor radii in m, κ is the elongation, and B_T is the toroidal field in T. A typical value for C-Mod conditions is 55 ms, which compares reasonably well with the measured values, when dW/dt corrections are not included. In some cases, however, the dW/dt term can be greater than half the ohmic input power, which, together with the short length of the ELM-free periods prevents a definitive analysis of confinement.

Central electron temperatures measured by ECE do not change significantly during the early part of the H-mode, indicating that the increased stored energy is mainly due to the increased density. Note, however, that the increasing density combined with the decreasing

toroidal field leads to a cutoff of the central emission, which prevents T_e measurements during much of the ELM-free phase in the lower field H-modes. The observed change in kinetic stored energy agrees with the change in stored energy calculated from magnetic measurements when temperature measurements are available.

In addition to the improved energy and particle confinement, there appears to also be improved impurity confinement. Z_{eff} increases from about 1.5 to 1.7, typically, during the density rise in the ELM-free H-modes. Fig. 2 shows the increase in the total radiated power with increasing electron density. The central soft x ray emission also increases with the total radiated power, but then remains high after the H-L transition until large sawtooth collapses reduce the soft x ray emission. This suggests that there may be increased peaking of impurities in the plasma center that remain peaked even after the H-L transition, until a large sawtooth collapse ejects the impurities and flattens the impurity profile across the plasma center.

The expected steepening of edge gradients in the plasma is observed with several diagnostics including the Langmuir probe arrays along the inner and outer divertor and on the outboard limiter as well as with the UV diode arrays viewing radially inward from the outboard wall. The Langmuir probe ion saturation current profile in the scrape-off layer mapped back to the midplane shows a gradual decay length of about $\lambda_{ISAT} \approx 10$ mm in the ohmic L mode that steepens to $\lambda_{ISAT} \approx 2$ mm in the ELM-free H-mode. Measurements were also made of the electron temperature and density from Langmuir probes in the outboard limiter, located about 4 cm outside the last closed flux surface in these discharges. For the discharge shown in Fig. 2, the density dropped by about a factor of two at the L-H transition, from about 2×10^{18} m^{-3} to 1×10^{18} m^{-3}, and remained lower throughout the ELM-free phase. Steepening of the edge gradients is also found in the UV radiation profiles. Figure 3 compares the UV profiles in ohmic L mode and ELM-free H-mode. The edge gradients are clearly much steeper in the H-mode. Phase and fluctuation level changes are also observed with a single channel reflectometer during ELMy H-modes. The frequency used was 60 GHz, so that the reflecting layer was at a density of about 4.5×10^{19} m^{-3}, which is near the last closed flux surface. The density fluctuation level dropped by at least a factor of two during the H-mode. The observed change in phase of the reflectometer signal at the L-H and H-L transitions is consistent with a steepening of the edge density profile during H-mode.

In addition to the H-modes at moderate toroidal field, a series of ELMy ohmic H-modes was achieved with $B_T \approx 5.25$ T, $I_p \approx 0.86$ MA, and line averaged electron densities of $0.9 < \bar{n}_e < 1.4 \times 10^{20}$ m^{-3}. These relatively high field transitions to ELMy H-mode occurred at constant toroidal field and lasted typically 50 - 200 ms. The ELMs were observed with a high sampling rate (100 kHz) on the $H_\alpha(D_\alpha)$ and CII signals and were found to be very regular, with a repetition rate of about 5-6 kHz (Figure 4). The ELM amplitude was largest near the X point and nearly unmeasurable at the midplane. These may be classified as Type III ELMs [10]. Despite the high frequency ELMs, the density and plasma stored energy rose typically by about 20% and the central electron temperature remained constant during the H-mode. Lithium pellets were injected throughout the day in which these relatively high field ELMy H-modes were achieved, suggesting that a wall conditioning effect similar to that observed in TFTR before supershots [11] may help to reduce the power threshold for achieving H-mode. In one

discharge, a lithium pellet was injected into the middle of an ELMy H-mode. Smaller amplitude and higher frequency (7.5 kHz) ELM-like oscillations persisted on the $H_\alpha(D_\alpha)$ signal viewing the X point for about 40 ms after the pellet, until the density returned to near the pre-pellet level, when the $H_\alpha(D_\alpha)$ emission at the midplane dropped sharply and the ELM amplitude and frequency returned to their pre-pellet levels as well. The H-mode apparently survived the Li pellet with only a transient return to L mode during the time that the density remained above about 1.2×10^{20} m^{-3}. Further experiments are planned to attempt to verify if indeed the addition of lithium to the plasma reduces the H-mode power threshold.

The latest scaling for the power threshold to achieve H-mode on ASDEX-Upgrade is [5]

$$P/S \ (MW/m^2) = 4.4 \times 10^{-3} \ \bar{n}_e B_T \ (10^{19} \ m^{-3} \ T)$$

where P is the input power, S is the plasma surface area, $\bar{n}_e$ is the line averaged electron density, and B_T is the toroidal field. The ASDEX-Upgrade results were obtained with boronized carbon walls at toroidal fields up to 1.35 T and densities up to 5×10^{19} m^{-3} including ohmic and ICRH induced H-modes. Figure 5 compares this power threshold scaling with the Alcator C-Mod and DIII-D results [4]. The DIII-D threshold coefficient is about a factor of two higher than the ASDEX-Upgrade coefficient. Note that both the DIII-D and the ASDEX-Upgrade points are all ELMy H-modes. Although the ohmic power in C-Mod could not be changed very much, the threshold power is determined by the changing values of $\bar{n}_e$ and B_T at the onset of H-mode for this scaling law. As can be seen in Fig. 5, the ELM-free H-modes and ELMy H-modes without lithium pellets at moderate toroidal field are reasonably consistent with the scaling, whereas the ELMy H-modes at higher toroidal field occur at about half of the predicted power threshold. If plasma physics alone governs the transition, then $P/(\bar{n}_e B_T R^{2.5})$ is a scale invariant parameter[12,13]. Therefore, it is possible that S should be replaced with $R^{2.5}$ or that the power law dependences of $\bar{n}_e$ or B_T are not exactly linear. Further experiments including additional heating with ICRF and direct comparisons with ASDEX-Upgrade will be performed to test this scaling in detail. Note that the C-Mod results extend the results of previous machines to much higher power densities and much higher values of $\bar{n}_e B_T$, approaching the values of the ITER CDA[14].

In summary, Alcator C-Mod has demonstrated ELMy and ELM-free ohmic H-mode operation at relatively high toroidal field with molybdenum plasma facing components. The plasma stored energy and density during the H-mode increase by at least 60% and the estimated particle confinement time more than doubles. While the ELM-free H-modes appear to fit the ASDEX-Upgrade H-mode power threshold scaling, the ELMy H-modes following lithium pellet injection occur at significantly lower input power. These results, together with previous results from other tokamaks[3-5], suggest that if the $\bar{n}_e B_T$ dependence of the H-mode power threshold is approximately correct, then there is also a dependence on wall conditions that can significantly lower the power threshold.

References

[1] Wagner, F., Becker, G., Behringer, K., Campbell, D., Eberhagen, A., et al., Phys. Rev. Lett., **49** (1982) 1408.

[2] Kikuchi, M., Shirai, H., Takizuka, T., Kamada, Y., Koide, Y., et al., Proc. 14th Int. Conf. Plasma Phys. and Cont. Nucl. Fus. Res., (1992, Würzburg, Germany) IAEA-CN-56/A-3-3.

[3] Schissel, D.P., Brooks, N., Burrell, K.H., et al., in Controlled Fusion and Plasma Physics (Proc. 16th Eur. Conf. Venice, 1989), Vol. 13B, Part I, European Physical Society (1989) 115.

[4] Osborne, T.H., Brooks, N.H., Burrell, K.H., Carlstrom, T.N., Groebner, R. J., et al., Nucl. Fus., **30** (1990) 2023.

[5] Ryter, F., Gruber, O., Büchl, K., Field, A.R., Fuchs, C., et al., in Controlled Fusion and Plasma Physics (Proc. 20th Eur. Conf. Lisboa, 1993), Vol. 17C, Part I, European Physical Society (1993) I-23.

[6] Tanga, A., Bartlett, D., Bures, M., et al., in Controlled Fusion and Plasma Heating (Proc. 15th Eur. Conf. Dubrovnik, 1988), Vol. 12B, Part I, European Physical Society (1988) 235.

[7] ASDEX Team, Nuclear Fusion, **29** (1989) 1959.

[8] Hutchinson, I.H., Boivin, R., Bombarda F., Bonoli, P., Fairfax, S., et al., submitted to Physics of Plasmas.

[9] Ryter, F., Gruber, O., Kardaun, O.J.W.F., et al, Nucl. Fus., **33** (1993) 979.

[10] Doyle, E.J., Burrell, K.H., Lehecka, T., et al., in Controlled Fusion and Plasma Physics (Proc. 18th Eur. Conf. Berlin, 1991), Vol. 15C, Part I, European Physical Society (1991) I-285.

[11] Snipes, J.A., Marmar, E.S., Terry, J.L., et al., J. Nucl. Mat. **196-198** (1992) 686.

[12] Connor, J. W. and Taylor, J. B., Nucl. Fus. **19** (1977) 1047.

[13] Lackner, K., private communication.

[14] ITER Concept Definition, IAEA Vienna, Vol. 1 (1989) 5.

Figure Captions

Fig. 1. Single null lower X point magnetic flux contours from a typical H-mode discharge in Alcator C-Mod. I_p = 0.65 MA, and B_T = 3.2 T.

Fig. 2. Electron density, plasma stored energy, $H_\alpha(D_\alpha)$ emission, Langmuir probe ion saturation current near the outer divertor strike point, total radiated power, and central soft x ray emission during a discharge with several ELM-free H-mode phases. A "dithering" or ELMy H-mode phase occurs from 0.45 to 0.525 s followed by an ELM-free phase until 0.575 s. Another ELM-free phase begins just before 0.6 s and returns to ohmic L mode at about 0.63 s. I_p = 0.7 MA, B_T is ramping from 3.3 T to 2.8 T during this time interval.

Fig. 3. Profiles of the UV radiation viewing the inner wall radially inward from the outboard midplane comparing ohmic L and ohmic H-modes. The box indicates the edge region, which was expanded to show the much steeper gradients near the plasma boundary in the H-mode.

Fig. 4. Electron density, midplane $H_\alpha(D_\alpha)$ emission, langmuir probe ion saturation current near the inner divertor strike point, and fast $H_\alpha(D_\alpha)$ emission from the X point during an ELMy H-mode. Note the fast regular ELMs on the divertor $H_\alpha(D_\alpha)$ emission with a repetition rate of about 5 kHz. B_T starts at 5.2 T, then begins ramping down at 0.81 s to reach 4.9 T by the end of this time interval. I_p = 0.85 MA until 0.91 s when it begins to ramp down to 0.8 MA by the end of this time interval.

Fig. 5. Alcator C-Mod data values taken at the time of L-H transition compared with the ASDEX-Upgrade and DIII-D H-mode power threshold scaling data. The ELM-free (closed circles) and ELMy (open circles) H-mode C-Mod data points without Li pellets were at $B_T \approx 3$ T, while the ELMy H-modes with Li pellets (open squares) were at $B_T \approx 5.2$ T.
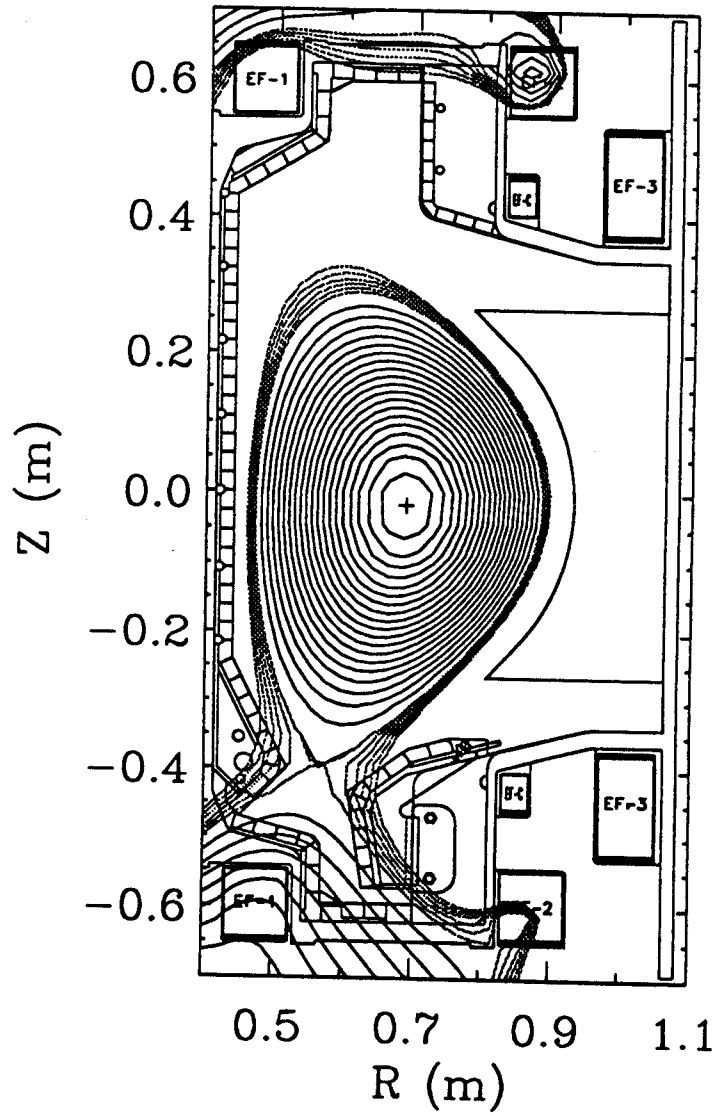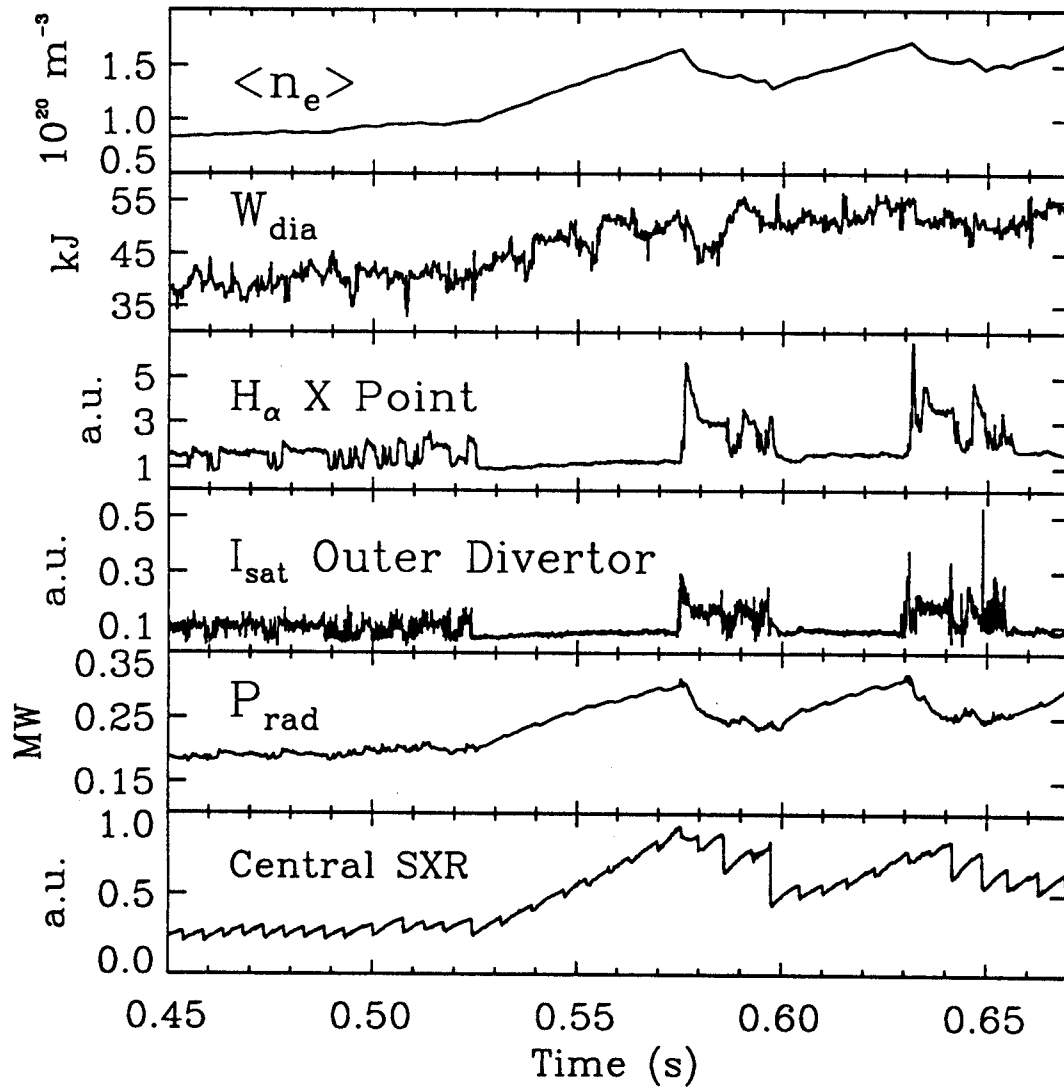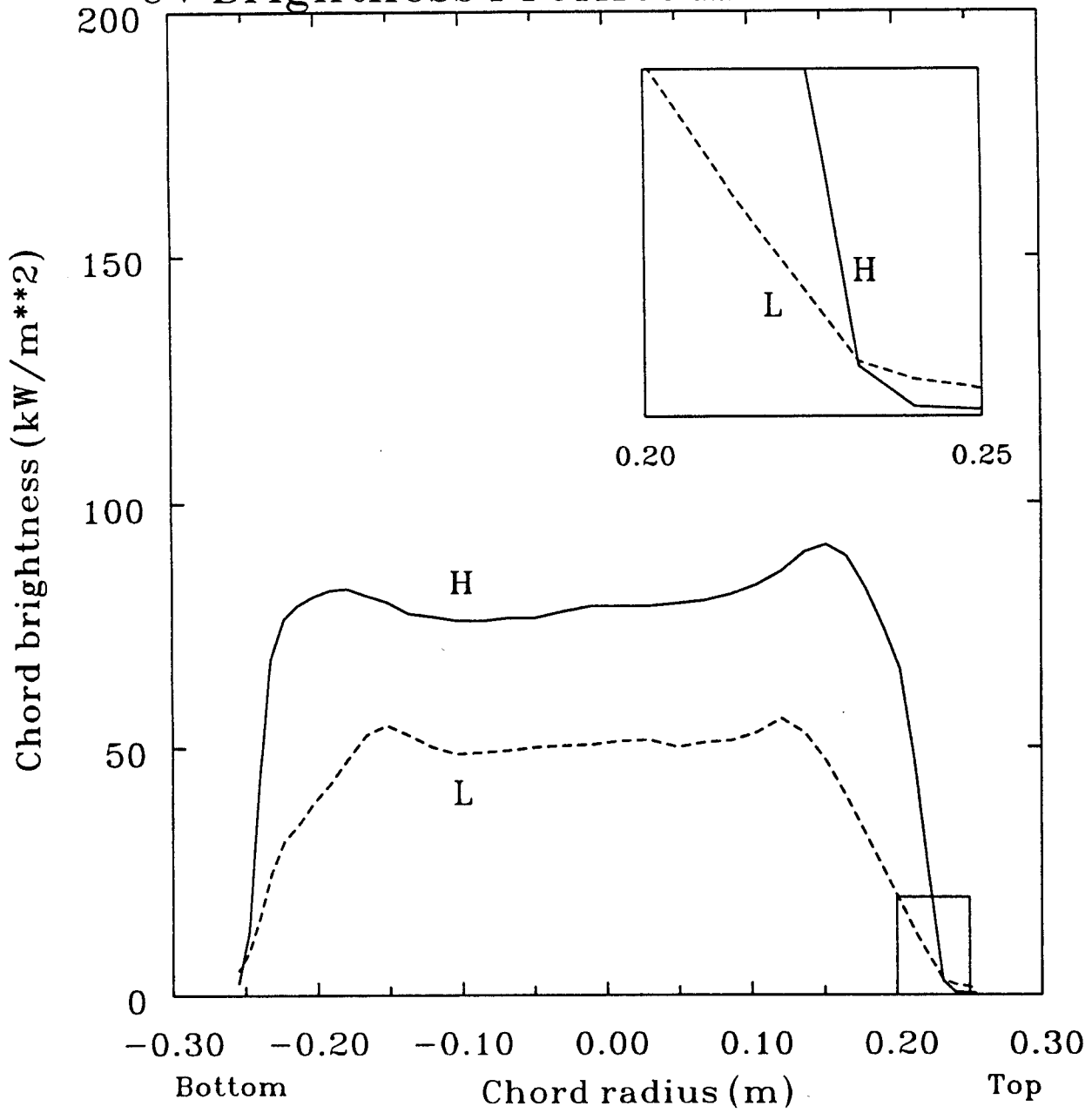
Alcator C—Mod

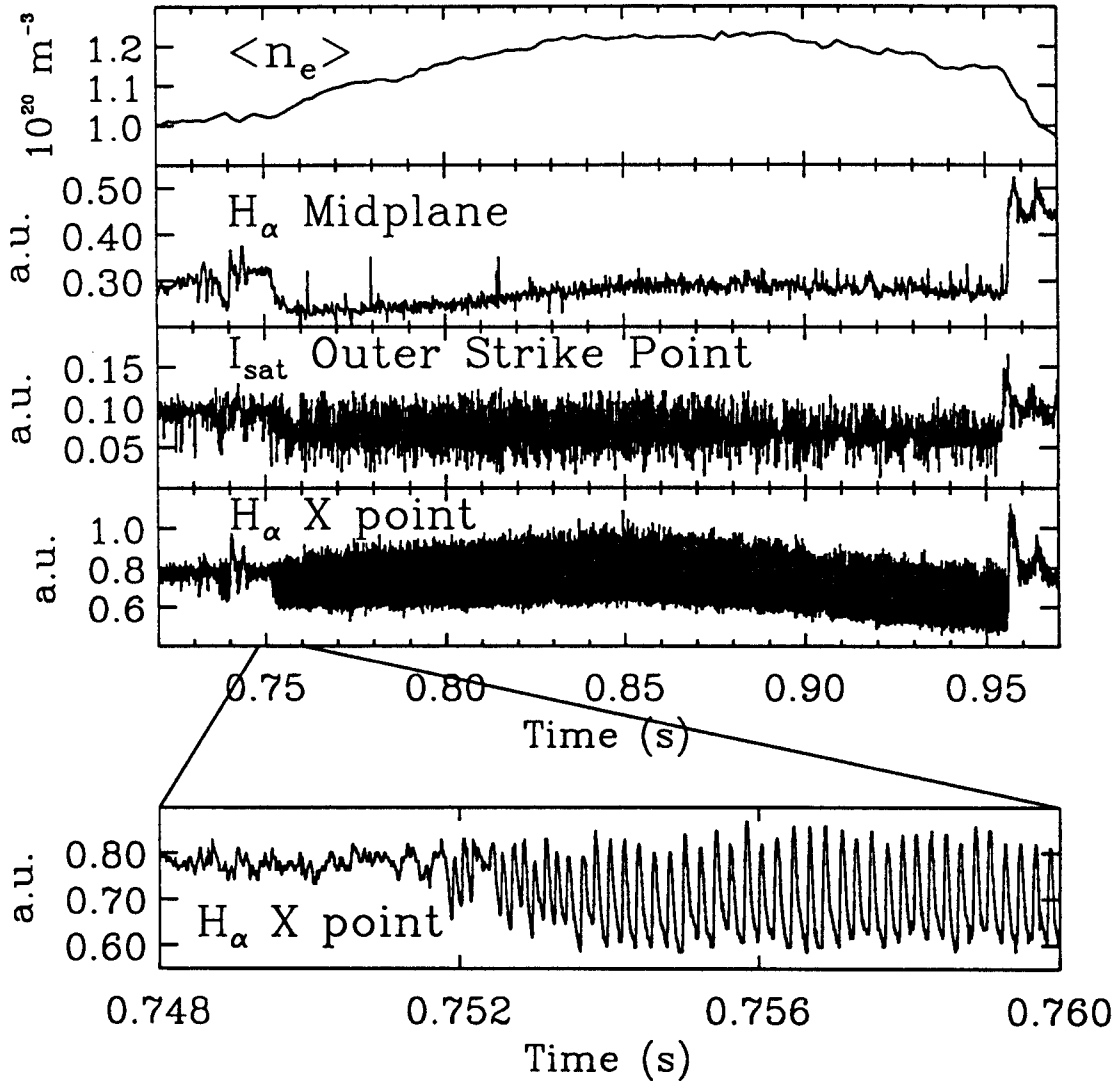Figure 1

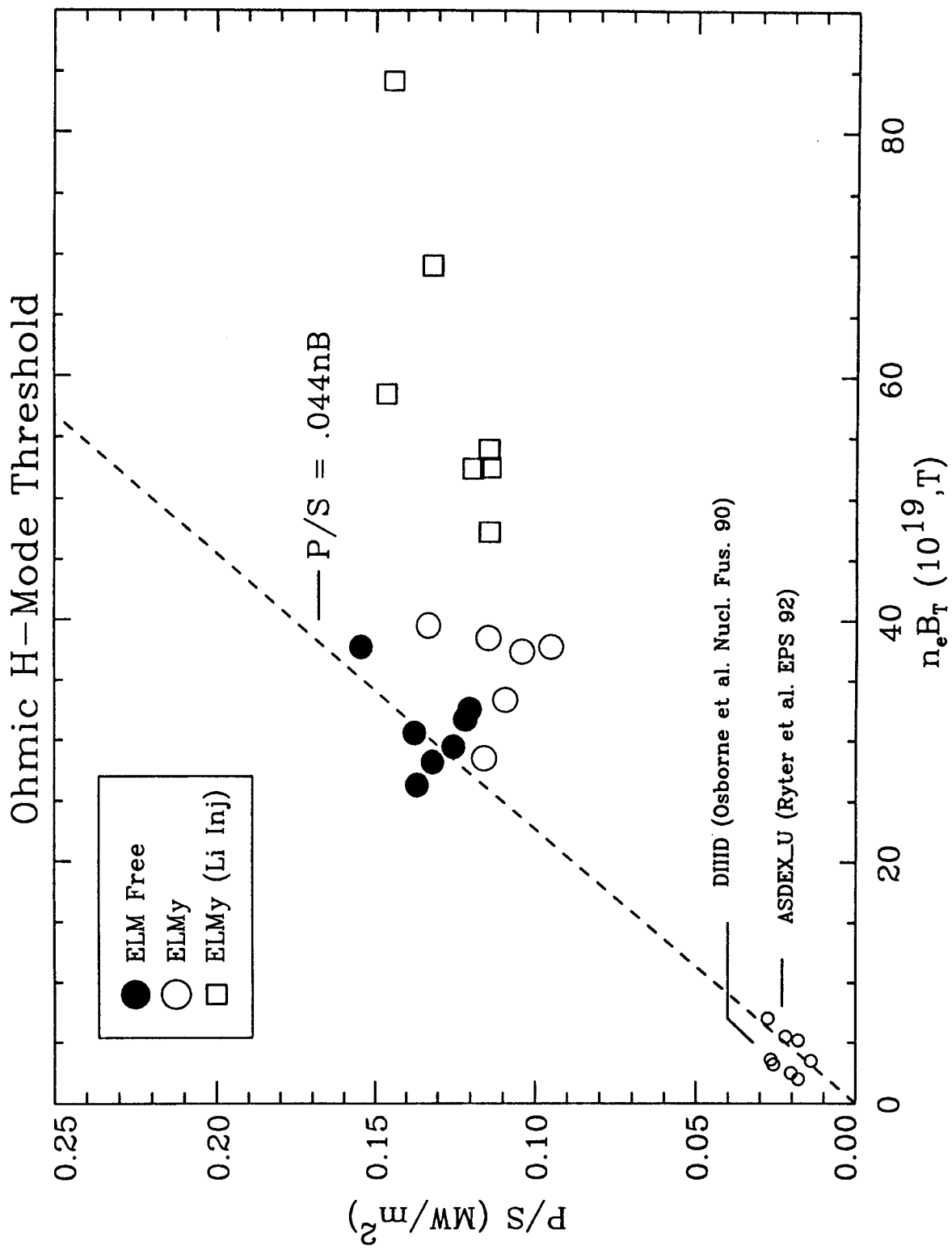Figure 2

UV Brightness Profiles in L and H Mode

Figure 3

Figure 4

Figure 5