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High Power Density H-Modes in Alcator C-Mod

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HIGH POWER DENSITY H-MODES IN ALCATOR C-MOD*

Abstract

Optimization studies of energy confinement in H-mode plasmas heated by ICRF waves were performed on the compact high-field tokamak Alcator C-Mod. Reduction of the radiated power from the main plasma by boronization of the molybdenum first wall made a major impact on improving the quality of H-mode, as characterized by the confinement enhancement factor over the ITER89-P L-mode scaling, $H_{\text{ITER89-P}}$. Longer ELM-free periods became possible, and $H_{\text{ITER89-P}} = 2.5$ was achieved transiently, but in this mode of operation impurity accumulation lead to eventual termination of H-mode. More favorable high quality quasi-steady-state H-modes which lead to steady-state levels of density ($\bar{n}_e = 4 \times 10^{20} \text{ m}^{-3}$), stored energy ($H_{\text{ITER89-P}} = 2.0$, $\beta_N = 1.5$), and radiated power ($P_{\text{rad}}^{\text{main}}/P_{\text{loss}} \leq 30\%$) were also achieved. This mode of operation is characterized by high levels of continuous D_α emission comparable to the L-mode level, with very little or no ELM activity. The H-mode behavior was affected by controlling the neutral pressure by wall conditioning and gas puffing.

1. INTRODUCTION

Study of the high confinement mode known as H-mode [1] has been an area of active research on many tokamaks. Energy confinement in H-mode plasmas is often characterized by the confinement enhancement factor ($H_{\text{ITER89-P}}$) over the well-established L-mode scaling [2]. Optimization of confinement enhancement in ICRF heated H-mode plasmas was a major research focus of the December 1995 – March 1996 operation campaign of the compact high-field tokamak, Alcator C-Mod [3] ($R = 0.67 \text{ m}$, $a = 0.22 \text{ m}$, $\kappa \leq 1.8$). Auxiliary heating was provided by radiofrequency (RF) waves in the ion cyclotron range of frequencies (ICRF). Unlike neutral beam heating, RF heating provides the additional input power without adding particles at the same time. Up to 3.5 MW of RF power at 80 MHz (extremely high power densities of 5 MW/m^3 volume averaged, 0.6 MW/m^2 surface averaged) was injected into the plasma during the course of this experiment using two “dipole” antennas, each with two current straps separated toroidally and excited out of phase [4]. With operational improvements such as plasma position feedback in combination with power feedback, it has become possible to maintain constant power through large load changes which occur during L-H transitions and ELMs.

Hydrogen minority heating in deuterium majority plasmas at 5.3 T was the main heating scenario, but a variety of other heating scenarios [5,6] was also used over the range $2.6 \leq B_T \leq 8 \text{ T}$ and $1 \lesssim \bar{n}_e \lesssim 4 \times 10^{20} \text{ m}^{-3}$, essentially covering the entire operating space of C-Mod. To date, H-mode was observed in deuterium majority plasmas with second harmonic H (2.6 T), second harmonic ^3He (4 T), fundamental H (5.3 T), and fundamental ^3He (8 T) minority heating, and at intermediate fields with off-axis minority heating. H-mode was also observed in combination with the PEP (pellet enhanced performance) mode [5], but detailed studies remain a subject of future investigation.

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Results from the previous campaign (up to June 1995) were reported in Ref. [5]. Details of the L-H transition and power threshold are described in Refs. [7] and [8]. In this paper, we report two types of H-mode observed in Alcator C-Mod: ELM-free H-mode and “enhanced- D_α ” H-mode. The effect of controlling the radiated power from the main plasma, primarily by boronization, is also discussed. The enhanced- D_α H-mode is particularly interesting since it can lead to steady-state while maintaining high confinement. The absence of large amplitude ELMs is another attractive feature of this type of H-mode. A third type of H-mode with frequent Type-III ELMs [9] was observed prior to boronization, and after boronization when the radiated power fraction was high. This type of H-mode resulted in lower confinement enhancement relative to L-mode, and will not be discussed in detail in this paper. H-mode with detached divertor similar to the CDH mode [10] was also observed [11].

2. EFFECTS OF BORONIZATION

Operation during this campaign was different from the previous campaign in two ways: (1) The gas leakage path from the divertor chamber to the main plasma chamber was closed. This change has resulted in greatly enhanced neutral pressure in the divertor chamber [12]. The neutral pressure at the outer midplane of the main plasma chamber was reduced by a small amount. (2) Boronization was applied to the molybdenum first wall, typically on a weekly basis for most of this campaign. There was a short period of operation without boronization but with the divertor leakage closed.

Boronization of the molybdenum wall has significantly reduced the molybdenum content and the radiated power from the main plasma, particularly at the low end of the density range ($\bar{n}_e \lesssim 1.5 \times 10^{20} \text{ m}^{-3}$), and for low single-pass absorption heating schemes (e.g., ^3He minority heating at 8 T). Energy confinement of L-mode plasmas was found to follow the ITER89-P L-mode scaling regardless of the level of radiated power. In contrast, the quality of H-mode was improved dramatically (by up to a factor of two in $H_{\text{ITER89-P}}$) by controlling the radiated power fraction to a low level, $P_{\text{rad}}^{\text{main}}/P_{\text{loss}} \lesssim 30\%$. Here, $P_{\text{rad}}^{\text{main}}$ is the radiated power from the main plasma, $P_{\text{loss}} = P_{\text{in}} - dW/dt$ is the “loss power”, P_{in} is the total input (not absorbed) power, and W is the total stored energy. H-mode plasmas are nearly thermal with $T_e \simeq T_i$. The high energy ion contribution to the total stored energy is typically 5% or less.

The confinement enhancement factor $H_{\text{ITER89-P}}$ is plotted as a function of the radiated power fraction in Fig. 1. The low radiated power results in a larger fraction of the input power conducted to the plasma edge, which is believed to help establish and maintain the edge transport barrier. The presence of the edge transport barrier is indicated by the build-up of the edge temperature pedestal after the L-H transition (0.686 s), as shown in Fig. 2 for an ELM-free H-mode. The edge electron temperature $T_e(r/a = 0.9)$ increases after successive sawtooth heat pulses, with no decay observed until the edge temperature pedestal is fully established. In enhanced- D_α H-modes the edge temperature pedestal is somewhat lower than in ELM-free H-modes (Fig. 3), but the density is substantially higher.

Lower radiated power fraction from the main plasma after boronization led to longer ELM-free H-modes with $H_{\text{ITER89-P}} \lesssim 2.5$, compared to $H_{\text{ITER89-P}} \lesssim 1.5$ observed in RF heated H-modes prior to boronization [5]. A quasi-steady-state

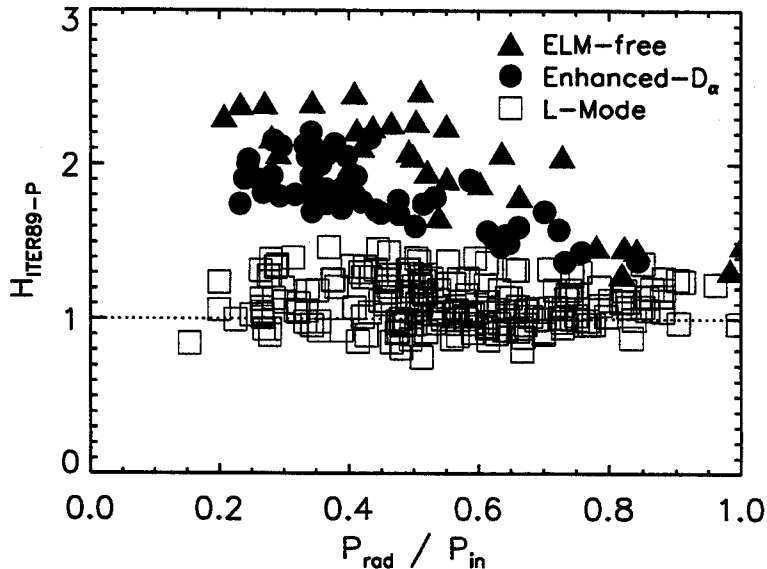


Fig. 1 Dependence of the H-factor on the radiated power fraction. Data were taken when $dW/dt \simeq 0$.

high-quality H-mode ($H_{\text{ITER89-P}} = 2.0$) with high levels of continuous D_α emission was also achieved. Very little variation in the stored energy increase was found as the power deposition layer (i.e., the minority resonance layer) was moved from $r/a = 0$ to 0.4 (just outside the sawtooth inversion radius) by changing the toroidal magnetic field. This is in contrast to pre-boronization L-mode results in which the stored energy increase during ICRF heating decreased by a factor of two as the resonance layer was moved out to $r/a = 0.4$ [5].

3. ELM-FREE H-MODE

ELM-free H-modes have the highest energy and particle confinement, but do not lead to steady state. An example of an ELM-free H-mode is shown in Fig. 2. The plasma pressure is expressed in terms of the normalized beta defined as $\beta_N = \beta_T a B / I$ (% m T/MA), where β_T is the ratio of the volume averaged plasma pressure to the toroidal magnetic pressure. The energy confinement is characterized by the ratios of experimentally determined confinement time to the three empirical scaling laws, ITER89-P L-mode scaling [2] and ITER93 ELM-free and ELMy H-mode scalings for the total stored energy [13] (note that the ELMy scaling predicts virtually the same confinement as L-mode for C-Mod). The power used in evaluating the energy confinement (both experimental and scaling) is the “loss power” $P_{\text{loss}} = P_{\text{in}} - dW/dt$. The radiated power is not subtracted. The particle confinement time is extremely long in ELM-free H-mode. The density and the impurity content, and consequently the radiated power continue to increase throughout the ELM-free phase. As the radiated power increases, energy confinement starts to degrade when the radiated power fraction exceeds a value of $P_{\text{rad}}^{\text{main}} / P_{\text{loss}} \simeq 0.5$, eventually leading to termination of the ELM-free H-mode as the radiated power fraction approaches 100%. The confinement enhancement factor reaches a value of $H_{\text{ITER89-P}} = 2.5$ at $t = 0.8$ s. The corresponding volume averaged plasma pressure, plasma stored energy, and energy confinement time at the time of maximum stored energy were 0.15 MPa,

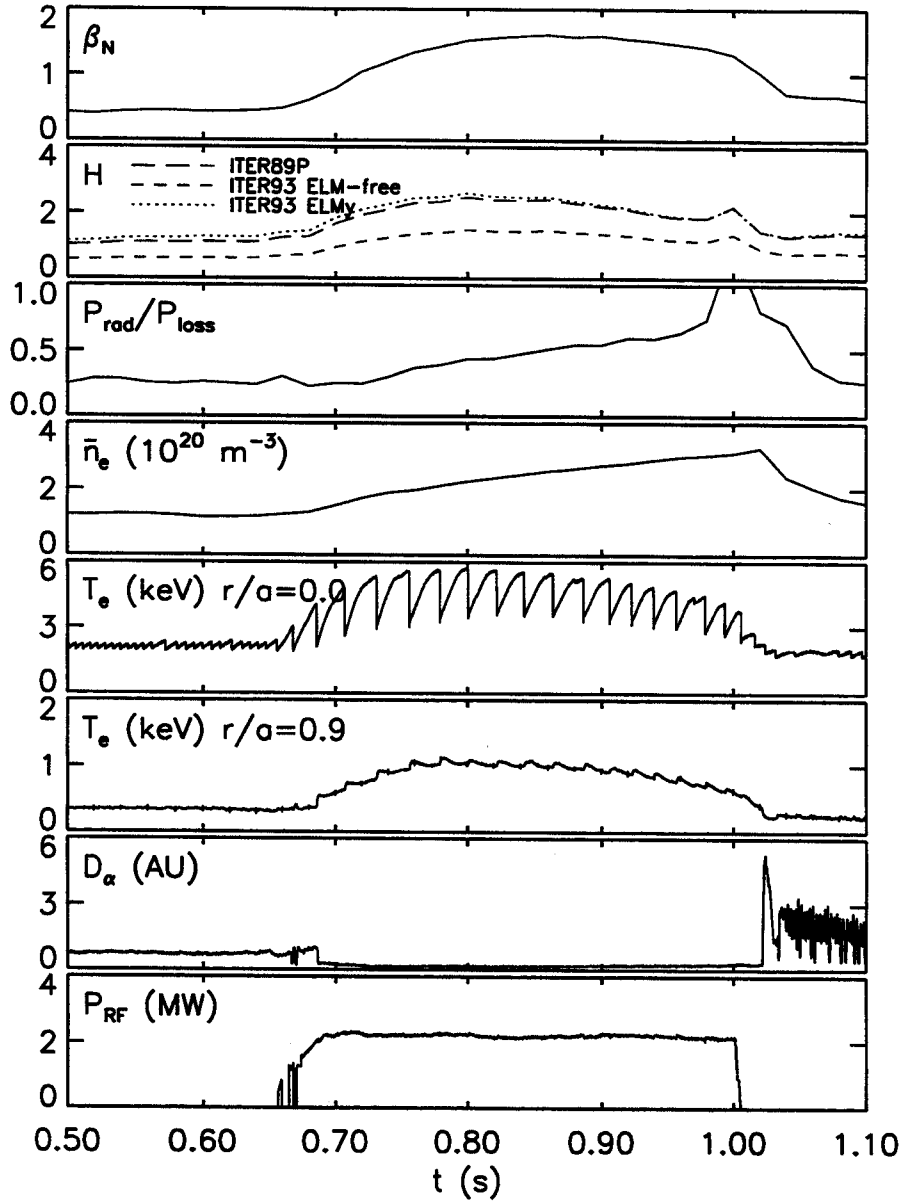


Fig. 2 An ELM-free H-mode (Shot 960116024), transiently reaching $H_{\text{ITER89-P}} = 2.5$ ($B_T = 5.3$ T, $I_p = 1.0$ MA).

0.21 MJ, and 0.075 s. The energy confinement time during H-mode was 50% higher than that of the ohmic target plasma (0.050 s).

4. ENHANCED- D_α H-MODE

A more favorable type of H-mode, which can lead to steady state levels of density, stored energy, and radiated power while maintaining high confinement, was also observed. This type of H-mode is characterized by high levels of steady D_α emission (often exceeding the L-mode level), sometimes but not always accompanied by occasional small-amplitude ELMs. We will refer to this type of H-mode as “enhanced- D_α H-mode” in this paper. In some respects this type of H-mode has characteristics similar to quasi-steady-state ELMy H-modes

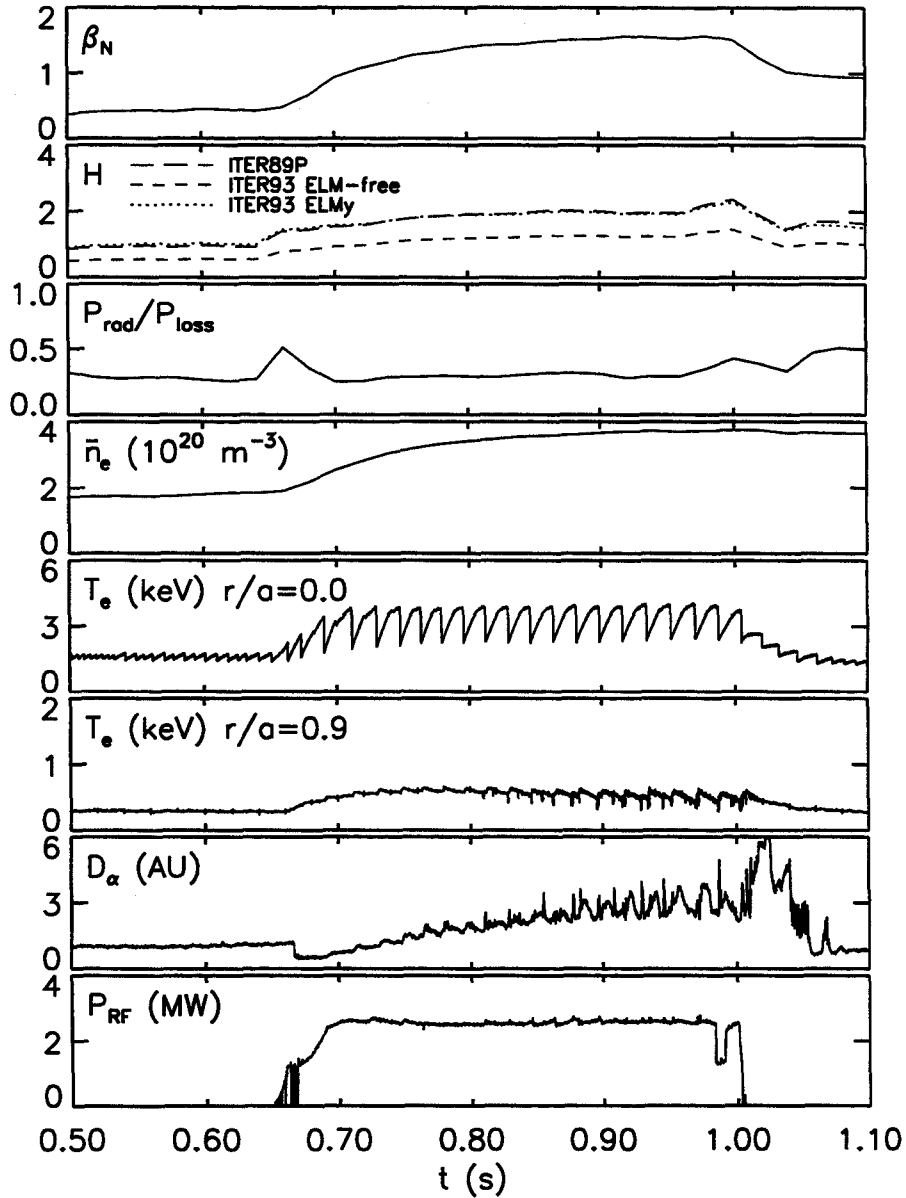


Fig. 3 A quasi-steady-state enhanced- D_α H-mode (Shot 960116027) with $H_{\text{ITER89-P}} = 2.0$ and $\beta_N = 1.5$ ($B_T = 5.3$ T, $I_p = 1.0$ MA).

[14], but the ELM behavior is qualitatively different. An enhanced- D_α H-mode with $H_{\text{ITER89-P}} = 2.0$ and $\beta_N = 1.5$, which approaches a steady-state towards the end of the RF pulse, is shown in Fig. 3. After a brief period of ELM-free phase, the D_α emission increases gradually to a higher level. In this example, small isolated ELMs are visible as sharp upward spikes on the D_α signal, with corresponding downward spikes on the edge electron temperature. The slower modulation corresponds to the sawtooth heat pulse reaching the plasma edge. Energy confinement relative to ITER93 ELMy and ELM-free scalings [13] were 2.0 and 1.3, respectively. In more traditional ELMy discharges with frequent ELMs the confinement enhancement is lower, typically $H_{\text{ITER89-P}} \lesssim 1.5$.

In enhanced- D_α H-modes, a region of intense D_α emission is observed in

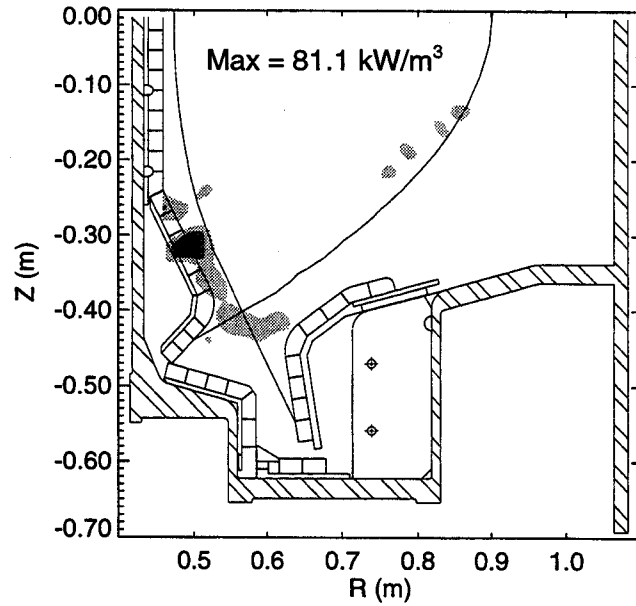


Fig. 4 Tomographic reconstruction of the D_α emission during an enhanced- D_α H-mode (Shot 960116010 at 0.9 s).

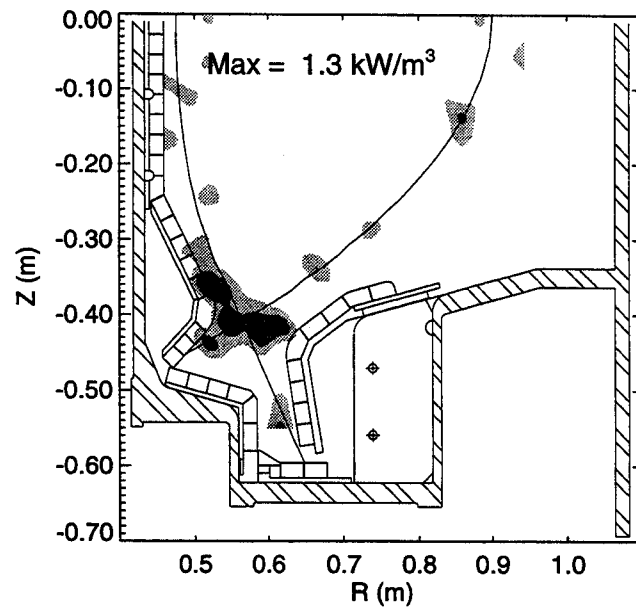


Fig. 5 Tomographic reconstruction of the radiated power during an ELM-free H-mode (Shot 960116024 at 0.8 s).

the scrape-off layer above the X-point adjacent to the inner divertor structure (the “inner nose”), in addition to a region of more faint emission below the X-point, as shown in Fig. 4. In ELM-free H-mode the intense D_α emission on the inner nose is absent, but the emission near the X-point is still observed, as shown in Fig. 5 (note the factor of 60 reduction in the maximum emissivity). The D_α signal plotted in Figs. 3 and 4 are from a view of the lower half of the inner wall, including the enhanced emission region on the inner nose. The D_α emission from the divertor region in enhanced D_α H-mode is higher than in ELM-free H-mode but usually not as high as in L-mode. The radiated power from the divertor

region in enhanced- D_α H-mode is concentrated near the X-point, as shown in Fig. 6. In ELM-free H-mode it is less intense and is more distributed along the inner and outer legs of the separatrix below the X-point. The radiated power from the main plasma is greatly different. As shown in Fig. 7, the radiated power in the ELM-free plasma (at the end of a 0.3 s RF pulse) is much higher than in the enhanced- D_α H-mode across the whole profile.

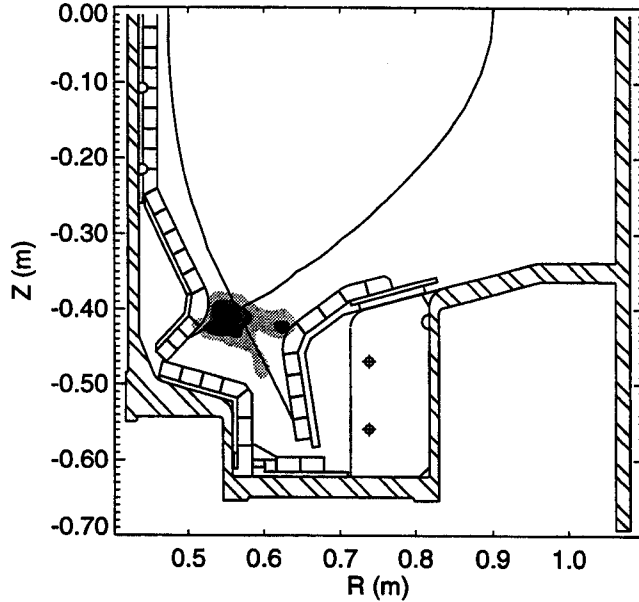


Fig. 6 Tomographic reconstruction of the radiated power from the divertor region during an enhanced- D_α H-mode (Shot 960116010 at 0.9 s).

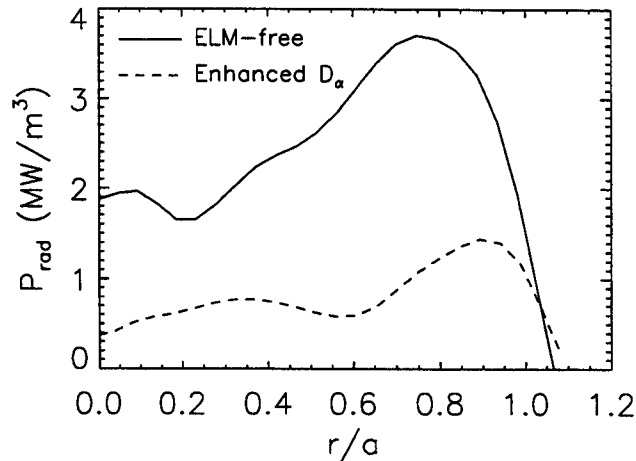


Fig. 7 Comparison of the radiated power profile for ELM-free H-mode (solid: 960116024 at 1.0 s) and enhanced- D_α H-mode (dashed: 960116027 at 1.0 s).

The “enhanced- D_α ” H-mode should not be confused with the “high-recycling” divertor discussed in Ref. [15]. The low radiated power from the main plasma, combined with steeper gradients in the scrape-off layer during H-mode, results in very high parallel heat flux into the divertor region, $q_{\parallel} \simeq 0.5 \text{ GW/m}^2$ [11], comparable to the value expected for ITER. Results of initial attempts to reduce the heat flux to the divertor target plates are reported in Ref. [11].

The enhanced- D_α H-mode was first observed during the early phase of this campaign with an unboronized molybdenum first wall. This mode was obtained using strong gas puffing during the H-mode phase. A quasi-steady-state condition was achieved with densities up to $\bar{n}_e = 3.7 \times 10^{20} \text{ m}^{-3}$. However, in these pre-boronization enhanced- D_α H-modes the radiated power fraction was high $P_{\text{rad}}^{\text{main}}/P_{\text{loss}} \simeq 0.6$, and the confinement enhancement factor was low, typically $H_{\text{ITER89-P}} = 1.2\text{--}1.3$.

The D_α behavior can be affected by controlling the particle source rate through wall conditioning and gas puffing. ELM-free H-modes can be obtained by outgassing the wall by He discharge cleaning and limiting the gas input to the plasma. As the divertor neutral pressure (measured before the H-mode transition) is increased, the H-mode character changes gradually from ELM-free to enhanced- D_α H-mode [16]. The transition usually occurs around several mtorr. However, enhanced- D_α H-mode has been observed with a divertor neutral pressure as low as 2 mTorr. For normal operating conditions, this corresponds to a target density of approximately $\bar{n}_e = 2 \times 10^{20} \text{ m}^{-3}$, but either type of H-mode can be produced at the same density depending on the neutral pressure. The level of D_α enhancement is higher when the power to the scrape-off layer $P_{\text{SOL}} = P_{\text{in}} - dW/dt - P_{\text{rad}}^{\text{main}}$ is higher. The best enhanced- D_α H-mode was observed slightly above the transition from the ELM-free H-mode regime to the enhanced- D_α H-mode regime. Excessive amounts of D_α emission resulted in poor H-factors.

Impurity particle confinement was studied using laser blow-off injection. In ELM-free H-modes the impurity confinement time is virtually infinite. The injected impurities remain in the plasma with no measurable decay, and intrinsic impurities (e.g., molybdenum) accumulate in the plasma core. The time histories of line emission from different charge states can be reproduced by a purely diffusive model in L-mode plasmas, but in enhanced- D_α H-mode a strong inward convection at the plasma edge is required in addition to an overall reduction of the diffusion coefficient. The impurity particle confinement time in enhanced- D_α H-modes was in the range 100–500 ms, much shorter than in ELM-free H-mode but still an order of magnitude longer than in L-mode plasmas (typically 20–30 ms). These H-modes had mild D_α enhancement (lower than the L-mode level) and good H-factors ($H_{\text{ITER89-P}} \gtrsim 1.8$).

4. DISCUSSION

The quality of H-mode was substantially improved by reducing the radiated power from the main plasma using boronization. Longer ELM-free periods became possible, and high quality quasi-steady-state H-modes were obtained. This mode of operation is characterized by enhanced levels of continuous D_α emission localized on the “inner nose” of the divertor and very little on no ELM activity. The H-mode behavior (ELM-free, ELM_y, or enhanced- D_α) was found to depend on the neutral pressure which can be controlled by wall conditioning and gas puffing.

The unique range of parameters obtainable in C-Mod (i.e., compact size, high magnetic field, and high density with $T_e/T_i \simeq 1$) provides critical tests of both empirical scaling laws and theoretical predictions. We note that H-mode confinement data points from C-Mod are found to lie well above the empirical scaling laws derived from larger tokamaks (ITER93H ELM_y and ELM-free [13], JET-DIII-D [17], etc.), pointing out the necessity to re-examine the H-mode

scaling laws. Such re-evaluation may have an important impact in extrapolating toward larger future devices such as ITER. C-Mod data have been added to the ITER H-mode confinement database [13]. A more detailed description of the data contributed to the database, including comparison with various H-mode scaling laws, is reported in Ref. [18]. (Note that the enhanced-D_α H-mode is referred to as “ELMy” H-mode in Ref. [18].)

Hardware upgrades in the near future (1997–1998) include addition of 4 MW of tunable frequency (40–80 MHz) ICRF power and a current drive antenna to allow on-axis fast wave current drive and off-axis mode conversion current drive, modification of the inner divertor to enable higher triangularity operation, and addition of a divertor cryopump to control the density rise during H-mode. Planned experiments include investigation of VH-mode, the combination of PEP mode and H-mode, and when off-axis current drive becomes operational, the reversed shear enhanced confinement mode.

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