

Enhanced D_α H-modes in Alcator C-Mod

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Introduction A new and potentially reactor relevant high confinement regime has been found on Alcator C-Mod at high electron density ($\bar{n}_e > 2 \times 10^{20} \text{ m}^{-3}$) with ICRF heating, called the Enhanced D_α H-mode (EDA H-mode) [1]. These H-modes reach a steady state density and total radiated power, yet remain free of discrete ELMs throughout the ICRF heating phase. The D_α emission drops initially as the plasma enters H-mode, then rises rapidly, often returning to L-mode levels at the midplane and in the divertor as the density reaches a steady state. The energy confinement of Enhanced D_α H-modes is slightly lower than that of the best ELM-free H-modes, but can still reach and maintain confinement enhancement factors up to two relative to L-mode. High frequency (50 - 100 kHz) density and magnetic fluctuations are often observed during EDA H-modes.

Method of Operation Enhanced D_α H-modes were first obtained after closing off some divertor bypass leaks, which increased the divertor/midplane neutral compression ratio from a range of 10-100 to a range of 50-250 in H-mode. The first moderately enhanced D_α H-modes were obtained before the machine was boronized by operating at high density ($\bar{n}_e > 2.5 \times 10^{20} \text{ m}^{-3}$) and high ICRF heating power ($P_{\text{ICRF}} > 2.5 \text{ MW}$) with strong gas puffing.

After boronization with B_2D_6 , EDA H-modes were obtained at high density without strong gas puffing. While high ICRF power is usually required to achieve EDA H-mode, some were achieved immediately after boronization with $P_{\text{ICRF}} < 1 \text{ MW}$. The divertor pressure in EDA H-mode is usually 2 - 10 Pa, but after a fresh boronization, EDA H-modes can occur with divertor pressures from 0.25 - 1 Pa. Boronization widens the operational range of EDA H-mode through lower core radiation and increased particle inventory.

Particle and Energy Confinement EDA H-modes have somewhat lower core particle and energy confinement than ELM-free H-modes in C-Mod. The core impurity particle confinement time was measured with trace scandium injection during an ELM-free H-mode that became an EDA H-mode before the scandium left the plasma (Fig. 1). In the ELM-free phase, the scandium did not decay, indicating an impurity confinement time much greater

than 0.2 sec. In the Enhanced D_α phase, the scandium left the plasma with a characteristic decay time of 0.1 sec. By comparison, in the L-mode phase, the scandium decay time was about 30 msec. So, in EDA H-mode, the core impurity confinement time is about three times higher than L-mode, but at least two times lower than ELM-free H-mode.

The reduced particle confinement of EDA H-mode relative to ELM-free H-mode leads to reduced impurity accumulation in EDA H-mode. The radiated power saturates in EDA H-mode at a

steady state value with $0.2 < P_{\text{rad}}/P_{\text{tot}} < 0.6$ rather than continuing to increase as in ELM-free H-mode (Fig. 2). The total radiated power profile across the main plasma, measured by bolometers, is substantially lower in EDA H-mode than in ELM-free H-mode. By contrast, the divertor radiation is substantially higher in EDA H-mode than in ELM-free H-mode. Z_{eff} is also lower in EDA H-mode than in ELM-free H-mode.

The peak energy confinement in EDA H-mode is generally slightly lower than in ELM-free H-mode, but can still reach $2 \times$ L-mode. Values of the thermal energy confinement time in EDA H-mode $\tau_{\text{Eth}}^{\text{EDA}} > 60$ msec have been achieved compared to ELM-free values up to $\tau_{\text{Eth}}^{\text{EFH}} \approx 80$ msec. The advantage of EDA H-mode over ELM-free H-mode is that the confinement remains high in steady state for as long as the ICRF pulse because the impurities do not accumulate and radiate away the thermal energy. This is accomplished without the large perturbations of Type I ELMs. So, EDA H-mode has the improved confinement of Type I ELMy H-mode, without the problems associated with large ELMs.

Divertor Physics Fast Scanning Probe upstream and outer divertor domed Langmuir probe measurements indicate that the EDA H-mode is in the High Recycling Divertor regime [2], where the measured electron pressure is approximately constant along the field, but the electron temperature falls between the upstream location and the divertor plate. The EDA H-

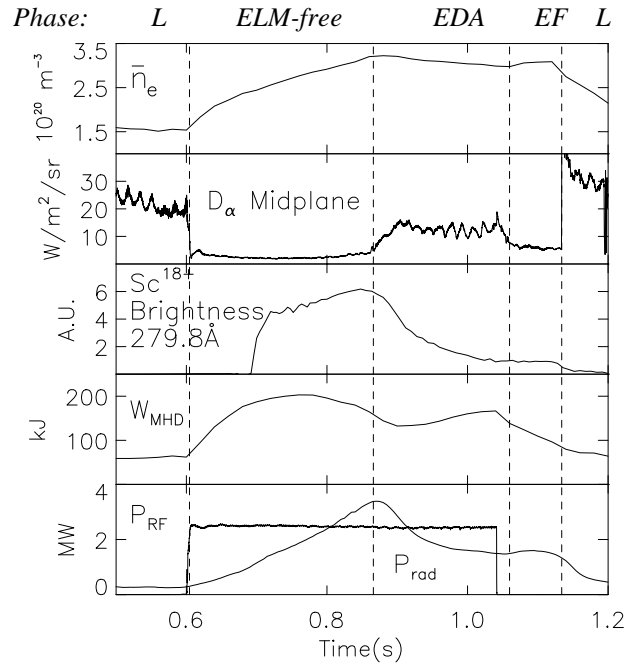


Fig. 1. Scandium injection at 0.7 sec to measure particle confinement in ELM-free and EDA H-mode.

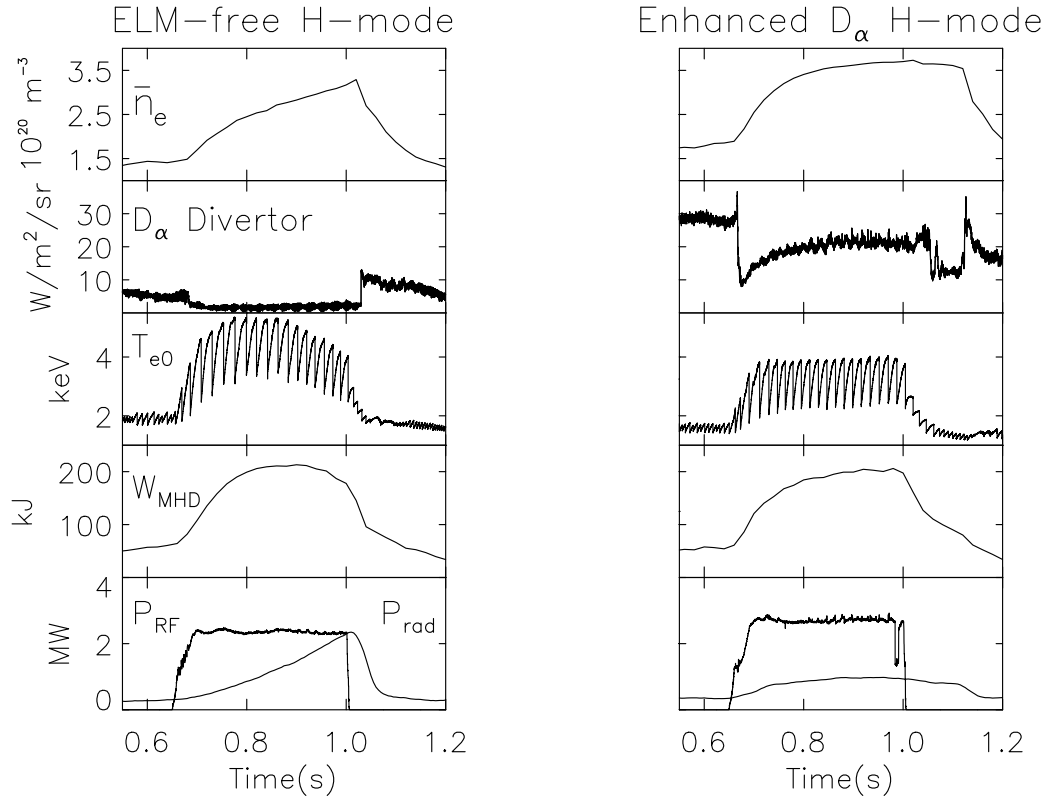


Fig. 2. Comparison of a) ELM-free H-mode and b) Enhanced D_α H-mode showing the line averaged density, divertor D_α emission, central electron temperature, stored energy, total radiated power and ICRF power.

mode occurs at high density when the power conducted to the divertor plate is sufficiently high (Fig. 3). Here $P_{\text{plate}} = P_{\text{in}} - dW/dt - P_{\text{rad}}^{\text{main}} - P_{\text{rad}}^{\text{div}}$ is the power that arrives at the divertor plate after subtracting the change in stored energy and both main chamber and divertor radiation. Figure 3 shows an EDA H-mode that turns into a detached divertor H-mode through intense nitrogen gas puffing. The enhanced D_α emission returns to ELM-free levels when the power conducted to the plate drops due to increased radiation, just as the divertor detaches.

Edge Fluctuations High frequency magnetic and density fluctuations are often observed during EDA H-

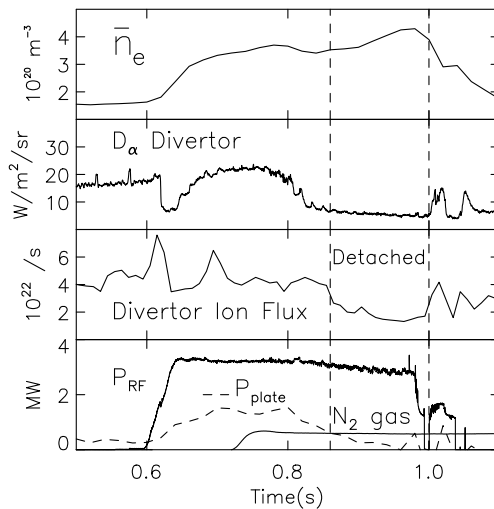


Fig. 3. Detached divertor H-mode with nitrogen puffing. The

mode. The magnetic perturbations are covered in a companion paper in these proceedings [3]. The density fluctuations are observed with an AM reflectometer at 88 GHz with a density cutoff in the steep gradient region at $1.5 \times 10^{20} \text{ m}^{-3}$. In EDA H-mode, there is an increase in the broadband fluctuations out to the 400 kHz anti-aliasing filter of the diagnostic and often

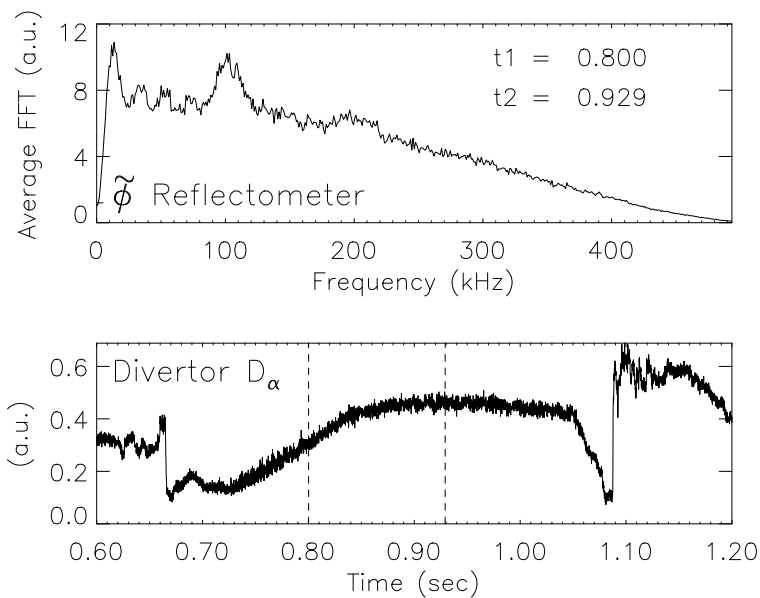


Fig. 4. Average of the Fourier transform of the density phase fluctuations from the reflectometer during an Enhanced D_α H-mode showing a clear peak in the fluctuations at about 100 kHz.

an additional coherent peak at typically 100 kHz (Fig. 4). Although the magnetic fluctuations are often at about the same frequency and time, there is no clear coherence between the magnetic and density fluctuations.

Conclusion The Enhanced D_α H-mode regime may prove to be a good compromise for ITER operation to obtain high confinement, avoid large ELMs, and maintain low Z_{eff} with high divertor radiation in steady state. In comparison with ELM-free H-modes, impurity accumulation is substantially reduced in EDA H-modes leading to lower Z_{eff} values and lower total radiated power across the main plasma and a factor of two higher radiated power in the divertor. The energy confinement is comparable in both types of H-mode. High frequency edge density and magnetic fluctuations are observed during EDA H-mode, though the role they play has not yet been determined.

References

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- [3] I H Hutchinson, et al., this conference.