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Studies of EDA H-mode in Alcator C-Mod

M Greenwald, R Boivin, P Bonoli, C Fiore, J Goetz, R Granetz, A Hubbard, I Hutchinson, J Irby, Y Lin, E Marmar, A Mazurenko, D Mossessian, T Sunn Pedersen, J Rice, J Snipes, G Schilling†, G Taylor†, J Terry, S Wolfe and S Wukitch

MIT-Plasma Science and Fusion Center, Cambridge, MA 02139, USA

† Princeton Plasma Physics Laboratory, Princeton NJ, USA

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Abstract. Studies of the enhanced D_α H-mode (EDA) have been extended to include ohmic plasmas. No clear difference in the EDA/ELMfree boundary or in other phenomenology are seen between ohmic and ICRF-heated plasmas, suggesting that neither the effect of ion tails nor direct RF/edge plasma interaction plays a role in EDA. Edge safety factor (q_{95}) is the principal variable which determines which regime a discharge will be in. When q_{95} is greater than 4.0 for standard-shaped plasmas, the discharge is almost always EDA, while when it is less than 3.5, the plasma is almost always ELMfree. New edge diagnostics have allowed measurement of pedestal profiles with resolution of the order of 1 mm. Sudden changes in profile widths are not seen when the plasma makes a transition from EDA to ELMfree; however, the widths do vary with the same parameters that determine the EDA/ELMfree boundary. Strong edge-density fluctuations are observed to accompany EDA and may be responsible for the change in particle transport which is observed. The fluctuations have a quasi-coherent component whose frequency varies inversely with the pedestal width as measured by a visible continuum diagnostic.

(Some figures in this article are in colour only in the electronic version; see `www.iop.org`)

1. Introduction

Alcator C-Mod is a compact high-field tokamak (minor radius = 0.22 m, major radius = 0.68 m, toroidal field = 3–8 T). The plasmas are shaped to match a closed divertor with kappa = 1.5–1.8 and average triangularity ~ 0.4 (measured at the separatrix). Plasma currents are typically in the range 0.4–1.4 MA. ICRF is the only auxiliary heating source, although at the high current densities that prevail, ohmic heating is never negligible. The plasma first wall is made of molybdenum tiles coated by in-vessel boronization.

Investigations of H-mode plasmas in Alcator C-Mod have centred on the EDA (enhanced D_α) regime. The potential advantages of this regime have been well documented [1, 2] and include good energy confinement, moderate particle confinement (no impurity accumulation) and no large ELMs. Recent work has emphasized the scaling of the EDA/ELMfree boundary and attempts to uncover the underlying physics of the regime. Scans of plasma current and toroidal field show that EDA predominates at higher values of edge safety factor with a transition in the range $q_{95} = 3.5$–4.0 [3]. Plasma shape has also been shown to be important, with ELMfree more likely for triangularity below $\delta = 0.35$. There are some indications that ELMfree predominates above $\delta = 0.55$ as well. The EDA/ELMfree boundary is very weakly affected by neutral density with EDA more likely at midplane pressures above 0.015 Pa. (When comparing with neutral densities in other devices, one must remember that the plasma density in C-Mod is about an order of magnitude higher than in low-field tokamaks). In some cases EDA discharges become ELMfree when input power is stepped down; however, statistical studies of fully developed discharges do not show any obvious dependence.

2. EDA in ohmic plasmas

The only auxiliary heating employed on C-Mod is ICRF. Previous experiments reported on EDA H-modes were all with strong ICRF heating including a regime similar in many ways to EDA observed on JET in ICRF-heated plasmas [4]. Despite previously reported C-Mod observations indicating that EDA was probably not a specific ICRF effect, these facts, combined with the apparent lack of EDA in neutral beam heated plasmas, have led to speculation that the heating method is crucial for its occurrence. However, new work on ohmic H-modes demonstrates that EDA is easily obtainable without ICRF heating. Figure 1 shows a number of traces from an ohmic EDA H-mode. In this discharge, the L/H transition takes place at about 0.83 s and the transition to EDA occurs at 1.0 s. The lack of EDA in previous experiments on ohmic H-mode is understandable. Since the H-mode power threshold increases with B_T, ohmic H-modes are easiest to obtain at low q where the heating power is maximized for a given field. It was shown subsequently that EDA is favoured by higher q. In the recent experiments, the toroidal field was ramped up after the L/H transition, raising q and accessing the EDA mode. The H-modes were maintained via a strong hysteresis effect seen in the power

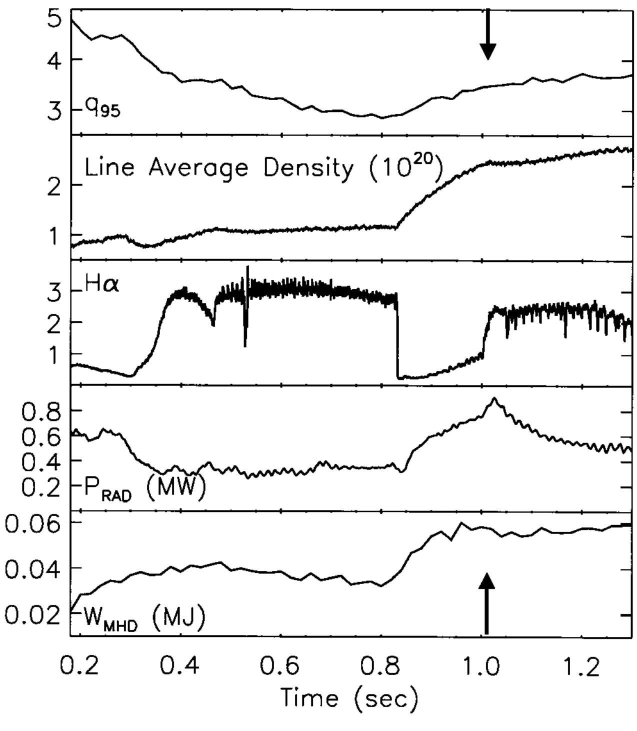
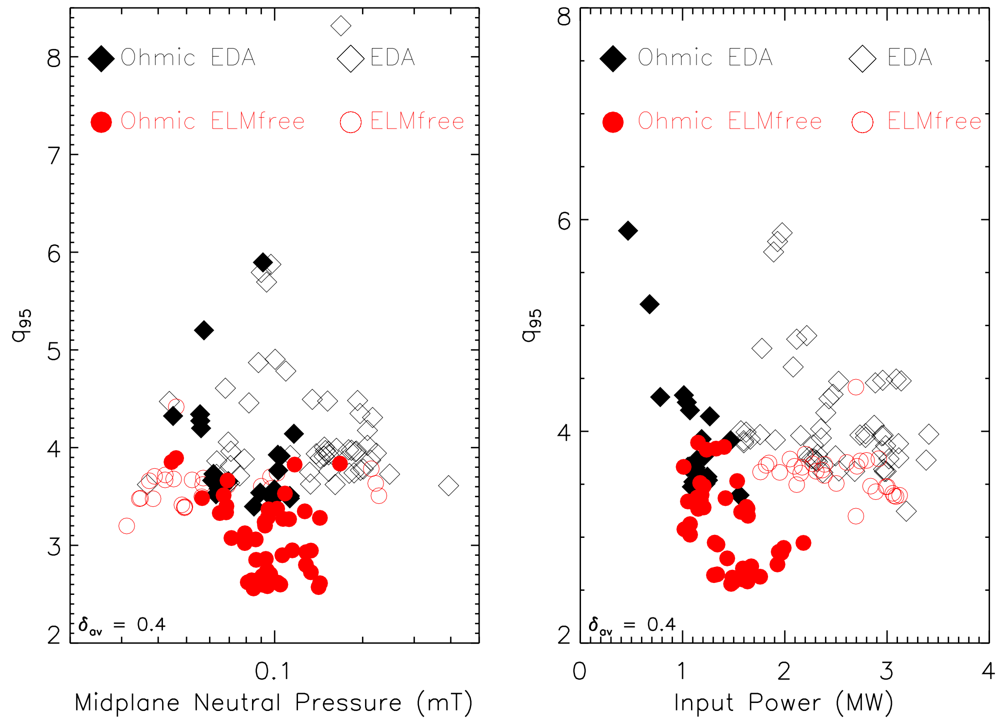


Figure 1. Traces from typical ohmic H-mode. B_T was ramped down to lower the L/H threshold (at 0.83 s), then ramped up to raise q and allow the transition to EDA (at 1 s, as indicated by arrows). Radiated power is integrated up to the separatrix, divertor radiation is not included.



(*a*) (*b*)

Figure 2. (*a*) A comparison of the EDA/ELMfree boundary for ohmic (filled symbols) and ICRF-heated discharges (open symbols). There is no significant difference between the two. With this data set, no dependence on midplane neutral pressure (which was changed by gas puffing) can be seen, although some small effect is seen when a larger data set is considered. (*b*) A comparison of the EDA/ELMfree boundary plotted against input power. Ohmic and ICRF-heated plasmas again show the same dependence on q_{95}. No obvious trend with input power is apparent.

threshold. (In these cases, the H-mode could be maintained to levels where $P/nBS \sim 0.01$ (where P is measured in MW, n in units of 10^{20} m^{-3}, B in T and S in m^2)). Similar results were obtained by ramping the plasma current down following an L/H transition. Figure 2(*a*) and (*b*) shows comparisons of the EDA/ELMfree boundary for ohmic and RF H-modes in which q_{95} is plotted against the midplane neutral pressure and total input power, respectively. EDA is observed over a slightly wider range of q values for the ohmic discharges although the difference is probably not significant. Considering a wider set of data than shown in the figure, there is evidence for a very weak dependence on neutral and plasma density. Despite anecdotal indications, no clear dependence on input power or net power across the separatrix is observed. The implication of obtaining EDA under the same conditions in ICRF and ohmic plasmas is that the physics associated with a particular heating scheme can be ruled out as a cause for EDA. These effects could have included the dynamics of energetic ion tails or the interaction between ICRF waves and the plasma edge. The former was never likely, since the high densities that prevail in C-Mod prevent ion tails of significant energy from forming. Earlier work which found a dependence on triangularity could not be tested in this study, since there was no variation in plasma shape for the ohmic H-modes.

3. Pedestal measurements

Because of its compact size, high field and high density, length scales, namely major radius, gyroradius (ρ_i), connection length (L_C), mean free path (λ_i), are all smaller in C-Mod than in other devices. (In the plasma edge, typical H-mode values are $\rho_i = 0.3$ mm, $L_C = qR = 2.4$ m, $\lambda_i = 0.8$ m). It therefore came as no surprise that pedestal widths in C-Mod H-modes were smaller as well, initially challenging the instrumental resolution of the edge diagnostics [5]. During the past two years, a number of diagnostics with significantly improved spatial resolution have been installed. These include: an edge Thomson scattering system with resolution of approximately 1.3 mm mapped to the midplane; a visible bremsstrahlung (VB) array with 0.6 mm resolution; a pair of soft x-ray arrays with 1.5 mm resolution; and a Lyα array, which can measure the ionization rate, with 2 mm resolution. Further details on these new diagnostics can be found in [6]. An ECE polychromator is also available. While its resolution is no better than about 8 mm, it seems sufficient to resolve the edge electron temperature profiles in H-mode which are in the range 6–12 mm. The pedestal width for electron density, on the other hand, seems to be much narrower, typically in the range of 2–4 mm. The VB array which observes continuum radiation whose emission scales like $n^2 Z_{EFF}/g(T_e)$ (and thus is most sensitive to density profiles) also sees narrow pedestal widths, but with greater variation, in the range 2–15 mm. The soft x-ray emission is believed to come from recombination of fully stripped fluorine and shows widths of 2–9 mm. Relatively little variation is seen in the

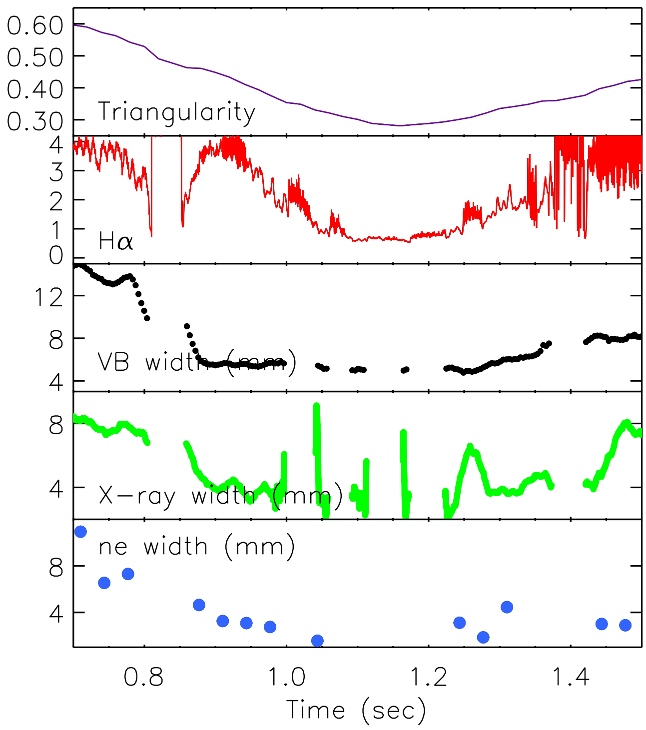


Figure 3. Pedestal widths from various diagnostics are plotted for a discharge where the triangularity was scanned from 0.6 to 0.28. Because of low input power, the H-mode was interrupted by back transitions to L-mode and periods of type III ELMs. (No data are plotted during these intervals). None the less, the widths show a clear covariance with triangularity.

electron temperature width; in particular, no difference is seen between temperature profile widths from EDA and ELMfree H-modes. The most significant dependence observed is an increase in T_e pedestal width as the net power through the separatrix increases [5]. No sharp difference is seen in the pedestal widths of any of these diagnostics as the plasma makes transitions between EDA and ELMfree H-mode. All, however, show some variation in direct proportion to δ and q_{95}, the variables which determine the EDA/ELMfree boundary. The VB and x-ray widths generally show the greatest increases. Figure 3 shows traces of H_α and the pedestal widths for a shot in which triangularity was scanned, causing the discharge to make a transition from EDA to ELMfree. On the same graph, one can see that there is less change in the density profile width as measured by Thomson scattering. The cause of this difference is not yet understood.

4. Fluctuations

In EDA, the edge pressure gradients can be at or above the ideal ballooning limit but are not relaxed by type I ELMs; instead a continuous process would seem to be at work. This process is probably related to broadband and quasi-coherent fluctuations which are observed during EDA. These fluctuations are seen with reflectometry, phase contrast imaging (PCI) and magnetic pick-up loops. The coherent component has a frequency of the order of 100 kHz with significant variation during and between shots. In general, higher frequencies are seen as

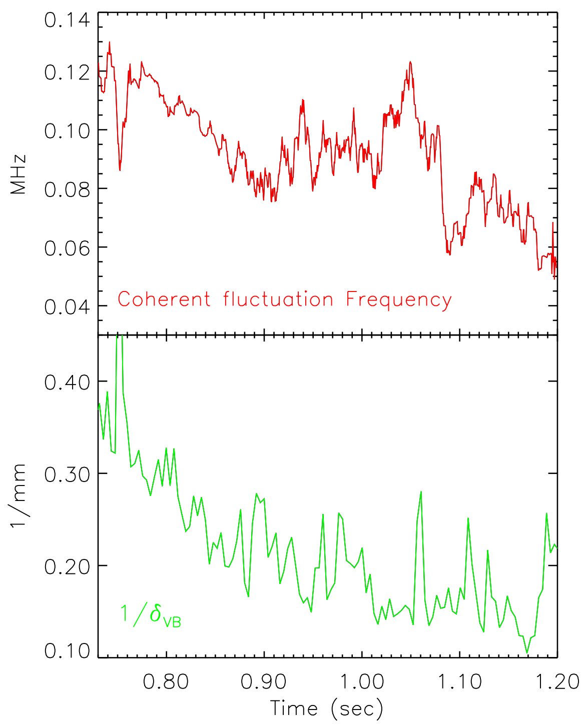


Figure 4. The frequency of the quasi-coherent fluctuation observed by reflectometry is plotted together with the inverse of the pedestal width as observed by visible bremsstrahlung radiation. The pedestal pressure does not vary much during this period, suggesting a diamagnetic origin for the variation of fluctuation with inverse scale length.

the plasma makes transitions into or out of EDA. Plasmas with some ELMfree characteristics (longer impurity confinement times) have higher-frequency coherent oscillations than those which are most clearly EDA. The reflectometer localizes the oscillations to the plasma edge where the Doppler shift in the shear layer is likely to make an important contribution to the laboratory frame frequency. The fluctuation frequency is seen to vary inversely with the pedestal scale length as measured by VB (figure 4) suggesting a diamagnetic origin. The coherent feature is dominant in the PCI measurements, which show a well-defined spatial structure with $k_R \sim 6\ \mathrm{cm}^{-1}$. PCI makes measurements averaged over a vertical chord, so with the observed fluctuations localized in the plasma edge by reflectometry, the measured k_R corresponds to k_θ. Magnetic diagnostics typically observe only the broadband fluctuations suggesting that the coherent feature either has a short wavelength (< 1–3 cm) consistent with PCI measurements, or has no significant magnetic component. In a few cases, weakly coherent fluctuations in the same frequency band as those discussed above are seen on pick-up coils located near the inner edge (small major radius) of the plasma. Coils on the outside never see this component of the fluctuations, possibly because they are 2 cm further from the plasma.

5. Discussion

EDA could be an interesting mode for a fusion reactor. It avoids the twin perils of the H-mode; impurity accumulation when ELMfree, and high-pulsed heat loads on the divertor in ELMy regimes. However, we cannot extrapolate the mode to a reactor with any confidence unless we understand the underlying physics. A number of effects seem to be ruled out. As discussed above, specific ICRF physics appears to play no role in the phenomenon. The lack of any important dependence on neutral pressure or density suggests that neutral losses or viscosity are unimportant. The strong dependences observed on q_{95} and triangularity [3], on the other hand, would seem to implicate MHD stability in the process. So far, however, calculations of ballooning stability find no clear trends that align with the EDA/ELMfree boundary. Moreover, when radiation or neutral pressures are high, low-performance EDA discharges are obtained. These have very poor confinement and small pedestals and are apparently quite far from the stability limits. It must be noted that these calculations are incomplete since current density profiles in the edge plasma are not yet available.

An interesting subsidiary question is whether the EDA represents a separate stable regime which is attained through a bifurcation process or whether it can be joined continuously to the ELMfree regime. Evidence on this point is inconclusive. On some discharges, the transition is accompanied by an abrupt change in H_α; on others it is not. Pedestal measurements do not, in general, show any abrupt change. On the other hand, impurity confinement does change dramatically and the density fluctuations, discussed above, turn on abruptly [3]. Dithers between EDA and ELMfree regimes, some lasting for as short a time as 1–2 ms, are seen on H_α and on the density-fluctuation diagnostics, suggesting limit-cycle behaviour.

Recent simulations of drift Alfvén turbulence [7] show a coherent mode arises as the pedestal pressure gradient approaches an MHD stability limit which can be several times the ideal limit. The predicted mode has $k_\theta \sim 2\pi/L_\mathrm{P}$ where L_P is the pedestal gradient length, consistent with the C-Mod observations. The frequency predicted is of the correct magnitude and dependence. The critical tests for this identification are: (a) does the mode preferentially drive particle transport and (b) are the dependences on shape and q reproduced? Answers to these questions will require further analysis and addition of more realistic geometry to the simulations.

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