H-mode edge stability of Alcator C-mod plasmas

D. A. Mossessian, A. Hubbard, J. W. Hughes, M. Greenwald, B. LaBombard , J. A. Snipes, S. Wolfe, P. Snyder *, H. Wilson **, X. Xu***, W. Nevins***

Massachusetts Institute of Technology, PSFC, Cambridge, MA 02139, USA
* General Atomics, San Diego, CA 92186, USA
** EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, UK OX14 3DB
** Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

For steady state H-mode operation, a relaxation mechanism is required to limit build-up of the edge gradient and impurity content. C-Mod sees two such mechanisms - EDA and grassy ELMs, but not large type I ELMs. In EDA the edge relaxation is provided by an edge localized quasicoherent electromagnetic mode that exists at moderate pedestal temperature T< 400 eV, high pedestal density and high edge safety factor, q>3.5 and does not limit the build up of the edge pressure gradient. The mode is not observed in the ideal MHD stability analysis, but is recorded in the nonlinear real geometry fluctuations modeling based on fluid equations and is thus tentatively identified as a resistive ballooning mode. At high edge pressure gradients and temperatures the mode is replaced by broadband fluctuations (f< 50 kHz) and small irregular ELMs are observed. Based on ideal MHD calculations that include the effects of edge bootstrap current, these ELMs are identified as medium n (10 < n < 50) coupled peeling/ballooning modes. The stability thresholds, its dependence on the plasma shape and the modes structure are studied experimentally and with the linear MHD stability code ELITE.

Formation of a transport barrier in high confinement mode (H-mode) is accompanied by a buildup of strong temperature and density gradients in a narrow region of the plasma in the vicinity of the separatrix (pedestal region). It has been shown, for example in [1,2], that total confinement and core transport are directly linked to the height and gradient of the temperature and pressure pedestal. When these gradients become sufficiently strong, they drive edge MHD instabilities that limit further pedestal growth. The most common type of such instabilities are edge localized modes (ELMs) – short bursts of transport that intermittently relax the pedestal gradients and provide steady state operation of H-mode discharges. Large type I ELMs, which are the major edge relaxation mechanism on most of the existing tokamaks, drive considerable particle and energy fluxes that present a significant power load on the divertor target plates. On Alcator C-Mod, however, type I ELMs have never been observed. Instead more benign instabilities appear to drive enhanced particle transport at the edge of H-mode plasmas, leading to steady state operation. We present the results of recent experimental and numerical studies of these edge instabilities on Alcator C-Mod.

The most extensively studied edge instability is a quasicoherent (QC) electromagnetic mode (f=50 – 150 kHz), localized in the outer part of the pedestal that appears to drive enhanced particle transport in Enhanced D-alpha (EDA) H-mode [3,4]. It is established experimentally that the QC mode exists in a well defined region of edge parameter space, requiring moderate pedestal temperature (T_e^{ped} < 400 eV), high pedestal density and high edge safety factor (q_{95}>3.5) [5]. Ideal MHD stability analysis that includes both pressure and current driven intermediate n modes (stability code ELITE, [6]) shows that the plasma edge is stable in typical EDA discharges. On the other hand, the nonlinear real geometry modeling based on Braginskii fluid equations (boundary turbulence code BOUT, [7]) shows, for an EDA plasma discharge, the existence of an edge localized resistive x-point mode with characteristics (location, wavenumber, frequency) similar to the measured parameters of the QC mode. Based on these results the QC mode was tentatively identified as a resistive ballooning mode.

In high density, high input power discharges with both edge pressure gradient and edge temperature higher than in the EDA region, the QC mode is replaced by low frequency (f<50 kHz) broadband fluctuations. In this regime small irregular ELMs are observed with average frequency around 600 Hz. In Fig. 1 the magnetic fluctuation spectrum of both the QC mode and ELMs together with traces of total radiated power, line average density and D_α radiation are shown for a pure EDA H-mode (Fig.1 a) and a discharge with marginal values of ∇P_e^{ped} and T_e^{ped} (Fig. 2 b). In an EDA discharge the QC mode is clearly seen in the fluctuation spectrum obtained by a magnetic coil installed on a tip of the scanning probe that is dwells near the plasma separatrix. In the ELMy discharge, as in a regular EDA, the QC mode with ramping down frequency appears after a brief ELM-free period (1.02 – 1.04 sec, Fig. 2b). The mode is replaced by ELMs (1.05 sec) when the pedestal temperature grows above 400 eV and reappears (1.23 sec) when the edge cools down slightly.

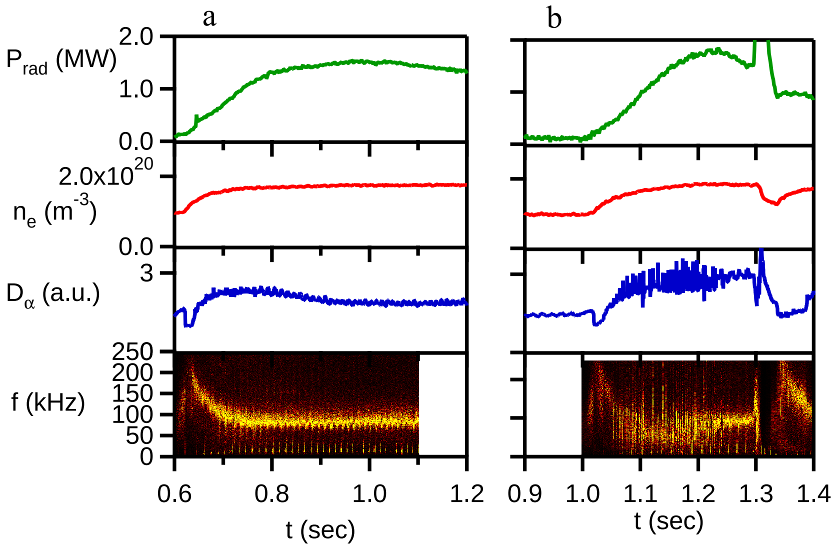

Fig.1 Magnetic fluctuation spectrum showing a QC mode and small ELMs (top) and divertor D_α signal (bottom). The QC mode starts at ~ 1.04 s following L-H transition (~1.02 s) and brief ELM-free period. The mode is replaced by broadband fluctuations (ELMs) at ~1.05 s and reappears at ~1.23 s when edge temperature drops.

The ELMs exhibit themselves as small irregular spikes in the divertor D_α signal.

It has been shown previously [5] that the quasicoherent mode characteristic for EDA regime exists in a well defined edge parameter space. Generally, the mode requires high values of edge q (q_{95} above 3.5) and moderate values of pedestal temperature. At higher T_e^{ped} or lower q_{95} the mode is usually replaced by ELM-free regime. The ELMy regime can be achieved at high q_{95} by simultaneous increase of edge temperature and density, which lead to higher edge pressure gradient. The boundaries between EDA, ELM-free and ELMy regimes are demonstrated in Fig. 2, where the values of T_e^{ped} and n_e^{ped} measured in the three types of H-mode are plotted.

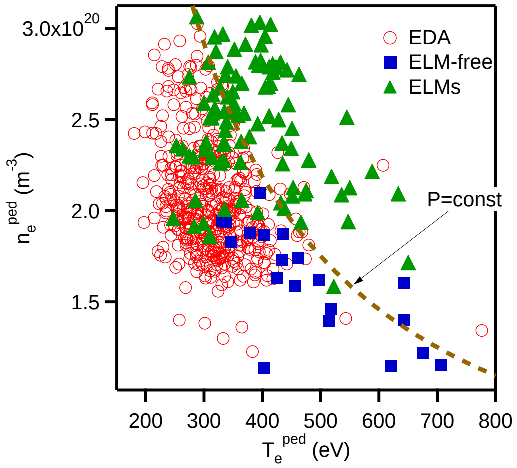

Fig. 2 Boundaries between EDA, ELM-free and ELMy regimes in pedestal parameter space. Each point on the graph is a time point that could be identified as one of the three H mode types by fluctuation diagnostics. ELMs appear in the high pedestal pressure region.

A clear transition between EDA and ELMy regime was demonstrated in a controlled power scan at constant target density (L-mode density prior to L-H transition) (fig. 3)

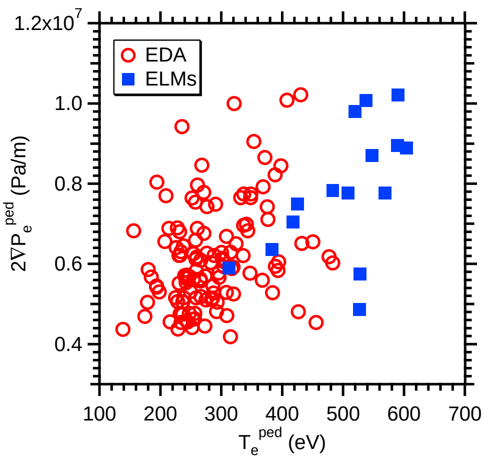

Fig.3 Power scan shows transition from EDA to ELMs in ∇P_e^{ped} - T_e^{ped} space. Each point on the graph represents single timeslice when pedestal parameters are recorded by Thomson scattering diagnostics. The points are classified as EDA/ELMs using magnetic fluctuation measurements.

It is seen that ELMs require higher edge temperature and generally appear at higher edge pressure gradient, although there is a considerable overlap with EDA regimes in edge pressure gradient range.

The observed characteristics of small ELMs are consistent with the proposed model of ELMs as intermediate n coupled peeling/ballooning MHD modes [6,8] driven by a combination of edge pressure gradient and edge current. The importance of the current driven term implies sensitivity of the mode stability to the edge temperature as well as pressure gradient. First results of the stability analysis performed with the linear ideal MHD stability code ELITE [6] show that the modes become unstable at the values of ∇P_e^{ped} and T_e^{ped} typical for small ELMy regimes on C-Mod [5]. A more comprehensive stability analysis was performed on a set of equilibria derived from the EDA and ELMy discharges obtained during the power scan experiment. In Fig.4 the pedestal measure temperatures are plotted against the $\alpha_{MHD} = \frac{2\mu_0 R q^2}{B_T^2} \bullet \frac{dP_e}{dr}$ parameter, derived from edge Thomson scattering measurements. Open blue circles represent the points corresponding to EDA regime, red circles – ELMy regimes. Squares mark the points that were analyzed using ELITE. The equilibriua for which the peeling/ballooning modes are found to have finite growth rate are marked as “unstable”.

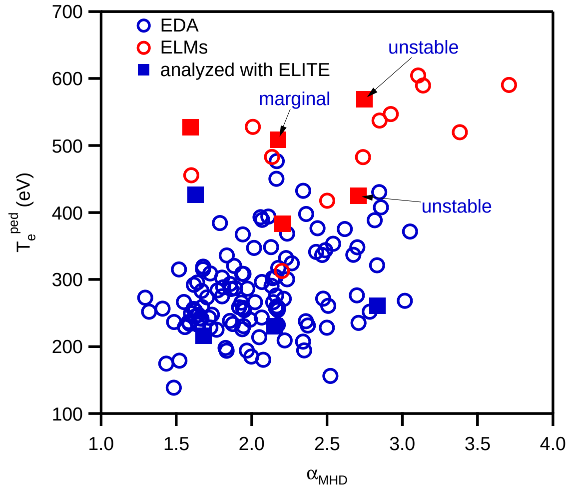

Fig.4 Stability analysis of a set of equilibria representing EDA and ELMy H-modes. See text for detailed explanation of symbols. Within uncertainties of j_{boot} calculations and experimental measurements ELITE shows stability boundary consistent with measurements

Within uncertainties of j_{boot} calculations and experimental measurements ELITE shows stability boundary consistent with measurements.

It was found experimentally, that transition to ELMy regime happens at lower input power in discharges with higher triangularity. Besides, in high triangularity plasmas the ELMs have larger amplitude and pedestal temperature and pressure gradient reach higher value at lower heating power. An example of two discharges with different upper triangularities but similar values of target density and heating power is shown in Fig. 5

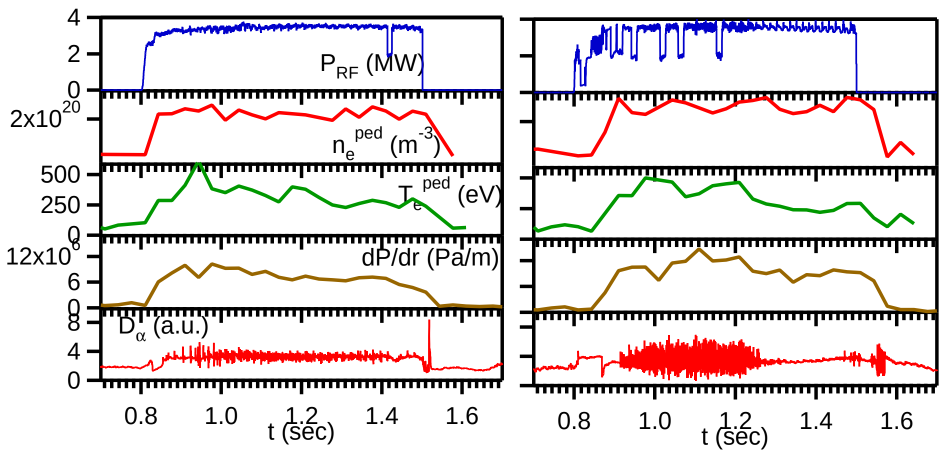

Fig.5 Traces of input power, pedestal density, temperature and pressure gradient and D_α intensity for discharges with upper triangularity of 0.32 (a) and 0.45 (b). Increase of ELM amplitude and pedestal height and gradient is seen in higher delta discharge.

This observation is consistent with the model of ELMs as coupled peeling/ballooning modes. Higher triangularity should lead to higher stability boundary, which allows the pedestal to grow larger before the limiting instability is triggered. The higher values of the pedestal gradient and height lead in turn to larger growth rates of the modes, leading to larger ELMs amplitude. This is demonstrated by the ELITE analysis that was performed using equilibria from the discharges shown in Fig. 5. The stability analysis shows higher growth rates for higher triangularity discharge.

Acknowledgements.

This work was supported by D.o.E. Coop. Agreement DE-FC02-99ER54512

References:

1. Osborne T. H., et. al. Plasma Phys. Control. Fusion 40 (1998) 845.
2. Greenwald M., et. al. Nuclear Fusion 37, (1997) 793.
3. Greenwald M., et. al. Phys. Plasmas 6, (1999) 1943.
4. Hubbard A. E., et. al. Phys. Plasmas 8, (2001) 2033.
5. D. A. Mossessian, et. al. Plasma Phys. Control. Fusion, 44 (2002) 423-437
6. Wilson H. R., et. al. Phys. Plasmas 9, (2002) 1277
7. Snyder P. B., et. al., Phys. Plasmas, 9, (2002) 2037
8. X.Q. Xu. R.H. Cohen, T.D. Rognlien, and J.R. Myra, Phys. Plasmas, 7, (2000) 1951.