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H-MODE PEDESTAL AND ELM CHARACTERISTICS AT HIGH DENSITY*

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Introduction. H-mode based burning plasma tokamaks require both high pressure at the inner edge of the H-mode transport barrier and small edge localized modes, ELMs. High density is required for high fusion power output, and for the flat density profiles generally obtained in ELMing H-mode discharges this implies high H-mode pedestal density. High Q requires high energy confinement, which in turn is predicted to increase strongly with pedestal temperature in stiff temperature profile turbulent transport models such as those based on ITG modes[1]. For ITER-FEAT in H-mode operation, the requirements are roughly $n_e^{PED} = 0.9x10^{20} m^{-3}$ and $T^{PED} = 5.5 keV$ [2] giving $W^{PED} = 3p_e^{PED}V \approx 200 MJ$. ELMs can result in a significant fraction of the pedestal energy, on DIII-D at low density typically 20 % of W^{PED}, being

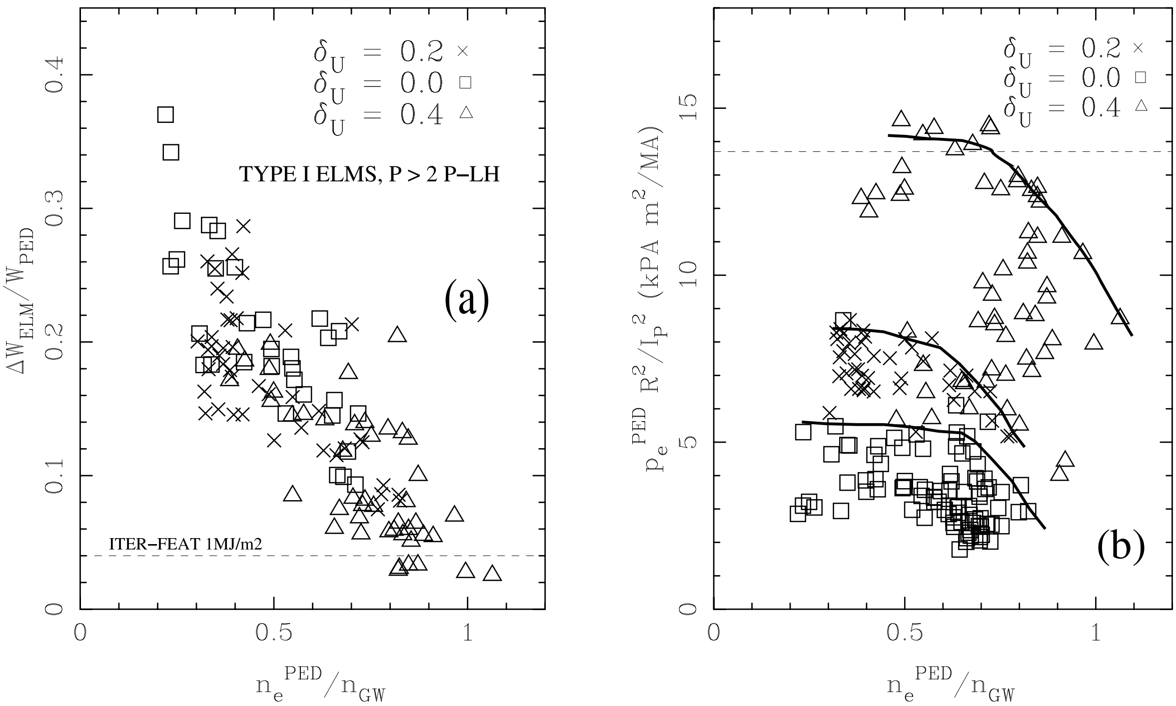

Figure 1: a) Type I ELM energy loss normalized to H-mode pedestal pressure decreases strongly with increasing pedestal density independent of triangularity b) pedestal pressure normalized to ballooning mode decreases with increasing density and is largest at high triangularity. Approximate requirements for ITER-FEAT are given as dashed lines.

released in a short time, typically < 1ms. This can result in large transient power flux to the divertor plates that can quickly erode the divertor material if the power is above a threshold value[3]. For ITER-FEAT to achieve the < 1MJ/m^2 for good divertor lifetime requires $\Delta W_{ELM}^{DIV} / W^{PED} < 4\%$. For Type I ELMs this small level of ELM energy loss can be obtained at densities near the Greenwald density limit on DIII-D.

Pedestal Pressure and ELM Energy Loss at High Density. The fraction of the H-mode pedestal energy lost at an ELM decreases strongly with increasing density in DIII-D (fig 1a.). Data from different triangularities, which show large variation in pedestal pressure for a given plasma current, have similar fractional ELM energy loss at a given density relative to the Greenwald density, $n_{GW}(10^{20} m^{-3}) = I_P(MA)/\pi a^2(m)$. At moderate density $\Delta W_{ELM} / W_{PED}$ has roughly the same value in the JET tokamak[3]. The H-mode pedestal pressure also decreases as the pedestal density increases (fig 1b.). At moderate power, the width of the transport barrier is observed to decrease, and the pedestal energy and ELM energy loss decrease, as the density is increased with gas puffing. In some cases this reduction in the width of the steep gradient region in the temperature profile occurs gradually over several hundred

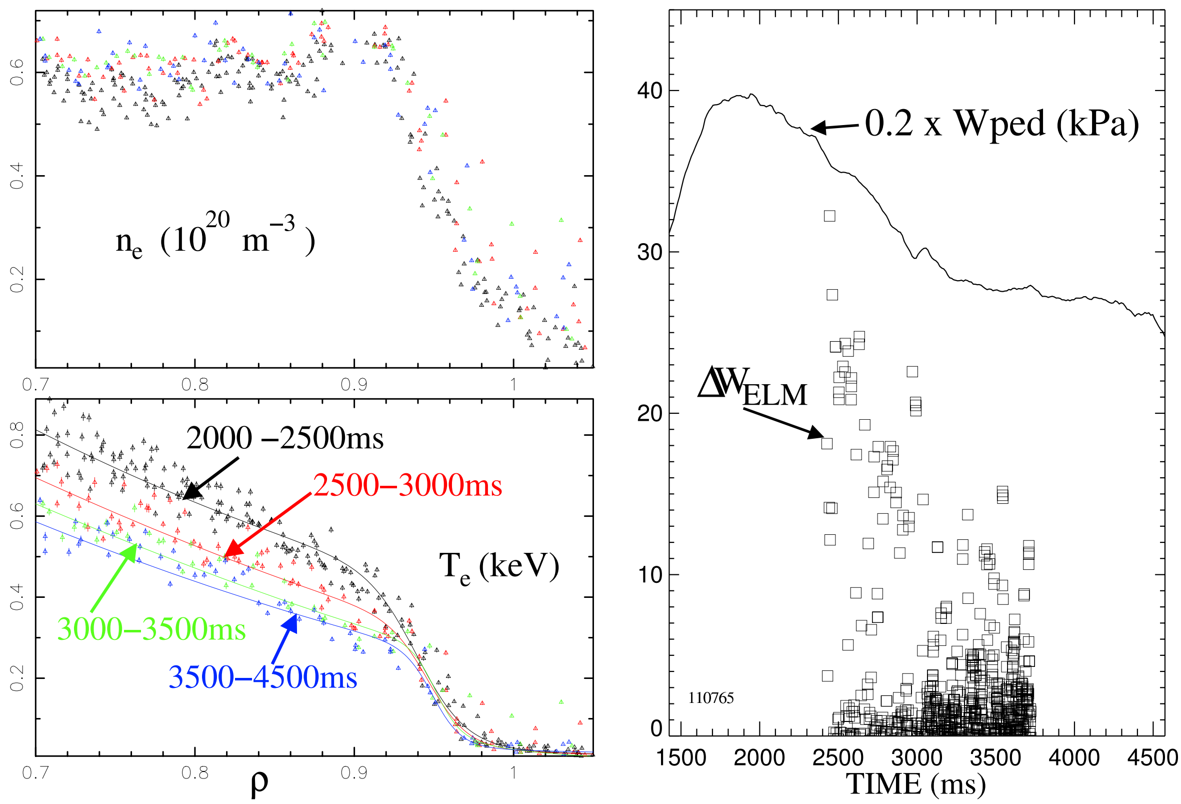

Figure 2: Width of the steep gradient region in the temperature profile narrows as the H-mode pedestal energy and ELM energy loss are reduced in a discharge with continuous D2 puffing and $n_e^{PED} / n_{GW} = 0.75$.

ms with little change in the pedestal density (fig 2). In the highest density discharges this decrease in the transport barrier width accounts for most of the edge pressure reduction. The data in figure 1b can be fit to a form for the pressure assuming the pressure gradient follows ballooning mode scaling modified by fitted terms for the plasma triangularity, elongation, and poloidal β, and assuming that the transport barrier width scales as $\Delta / R \propto \left(\rho_{POL}^{PED} / R\right)^{\alpha}$ where $\rho_{POL}^{PED} \sim (T^{PED})^{0.5} / B_{POL}$. A value of $\alpha = 0.58$ roughly accounts for the density dependence in the pressure. However this scaling does not correctly predict the pedestal pressure in JET, and does not fit the results of divertor pumping experiments [4].

ELM Size and Mode Structure. We have proposed that the ELM energy loss is related to the width of the eigenmode of the peeling-ballooning mode associated with the ELM[5,6]. This is consistent with the appearance of small ELMs in high q, high triangularity discharges on JT60-U[6]. The mode width is expected to decease with increasing toroidal mode number, decrease with increasing q, and increase with increasing width of the steep gradient region. In a discharge that went from n/n_{GW} =0.5 to 0.8, the toroidal mode number of the mode associated with the ELM increased from about 6 to 30. This increase in mode number is consistent with ELITE[7] code calculations showing that the most unstable n increases as the edge current density decreases as would be expected at high density due to suppression of the bootstrap current at high collisionality. Calculations for two discharges covering a similar range in density indicated a similar n increase and a narrowing of the mode width consistent with the increased n and reduced width of the steep gradient region (fig 3).

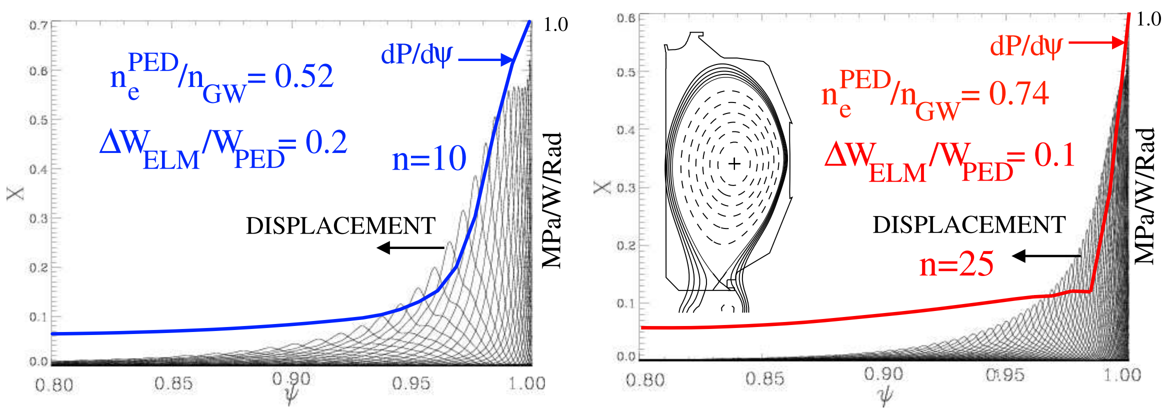

Figure 3: Comparison of peeling-ballooning eigenmode structure for low and high density discharge showing shrinking of mode width and increase in n for high density case with narrower high p' region.

The observed width of the ELM induced perturbation in the density and temperature profiles remains nearly unchanged (into r/a=0.8) as the density is increased in contrast to what might be expected from the mode width calculations. We also find that for densities below roughly n/n_{GW} =0.7 the reduction in ELM energy loss is primarily in the conduction channel, $n\Delta T$, while both conductive and convective, $T\Delta n$ terms are reduced above this density.

Discussion. DIII-D results show that it is possible to achieve high pedestal pressure with small ELMs at high triangularity. However, more progress needs to be made in the understanding of the processes which set the H-mode transport barrier width. Figure 1b shows that for shapes similar to ITER-FEAT at moderate density the edge pressure requirement is met at high triangularity with the same transport barrier width relative to machine size as on DIII-D. In addition the transport barrier width scaling appears to play a role in both the reduction in pressure at high density and possibly the size of the ELM energy loss. The width of the steep gradient region in the density profile on DIII-D is found to follow a scaling consistent with the neutral penetration depth, λ_N[8], and increased heating power might also be expected to widen the transport barrier[9]. In fact, some recent analysis of DIII-D discharges also indicates that the H-mode transport barrier may expand as the heating power is increased at high density without a corresponding increase in ELM size. It is possible that neutral penetration controls the width with strong gas puffing at low power but other effects enter at high power flux. The data suggests a connection between the peeling-ballooning eigenmode width and the size of the ELM energy loss. However more work needs to be done to understand the nonlinear development of this instability and to describe the mechanism of the energy loss. The difference between the behavior of the conductive and convective losses suggests that transport processes in the SOL may also play a role in the variation of ELM energy loss with density. This is also suggested by the fact that the time scale for the ELM event ~ 100 μs is close to the particle transport time to the divertor plates at the sound speed which is 50-200 μs and increasing with density.

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