Tolerable ELMs at High Density in DIII–D*

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GENERAL ATOMICS

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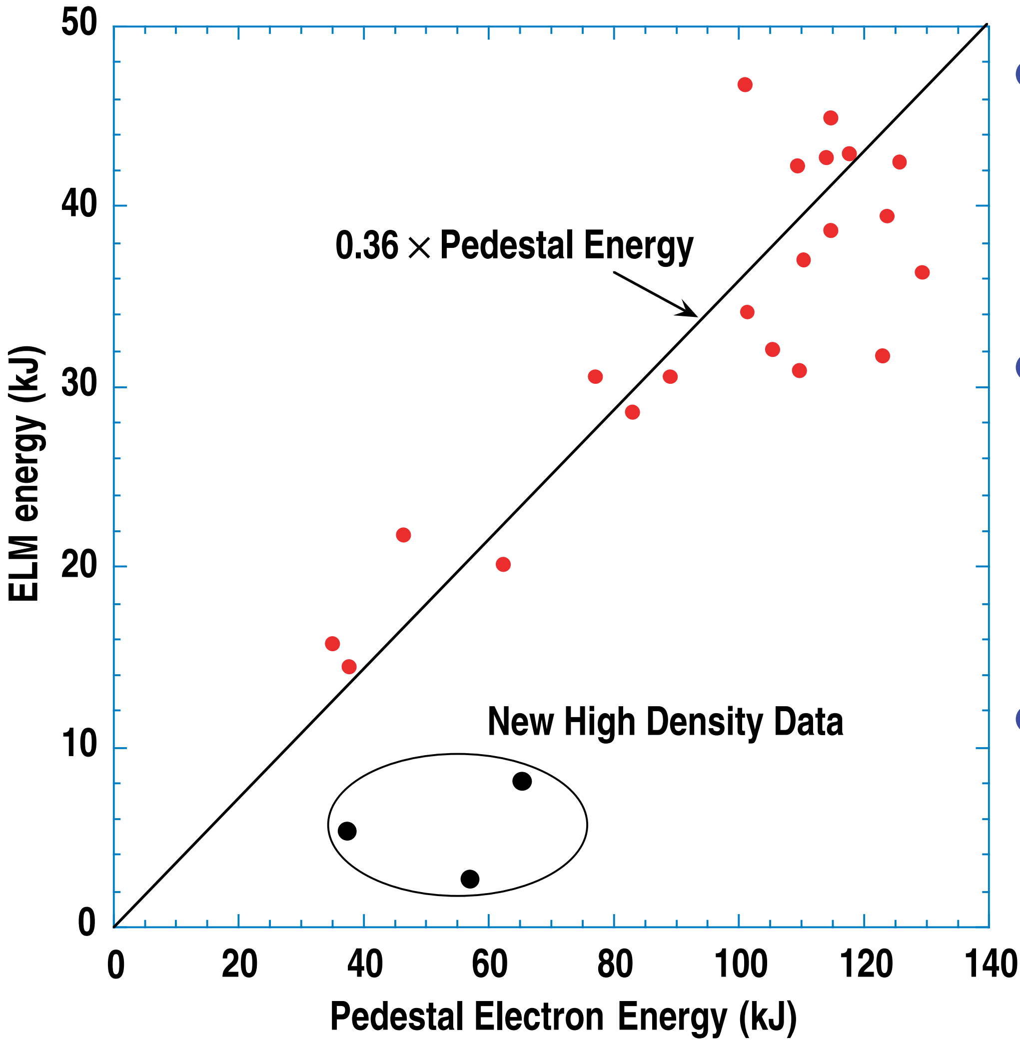
INTRODUCTION

- The ELM (Edge-Localized-Mode) instability during H–mode triggers a rapid loss of edge pressure which can propagate inward and destroy central confinement. The lost ELM energy is transported outward into the SOL, flowing into the divertor where it may damage plasma facing components. At low or moderate density the ELM energy loss scales proportionally with the edge pedestal pressure. However at high density the ELM perturbations to the temperature profile become small resulting in a much smaller and more tolerable ELM energy loss. These small ELMs can be achieved while maintaining good pedestal and confinement. At low density losses to both temperature and density are observed just inside the separatrix. At higher density the density loss remains, but the temperature perturbation is much reduced. The magnetic fluctuations at the ELM instability are also reduced at high density. Implications and future work are discussed

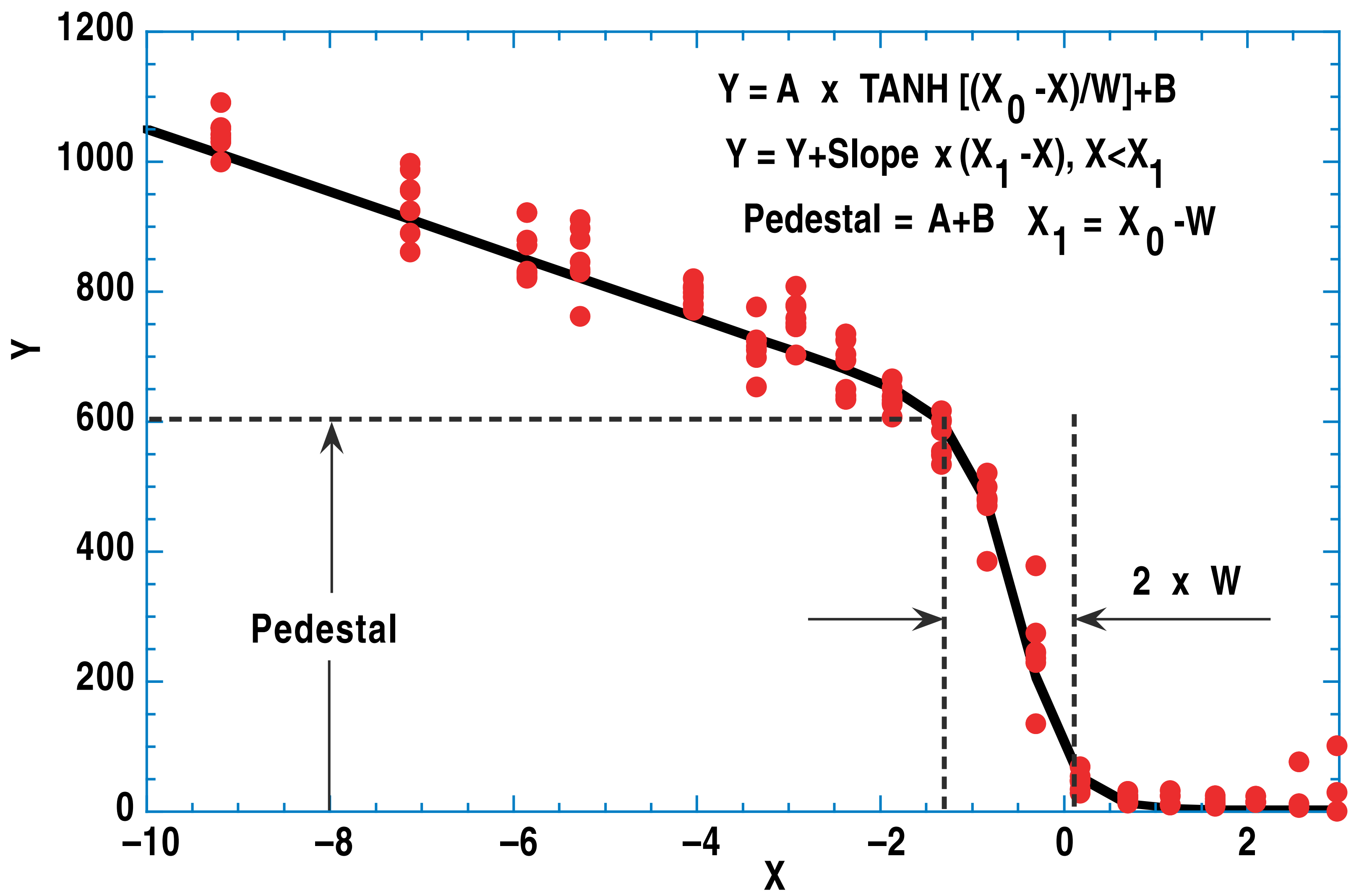
AT LOW DENSITY ELM ENERGY SCALES WITH EDGE PRESSURE PEDESTAL



- Previous ELM scaling[1] of ELM energy; $\Delta W \approx$ 1/3 of E_{ped} for DIII–D. E_{ped} defined as electron pressure at top of pedestal multiplied by the plasma volume
- This scaling predicts ELMs a factor of 3-4 too large for ITER's divertor at the desired pedestal values, or conversely, pedestal a factor of 3-4 below desired for optimal confinement
- An ideal ELM is of small amplitude, but still allows a robust pedestal. New data at higher density indicates this may be possible

[1] A.W. Leonard, et al. J. Nucl. Mater. 266-269 (1999) 109

EDGE PROFILE MODELED WITH TANH FUNCTION



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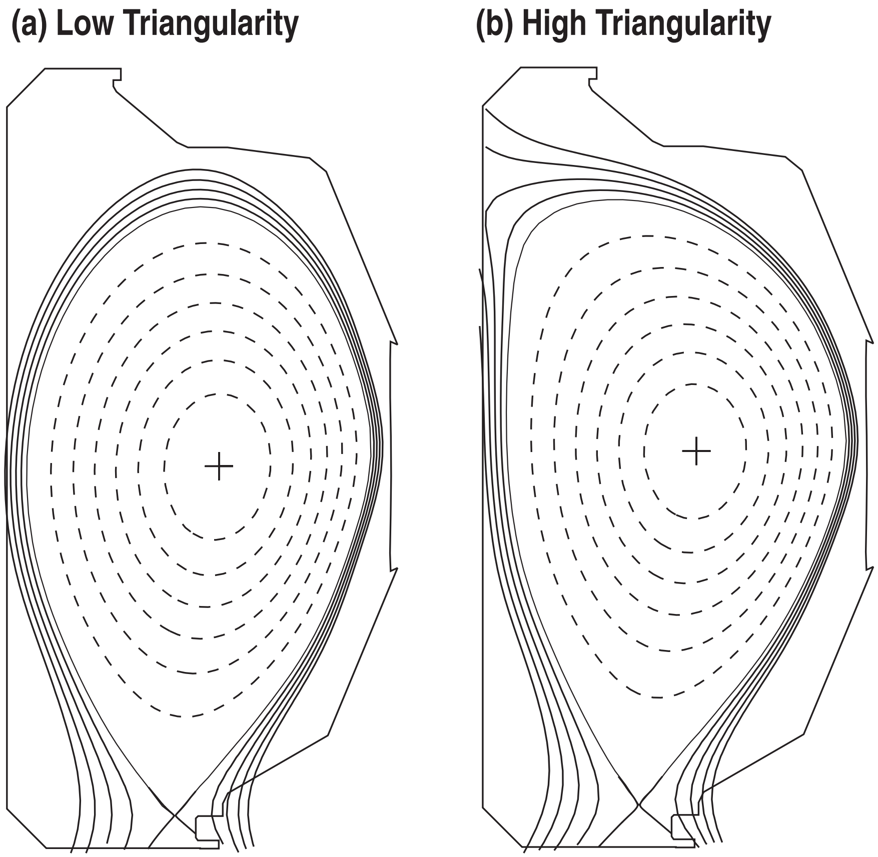
DENSITY AND TRIANGULARITY VARIED



- High density, high confinement discharges are produced with moderate gas puffing and divertor pumping to regulate edge conditions
- Upper triangularity is varied between δ~0.0 and δ~0.36, lower triangularity constant at δ~0.1
- ELM energy determined from fast MHD equilibrium analysis. Uncertainty in energy analysis is ~5 kJ
- Edge profiles are measured with high spatial resolution Thomson scattering

At moderate gas puffing levels, pedestal density increases to $n_{e,ped}$~0.7 n_{GW}, $\bar{n}_e$~0.9 n_{GW}, with little degradation in pedestal pressure and confinement. ELM frequency increases factor of 3–5 with similar decrease in ELM energy. At higher gas puff, and $n_{e,ped}$ levels, pedestal begins to degrade. Low and high triangularity behave similarly, but with higher pedestal pressure in high triangularity configuration.

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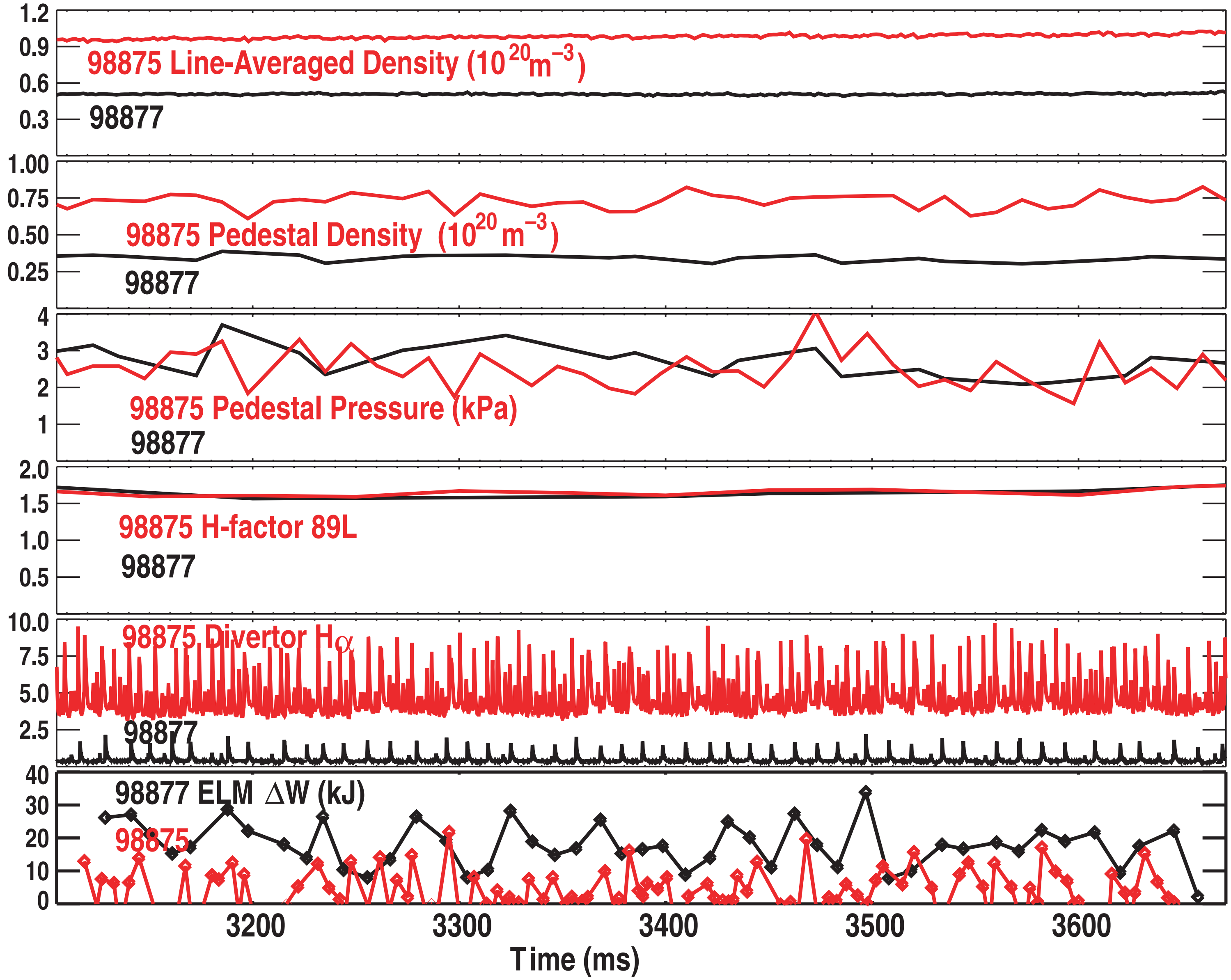
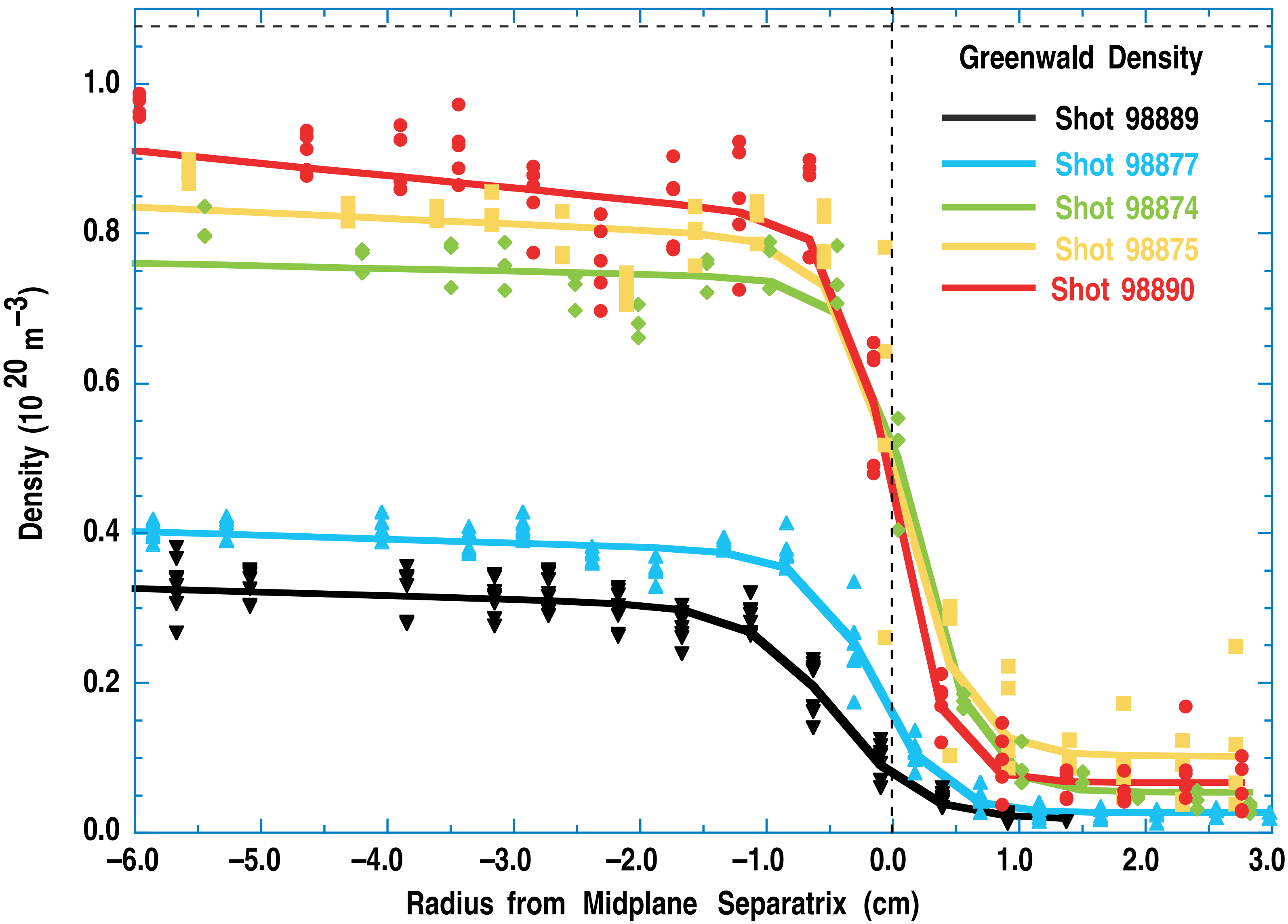
ELMs SMALL AND RAPID AT HIGH DENSITY, WHILE GOOD CONFINEMENT MAINTAINED



LOW TRIANGULARITY DENSITY SCAN



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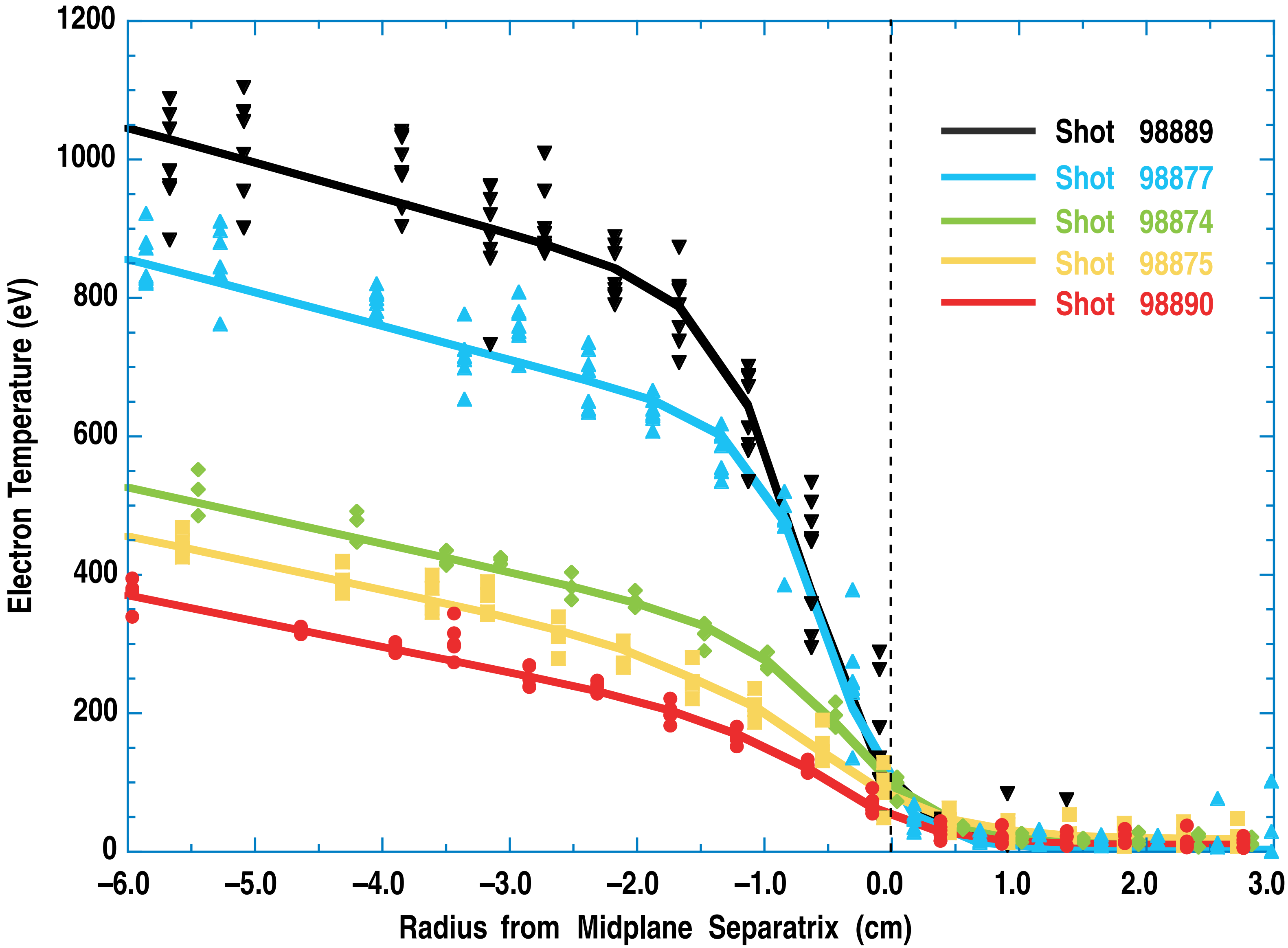
T_e DROPS WITH INCREASING DENSITY



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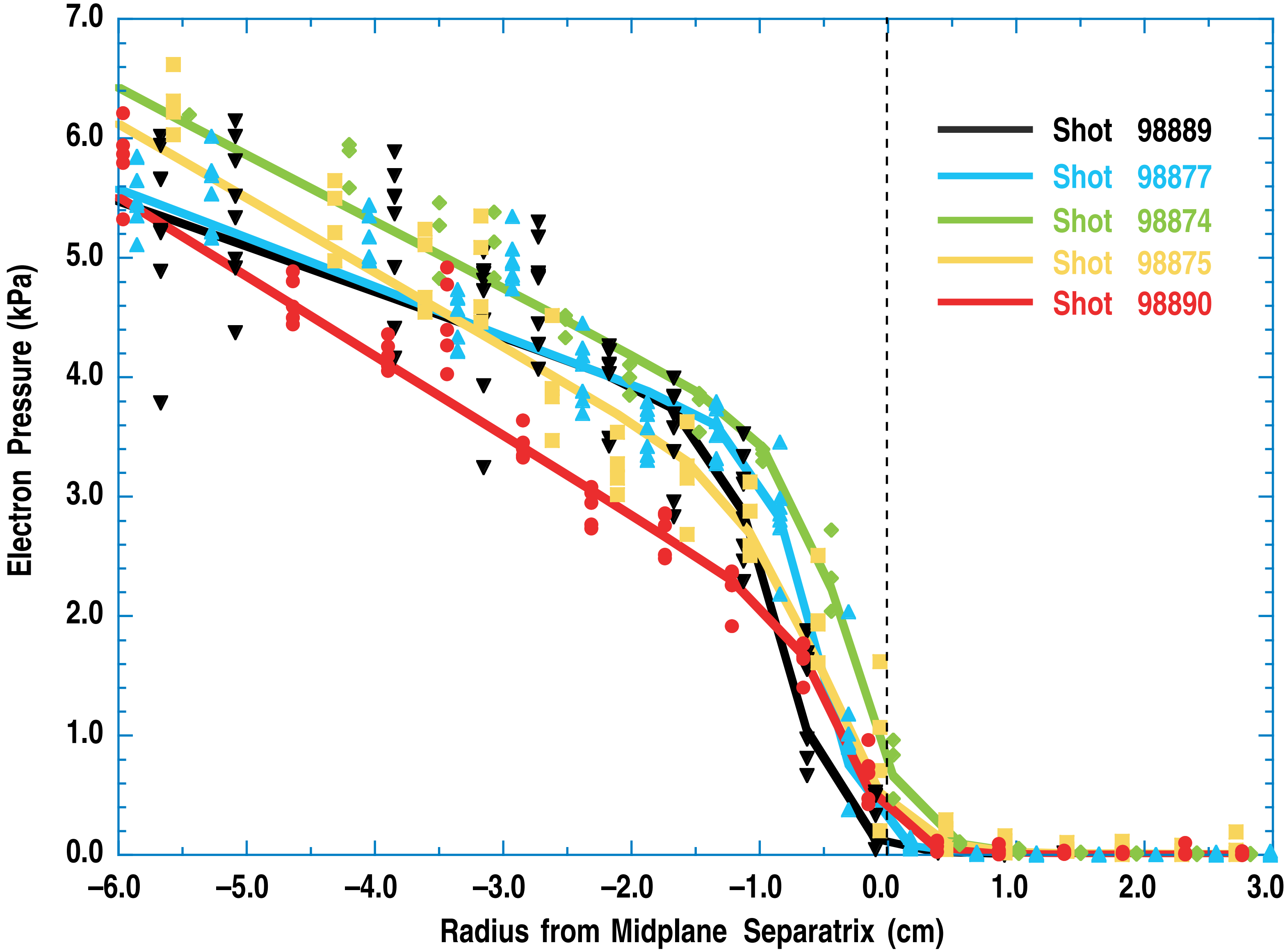
ELECTRON PRESSURE MAINTAINED



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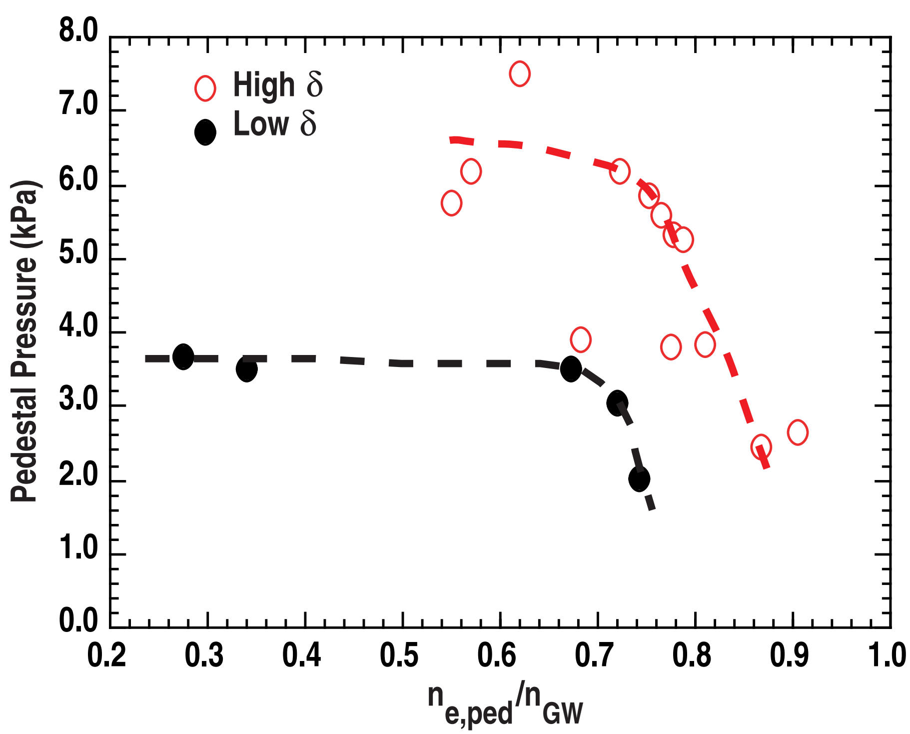
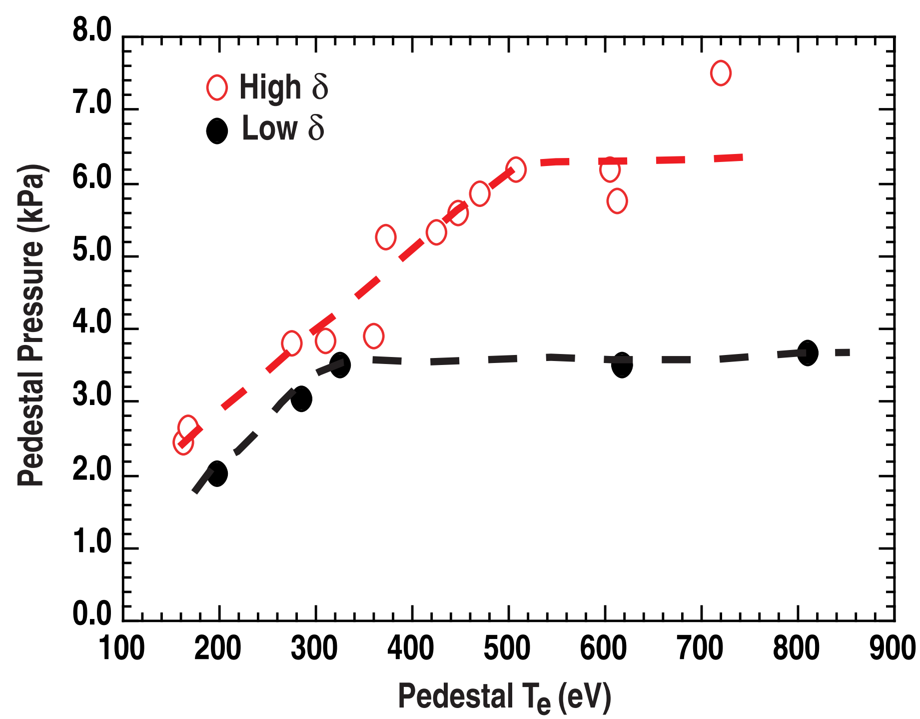
PEDESTAL DEGRADES AT HIGH DENSITY AND LOW T_e





- High triangularity configuration displays higher edge stability limit at low to moderate density. At $n_{e,ped} \geq 0.7$-$0.75\ n_{GW}$, $\bar{n}_e > 0.95\ n_{GW}$, pedestal pressure quickly degrades. Pedestal pressure appears highly correlated with $T_{e,ped}$, but degradation threshold at high triangularity is at higher T_e

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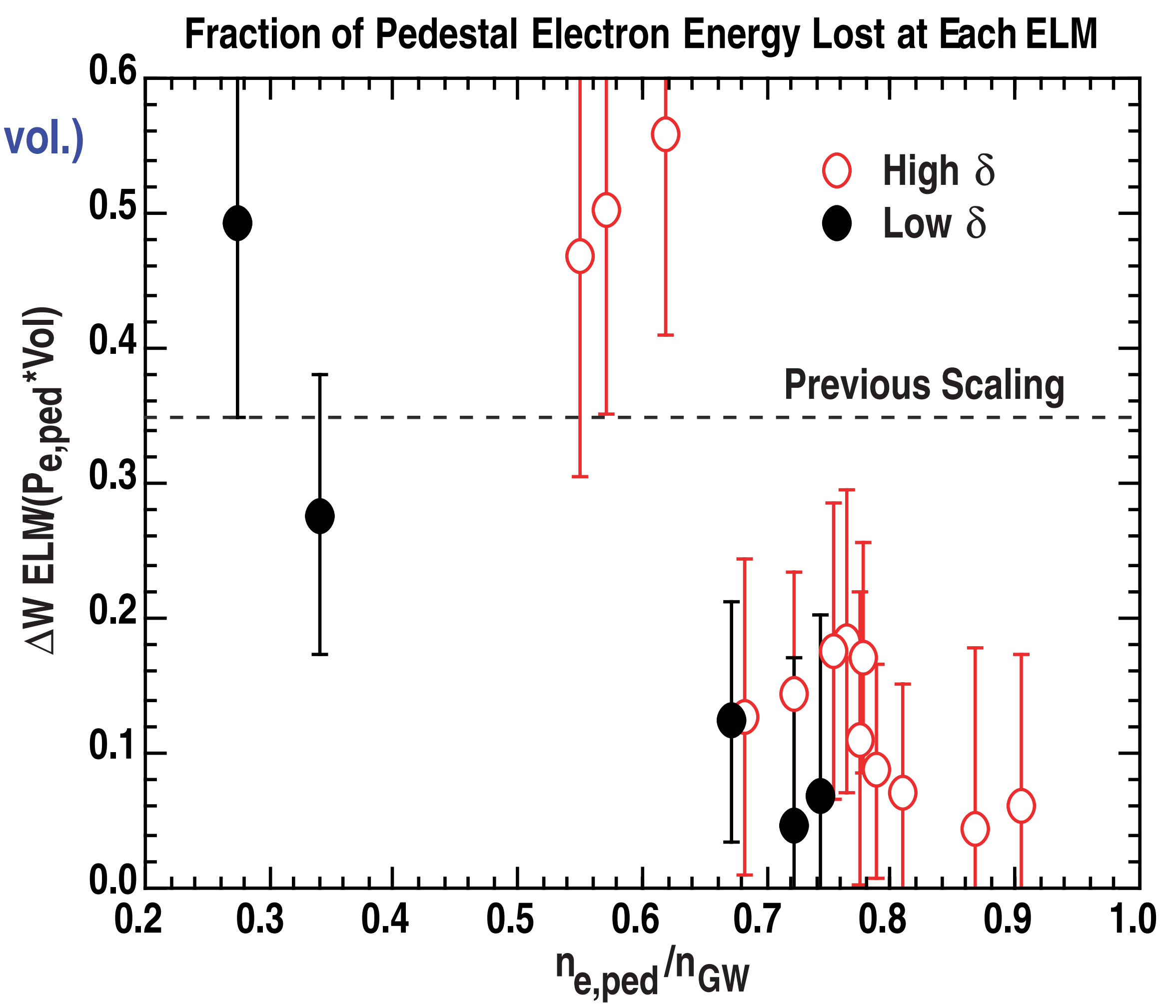
ELM ENERGY DECREASES AT HIGHER DENSITY

- ELM energy is normalized to pedestal pressure, ($P_{e,ped}$ x Plasma vol.)
- ELM size decreases by factor >5 as density increases; Only at highest density does edge pressure begin to decrease
- At high triangularity normalized ELM energy decreases at higher density than low triangularity
- Error bars due equally to ELM variability and measurement uncertainty



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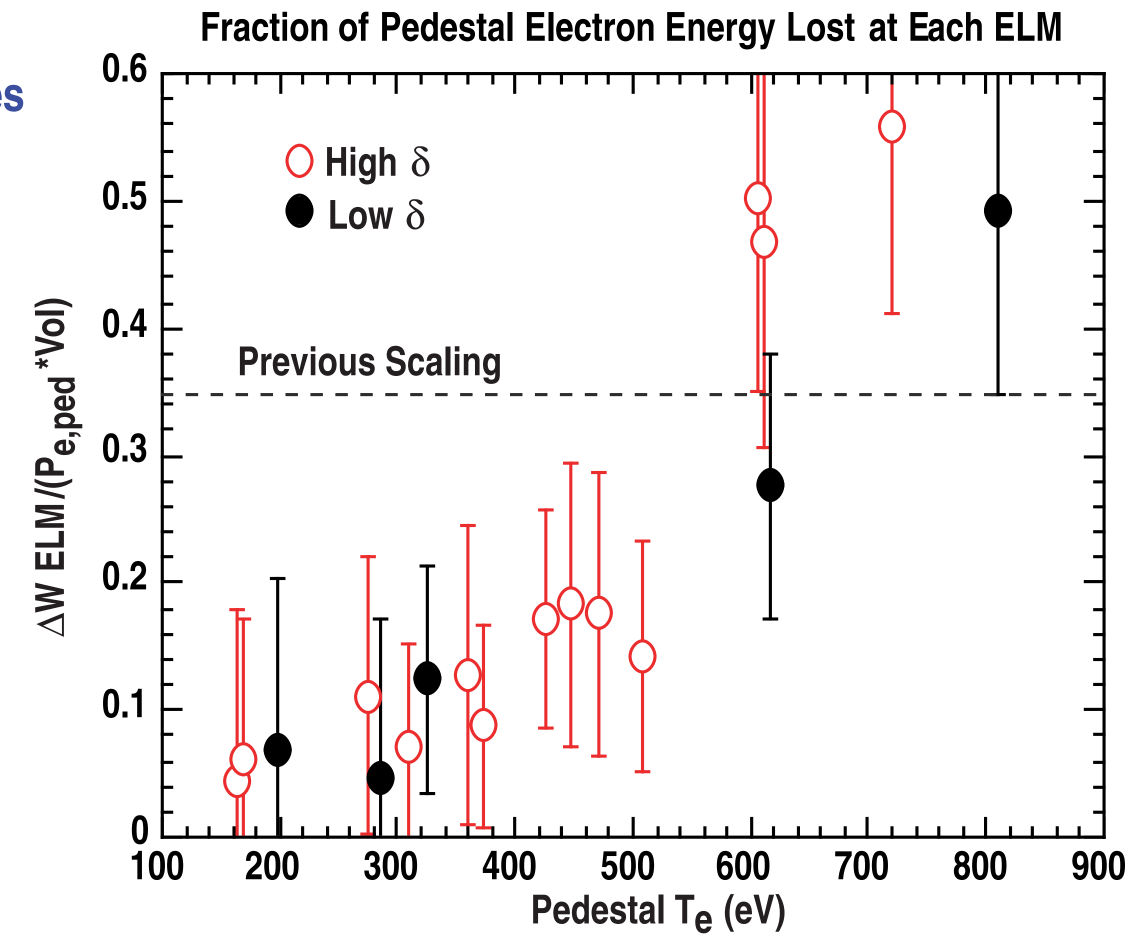
ELM ENERGY CORRELATES STRONGLY WITH PEDESTAL T_e

- The normalized ELM energy decreases for both low and high triangularity at a similar pedestal temperature
- A pedestal T_e range of 300–500 eV for small ELMs and a robust pedestal for attractive operation. Corresponds to a smaller density range, $n_{e,ped}$ = 0.7–0.8 n_{GW}
- Scaling of these results to a larger tokamak is uncertain



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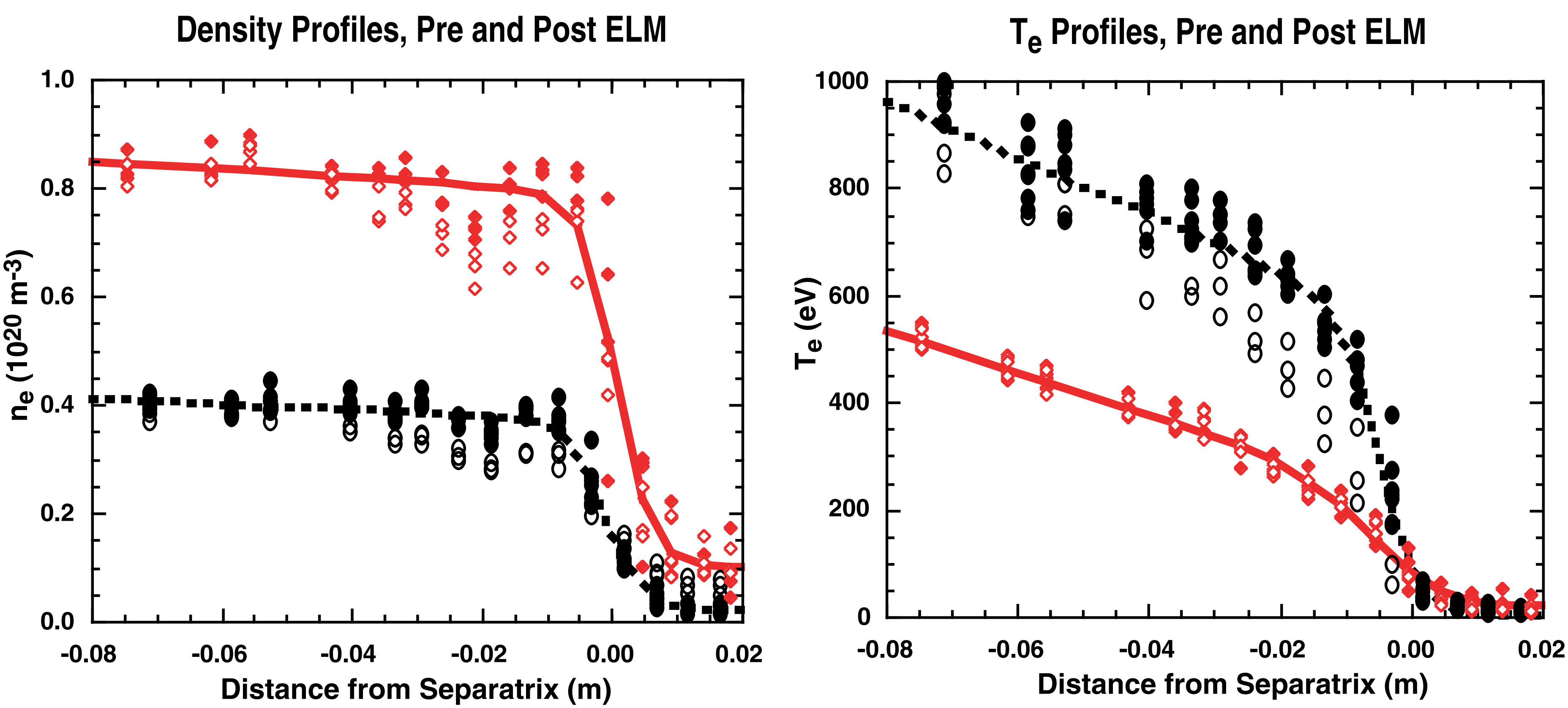
PEDESTAL T_e STRONGLY PERTURBED BY ELMS AT LOW DENSITY



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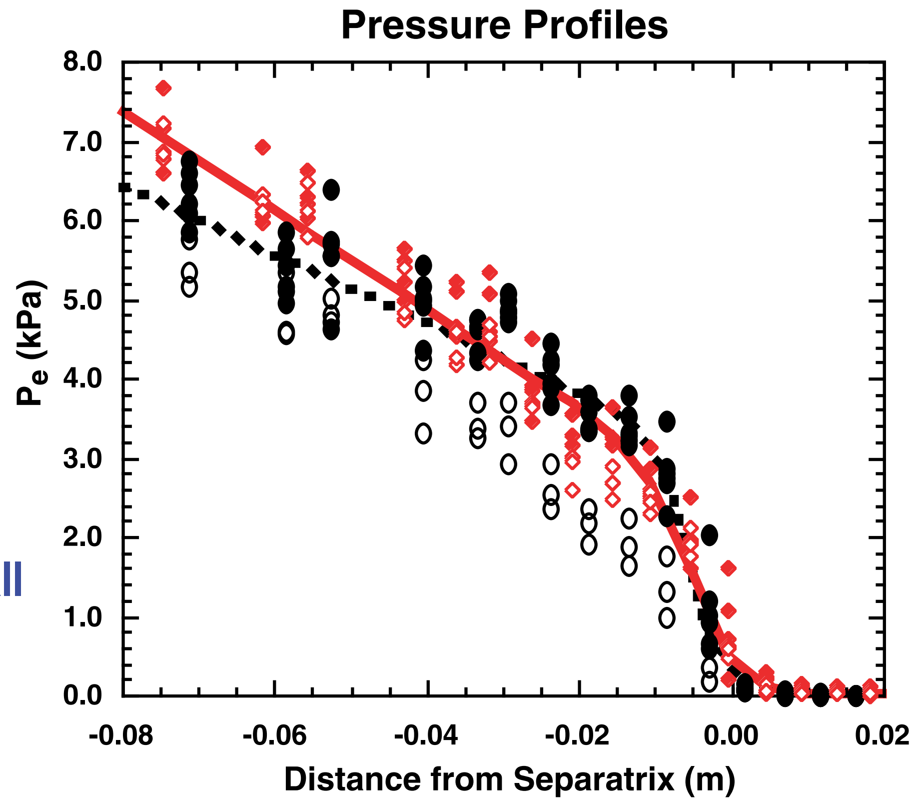
PRESSURE PERTURBATION GREATER AT LOW DENSITY

- Pre-ELM profiles are collected from Thomson scattering times 0.6-1.2 ms before ELM
- Post-ELM profiles are collected 0.6-1.2 ms after individual ELMs
- At low density significant perturbations to both n_e and T_e extend into the main plasma
- At high density T_e perturbations become very small The n_e perturbations maintain their amplitude, but are more limited in radial extent
- The electron pressure drop at an ELM is much smaller for the high density case



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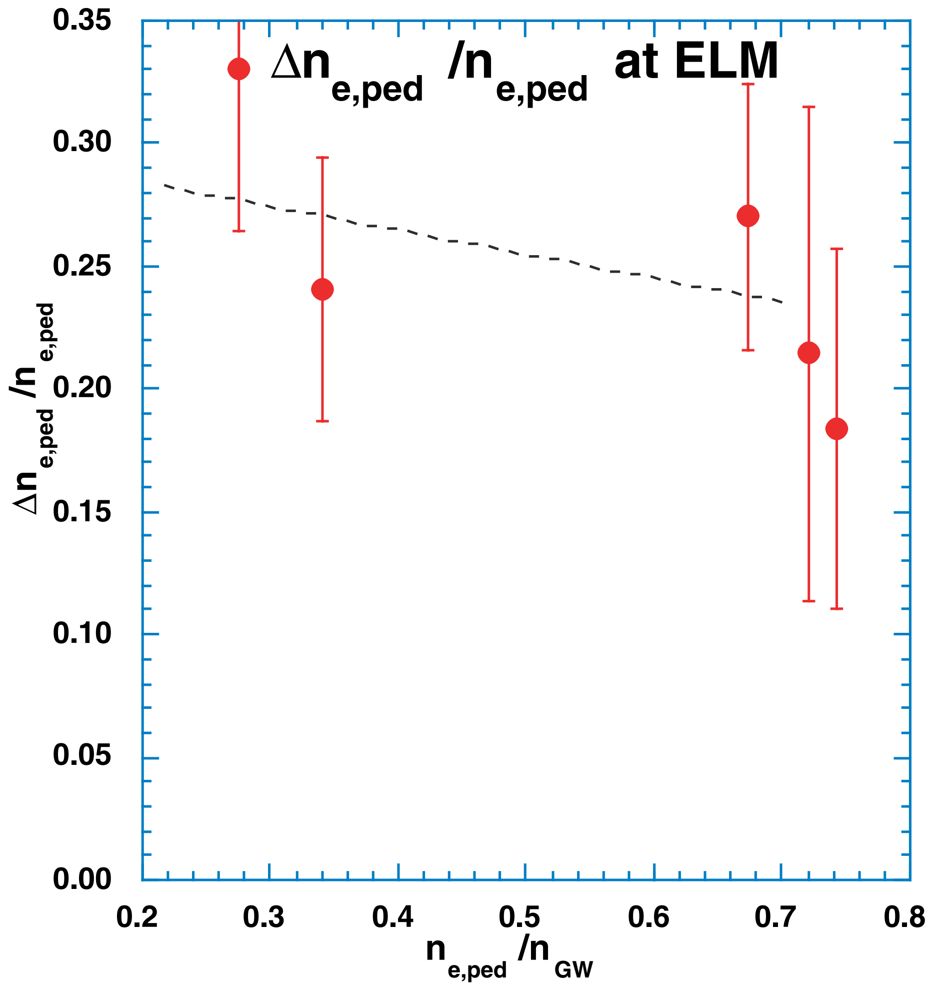
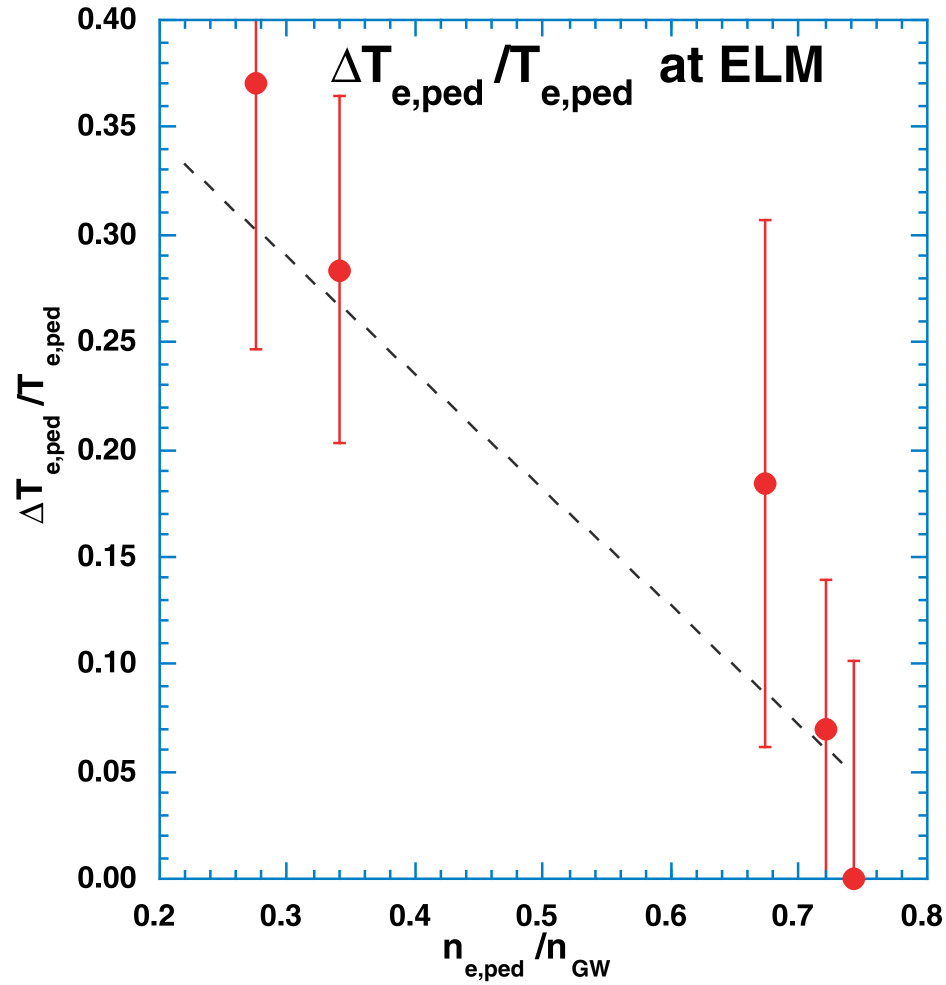
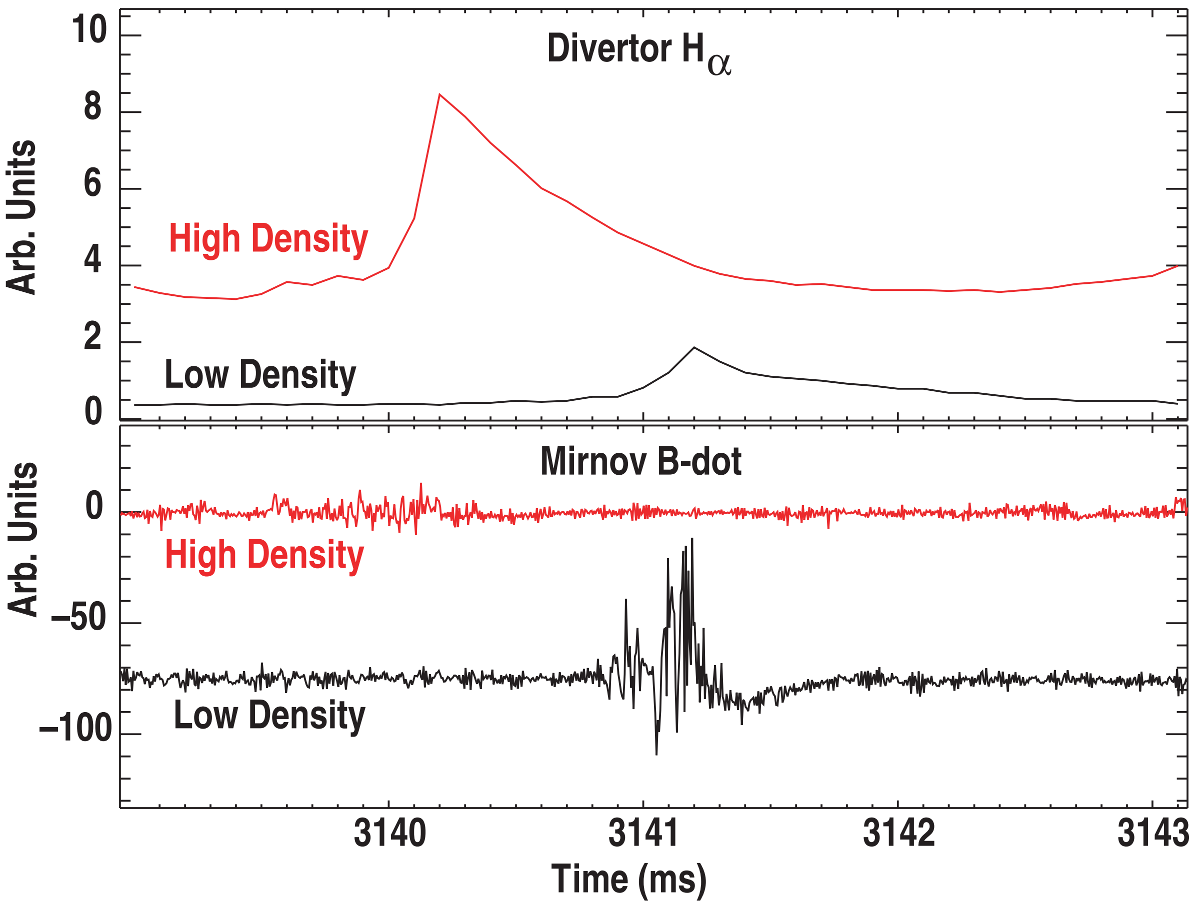
RELATIVE DENSITY LOSS AT ELM REMAINS CONSTANT BUT T_e PERTURBATION BECOMES SMALL AT HIGH DENSITY





ELM MAGNETIC FLUCTUATIONS REDUCED AT HIGH DENSITY



- Even though the ELM energy loss is smaller at high density, the H_α peak due is actually larger than for low density. The H_α level is more a function of density, ions and neutrals, than energy

- The measured magnetic fluctuations due to an ELM is 5-10 times smaller at high density. This may be due to a reduction in amplitude, and/or an increase in mode number of the instability which will cause the perturbation to fall off more rapidly from the instability surface

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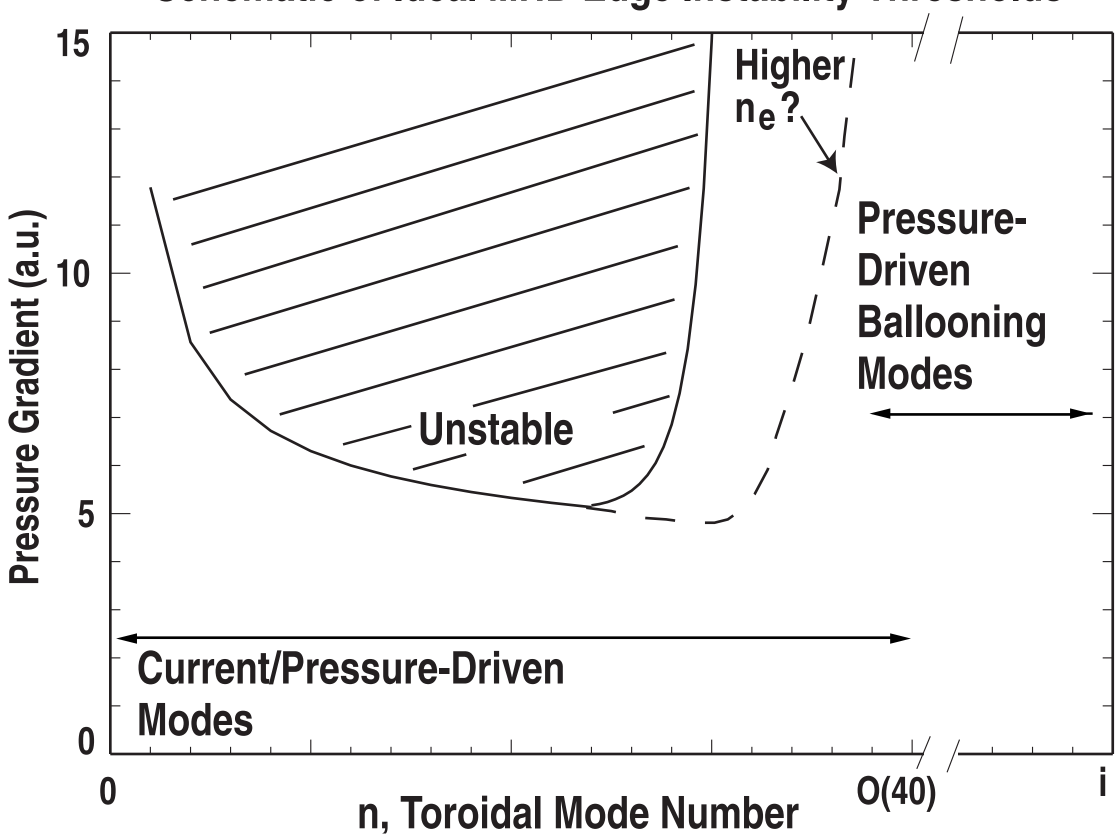
SUMMARY OF OBSERVATIONS

- Ratio of ELM energy to pedestal pressure decreases $\geq$ factor of 5 as line-averaged density approaches Greenwald limit. If this fractional ELM energy loss, $\Delta W/(P_{e,ped} \times Vol)$, can be held to <5%, as demonstrated on DIII–D, a robust pedestal for high confinement can be compatible with safe divertor operation in a reactor scale tokamak. However, it is unknown how the ELM size vs. density will scale to a larger tokamak in a different parameter regime
- Pedestal pressure just before ELM remains nearly constant, maintaining good confinement, until $n_{e,ped}$ ~$0.7n_{GW}$, $\bar{n}_e$~$0.9\ n_{GW}$. At higher densities the pressure pedestal begins to degrade, but density profile peaking maintains the good confinement
- At high density $\Delta n_{e,ped}/n_{e,ped}$ at an ELM remains nearly constant, but $\Delta T_{e,ped}/T_{e,ped}$ drops dramatically
- Magnitude of magnetic fluctuations during ELM drops factor of 5–10 at high density, while the duration of the fluctuations nearly constant at ~400 ms
- At high triangularity ELM energy is also reduced at high density. The pedestal pressure for high triangularity is generally higher than low triangularity, but degrades at a similar density
- ELM energy and pedestal pressure more closely correlated with $T_{e,ped}$ than $n_{e,ped}$

A POSSIBLE EDGE STABILITY MODEL

Schematic of Ideal MHD Edge Instability Thresholds



- ELMs are thought to be driven by gradients in the edge pressure and/or current
- MHD calculations have shown that higher n modes can be stabilized by the edge bootstrap current
- At higher density and collisionality a lower bootstrap current may increase the mode number n of the most unstable mode. However, these experiments show only a modest decrease in edge pressure gradient at the higher density
- Increasing resistivity at high density may also be playing a role in the growth rate of edge instabilities

FUTURE WORK

- Measure changes to ion pressure gradient at higher density with CER
- Other divertor configurations often have a lower density limit. Compare different divertor configurations for access to high density with small ELMs and good confinement
- Scaling of ELM energy and pedestal pressure with plasma current, shaping and input power to separate scaling of parameters, such as T_e, n_e, or bootstrap current profile
- Mode analysis of magnetic fluctuations during ELMs to determine changes to mode number of ELM instability as density increases
- Cross-machine comparison, i.e. JET, JT-60U, for size scaling
- Stability analysis to calculate effects of change in density and temperature on edge bootstrap current, resistivity and edge stability