ELM Energy Scaling in DIII-D H-mode Plasmas

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ELM Energy Scaling in DIII-D H-mode Plasmas[1] A.W. LEONARD, M.A. MAHDAVI, T.H. OSBORNE, T.W. PETRIE, General Atomics, M.E. FENSTERMACHER, C.L. LASNIER, Lawrence Livermore National Laboratory, J.G. WATKINS, Sandia National Laboratories — 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 also has the potential to damage plasma facing components. We correlate the rapid loss of plasma stored energy during an ELM with changes to the edge pedestal density and temperature profile changes as measured by Thomson scattering, ECE radiometry, and microwave reflectometry. At low or moderate density the ELM energy loss scales proportionally with the edge pedestal pressure. However at higher density the ELM perturbations to the temperature profile become very small resulting in a much smaller ELM energy loss. Correlations of the ELM energy loss to local and global parameters is explored. The inward propagation of the edge temperature perturbation is also investigated.

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☐ Prefer Oral Session
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Special instructions: DIII-D Poster Session 2, immediately following MA Mahdavi

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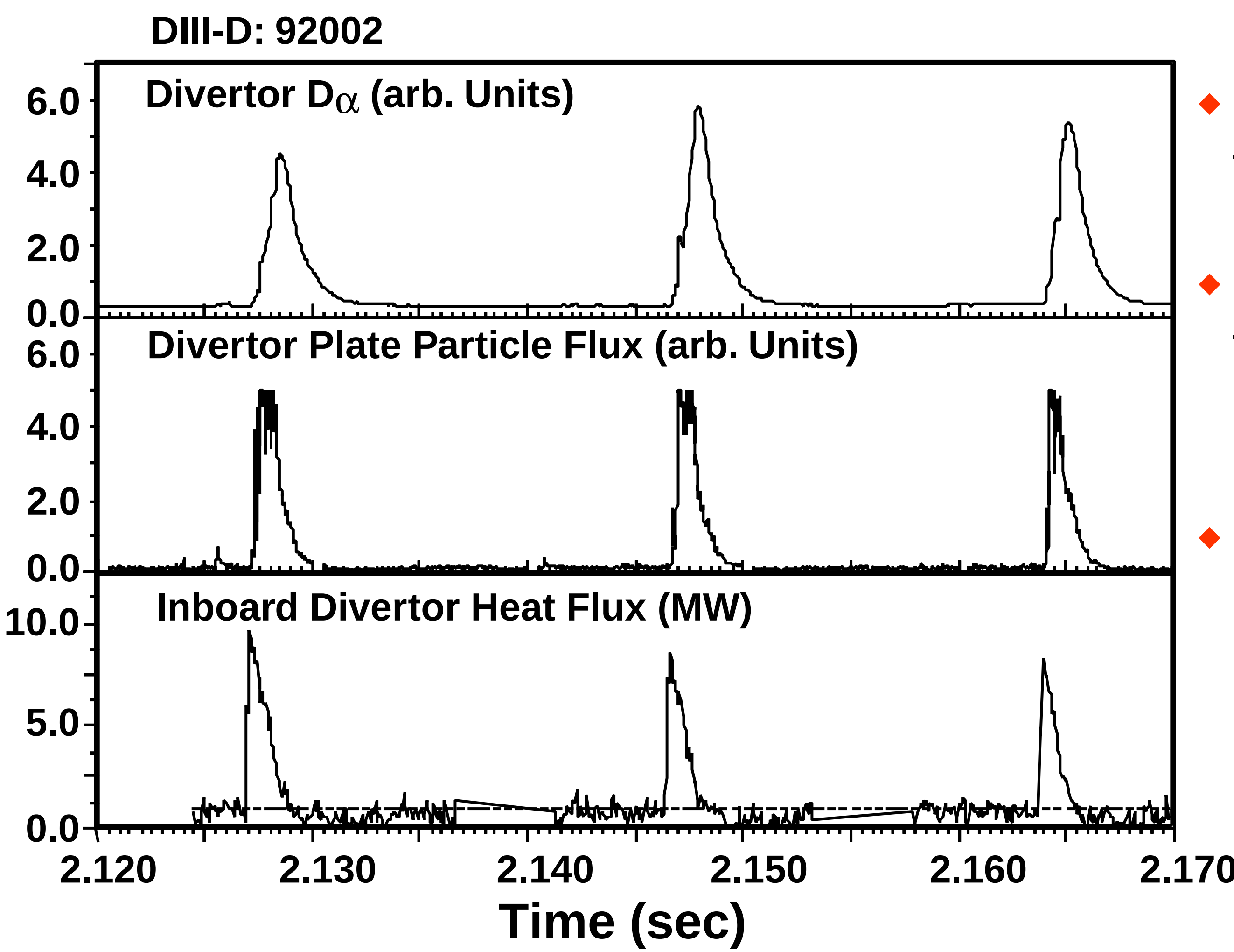
Introduction

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 also has the potential to 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.

ELMs Release Particles and Energy into the SOL

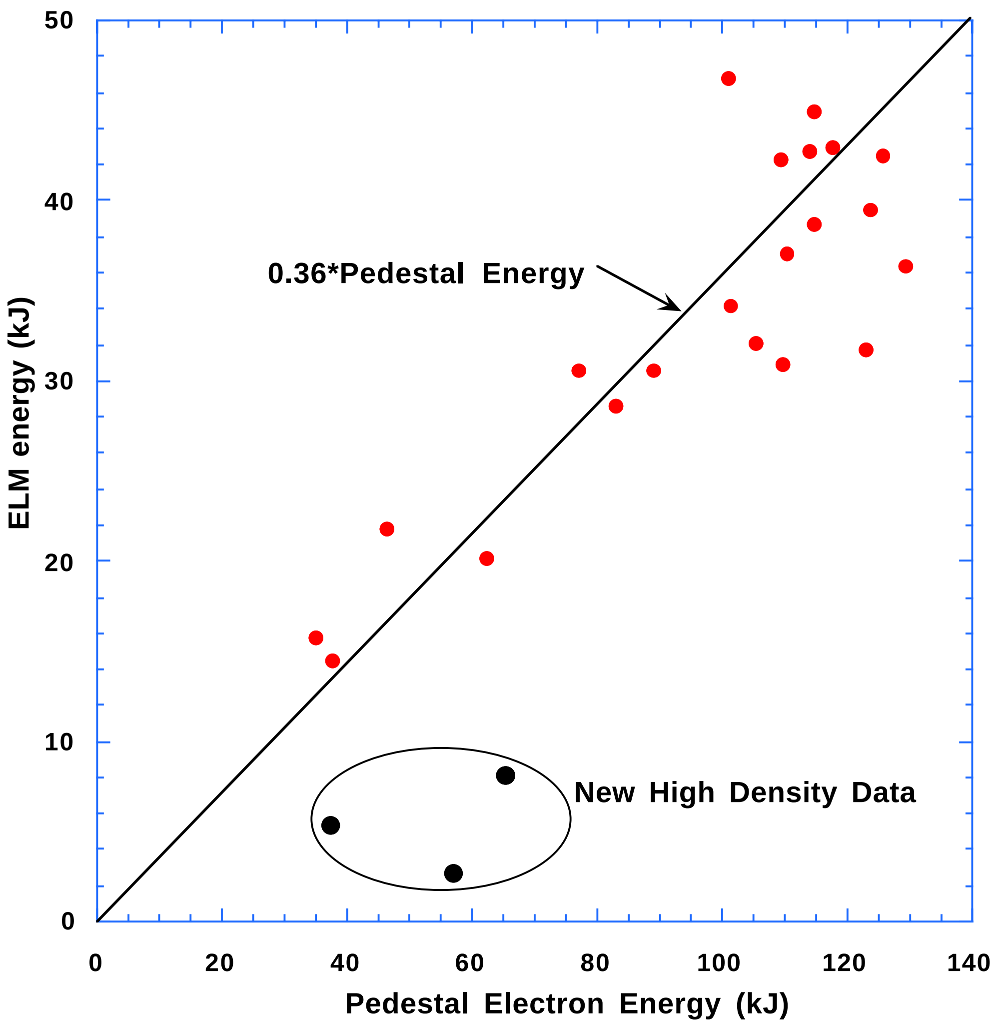


- ELMs are a common feature of H-mode.
- ELM instability results from steep gradients just inside separatrix.
- Fast parallel transport produces large perturbation to divertor plasma.

ELMS: The Good the Bad and the Ideal

- The good ELM: They help regulate density and impurity accumulation during H-mode.
- The bad ELM: Pulse of heat flux to divertor can cause target ablation and shorten divertor lifetimes. Perturbations propagate to center where they can be deleterious to central confinement, as with Internal Transport barriers.
- The Ideal ELM: Small perturbation, but rapid enough to control density and impurities. Must allow a significant time-averaged edge pressure pedestal consistent with high confinement.

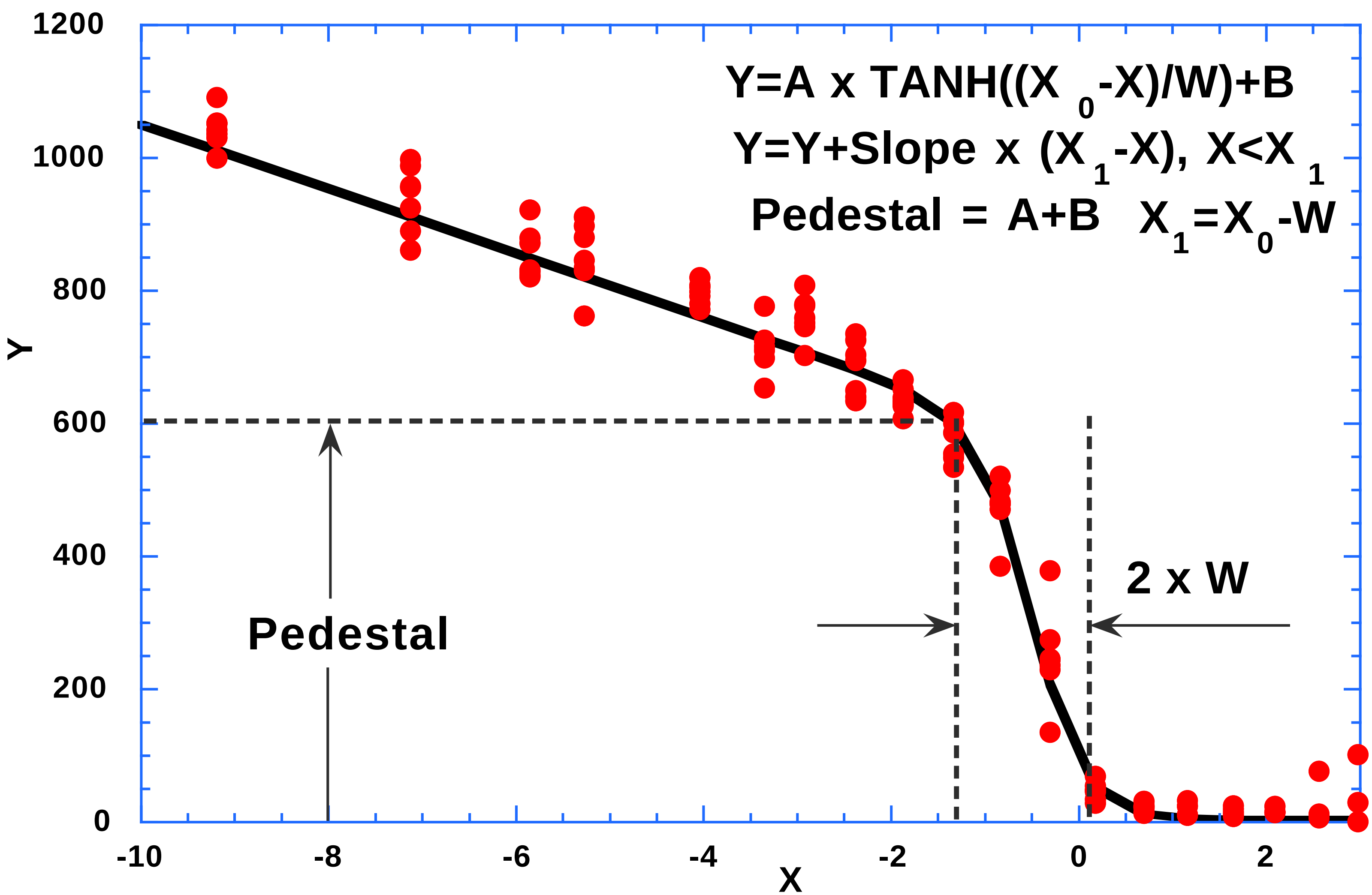
At Low Density ELM Energy Scales with Edge Pressure Pedestal



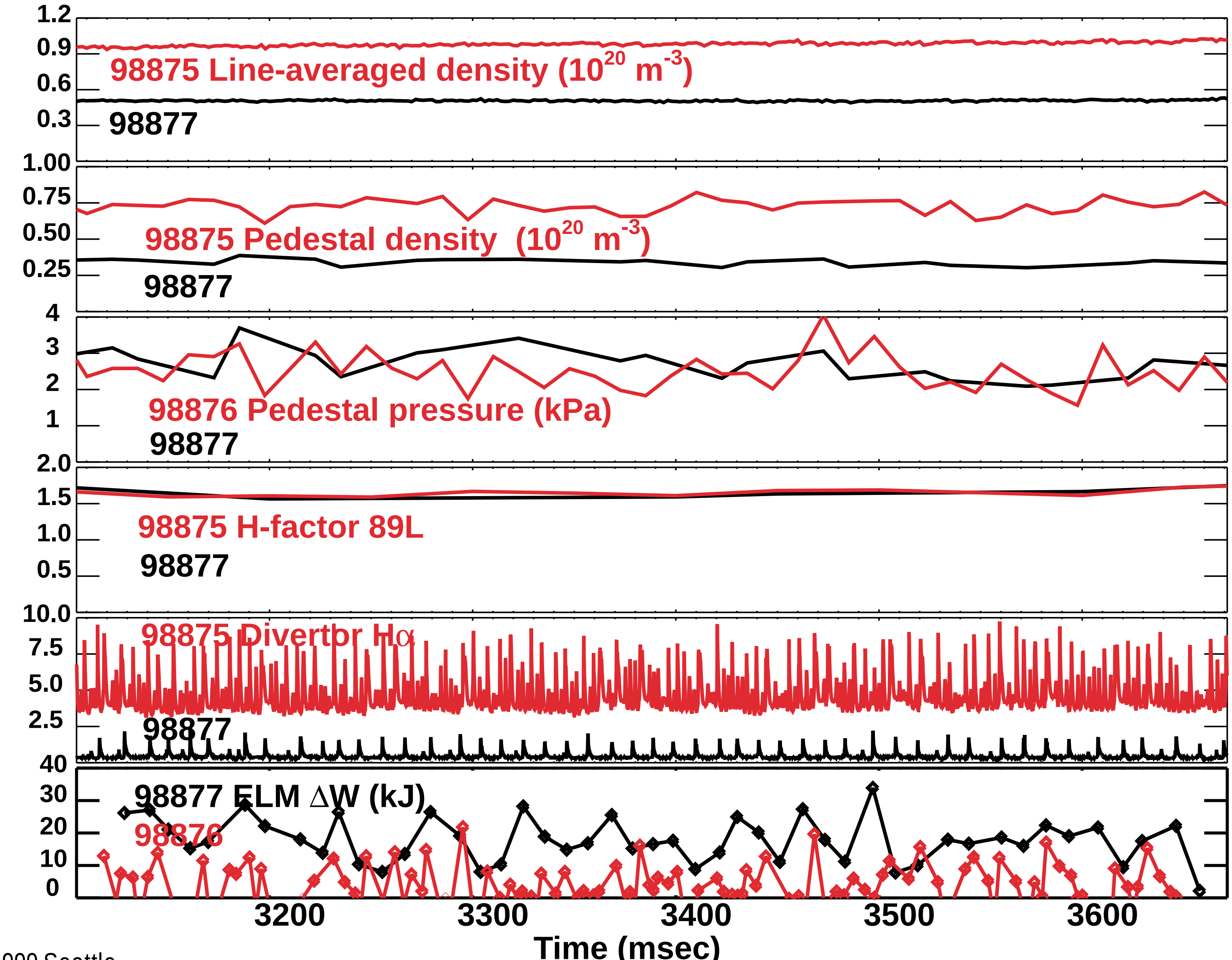
- Previous ELM scaling[1] of ELM energy; $\Delta W \approx 1/3$ of E_{ped} for DIII-D. E_{ped} defined as electron pressure at top of pedestal multiplied by the plasma volume.
- This scaling predicts ELMs a factor of 3-4 too large for ITER's divertor at the desired pedestal values, or conversely, pedestal a factor of 3-4 belowdesired for safe divertor operation.
- 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



ELMs Small and Rapid at High Density, while Good Confinement Maintained

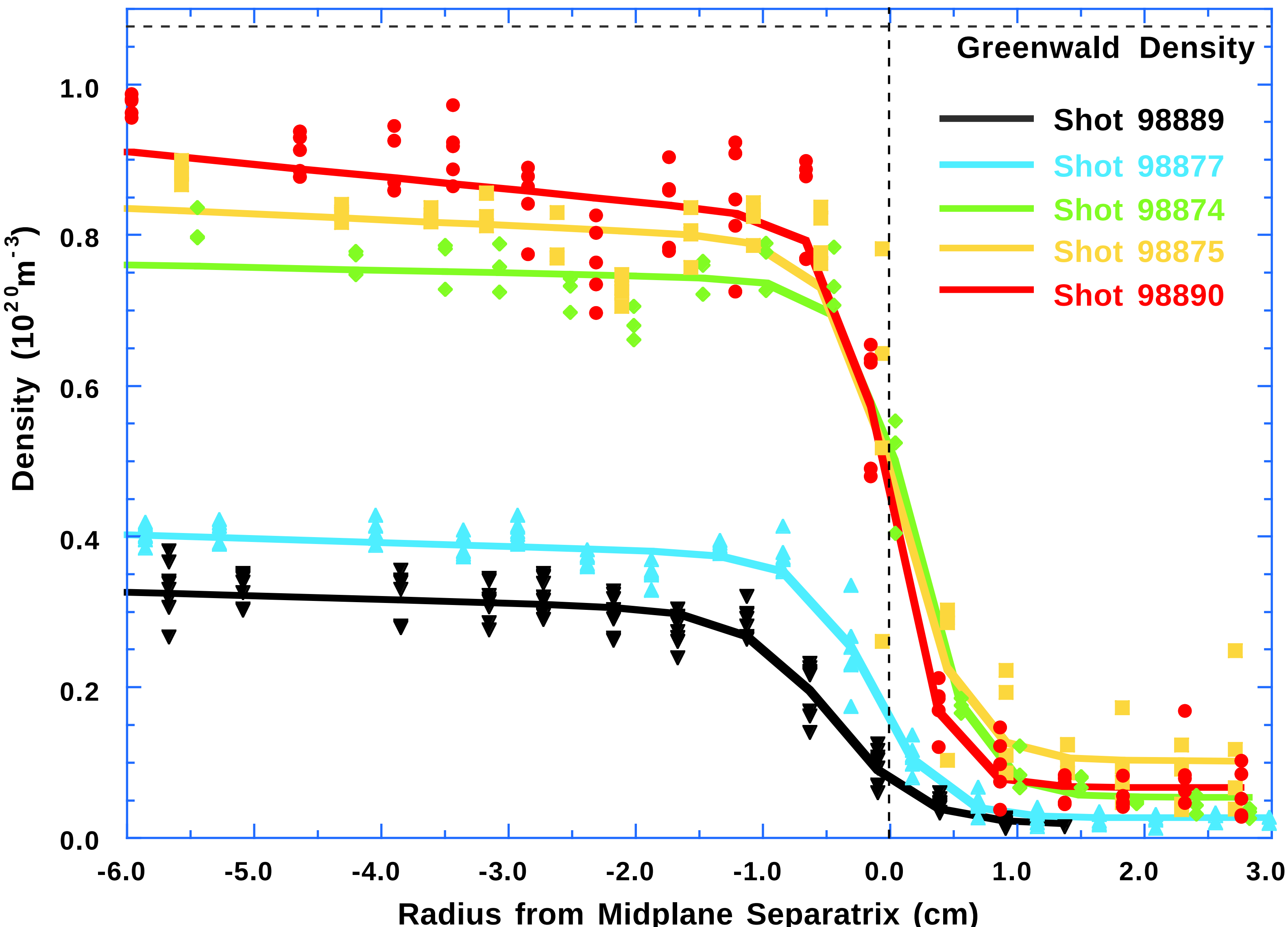


- High density, high confinement discharges are produced with moderate gas puffing and divertor pumping. The pedestal density increases factor of~2 with time-averaged pedestal pressure nearly unchanged, maintaining good confinement.
- ELM frequency increases factor of >3, with a similar decrease in average ELM energy.
- ELM energy determined from fast MHD equilibrium analysis. Uncertainty in energy analysis is ~5kJ.
- Edge profiles are measured with high spatial resolution Thomson Scattering.
- ELM H_α height not a good substitute for ELM energy. H_α varies with n_e, T_e and neutral density.

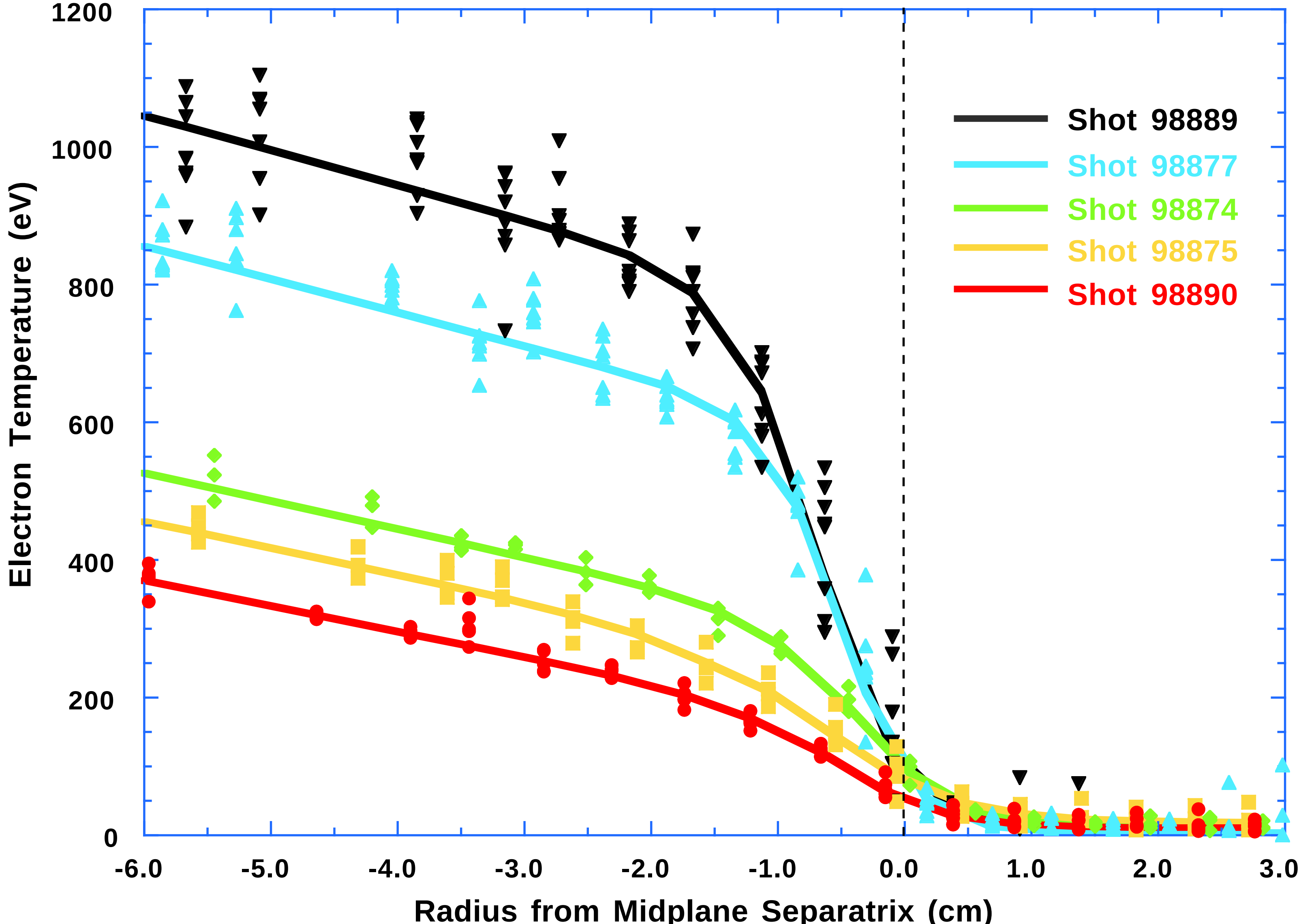
Edge Profiles for Density Scan

- Density scan obtained by varying the gas puff rate while providing divertor pumping to limit the private flux neutral pressure build up. Nearly steady-sate edge conditions are obtained while the central density slowly increases.
- Edge profiles are obtained from high spatial resolution Thomson Scatter measurements.
- During Steady-state phase only Thomson measurements obtained <1.0 msec before an ELM are collected. All of the appropriate profiles are combined and modeled with the Tanh function.
- As gas puff rate is increased, n_e rises, T_e drops, while the pressure remains nearly constant. At the highest density the pedestal begins to degrade with intermittent L-mode and possible Type III ELMs.

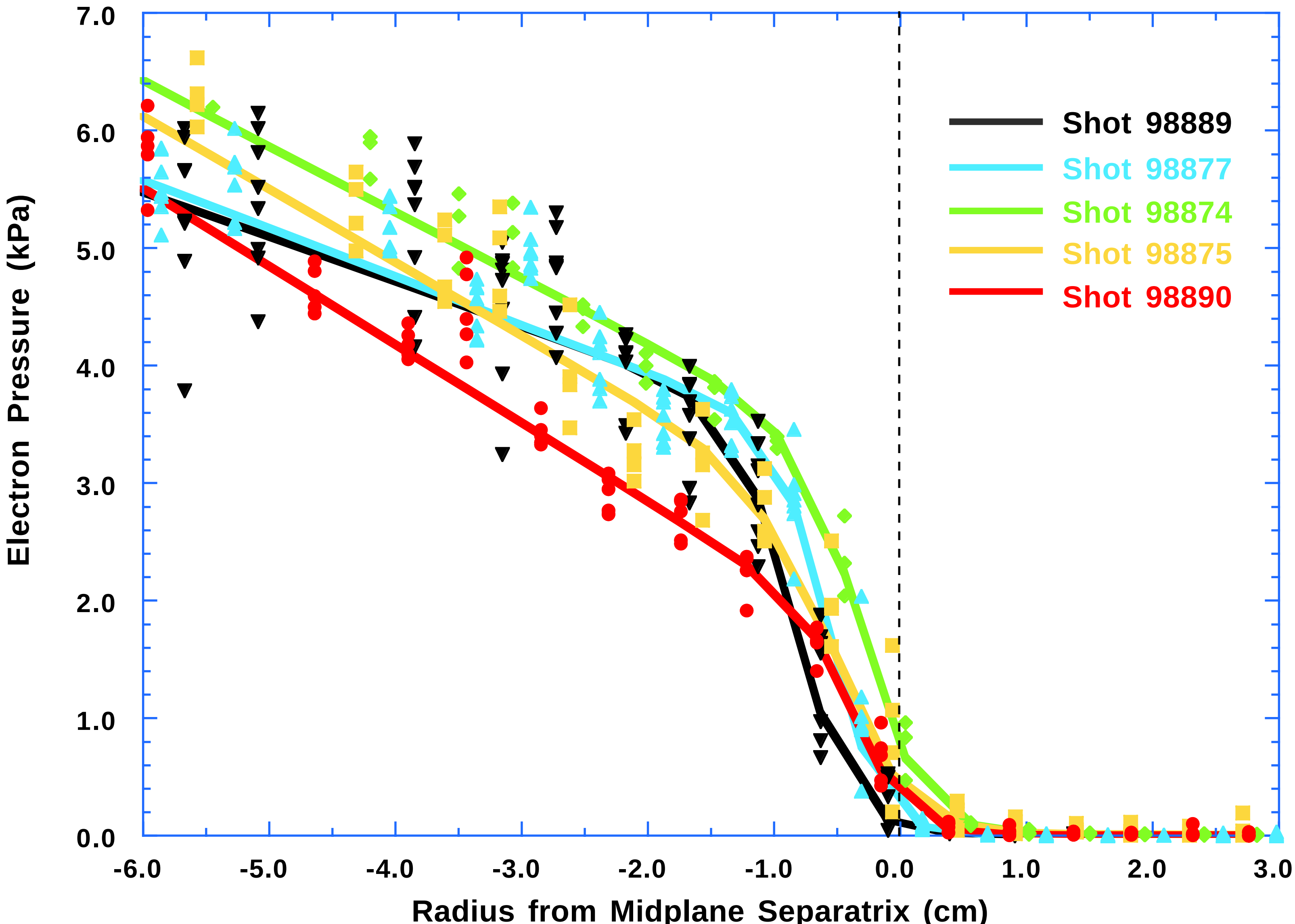
Electron Density Increases



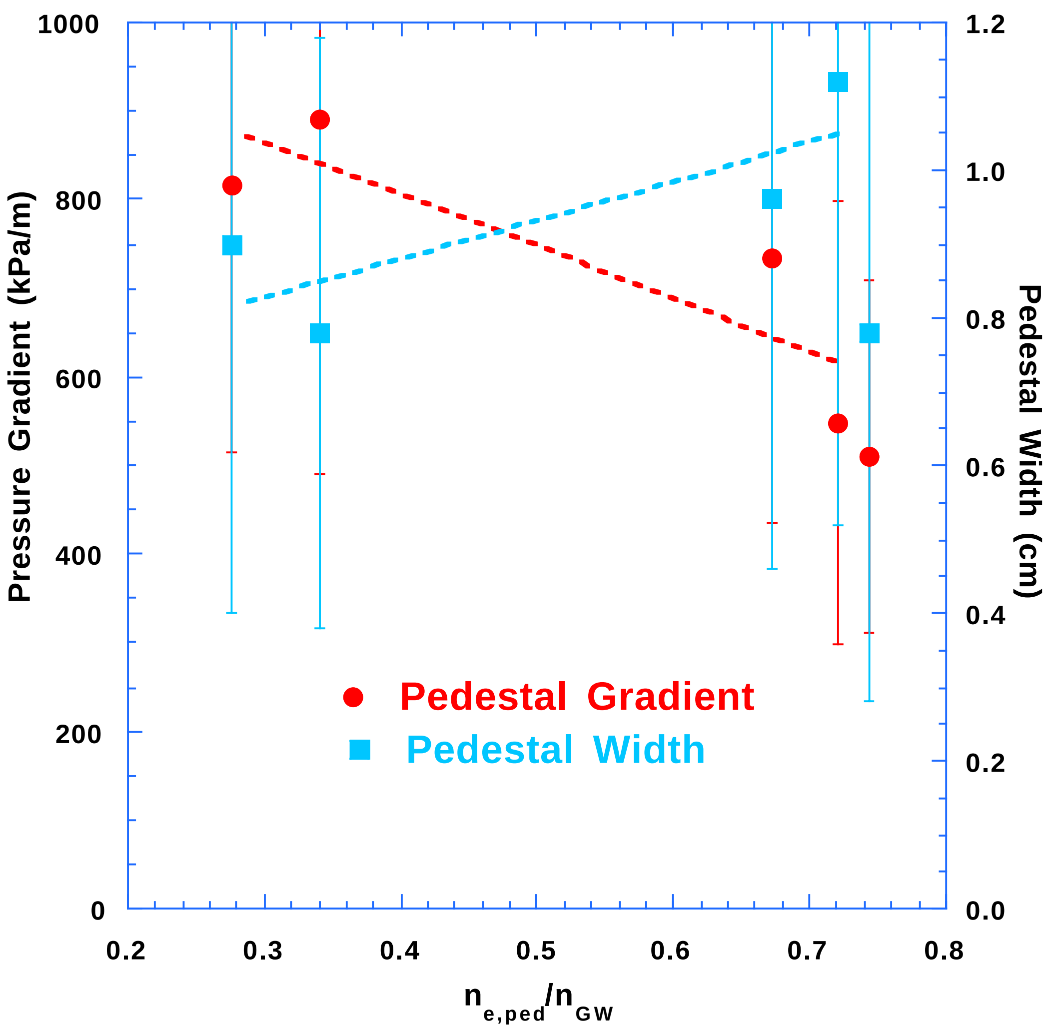
Electron Temperature Decreases



Electron Pressure Maintained



Pedestal Gradient Decreases and Width Increases Slightly with Density

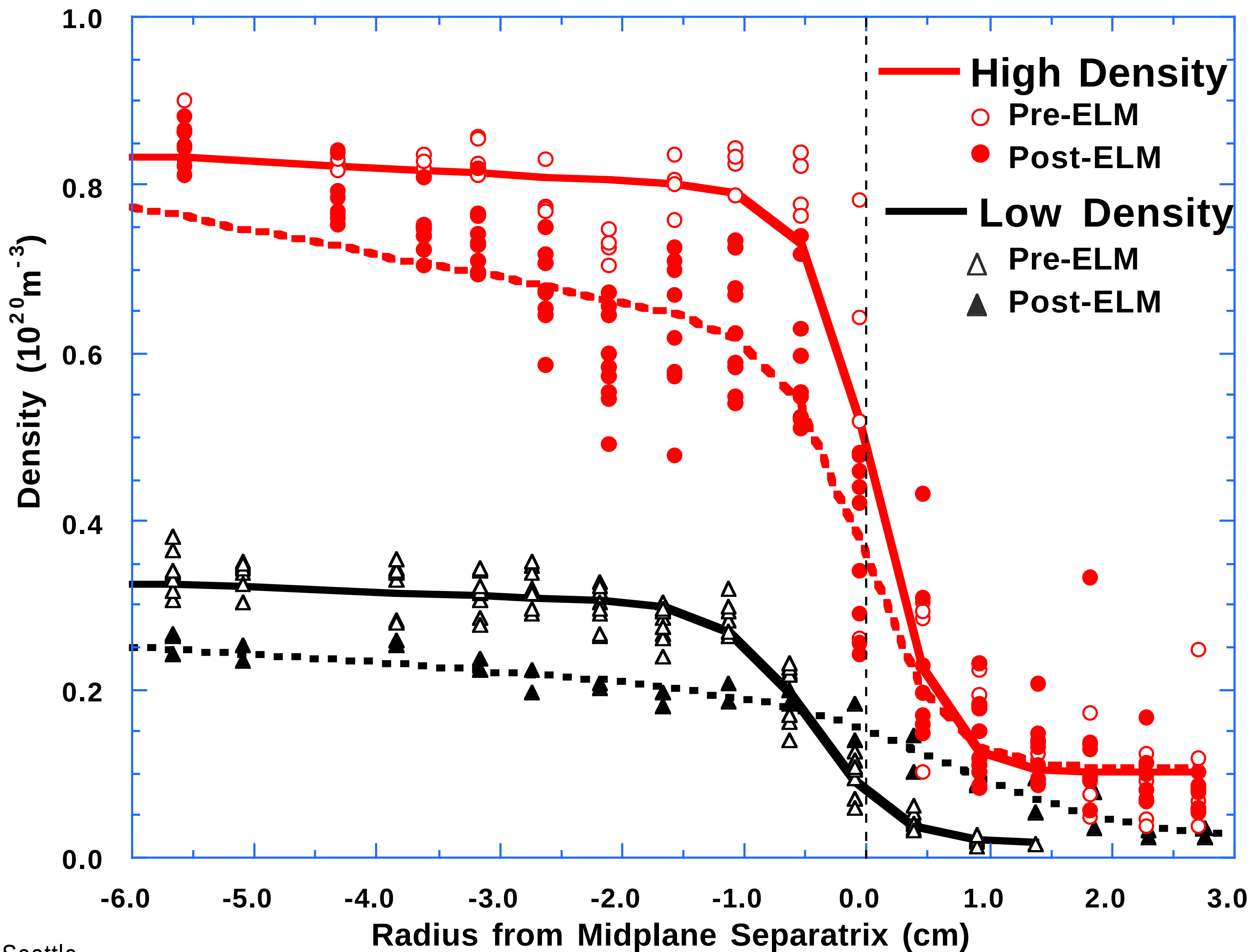


- As density increases the pedestal gradient appears to decrease slightly and width increase to keep the height nearly constant. At the highest density the pedestal degrades.
- The pedestal height is a more accurate measurement than the separate gradient and width. However, these separate parameters are important for understanding the edge pedestal formation and stability.

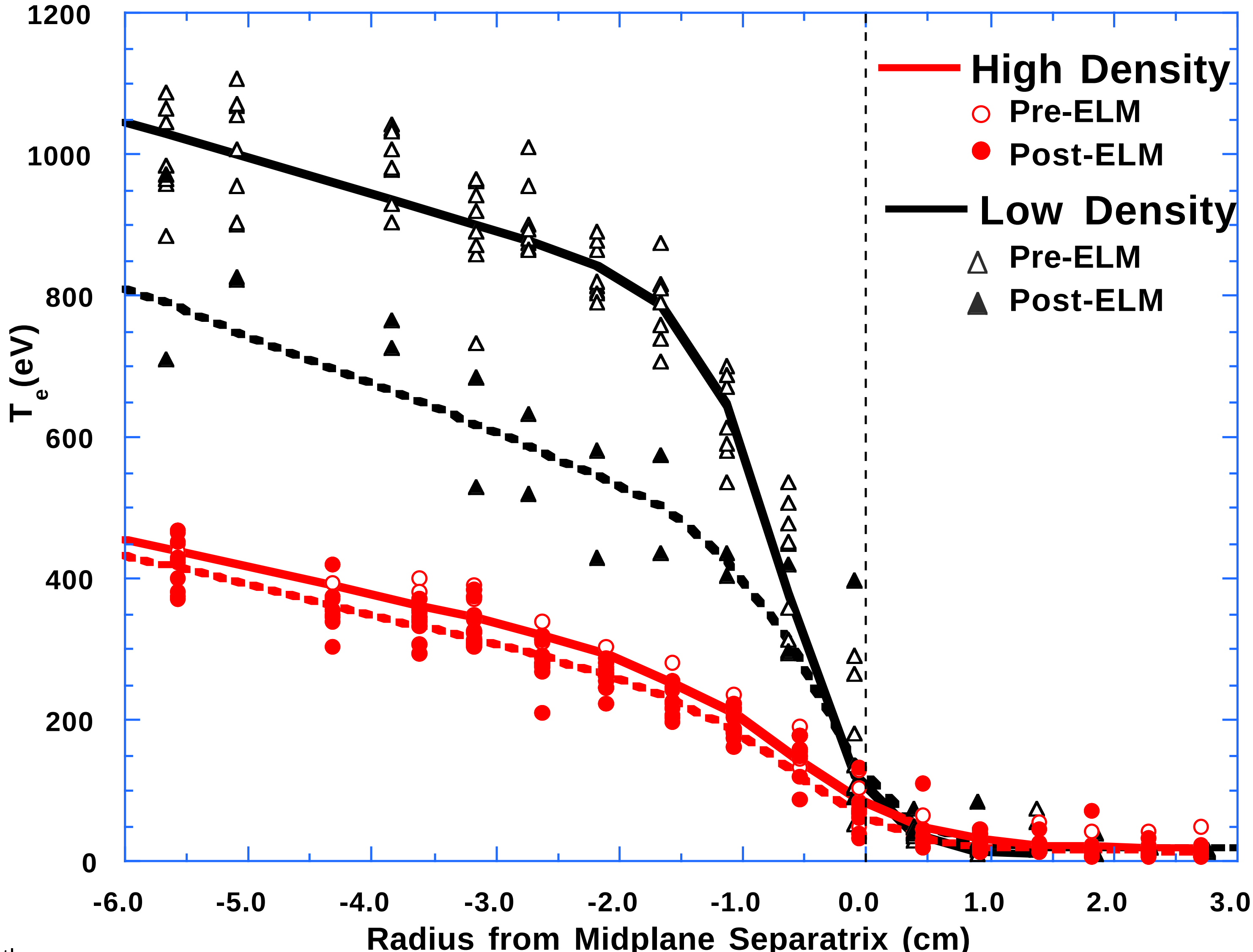
Edge Profiles Across ELM

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

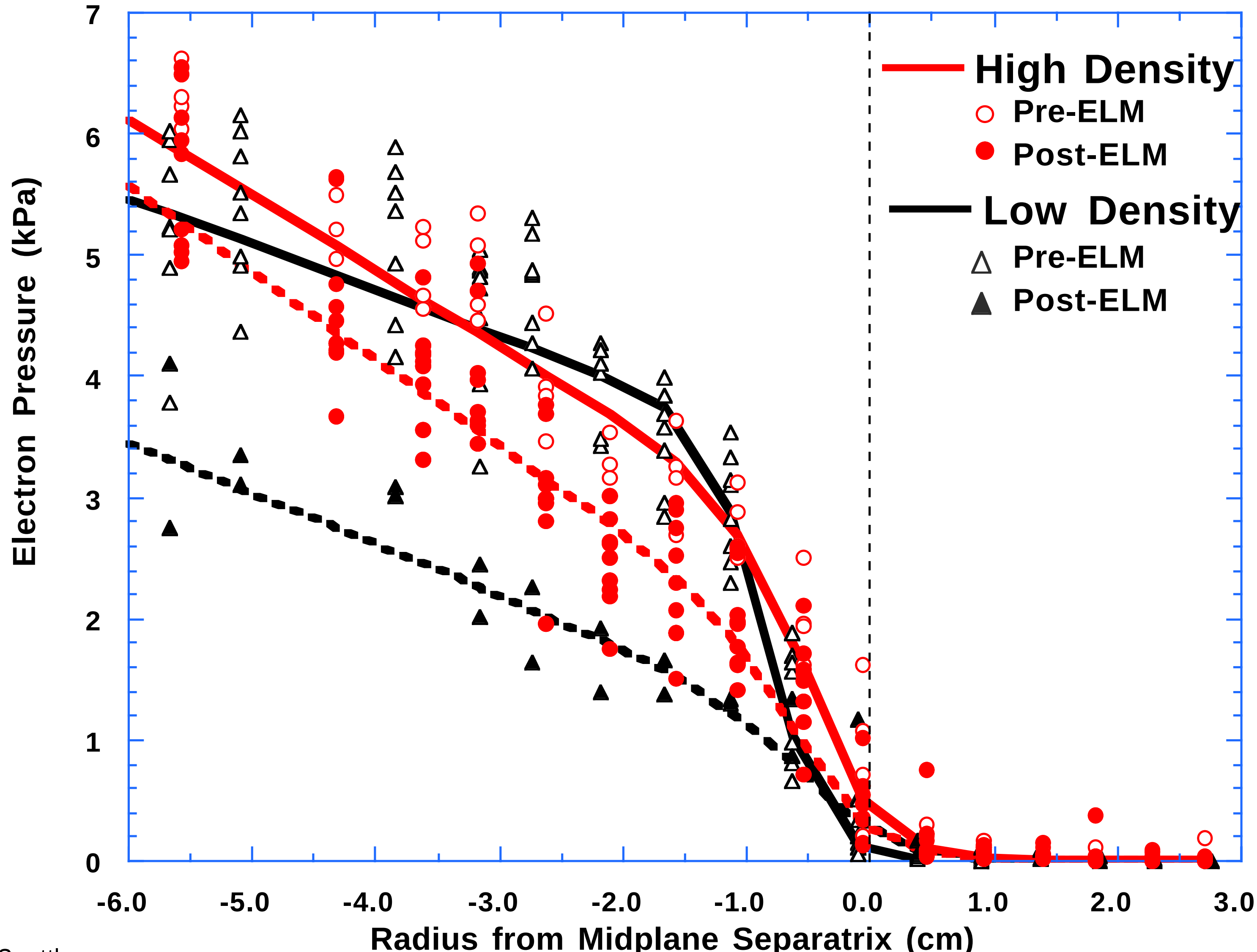
Density Drops for both High and Low n_e



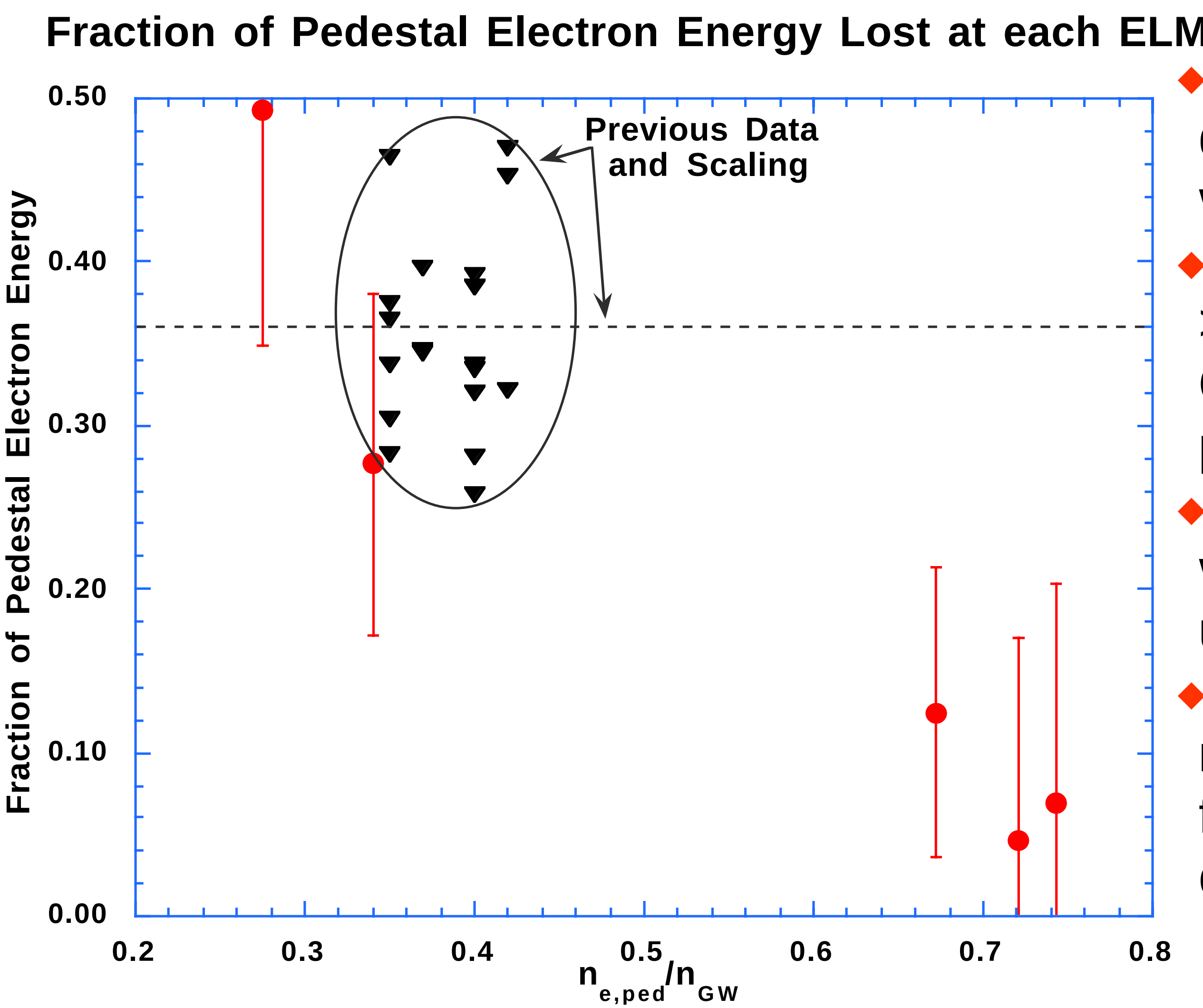
T_e drops only for Low n_e



P_e drop is larger for Low n_e

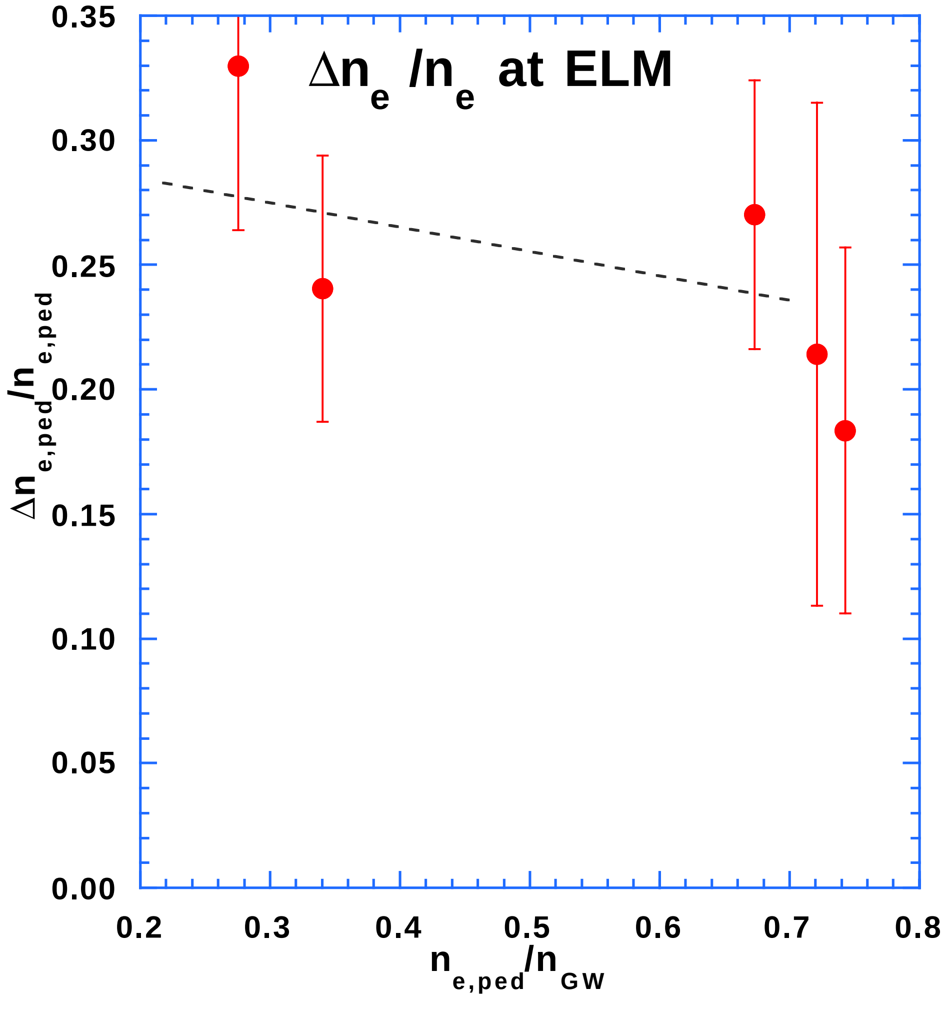


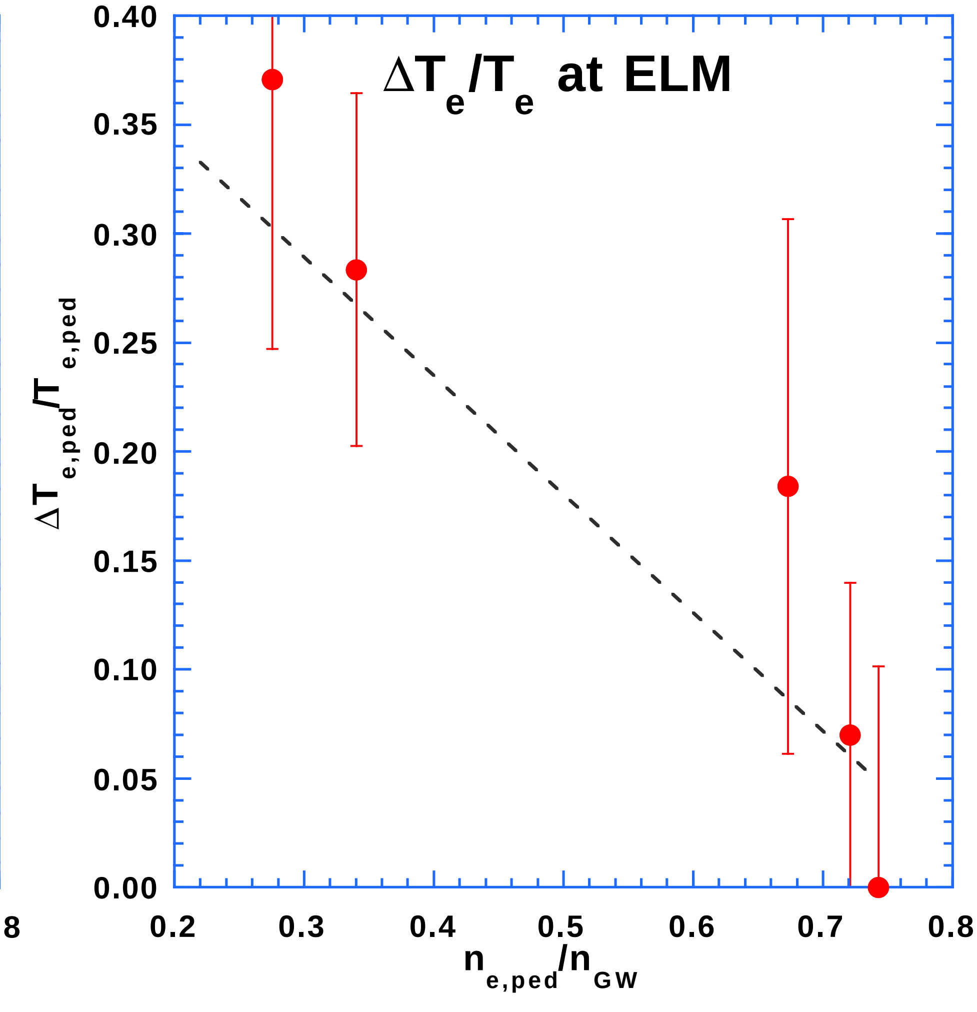
ELM Energy Decreases at Lower Pedestal Temperature



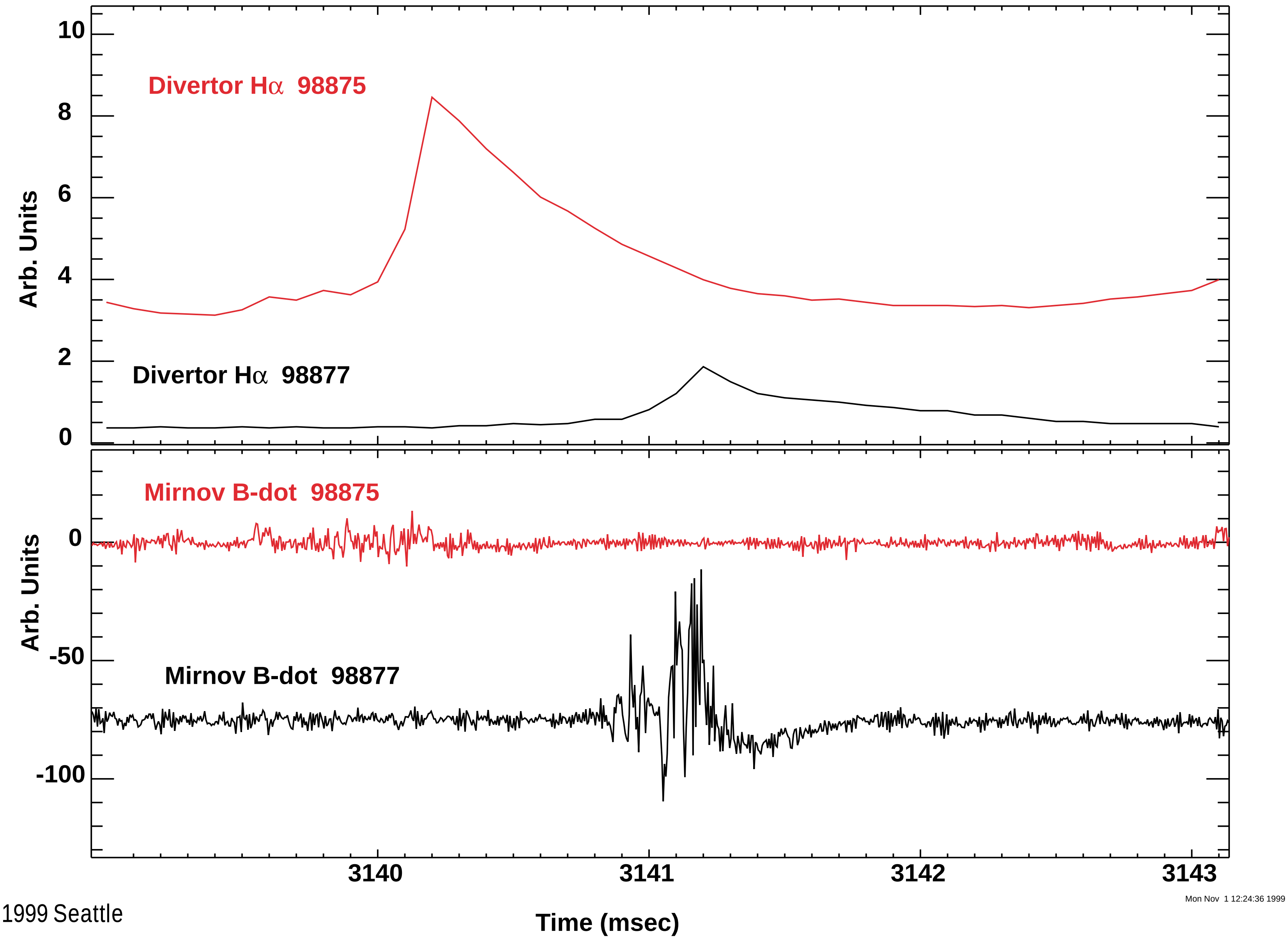
- Pedestal electron energy defined as $P_{e,ped}$ x plasma volume.
- ELMsize decreases by factor >5 highest density, lowest T_e. Only at highest n_e does edge pressure decrease.
- Error bars due equally to ELM variability and measurement uncertainty.
- Some larger ELMs at highest n_e due to extended L-mode following small ELM, or compound ELM.

Relative Density Loss at ELM remains constant but T_e perturbation small at high density

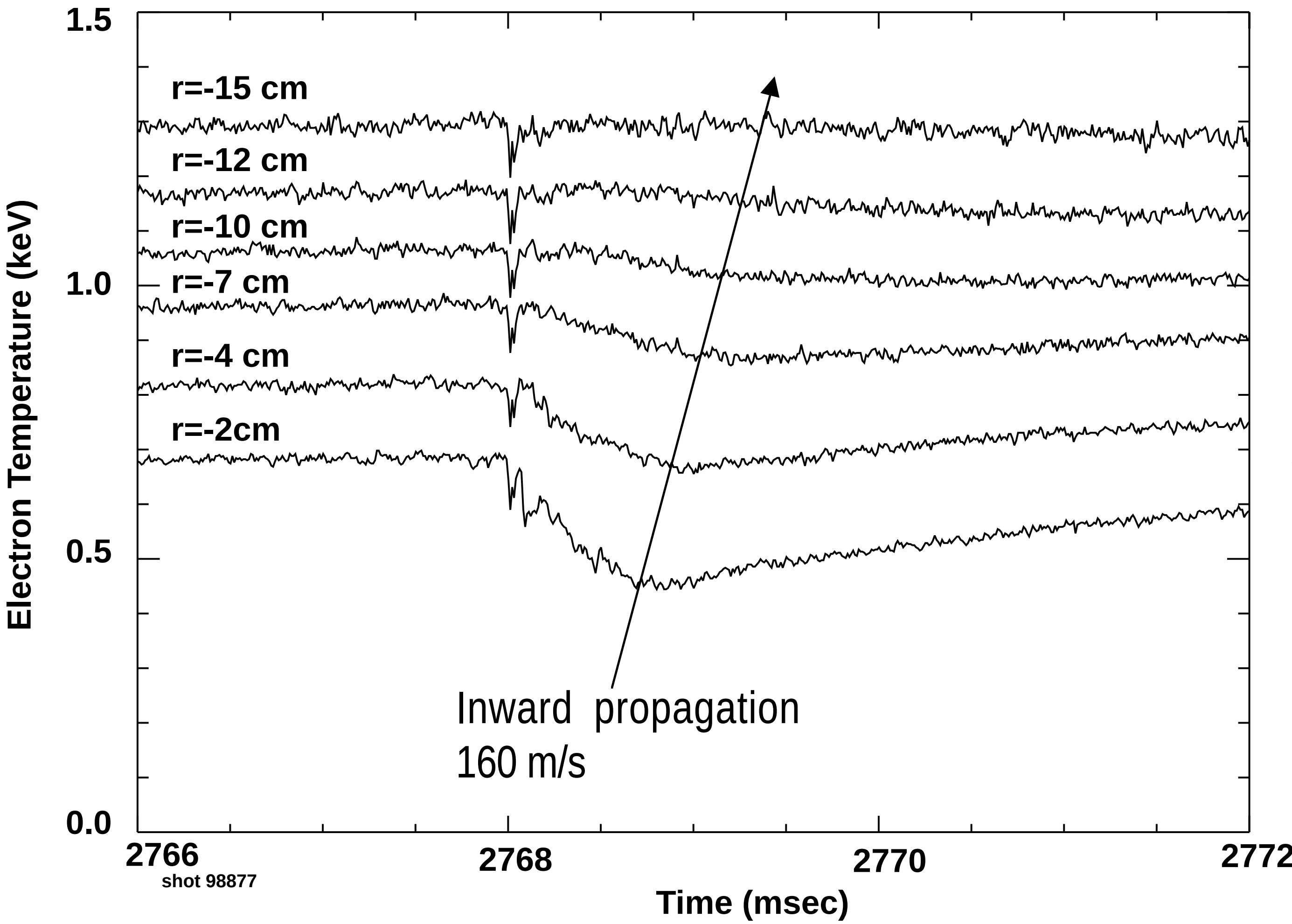




ELM Magnetic Fluctuations Reduced at High Density



Low density ELM perturbs edge T_e



- Edge T_e drops during ELM duration of ~500 μsec, as measured by ECE.
- Outer 6-7cm at midplane perturbed during ELM.

Summary of Observations

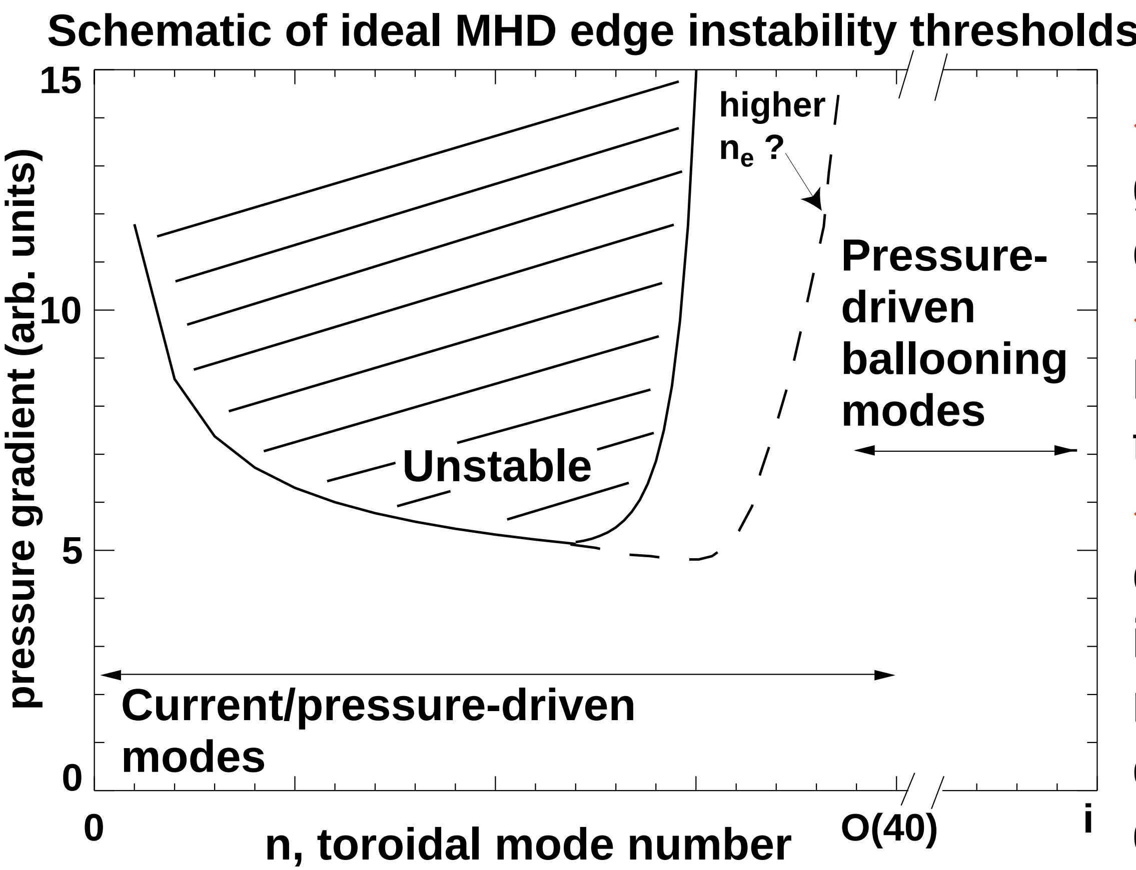
As density increases:

- ELM frequency increases, Energy lost at each ELM, ΔW, decreases.
- Pedestal pressure just before ELM remains nearly constant, maintaining good confinement. At the highest density the pressure pedestal begins to degrade.
- $\Delta n_{e,ped}/n_{e,ped}$ at an ELM remains nearly constant, but $\Delta T_{e,ped}/T_{e,ped}$ drops dramatically.
- Width of perturbation, $\Delta n_{e,ped}$ and $\Delta T_{e,ped}$ decreases.
- Magnitude of magnetic fluctuations during ELM drops factor of 5-10, while the duration of the fluctuations nearly constant at ~400 μsec.

Implications and Conjectures

- If fractional ELM energy loss, $\Delta W/(P_{e,ped} x Vol)$, 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 large tokamak such as ITER. However, it is unknown how the ELM size vs. density will scale to a larger tokamak with different parameters.
- Fueling becomes more difficult at higher density and power. Constant Δn_e at each ELM implies higher particle transport as ELM frequency scales with density and power.
- Possible mechanisms for smaller ELMs at high density:
  - Higher density leads to a higher mode number instability, which may not couple as deeply into the main plasma.
  - Finite resistivity at lower T_e may reduce growth rate of ELM instability.
  - Parallel transport limitations appear unlikely. Assuming stochastic edge during ELM allows parallel transport from pedestal to SOL, T_e is sufficient even at highest densities for much higher conducted power, $q_{||}=\kappa T^{7/2}/L_{||}$. Also divertor sheath limitation should be less restrictive at high density.

Stability Analysis of Plasma Pedestal



- 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 lower Bootstrap current and/or finite resistivity 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.

Future Work

- Measure ELM energy with divertor heat flux IR camera, a more sensitive measurement at small ELM amplitude.
- Measure changes to Ion pressure gradient at higher density with CER.
- Scaling of ELM energy 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 ELM 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 on finite n kink/ballooning instability.