Edge Pedestal and ELM Scaling with Density in DIII-D

A.W. Leonard, T.H. Osborne, M.E. Fenstermacher,
C.J. Lasnier, M.A. Mahdavi, T.W. Petrie, and J.G. Watkins

42nd Annual Meeting of APS Division of Plasma Physics
Oct. 23-27, 2000, Quebec, Canada

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Introduction

Next generation tokamaks will require:

– High density for high fusion gain.

– A robust H-mode pedestal for high confinement.

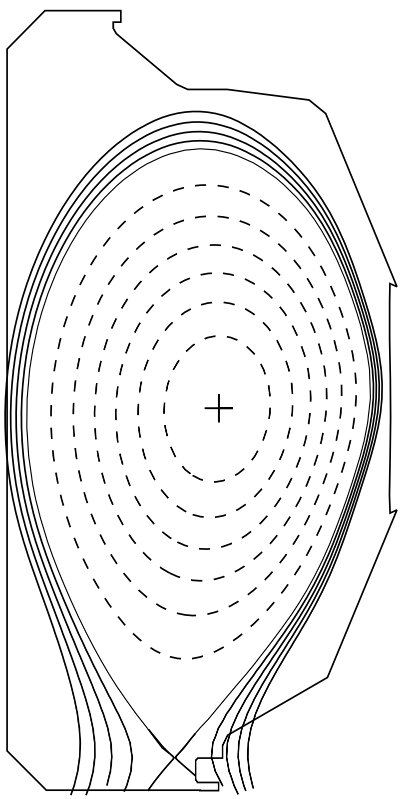
– Small ELMs to protect the divertor.

Goal of this study:

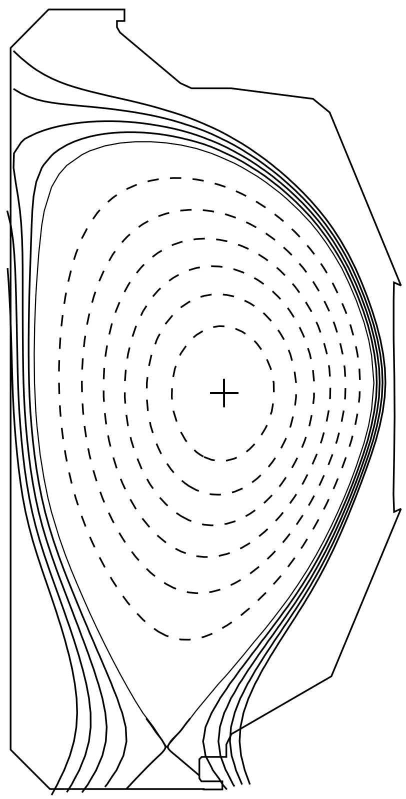
To understand relationship between high density, edge plasma current and edge stablity with changes to edge pedestal characteristics and ELM behavior.

Density and Triangularity Variations

(a) Low Triangularity



(b) High Triangularity

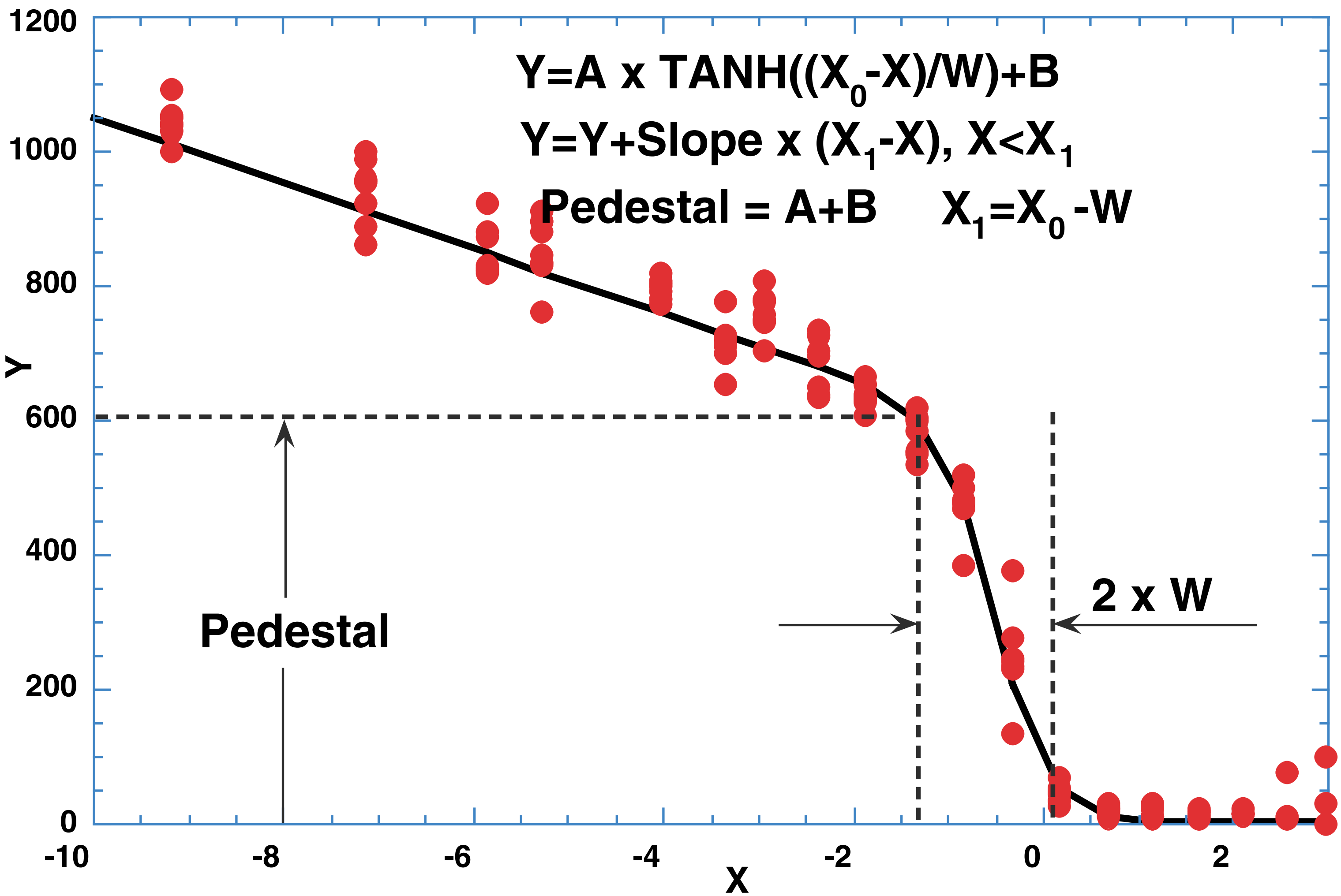


- High density, high confinement discharges are produced with moderate gas puffing and divertor pumping to regulate edge conditions
- Upper triangularity is varied between δ~0.0 and δ~0.36, lower triangularity constant at δ~0.1
- Edge pedestal profiles are measured with high spatial resolution Thomson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

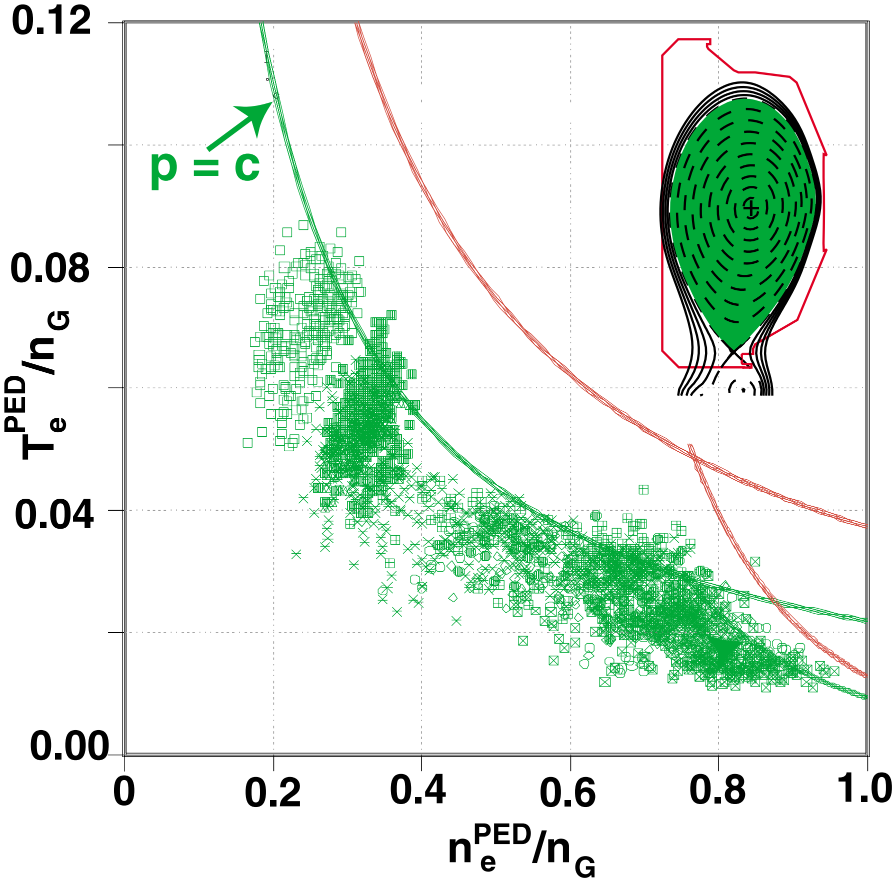
– The triangularity variation allows separation of density and temperature depedence for the pedestal characteristics. The higher stability at high triangularity allows a higher pedestal temperature at the same normalized density.

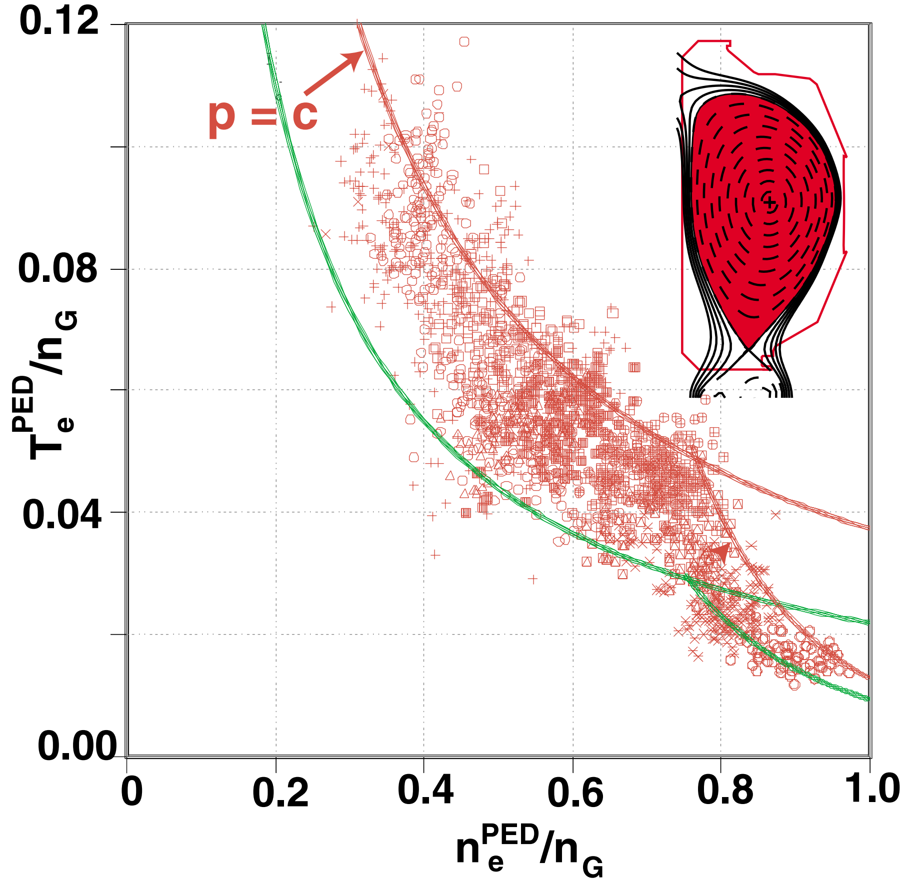
– The low triangularity divertor with private flux pumping was found experimentally to allow the highest pedestal density while maintaining H-mode operation.

EDGE PEDESTAL MODELED WITH TANH FUNCTION



Pedestal Degradation at High Density

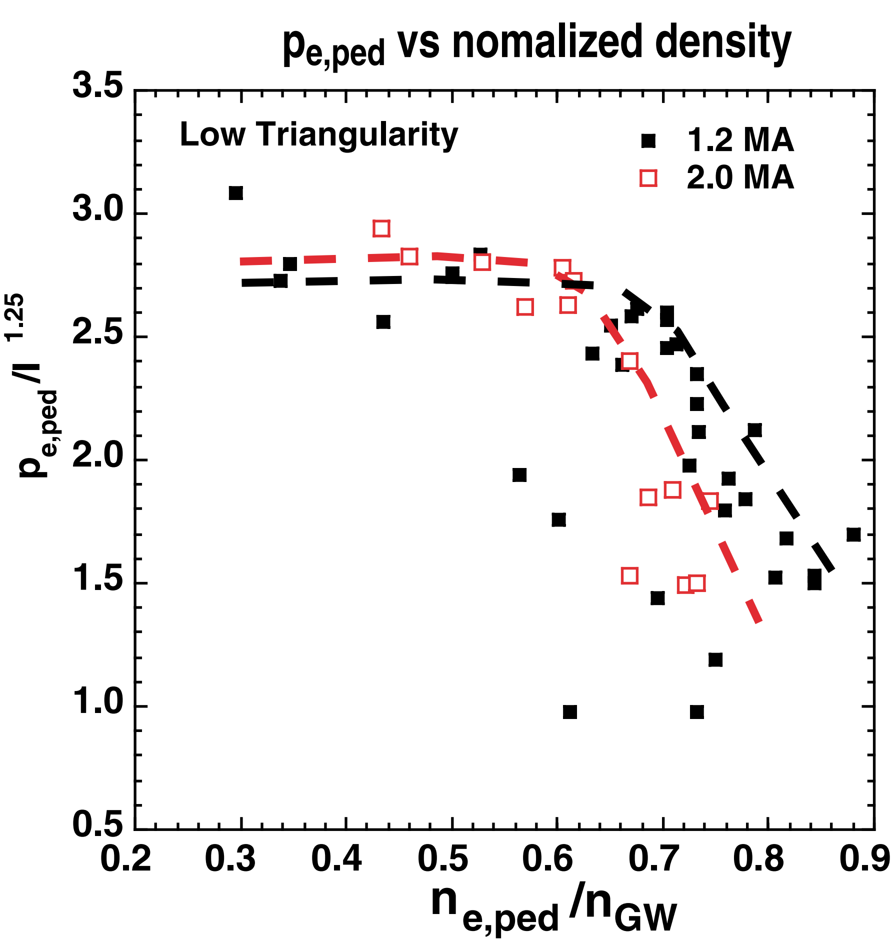


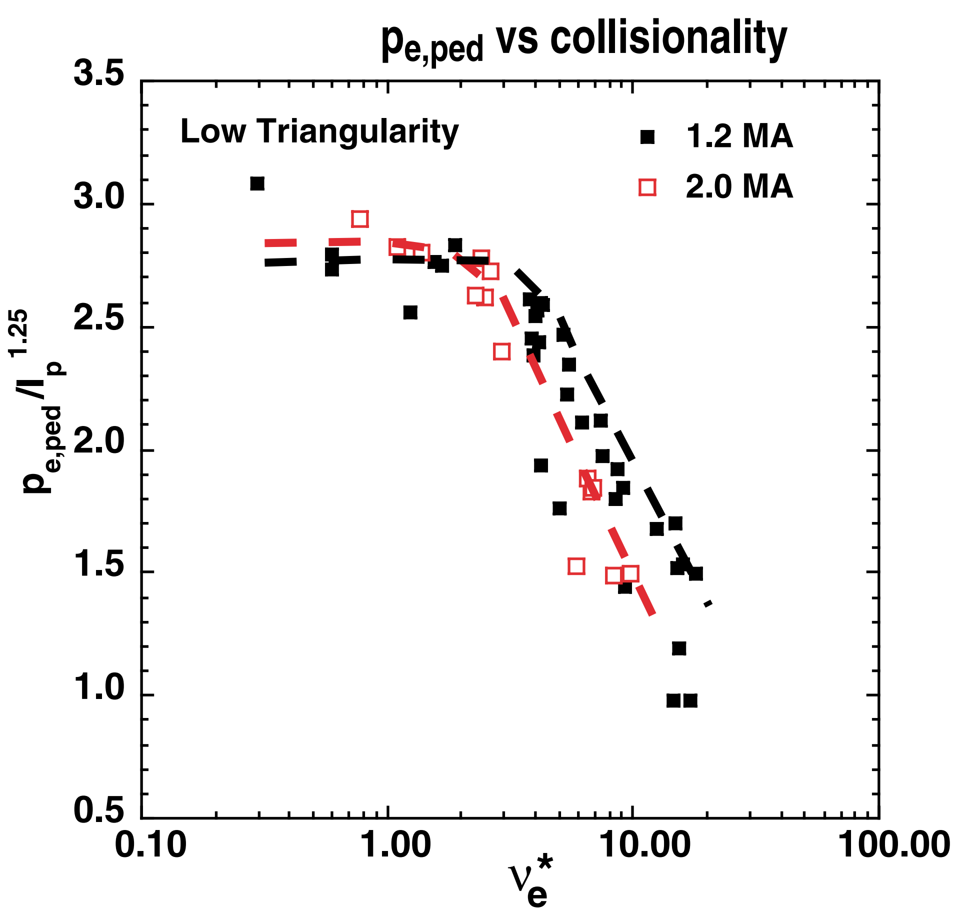


– Pedestal pressure remains constant over a range of density for $n_e/n_{GW} < 75\%$.

– Much of high triangularity advantage is lost due to increased pedestal degradation at high density.

Pedestal Degrades at Similar Collisionality for Low and High Plasma Current





– Pedestal pressure normalized by Ip1.25 as determined from low density low triangularity plasma current scaling.

A low triangularity density scan at 1.2 MA and 2.0 MA reveals:

– The pedestal, $p_{e,ped}$, at low density scales with the plasma current as,

$$p_{e,ped} \propto I_p^{1.25}$$

consistent with $p' \propto I_p^2$ (ideal ballooning) and width $\propto I_p^{-0.75}$ (inversely with β_p or $\rho_{i,poloidal}$).

– At high I_p, $p_{e,ped}$ degrades at slightly lower $n_{e,ped}/n_{GW}$.

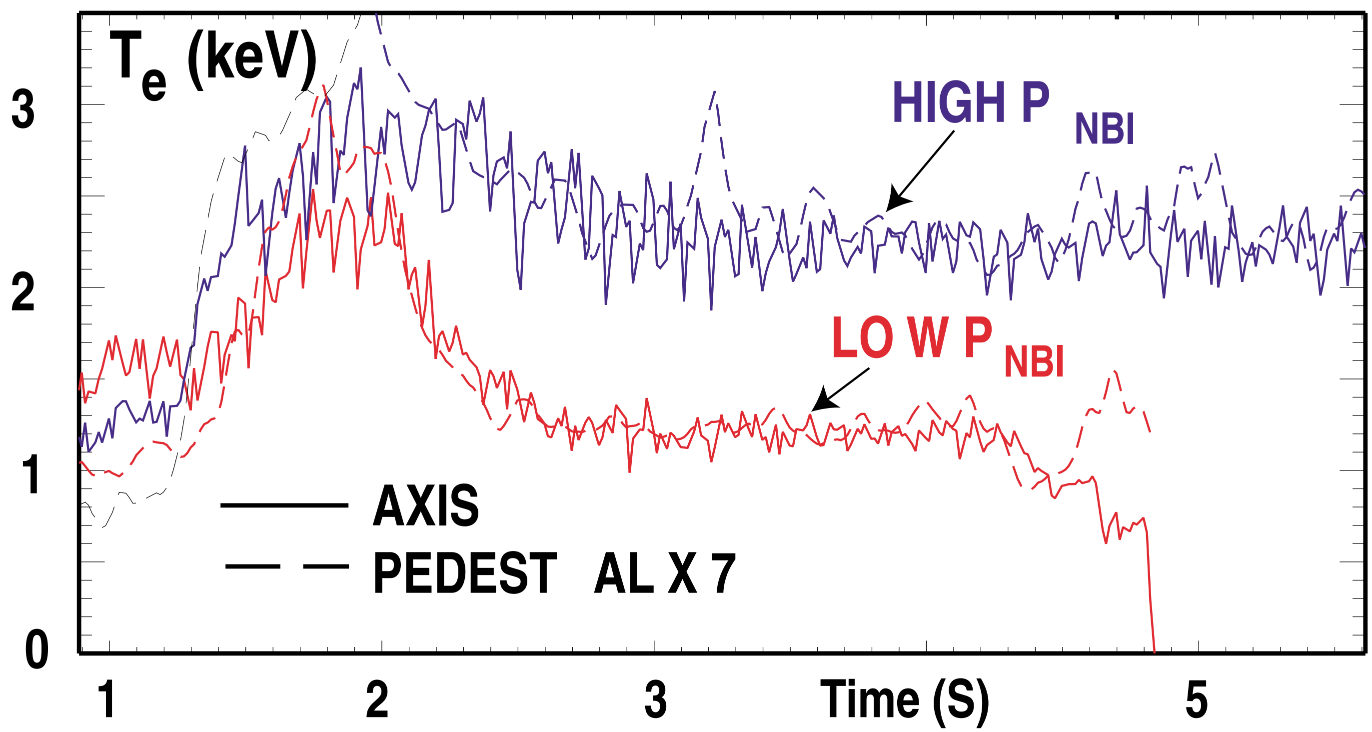
– $p_{e,ped}$ degrades at same collisionality for both low and high I_p.

Collisionality scaling consistent with loss of edge bootstrap current reducing edge stability limit. Assuming the low density pedestal scaling, collsionality scales as,

$$\nu_e^* \propto n_e/T_e^2 \propto (n_e/n_{GW})^3 \, I_p^{1/2}$$

Collisionality a strong function of normalized density and weak function of plasma current.

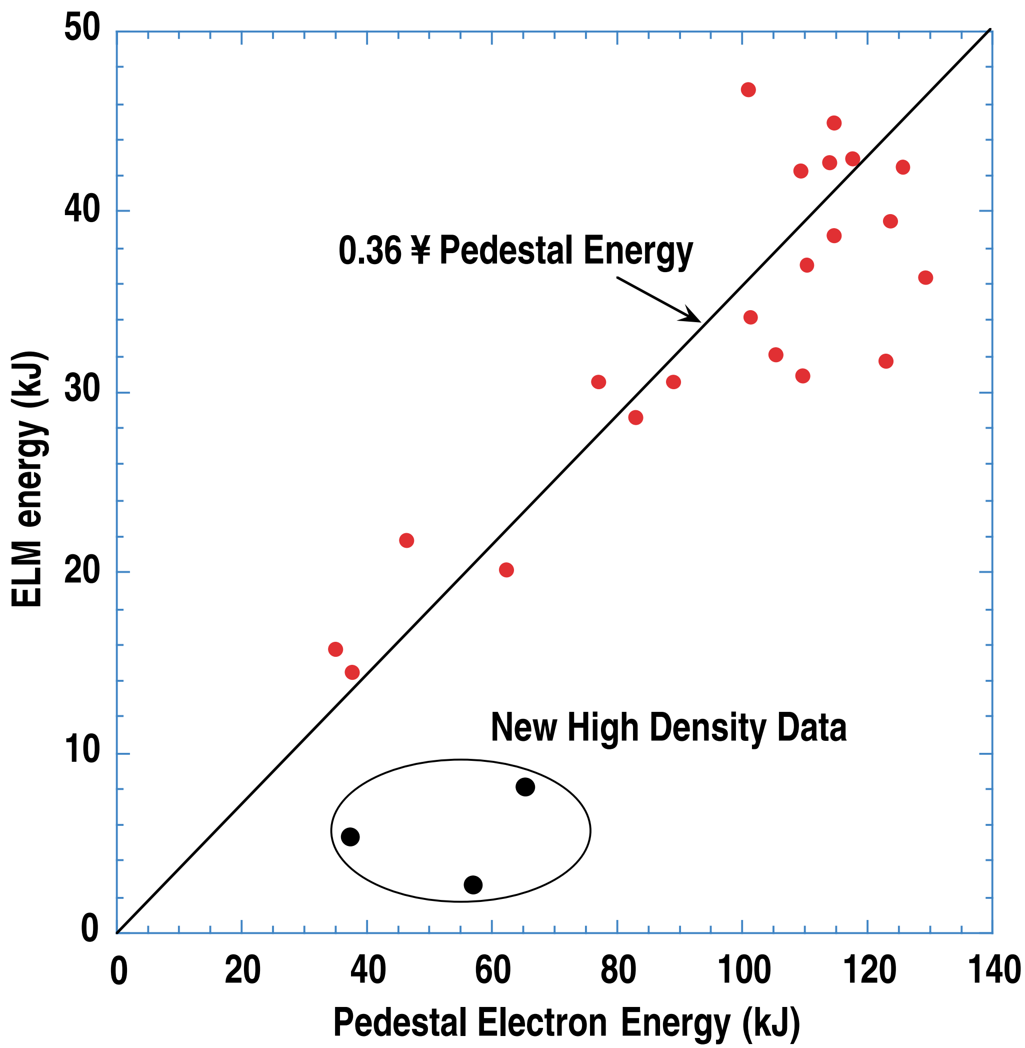
Stiff Temperature Profiles on DIII-D



- With stiff temperature profiles central T_e follows pedestal T_e.

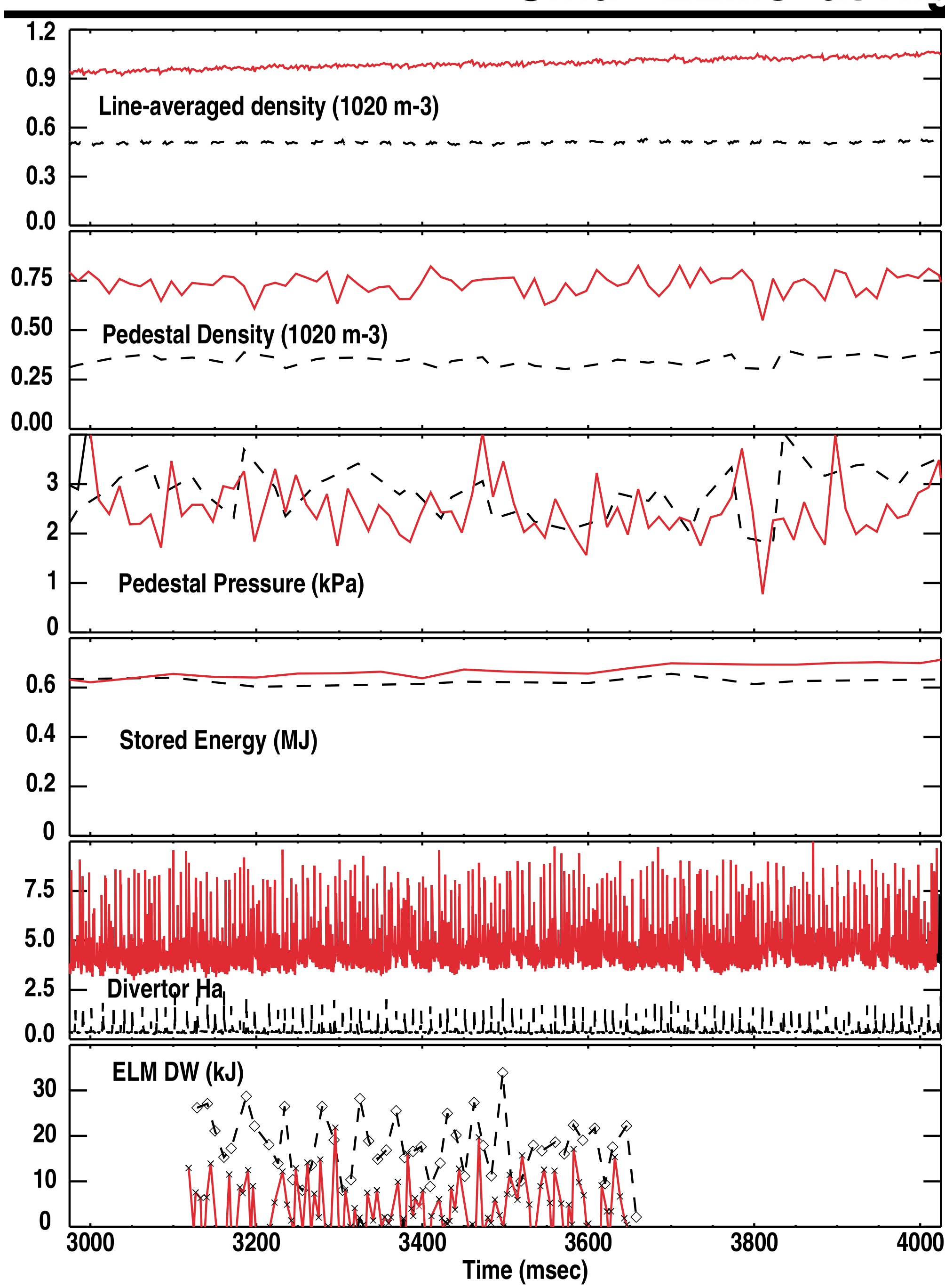
- For stiff temperature profiles confinement scales with pedestal pressure.
  It is important to maintain a robust pedestal for optimal H-mode confinement.

ELM Energy Scaling with Pedestal Pressure



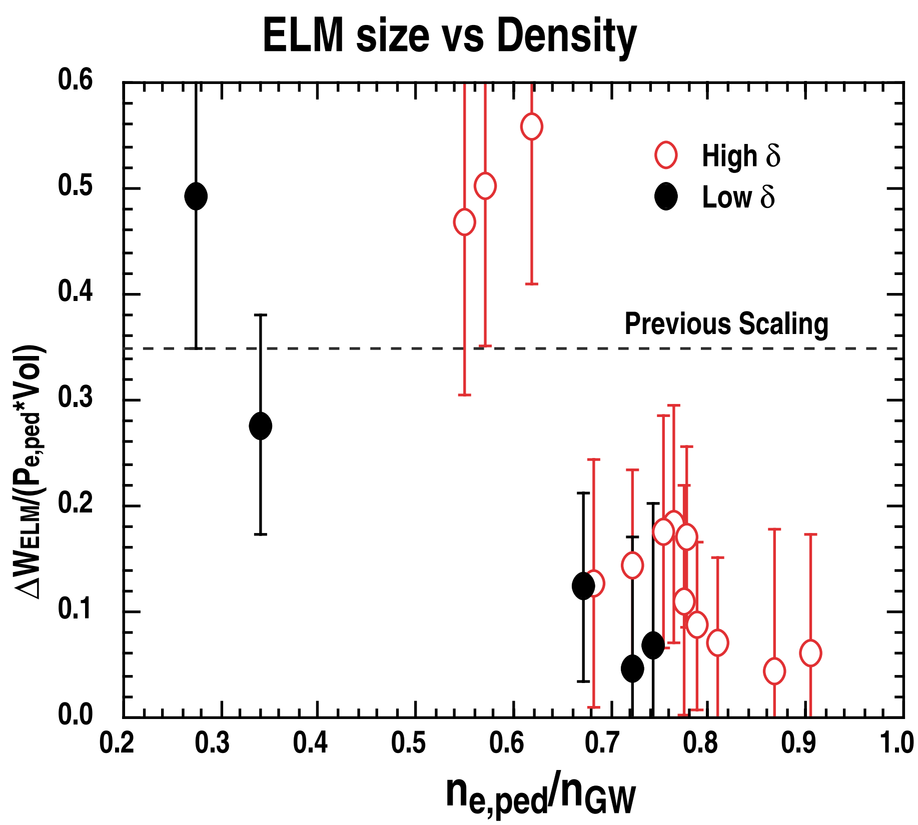
- Previous ELM scaling of ELM energy; DW≈ 1/3 of E_{ped} for DIII-D. E_{ped} defined as electron pressure at top of pedestal multiplied by the plasma volume
- This scaling predicts ELMs too large for future large tokamaks, or conversely, the edge pedestal must be maintained too small for optimal H-mode confinement.
- An ideal ELM is of small amplitude, but still allows a robust pedestal. New data at higher density indicates this may be possible

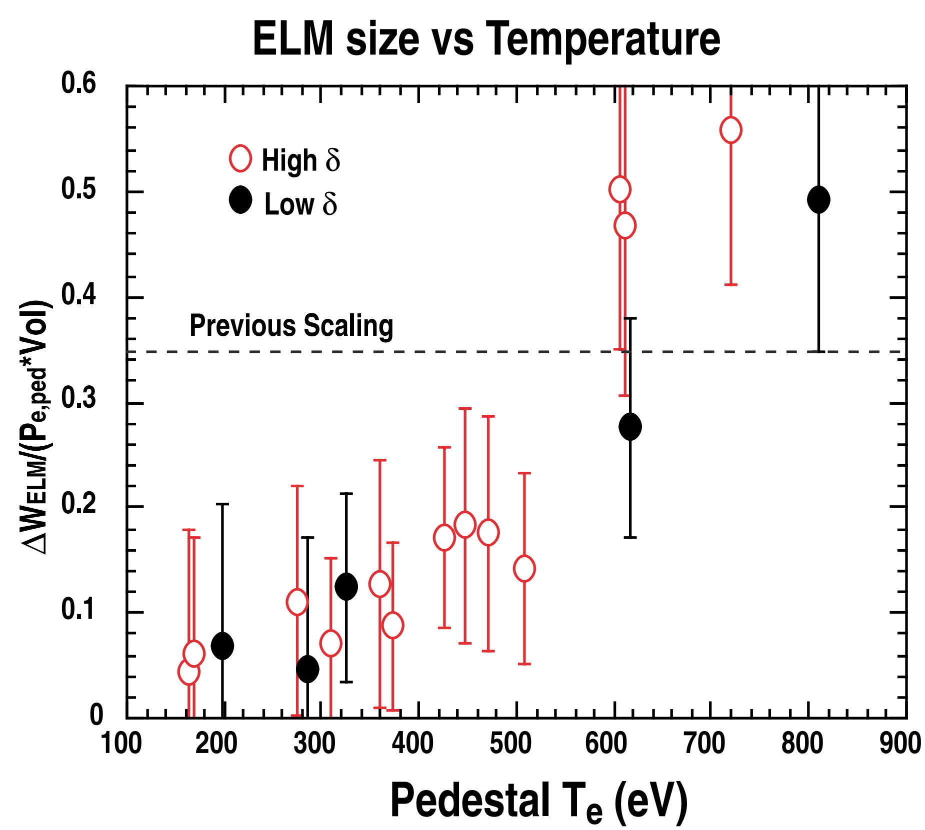
Small ELMs at High Density



- In low triangularity discharge pedestal n_e/n_{GW} ~ 0.7 and n_e/n_{GW} ~0.9, pedestal pressure and confinement similar to low density case.
- Average ELM energy decreases factor of 3-5 with similar increase in ELM frequency.
- ELM energy decreases while the pedestal remains robust!
- The ELM energy is calculated by fast MHD equilibrium analysis of plasma stored energy 1.5 ms before and after each ELM.

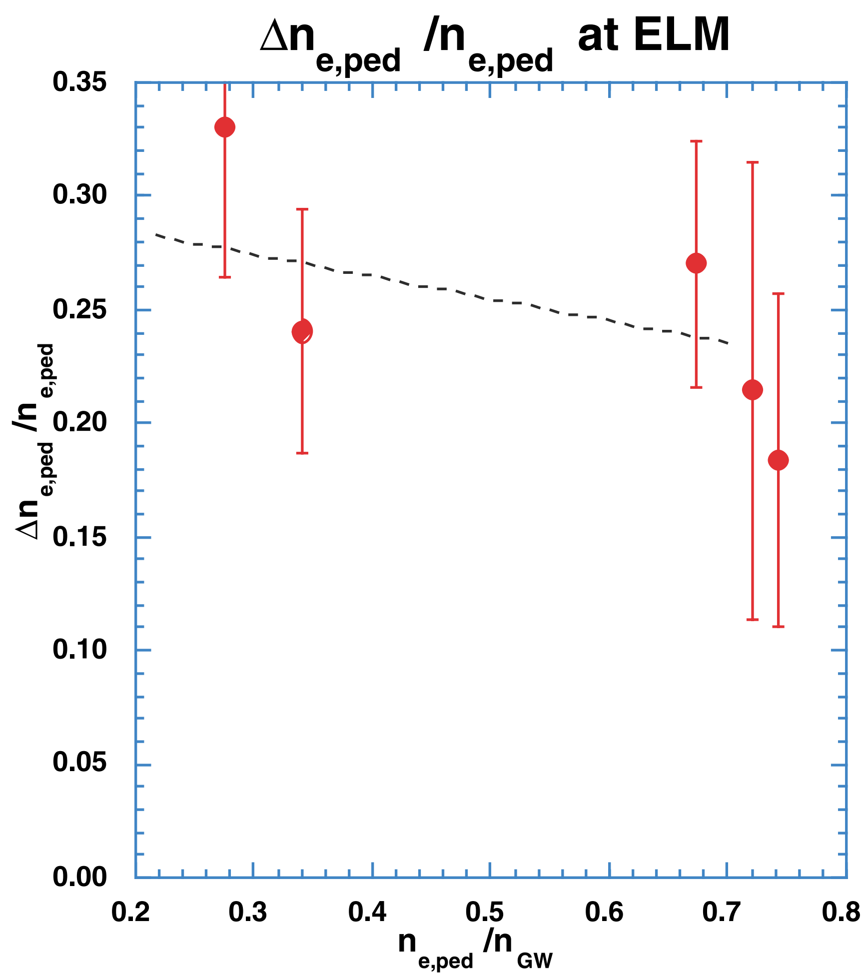
Small ELMs at High Density and Low Temperature

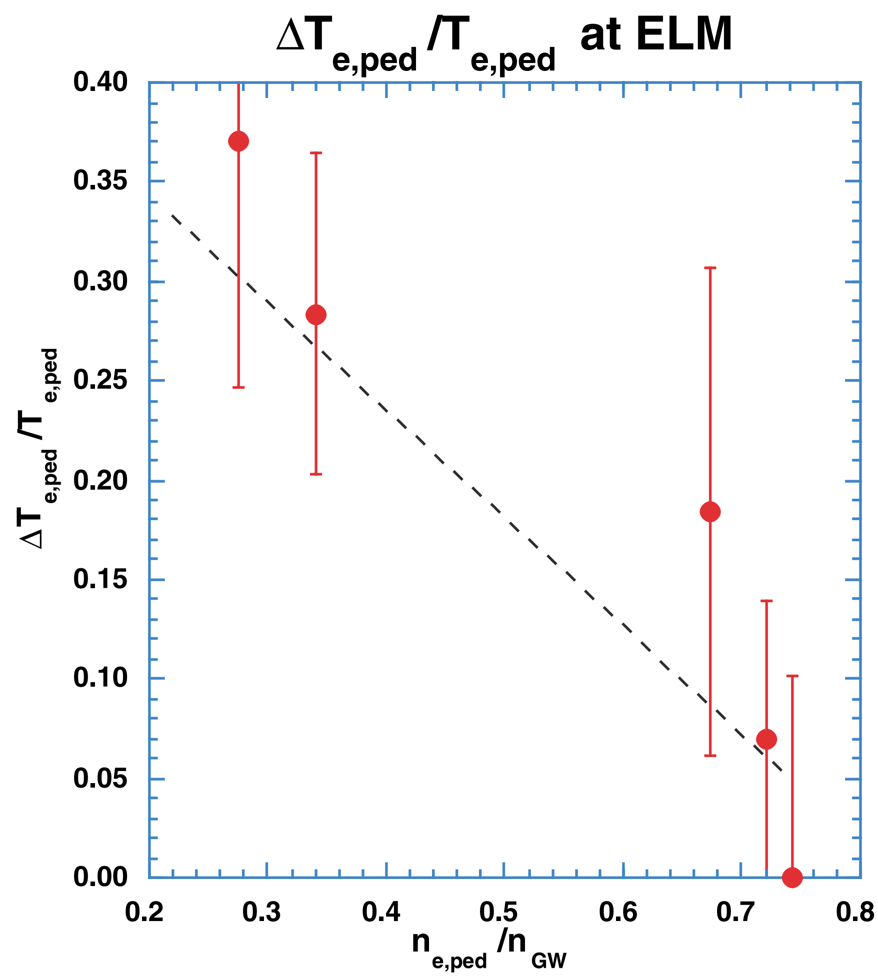




- ELM energy is normalized to pedestal electron energy ($P_{e,ped}$xVolume).
- Normalized ELM energy for low and high triangularity fit better to T_e than n_e.
- An attractive range of operation appears possible with small ELMs and slightly degraded pedestal.

ELM Perturbation to T_e becomes Small at High Density





- ELM profiles are collected from Thomson diagnostic 0.6-1.2 ms before and after ELM. Δn_e and ΔT_e are measured at top of pedestal.

- Drop in ΔT_e at high density suggests change in ELM from conductive to convective transport.

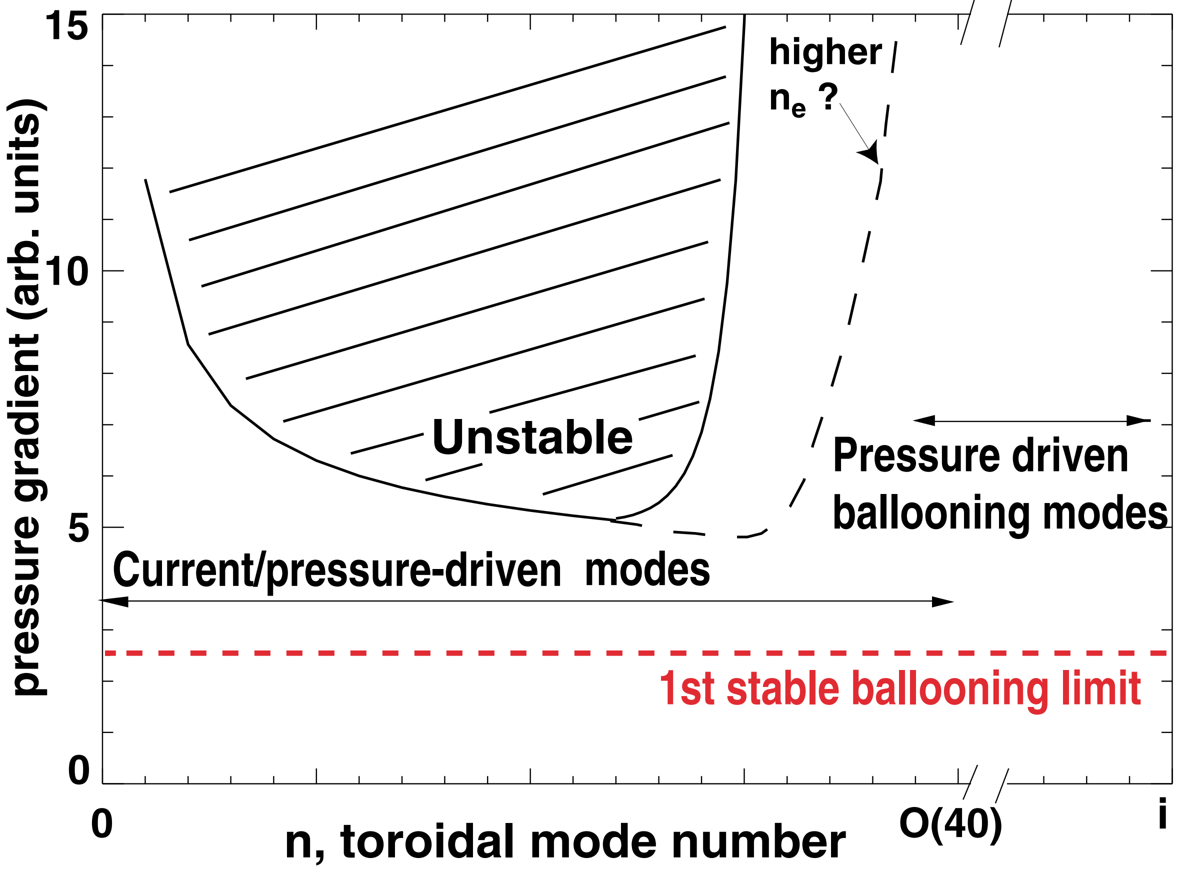
Edge Stability at High Density

- Large Type I ELMs; intermediate to low n modes driven by edge pressure and/or current gradients. High n pressure driven ballooning modes stabilized by edge bootstrap current.

- High density, high collisionality can reduce edge bootstrap causing increase in mode number of most unstable mode or even deny access to 2nd stability for high n ideal ballooning modes.

- Higher mode instabilities should not couple as deeply into the pedestal resulting in smaller release of ELM energy.

Schematic of ideal MHD edge instability thresholds



Edge Stability Analysis

Goal: Analyze edge stability at low and high density for low and high triangularity and compare with pedestal and ELM size.

Method:

1. Identify low and high density timeslices just before an ELM. Choose high density case with small ELMs (>50% reduction) while pedestal pressure is maintained (<10% reduction).

2. Measure edge profiles of T_e, T_i, n_e, and impurities. Use transport code ONETWO with collisional bootstrap model to predict edge current density.

3. Obtain equilibrium from EFIT using measured pressure profile while adjusting fitting parameters to obtain predicted edge current density (DIII-D diagnostics are not yet adequate to determine edge current density).

4. Carry out stability analysis on obtained equilibrium using BALOO for ideal ballooning, ELITE for intermediate n ballooning/peeling, and GATO for low n kink modes.

5. Compare predicted stability for pressure gradient and toroidal mode number with measured pressure profile and ELM energy.

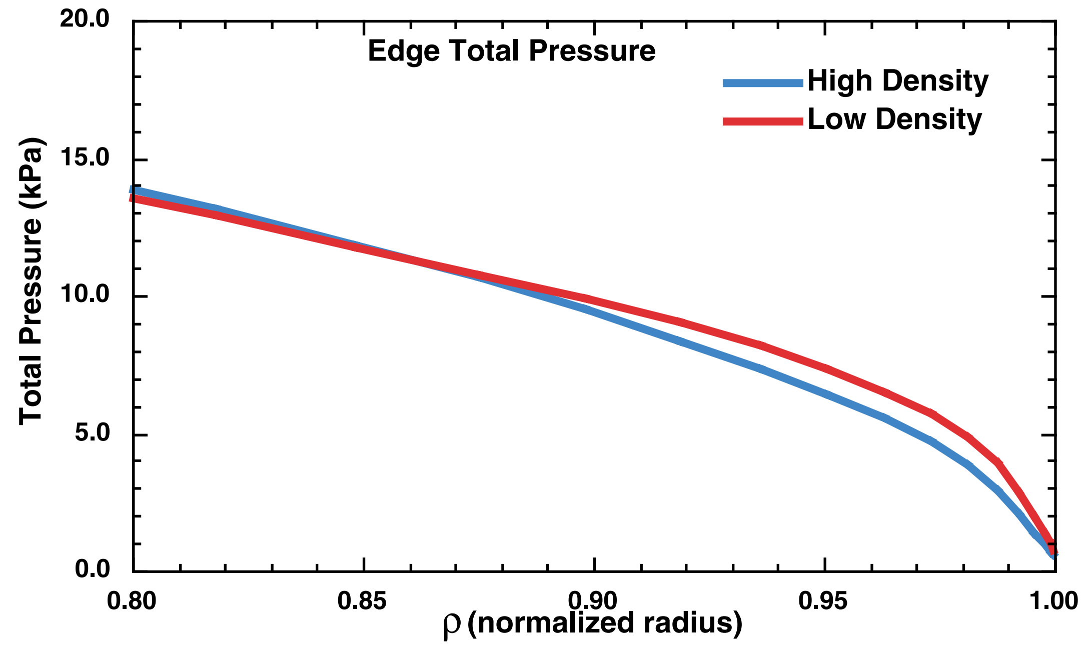
Low Triangularity Edge Pressure at High Density; Loss of edge bootstrap current with small reduction in edge pedestal

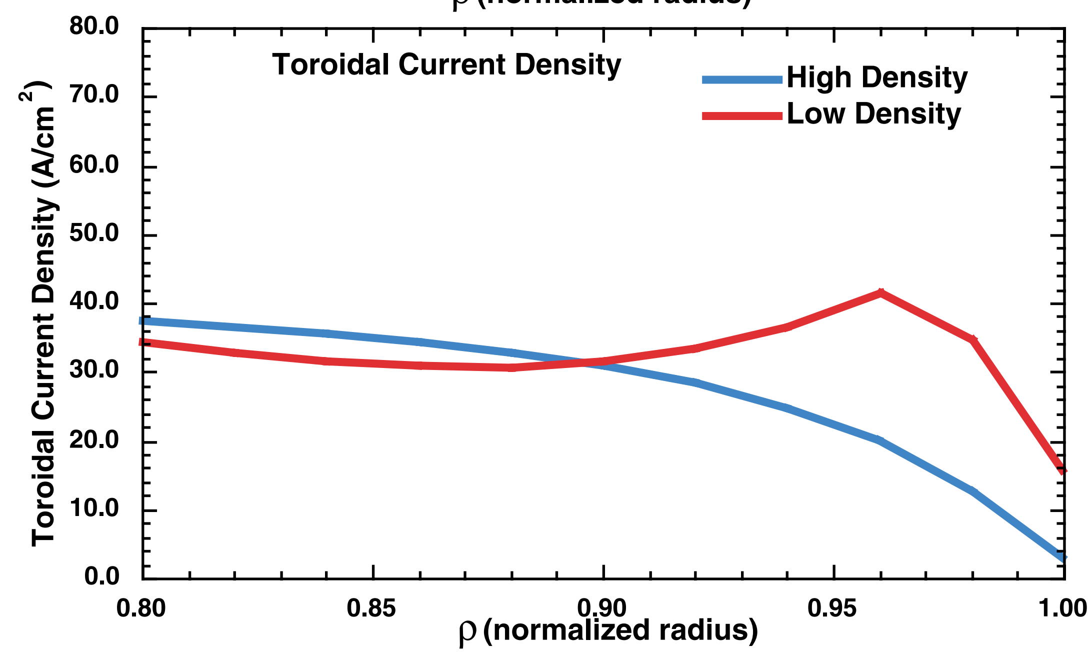
Low density:
$n_{e,ped} \sim 0.35\ n_{GW}$
$T_{e,ped} \sim 600$ eV

High density:
$n_{e,ped} \sim 0.74\ n_{GW}$
$T_{e,ped} \sim 280$ eV

Pressure profiles combined from T_e, T_i, n_e and impurity density measurements.

Edge current density is modeled by the transport code ONETWO. The increased collisionality leads to reduced edge bootstrap current.





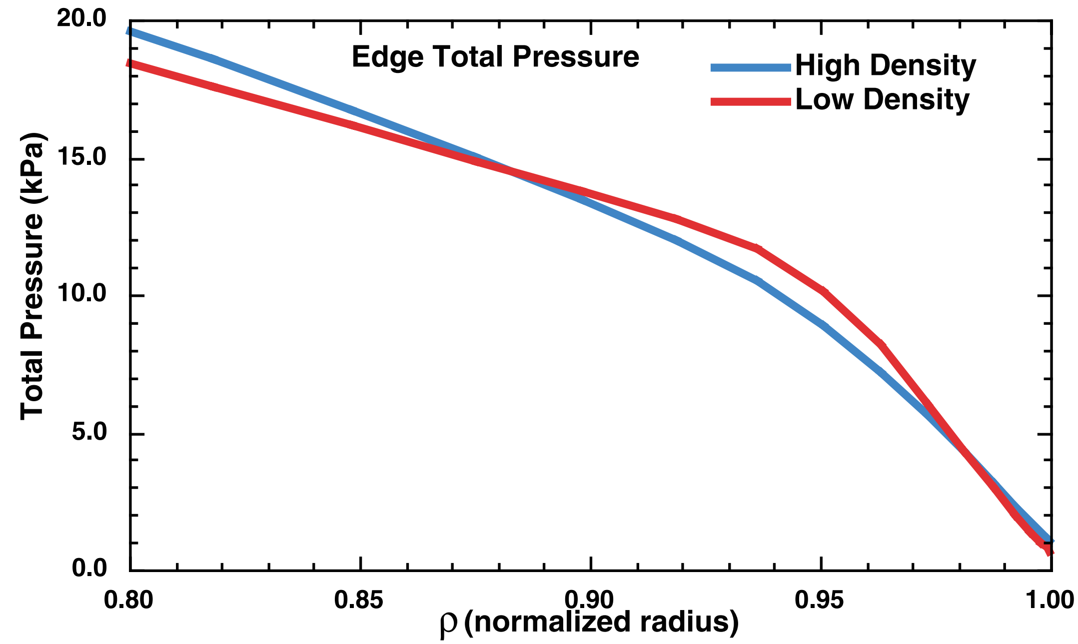
High Triangularity Edge Pressure at High Density; Higher pedestal maintained though loss of edge bootstrap current

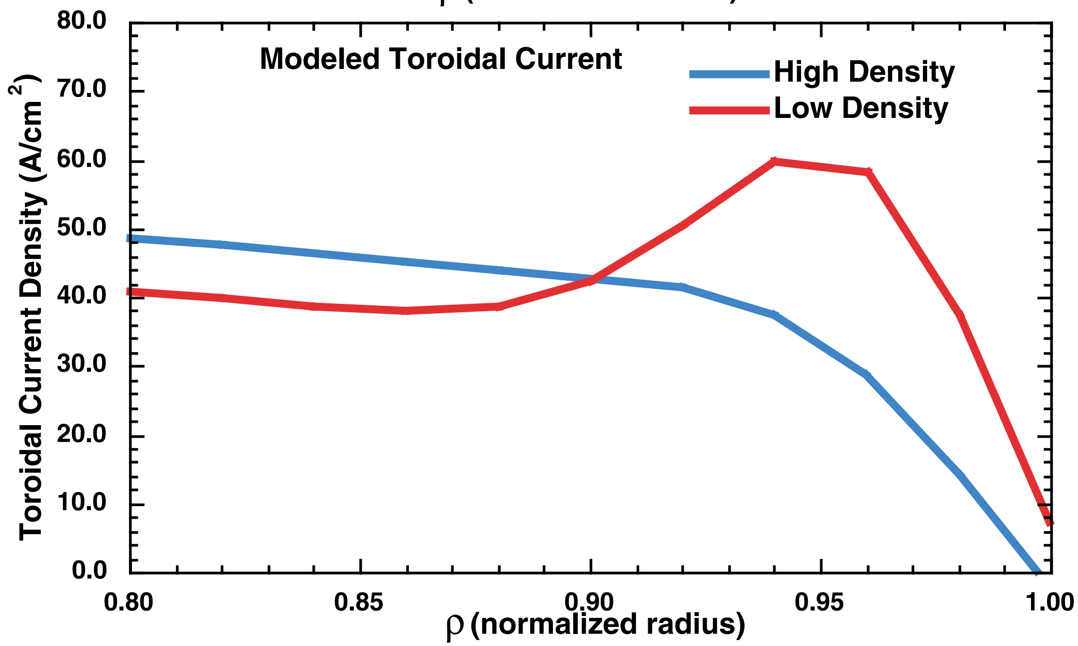
Low density:
$n_{e,ped} \sim 0.55\ n_{GW}$
$T_{e,ped} \sim 615$ eV

High density:
$n_{e,ped} \sim 0.78\ n_{GW}$
$T_{e,ped} \sim 425$ eV

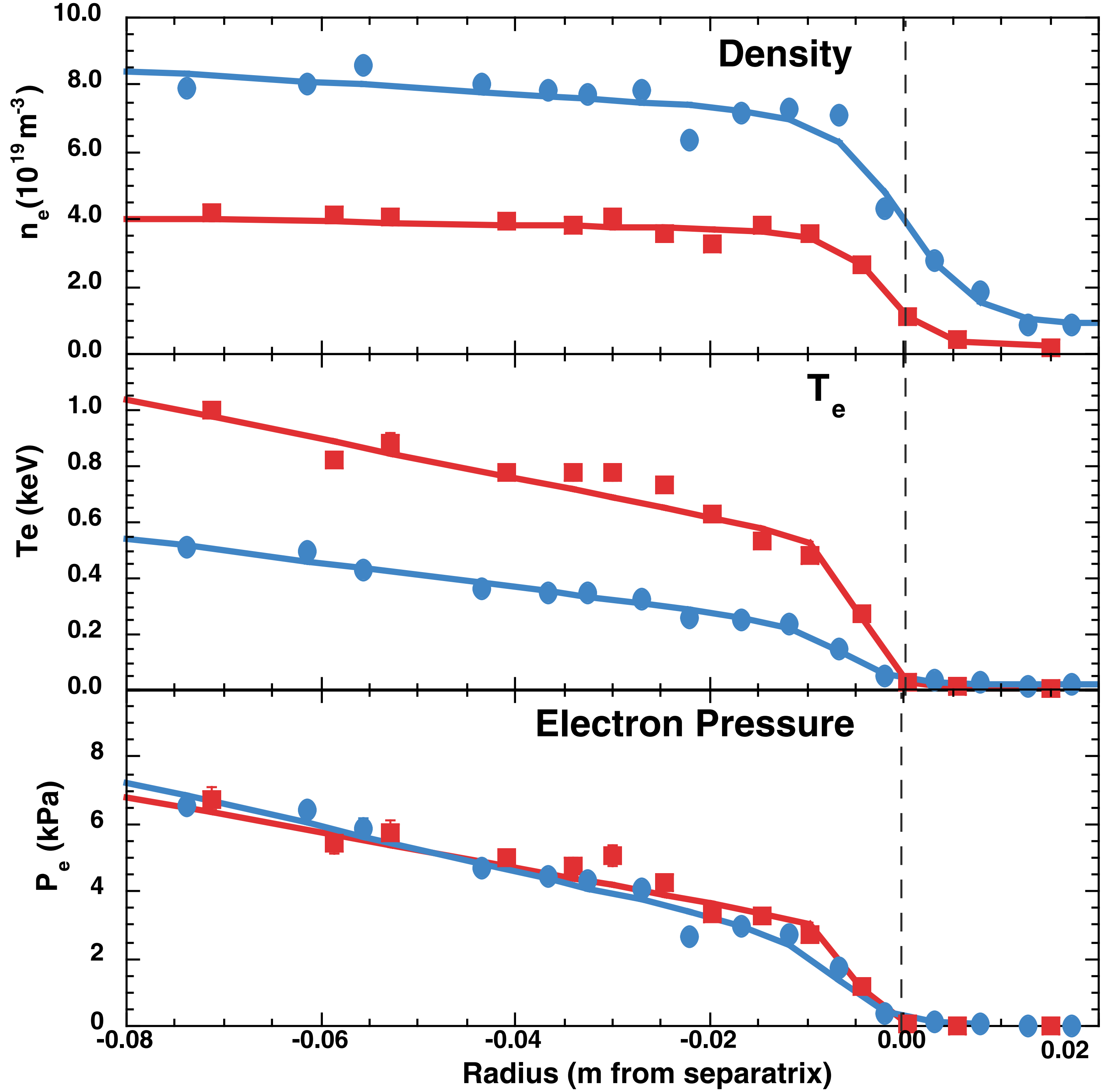
Edge pressure gradient at high triangularity is generally higher due to improved stability.

Even though pedestal T_e is higher for high triangularity edge bootstrap current is still strongly suppressed.

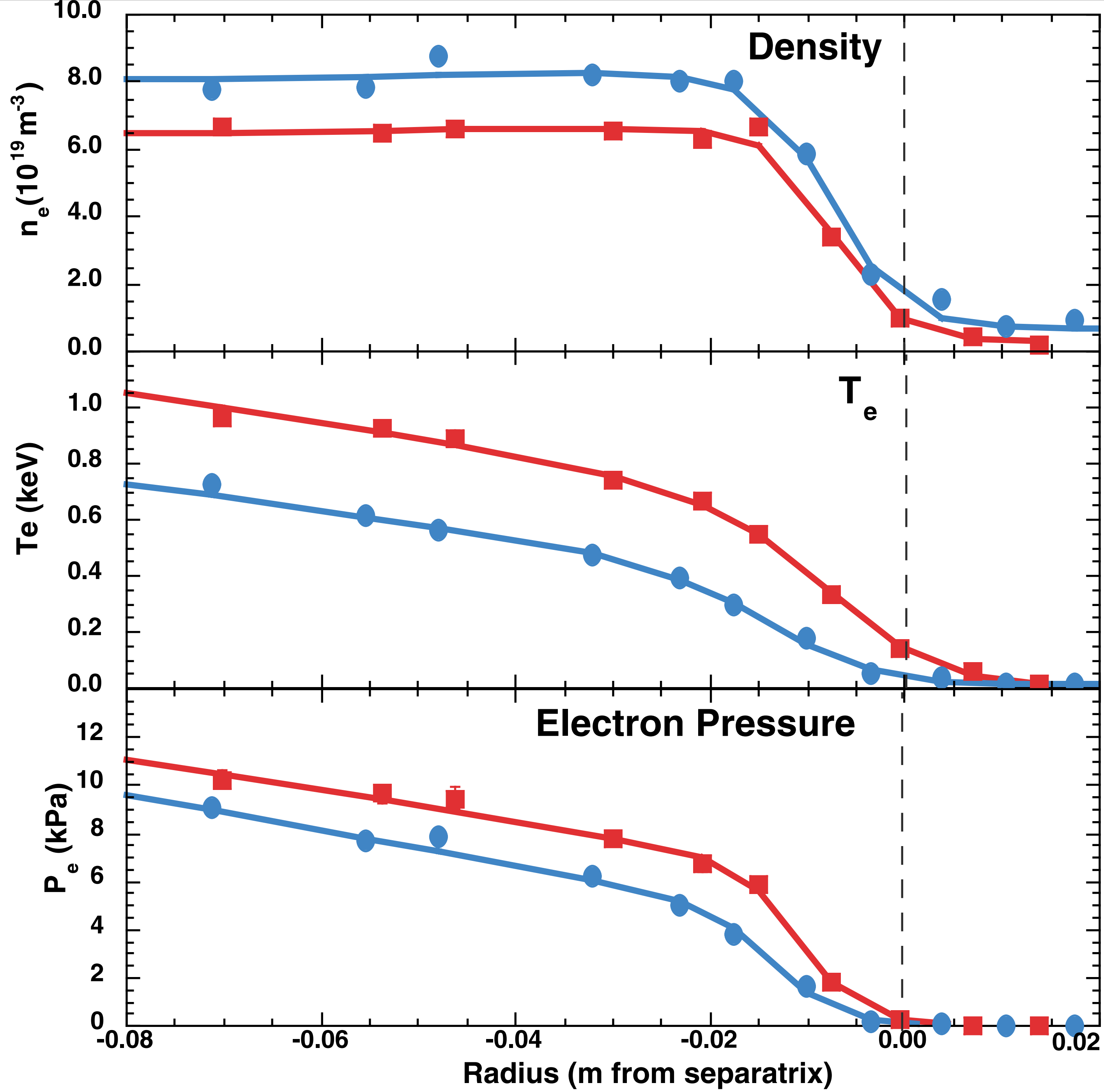




Low Triangularity Edge Profiles

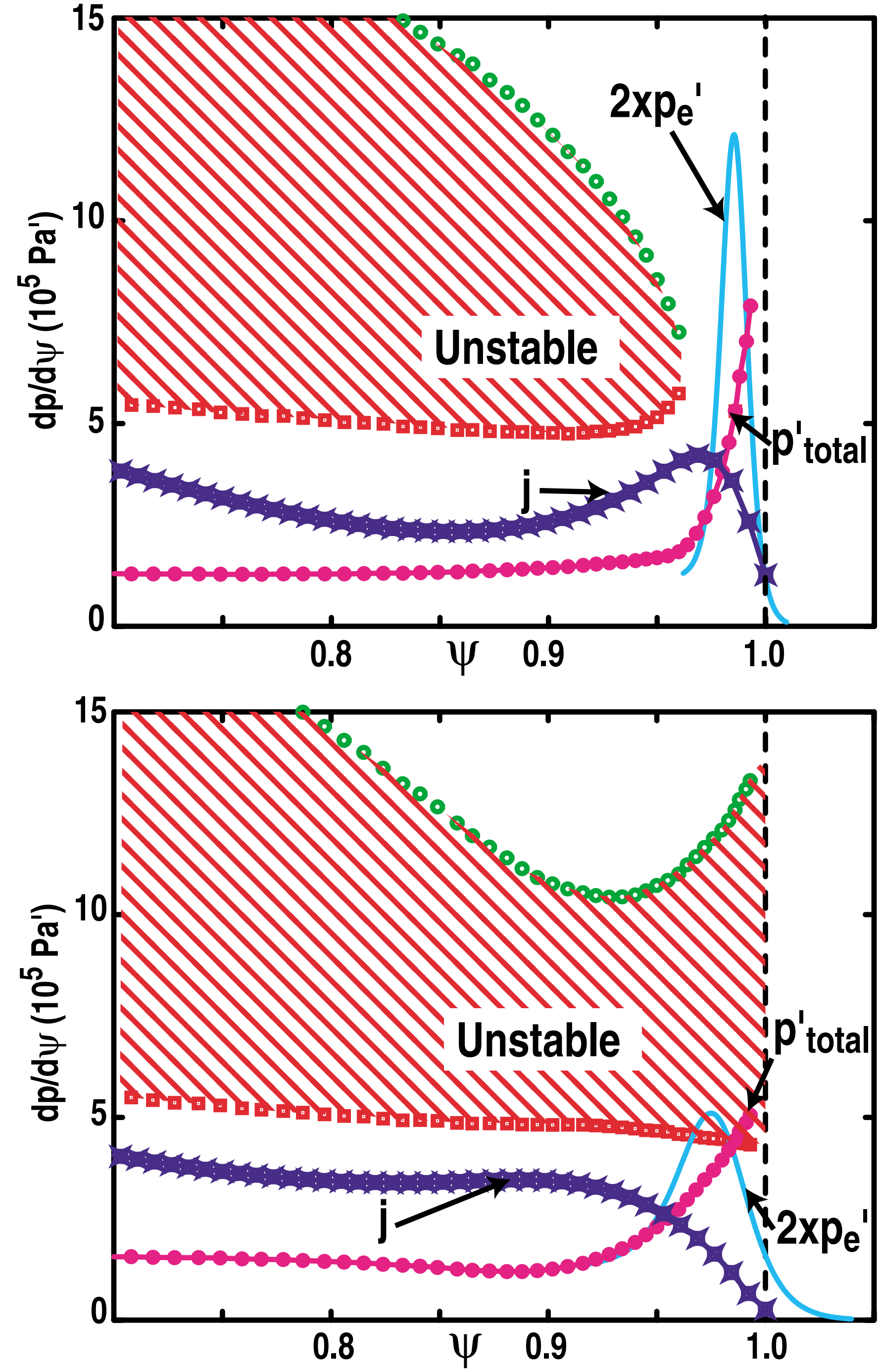


High Triangularity Edge Profiles



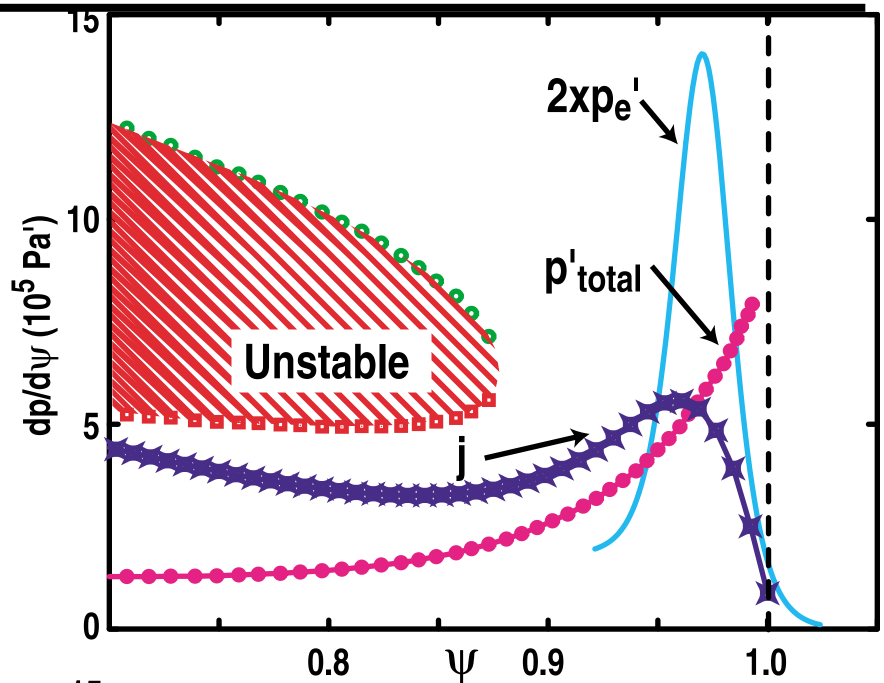
Ballooning 2nd Stable Access Lost at High Density and Low Triangularity

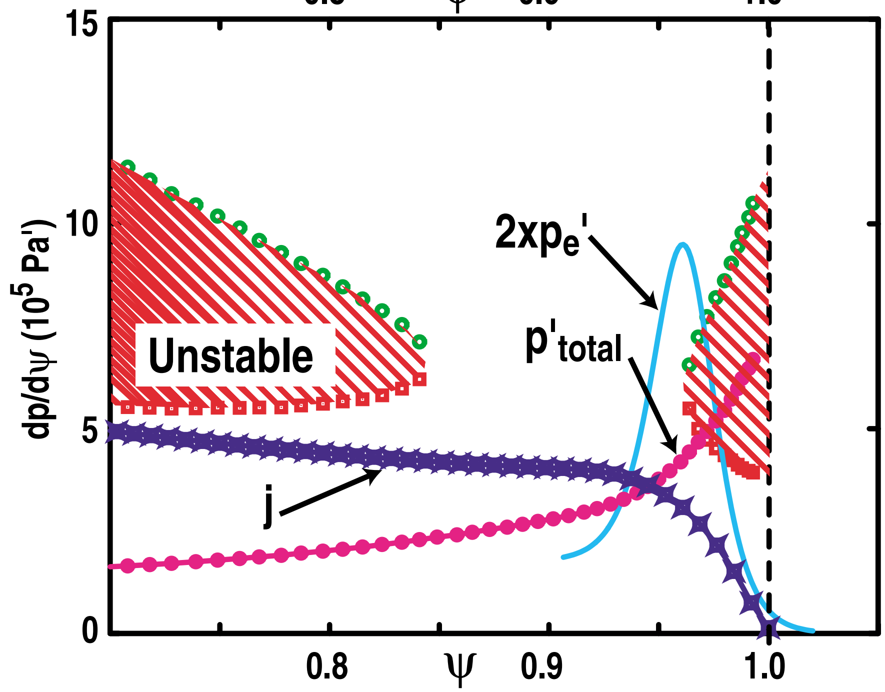
- Low density p′ is approximately twice that of ideal ballooning 1st stable limit, with small region of 2nd stability access.
- High density p′ is approximately at 1st stable limit with loss of 2nd stable access due to reduced edge bootstrap current.
- Wider pedestal at high density results in only small reduction in pedestal height.
- ELM amplitude reduced by >80% at high density.



Ballooning 2nd Stable Access Maintained at High Density and High Triangularity, though Pressure Gradient Reduced

- At high triangularity 2nd stable access for both low and high density, with edge p′ greater than 1st stable limit in both cases. Edge p′ likely determined by lower n modes.
- Edge p′ decreases at high density, but wider pedestal results in only slightly degraded total pedestal pressure.
- Difference between total p′ and $2xp_e'$ due to smaller gradient in T_i than T_e.
- ELM amplitude reduced by >65% at high density. Finite n analysis, kink/peeling, is needed to determine edge pressure stability and mode number.





Summary

- At high density and high edge collisionality, reduction of edge bootstrap current can affect edge stability.

- At low triangularity high density can cut off access to ballooning 2nd stability. The ballooning mode with higher toroidal mode number should be more localized to the edge, resulting in smaller ELMs.

- At high triangularity high density plasmas still have access to ballooning 2nd stability. The observed reduction in edge pressure gradient and ELM energy is presumably due to changes in low to intermediate mode number stability.

- At high density with only modest pedestal degradation, edge pressure gradient is decreased but pedestal is wider for unknown reasons.

- Still a work in progress. Have not yet analyzed intermediate to low n stability, and higher density where edge pedestal is significantly reduced.

- In future large tokamaks collisionality affect may be smaller, though it may still play a role.

Future Work

- Carry out low to intermediate n kink/peeling mode analysis with GATO and ELITE codes for discharges where 2nd stable access is maintained.
- Analyze edge stability at higher density where the edge pedestal is significantly degraded. Determine if pedestal degradation is due to reduced p' and lower 1st stable limit, or if the pedestal width decreasing at high density.
- Characterize and understand increase in pedestal width at high density.
- Parallel transport might limit ELM energy for low n ELM instabilities with short connection length to SOL and divertor. Determine what role parallel transport may be playing in ELM energy.
- Scale results to future large tokamaks to determine if high density operation will affect edge stability limits.