Pedestal Optimization Through Shape Variation in DIII-D

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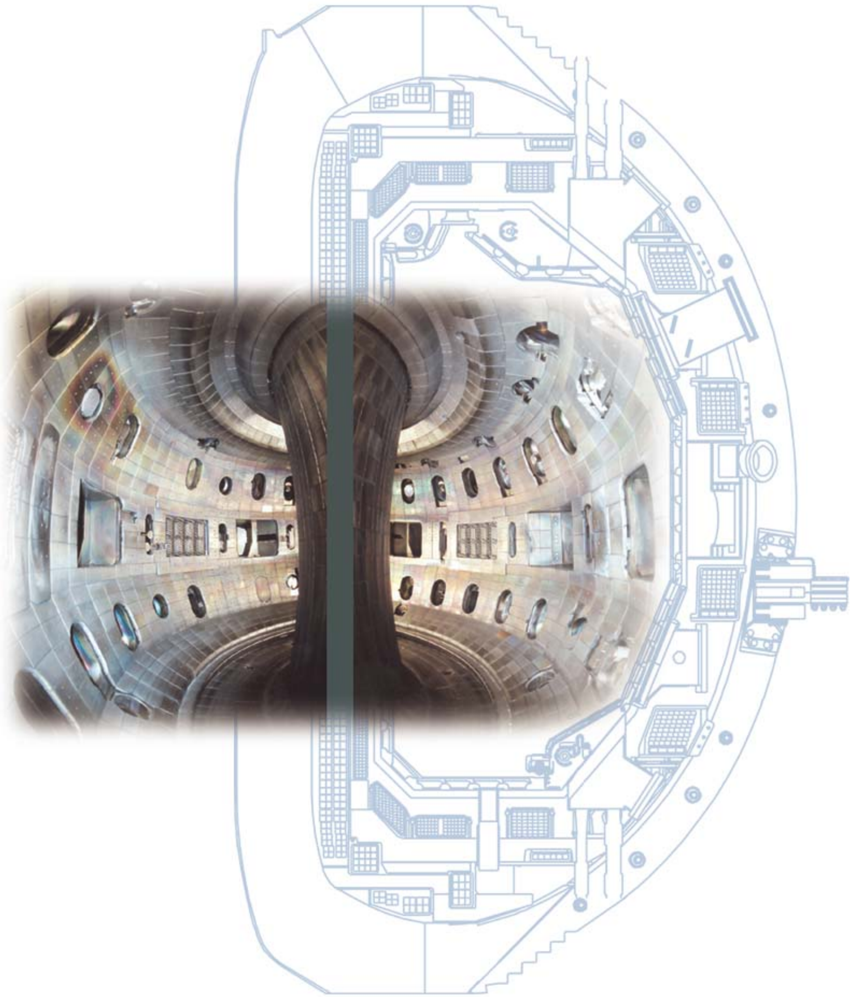

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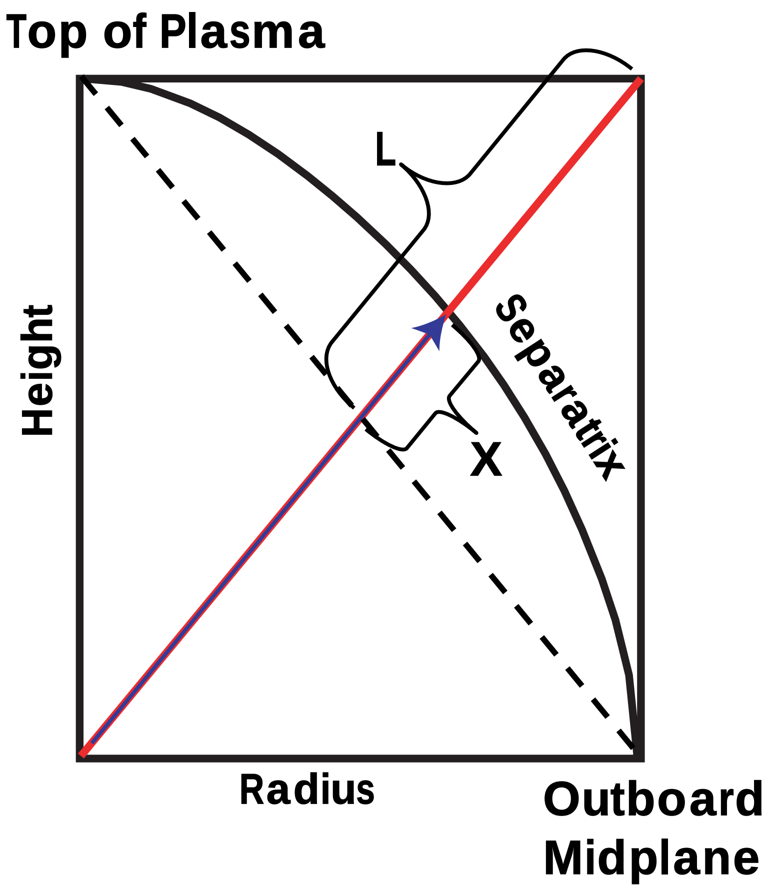
Pedestal and ELM Characteristics May be Optimized by Shape

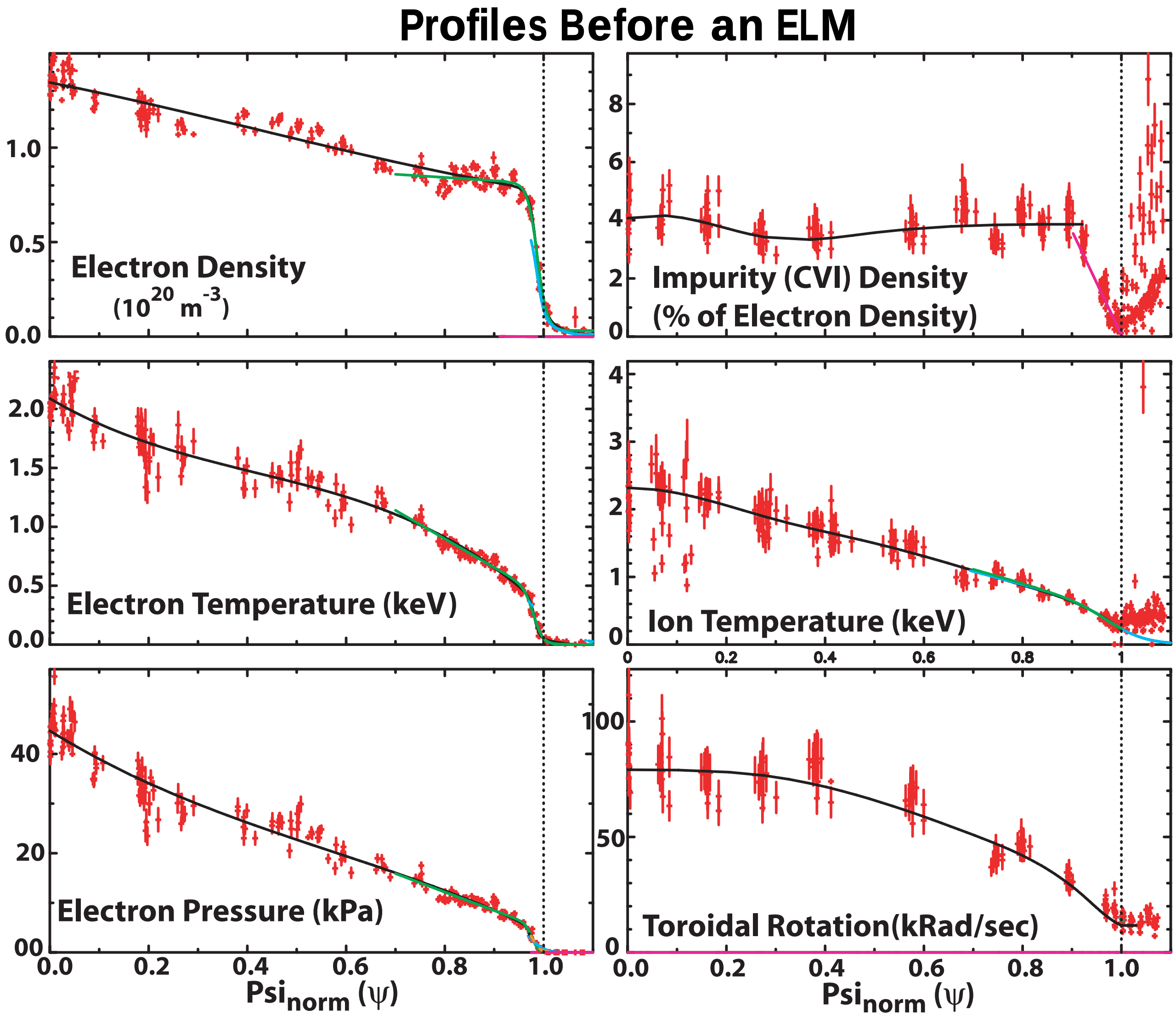
- In addition to triangularity, squareness has also been shown to modify edge stability (Ferron, PoP 2000)
- Advantages of using squareness to control pedestal characteristics
  - Pedestal and ELMs can be optimized while leaving the divertor configuration unchanged, i.e., recycling, fueling and pumping
  - A probe of pedestal stability characteristics and ELM dynamics
  - Optimize use of existing coil geometry
- Dedicated experiments find the pedestal pressure can be varied continuously by ~ 50% through squareness variations
- This study details pedestal and ELM characteristics vs. squareness
  - Pedestal pressure increases with lower squareness for low triangularity, high triangularity and for the ITER shape
  - Pedestal height just before an ELM is consistent with stability analysis using variations of model equilibria about the experimental parameters
  - ELM amplitude decreases with pedestal pressure for lower squareness

Squareness is Used to Describe Outboard Plasma Shape



- Outer upper (lower) quarter of boundary defined by Vertical maximum (minimum and Radial Maximum
- Squareness definition for this study: Sq=X/L
  - Fraction of separatrix distance (X) from triangular to rectanglular (L) shape
- Other shape definitions are equally valid
  - Other definitions could include integral moments of shape, or average curvature
  - While the stability limit is not inherently dependent on shape, shape parameters, i.e., triangularity, squareness, etc., capture aspects of physically relevant parameters such as average magnetic well depth and magnetic shear

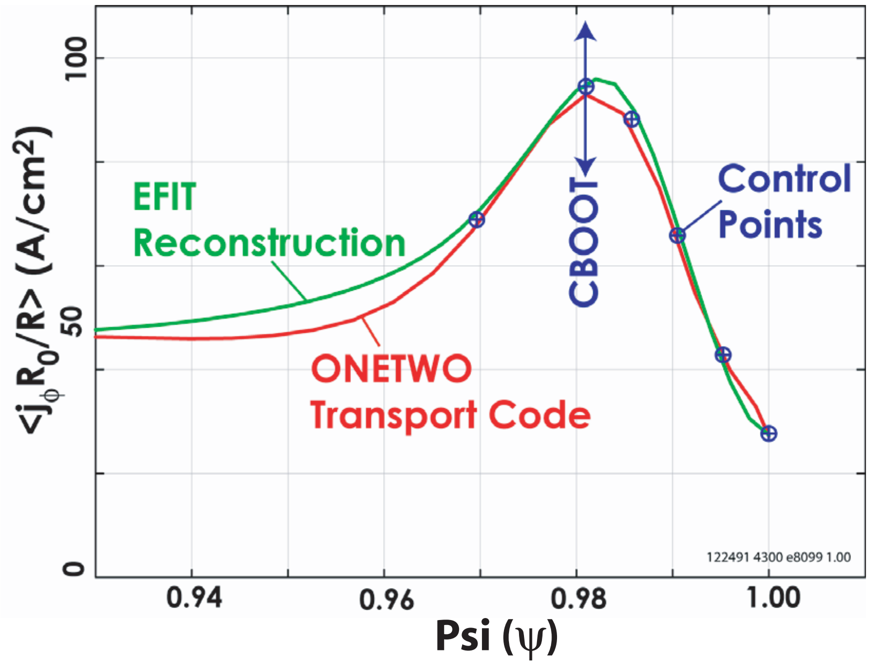
Pedestal Profiles are Characterized Just Before an ELM



- Data is collected in <u>last 20% of ELM cycle</u> during constant ELMing conditions of at least 500 ms duration.
- Profiles of T_e and n_e from Thomson scattering are fit to normalized Psi (ψ) and radius (ρ) with preliminary equilibrium from EFIT
- Ion temperature and density profiles obtained from CER (CVI)
- Fast Ion pressure calculated from ONETWO transport analysis
- Total pressure is then used to constrain EFIT equilibrium reconstruction

Equilibrium Constrained by Bootstrap Model and Measured Pressure

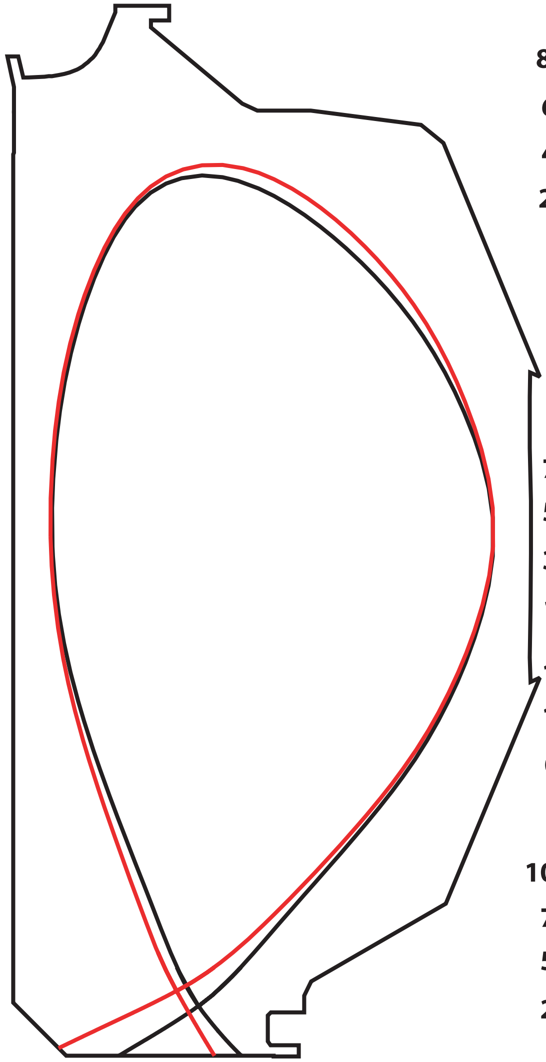
Edge Current Density

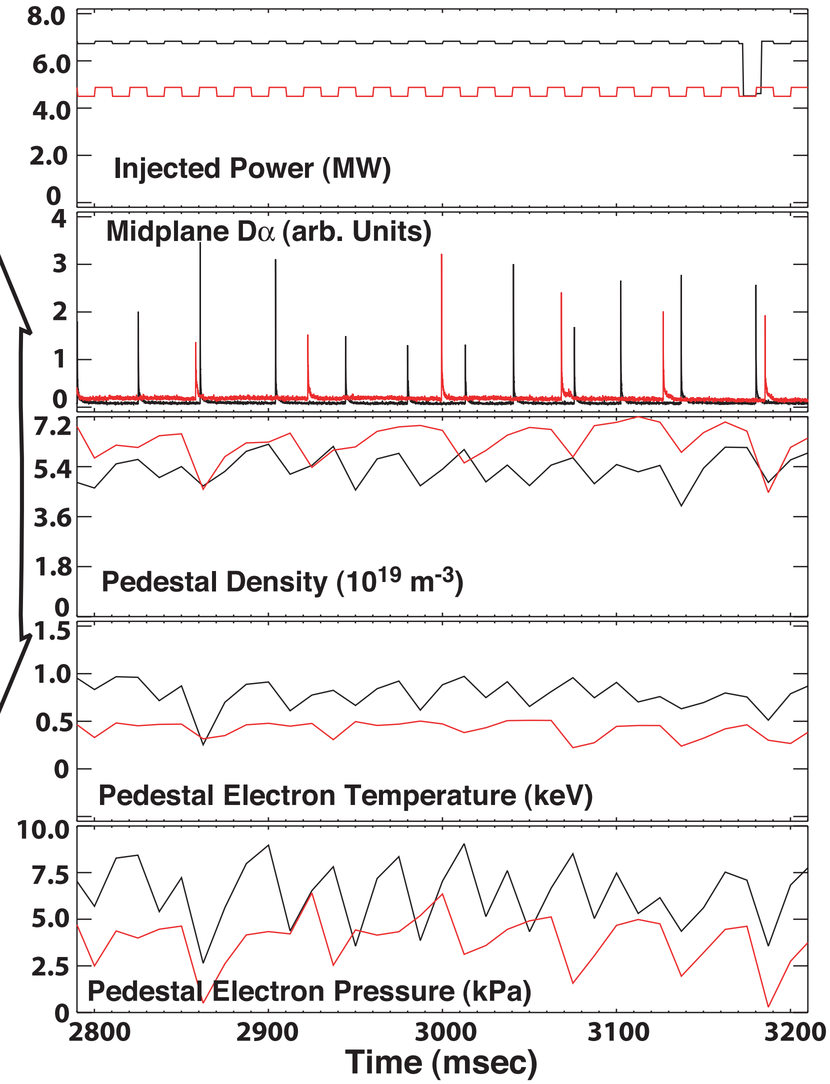


- Edge current determined from ONETWO transport code using Sauter bootstrap model and fully relaxed ohmic current profile
- Operating point equilibrium from EFIT constrained by measured pressure and edge current model
  - Tighter constraint on edge pressure
  - Edge current constrained by model while central current fit from magnetics and MSE measurements
- Sensitivity of edge stability to current and pressure gradients mapped by creating model equilibria about operating point
  - Edge pressure scaled while keeping central pressure constant.
  - Bootstrap current model applied for each pressure assuming constant collisionality
  - Bootstrap current multiplier varied for each pressure variation
  - Growth rate of instability calculated by ELITE for each constructed equilibrium

Low Triangularity

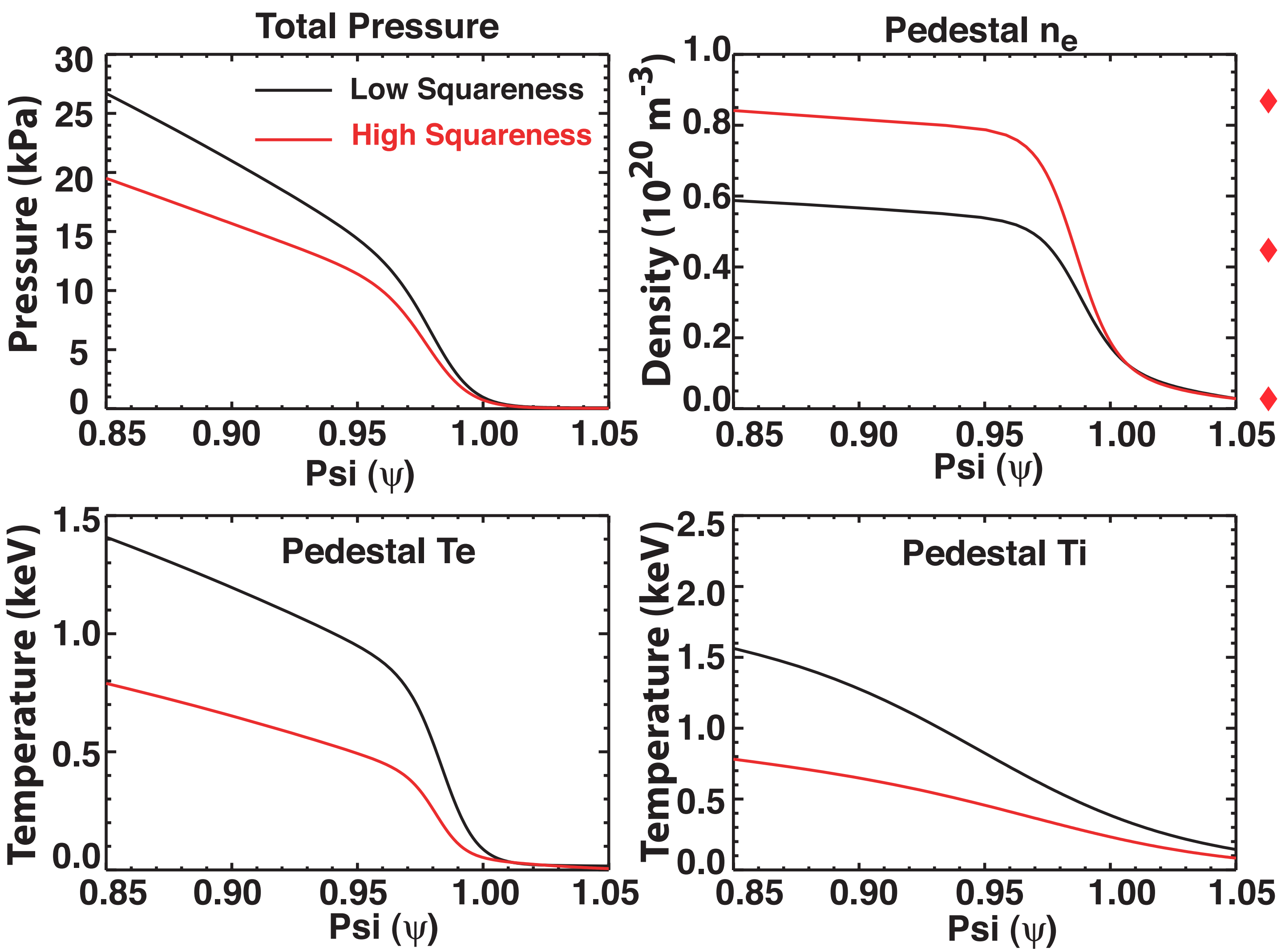
Squareness Varied for Fixed Average Triangularity





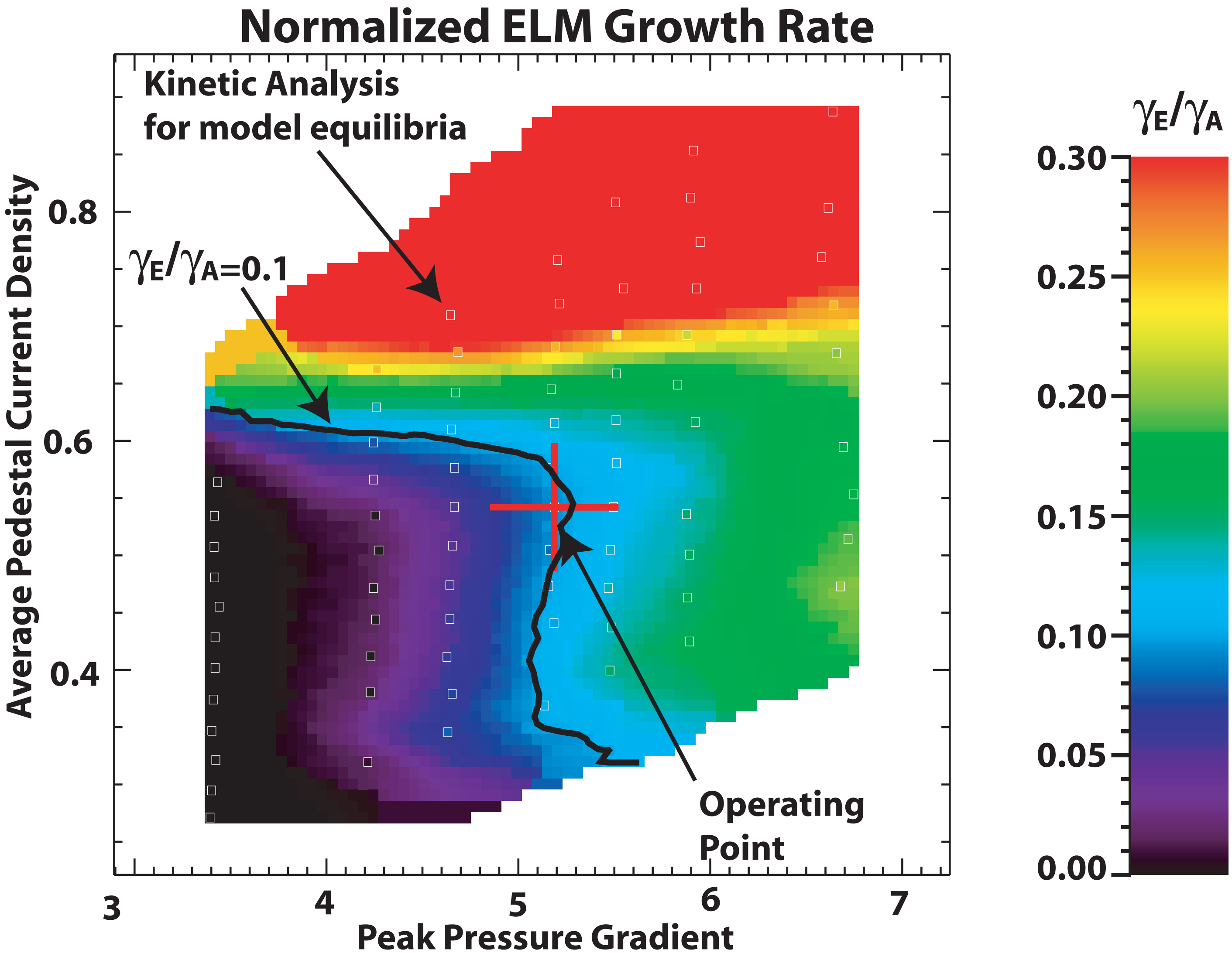
- Significantly higher pedestal electron pressure at low squareness
- Both discharges; 1.4 MA, and 2.0 T
- Same average triangularity, $\langle\delta\rangle \sim 0.35$
- Upper squareness variation of 0.31 to 0.34
- Higher power at low squareness was required to maintain regular ELMs instead of ELM-free
- Pedestal density somewhat lower for low squareness

Higher Pedestal Pressure at Lower Squareness



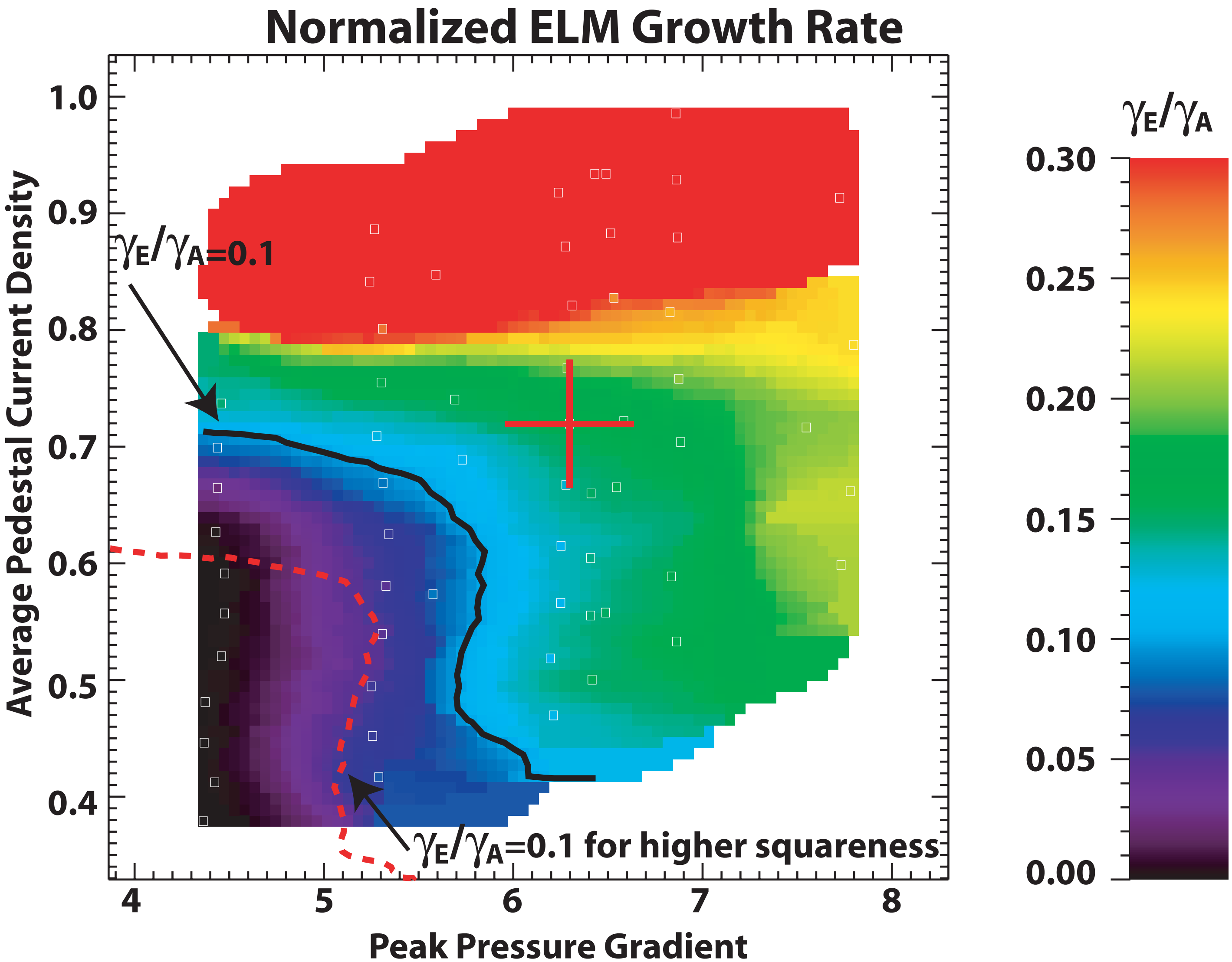
- Pedestal pressure increases ~30% for lower squareness
- Pedestal density and temperature widths similar
- Lower collisionality, 0.3 vs. 1.5 could be partially responsible for improved stability at lower squareness

Measured Pedestal Gradient Near Expected Stability Limit



- ELM growth rate normalized by Alven frequency
- ELM instability expected for γ_E/γ_A near 0.1 at typical densities
- Error bars represent typical uncertainties in measured pressure gradient

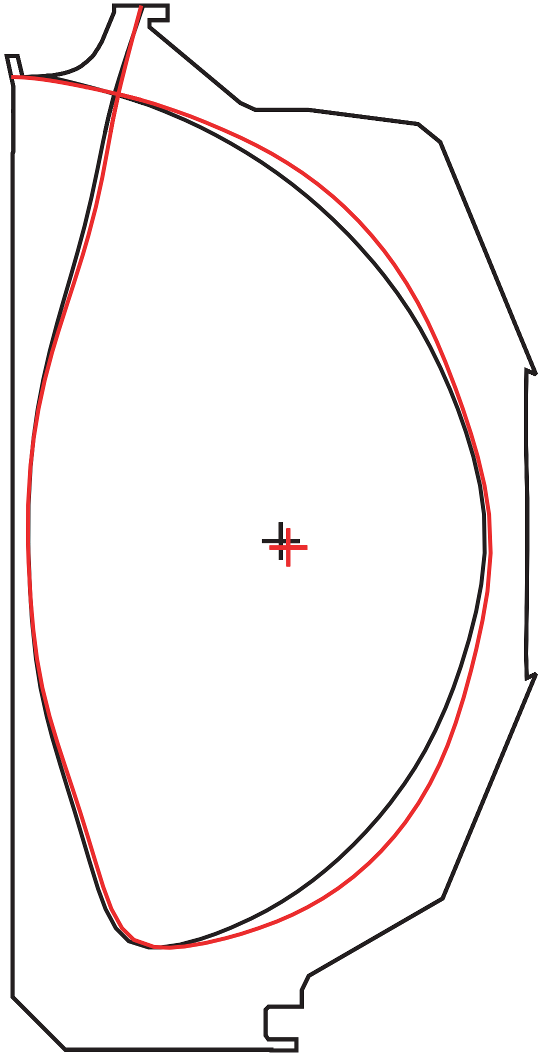
Lower Squareness Exhibits Higher Stability Limit

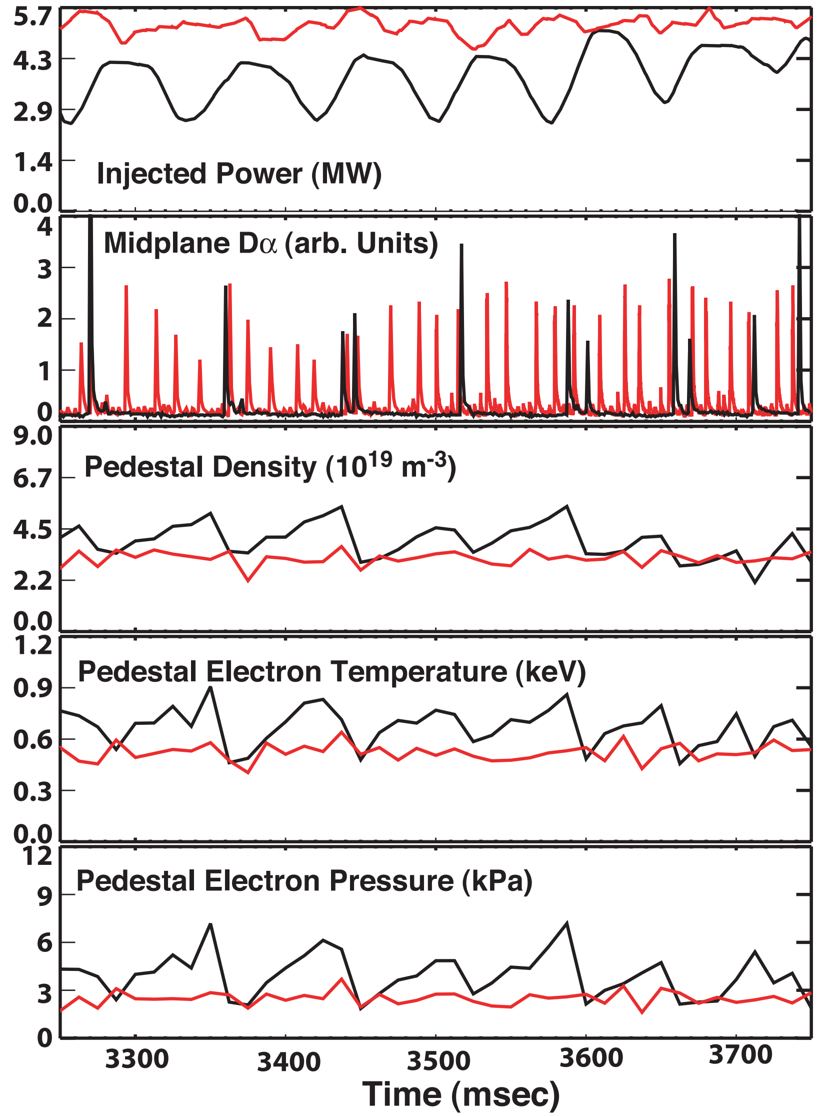


♦ **Increase in expected pressure gradient less than measured increase may be due to resolution of edge measurements**

High Triangularity

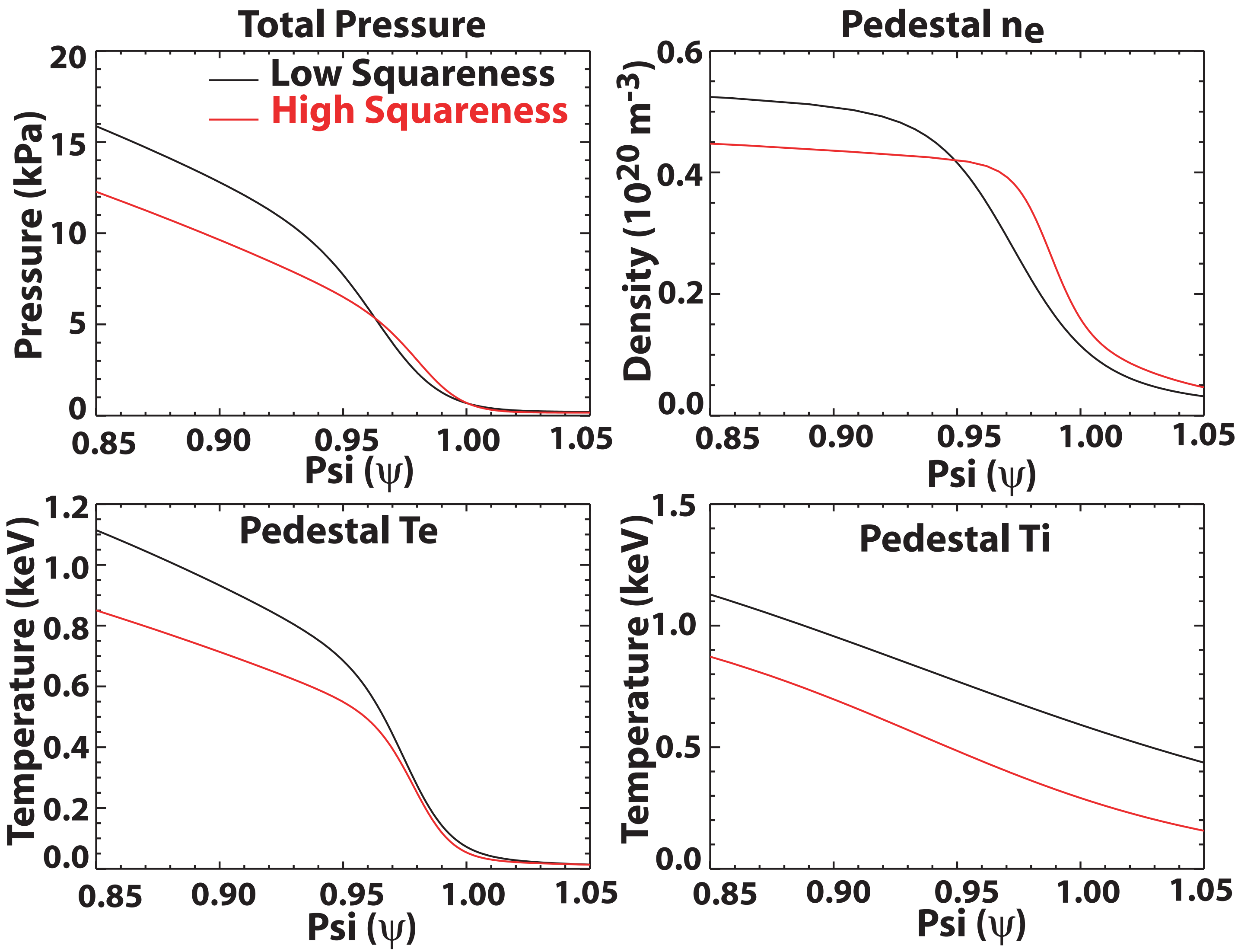
Low Squareness also Increases Pedestal Pressure for High Triangularity





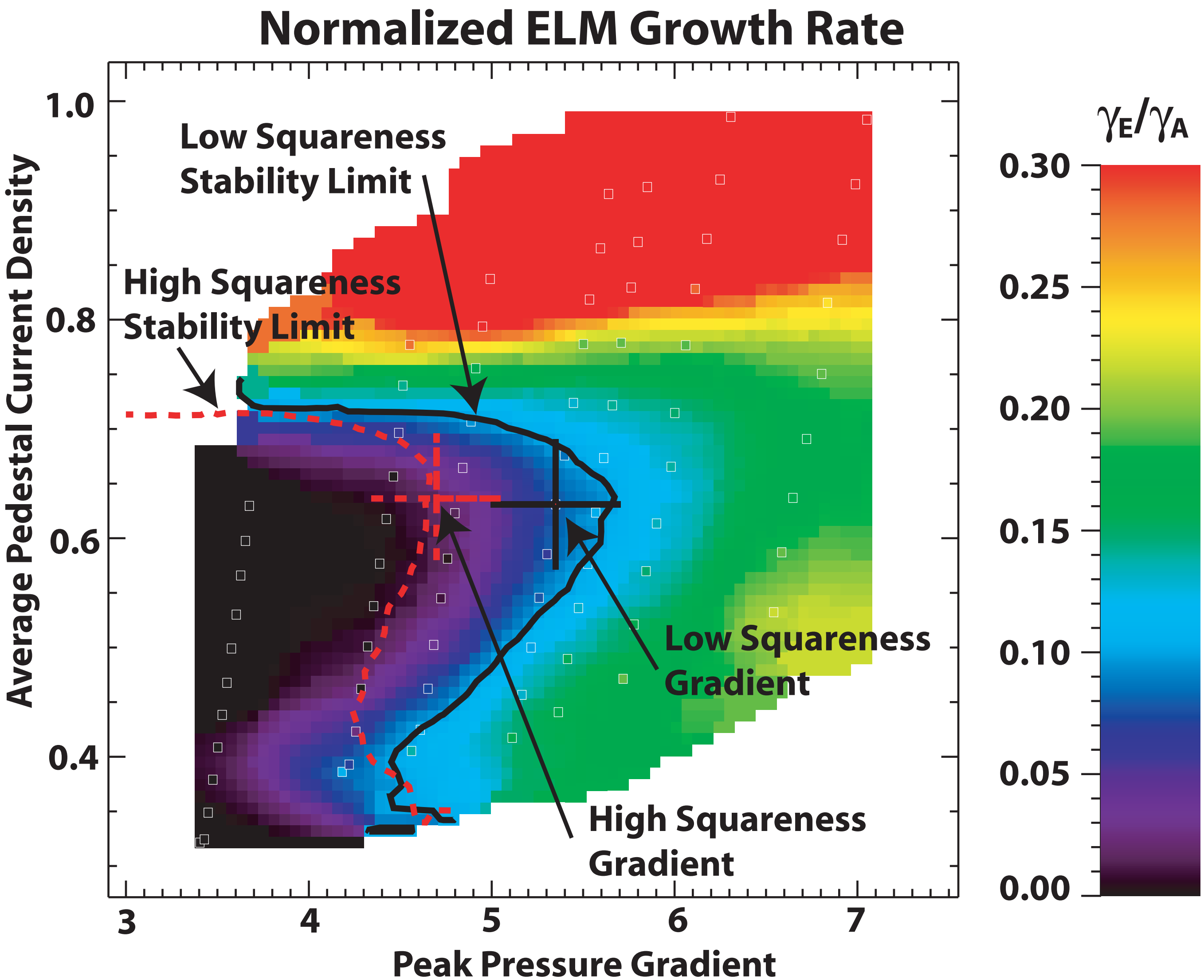
- Higher pedestal density and temperature leads to higher pressure at low squareness
- Both discharges; 1.2 MA, and 1.25 T
- Same average triangularity, <δ>~0.5, lower squareness variation of 0.37 to 0.42
- Lower power at low squareness was required to avoid NTM instabilities

Higher Pedestal Pressure at Lower Squareness



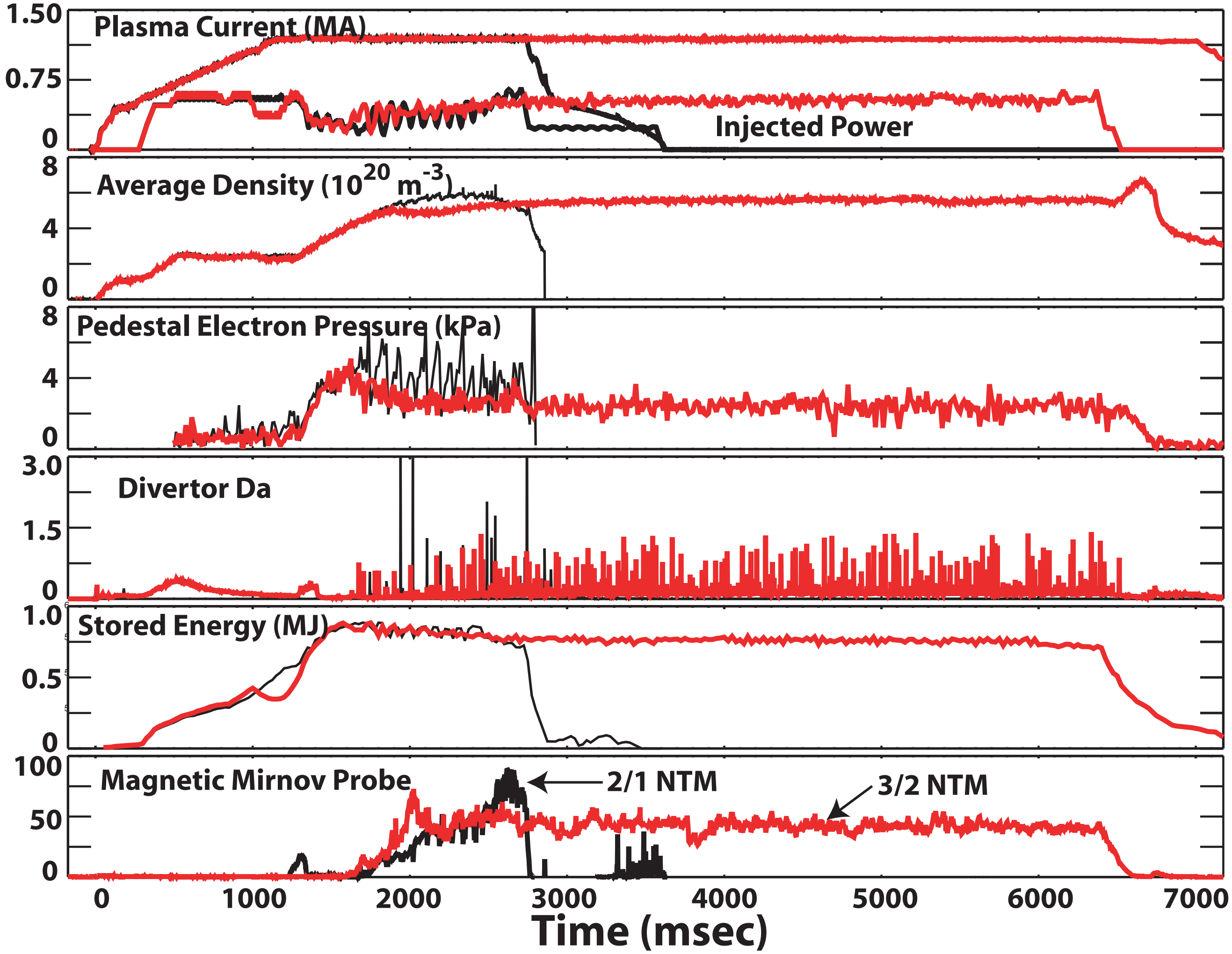
- Pedestal pressure increases ~40% at low squareness
- Higher electron and ion temperature even with lower input power
- Narrower density pedestal for higher squareness marginally within measurement uncertainty

Larger Stability Increase at Higher Shaping



- Increase in expected stability limit somewhat greater than measured pressure gradient increase, but smaller than pedestal top pressure increase
- Difference between pedestal top and peak gradient likely due to measurement resolution
- From stability studies, pedestal pressure expected to increase less than linear with pedestal width

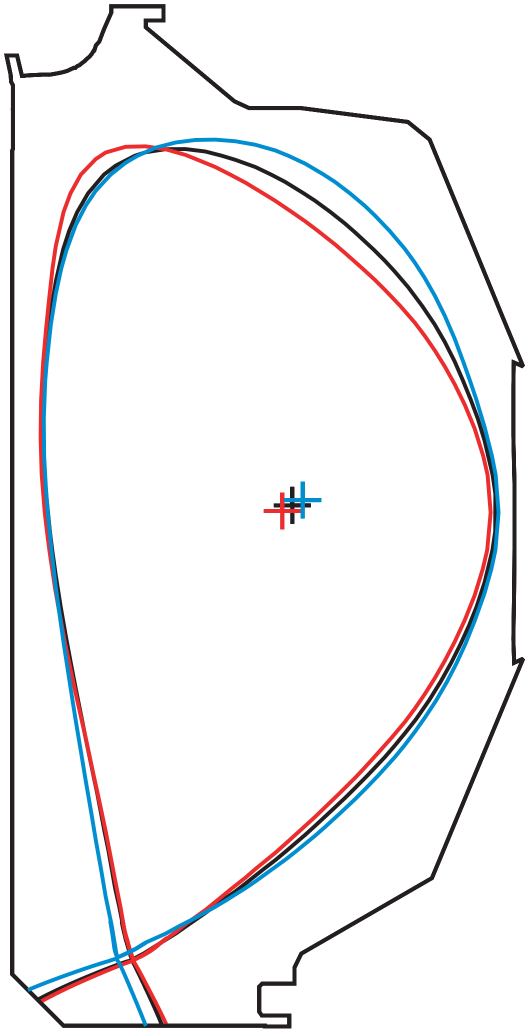
Pedestal Control Used to Optimize Discharge and Avoid NTMs

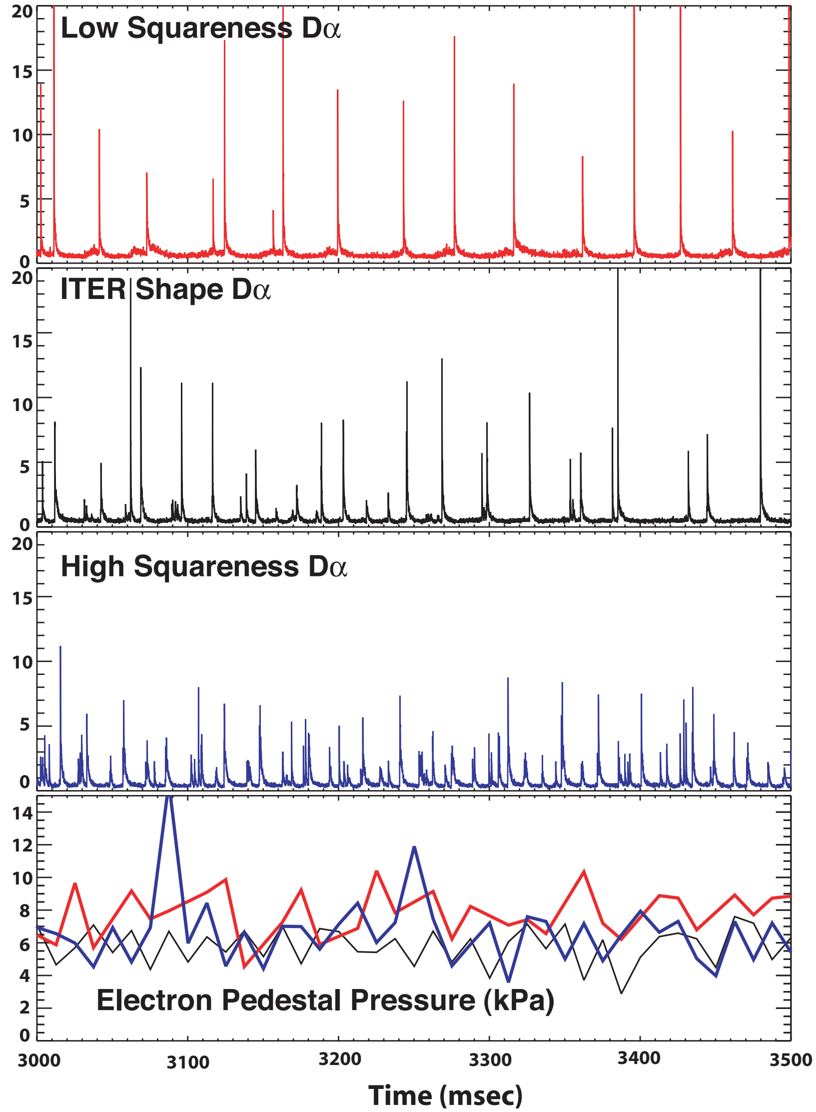


- In high performance Hybrid discharges with low squareness minimum power required for regular ELMs leads beta and ELM size exceeding 2/1 NTM threshold
- By tuning squareness pedestal pressure and ELM size is reduced resulting in steady ELMing discharge with benign 3/2 NTM

ITER Shape

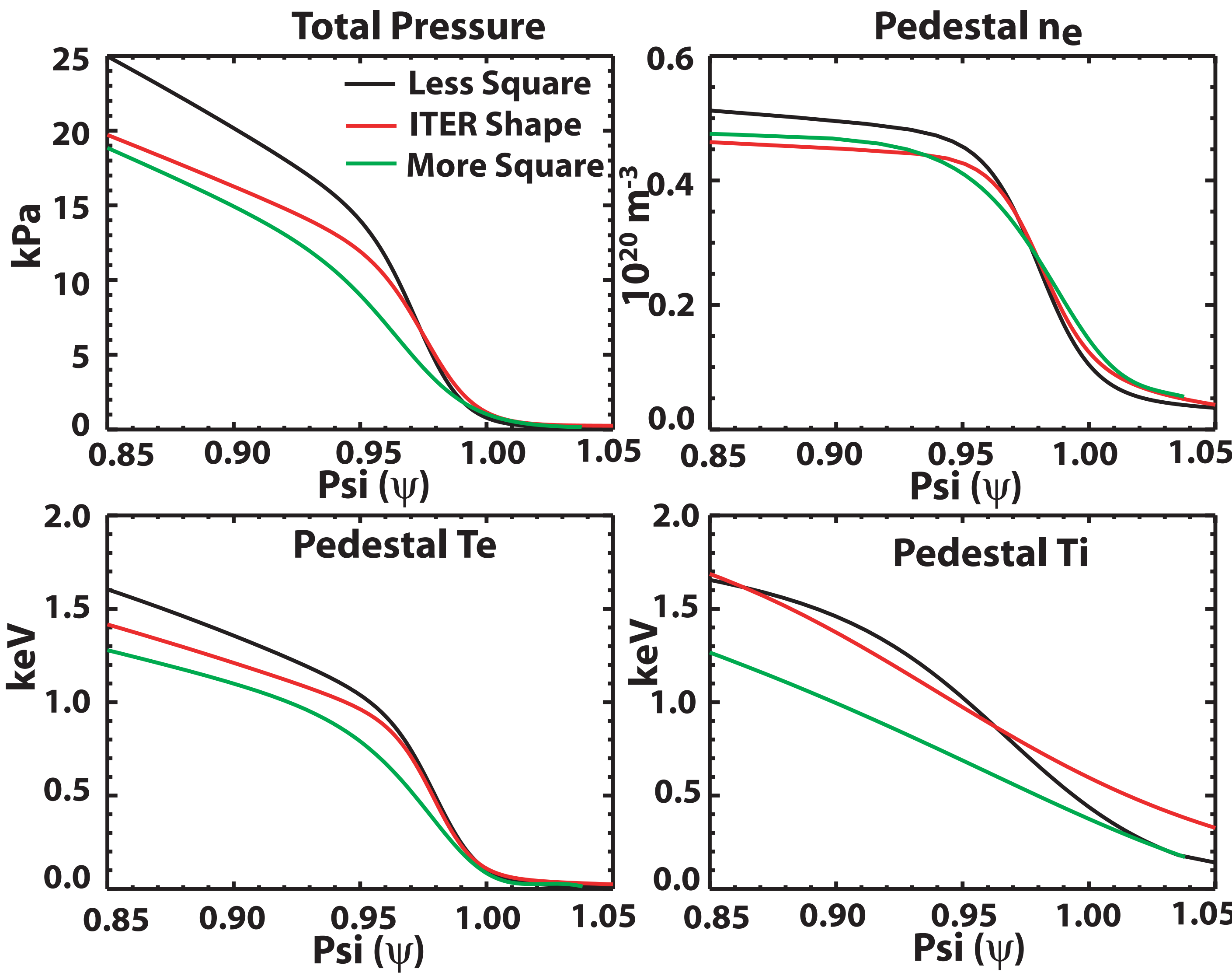
Upper Outer Squareness Scanned about ITER Shape





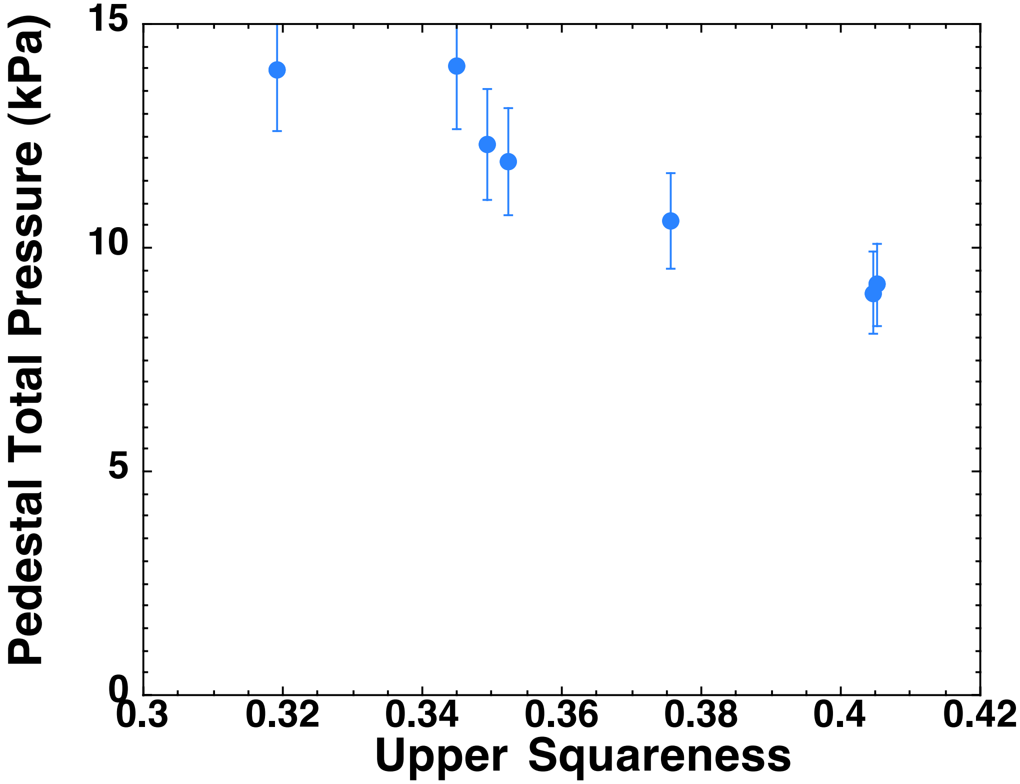
- ♦Upper outer squareness was scanned about ITER shape, Sq=0.32-0.41 with modest changes to average triangularity
- ♦Plasma Current 1.5 MA, Toroidal field 1.8 T
- ♦q_{95} ~3.7 somewhat higher than ITER target
- ♦Constant injected power, 6.8 MW
- ♦With increasing squareness ELM frequency increases and pedestal pressure decreases

Pedestal Pressure Increased due to Squareness Scan



- Pedestal pressure continuously increased with less squareness
- Pressure increase primarily due to temperature
- Collisionality decreases with less squareness, 0.45-0.21

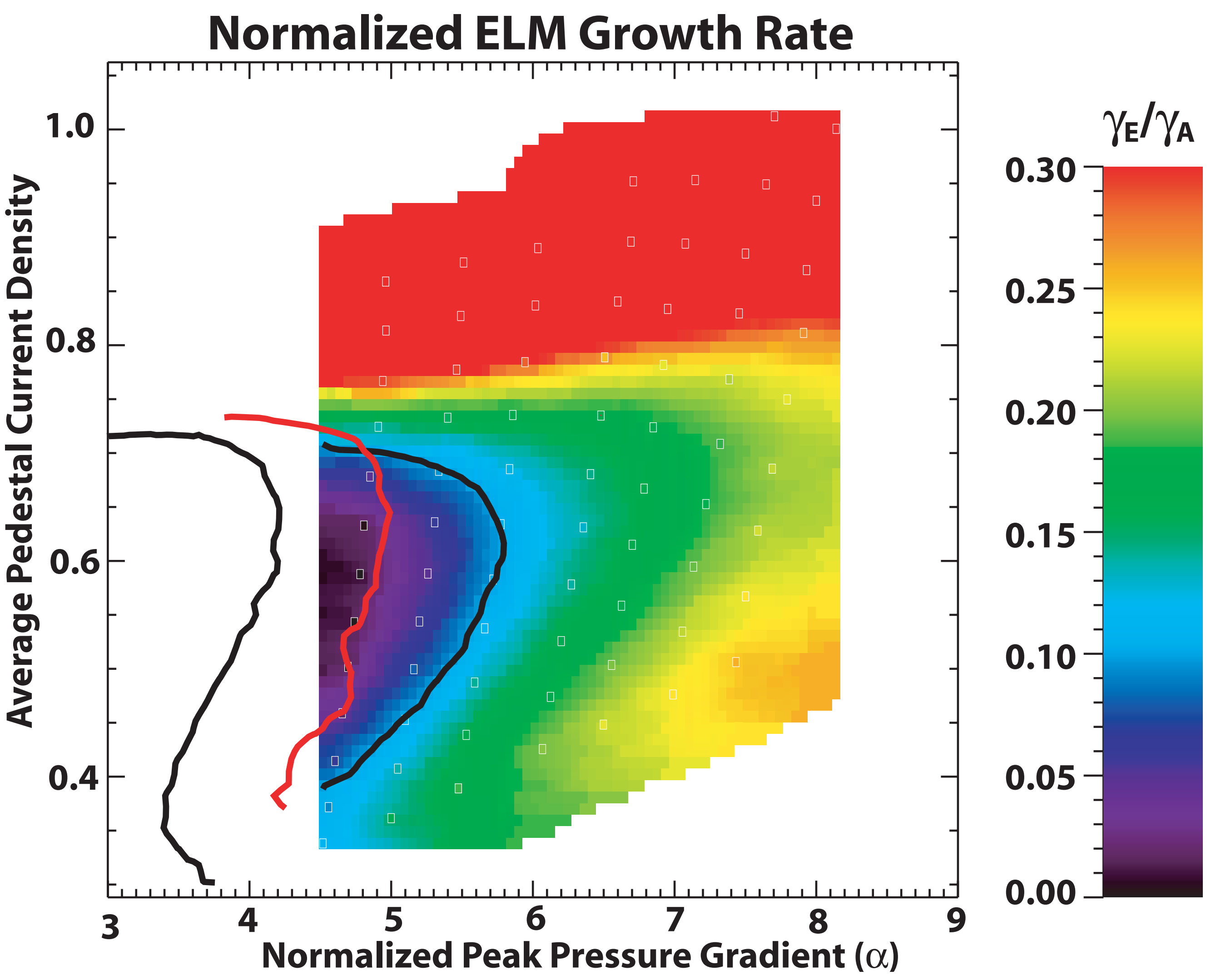
Pedestal Pressure Varies Inversely with Squareness



- Pedestal pressure increases ~50% from highest to lowest squareness
- Average triangularity increases from $\langle\delta\rangle=0.48$ to $\langle\delta\rangle=0.56$ with scan to lower squareness. From previous study[1] this triangularity variation would be expected to account for only 20% increase in pressure, $p \propto (1+\delta)^{1.7}$

[1] P.B. Snyder, PPCF 2004

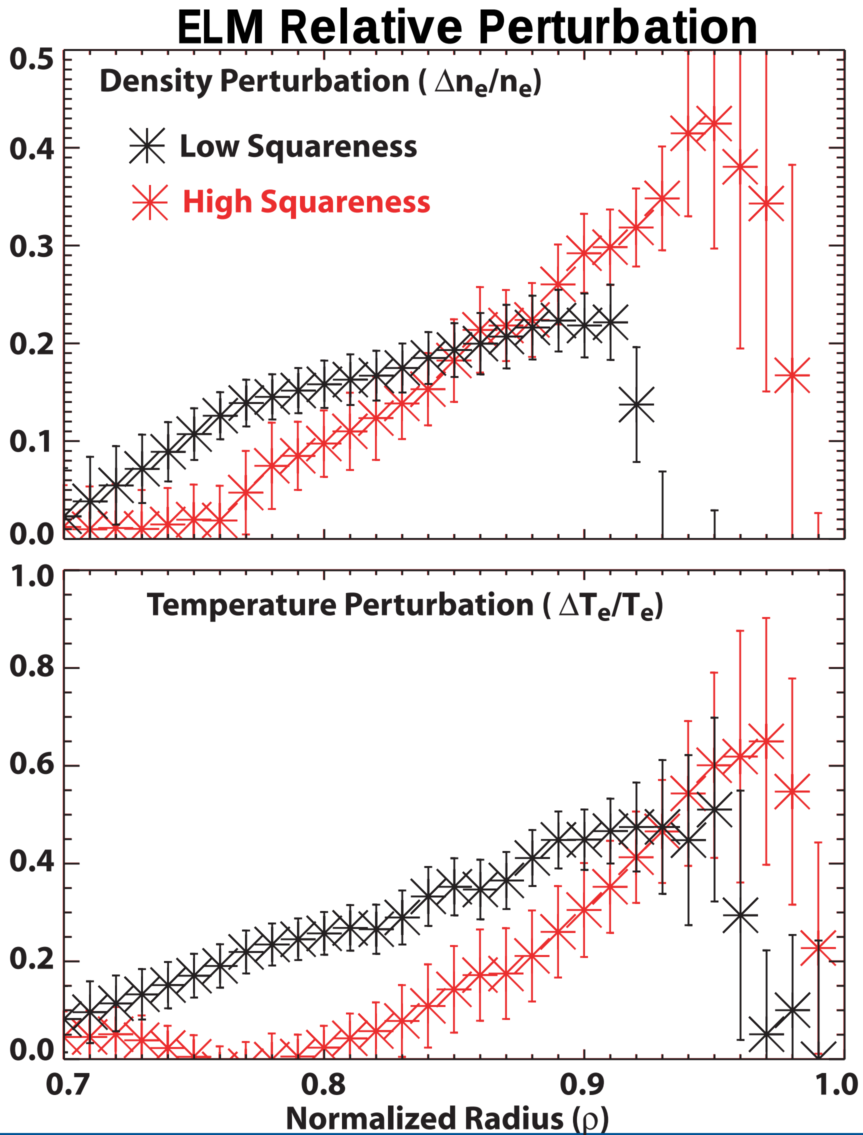
Pedestal Stability in ITER Shape Increases with Less Squareness



- Stability limit increase for pressure is nearly equal to observed increase in pedestal pressure for low squareness
- Most unstable toroidal mode does not change significantly over this scan, n=10-20

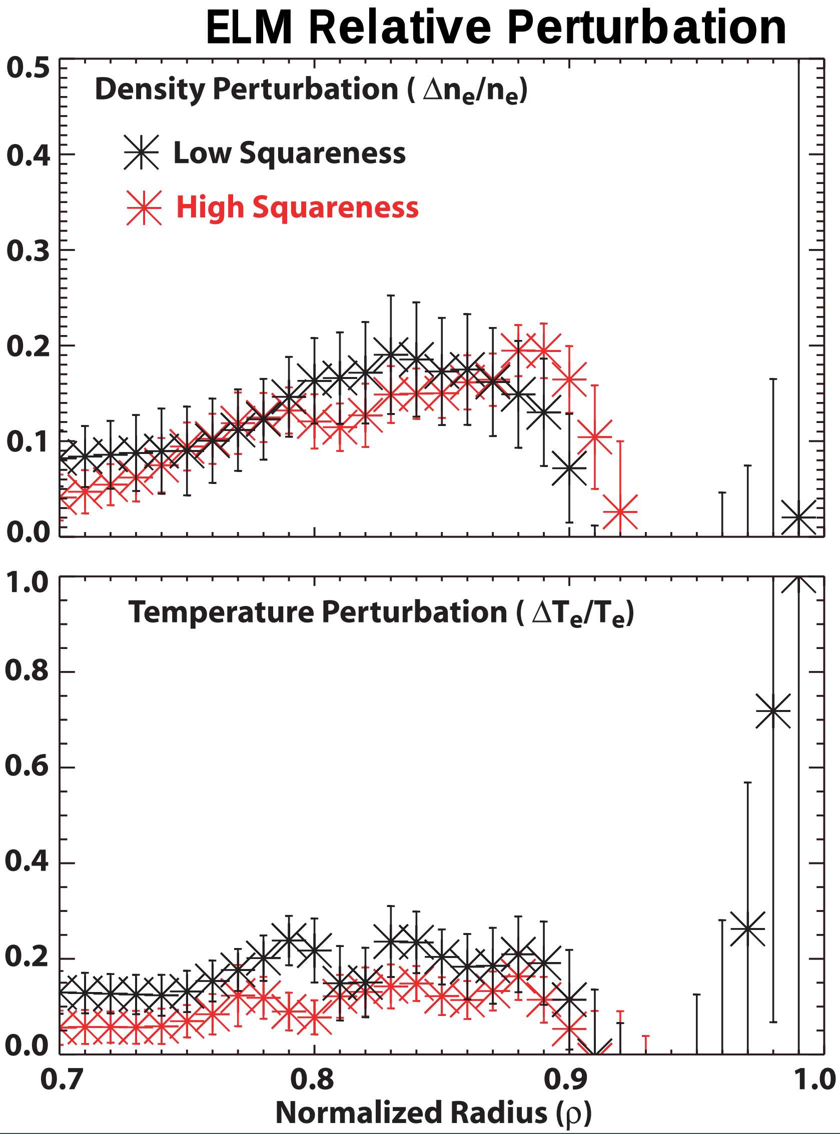
ELM Characteristics

For Low Triangularity ELM Loss Narrower for High Squareness



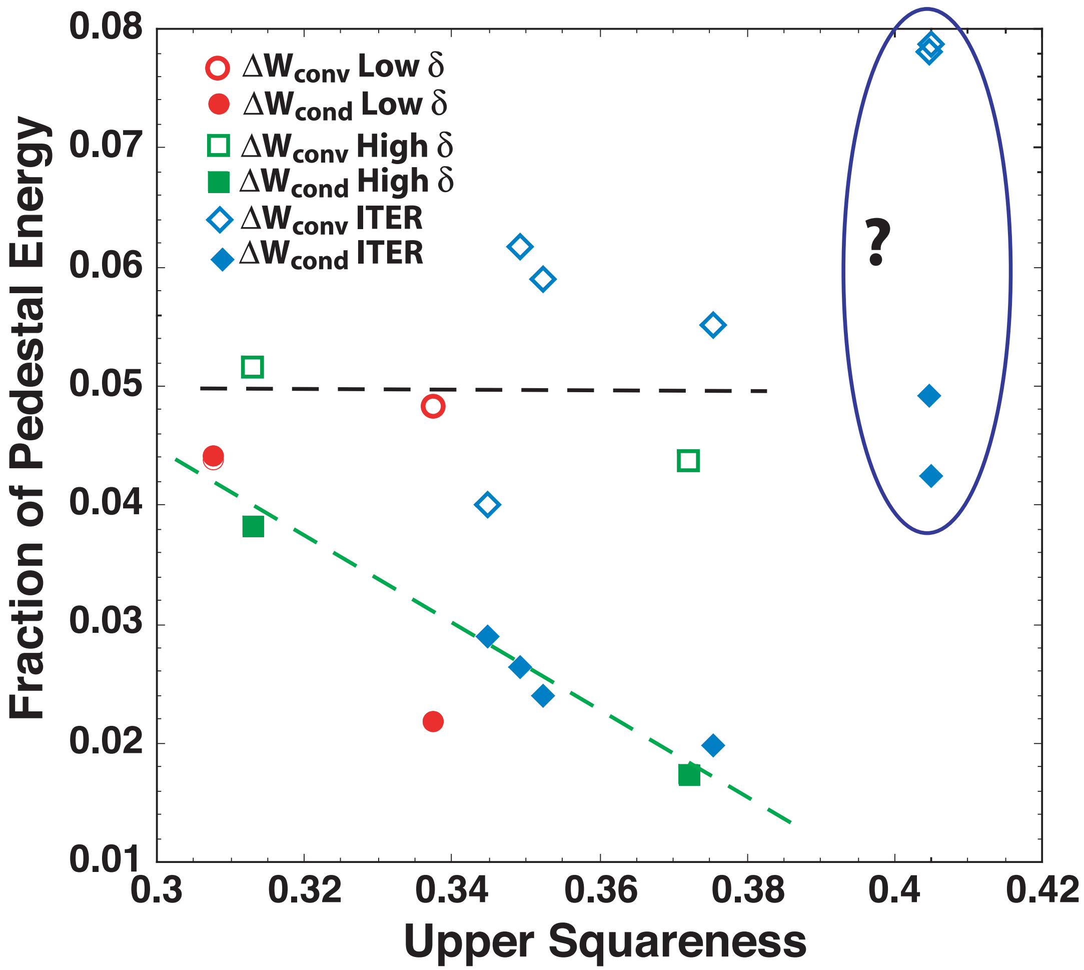
- **Low Squareness**
  - $\Delta W_{conv}(\Delta n_e)$=26.3 kJ
  - $\Delta W_{cond}(\Delta T_e)$=26.5 kJ
- **High Squareness**
  - $\Delta W_{conv}(\Delta n_e)$=23.5 kJ
  - $\Delta W_{cond}(\Delta T_e)$=10.6 kJ
- **The narrower perturbation in the T_e profile results in convected energy loss more localized to the edge**
- **Uncertainty in the separatrix location accounts for the shift in profile between low and high squareness**
- **This is the only case analyzed at low triangularity; more statistics needed**

Conducted ELM Energy less for High Squareness and High Triangularity



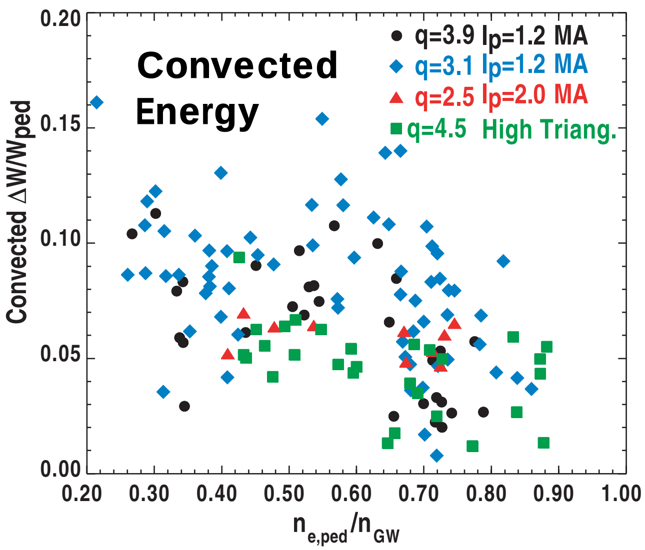
- **Low Squareness**
  - $\Delta W_{conv}(\Delta n_e)$=18.5 kJ
  - $\Delta W_{cond}(\Delta T_e)$=13.7 kJ
- **High Squareness**
  - $\Delta W_{conv}(\Delta n_e)$=13.8 kJ
  - $\Delta W_{cond}(\Delta T_e)$=5.5 kJ
- **The temperature perturbation is the same width for High squareness, but lower in amplitude**
- **While both low and high triangularity exhibit a reduced conducted ELM loss, more data analysis is needed to understand profile effects**

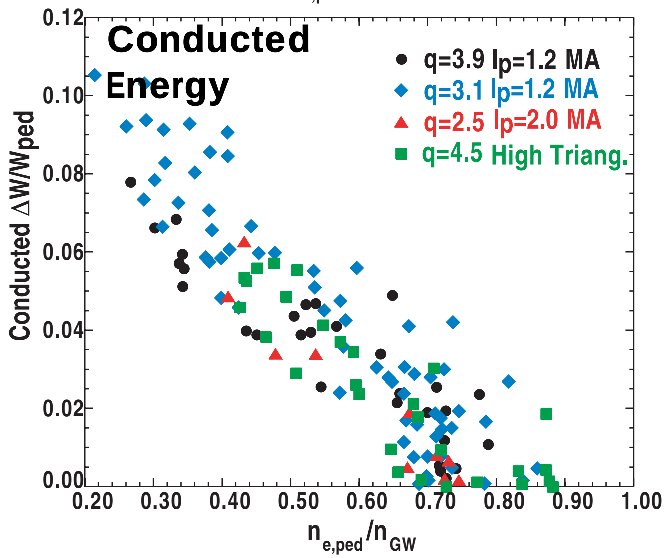
Fractional ELM Loss is Reduced Due to Lower Conduction



- The energy convected by an ELM remains a fixed fraction of the pedestal pressure, I.e., as the pressure is reduced by increased squareness the convected energy decreases proportionally
- Curiously, the ELM conducted energy fraction is reduced with increasing squareness
- The cause of the larger relative ELM size for high squareness in the ITER shape is not understood and warrants further study

ELM size in Squareness Scans are Roughly in Line with Previous Studies





- In the previous study the ELM convected energy, or density loss, was 5-10% of the pedestal energy, similar to the squareness scan data
- Most of the squareness scan data was at a density of 30-40% of $n_{Greenwald}$, and electron collisionality of 0.2-0.4, with an ELM conducted energy somewhat less than the previous study would indicate
- The mechanism controlling ELM conducted energy is not understood. This is an active area of research with significant implications for ITER divertor operation. Careful systematic studies of ELM characteristics with squareness variations could aid in understanding ELM dynamics

Discussion

- Squareness can be used for fine scale control of pedestal and ELM characteristics
  - Continuous control of pedestal height over range of ±30%
  - Pedestal control without changing divetor configuration; pumping and recycling
  - Pedestal height (confinement) can be traded off for ELM size
  - Pressure peaking (global stability) may be adjusted by controlling ELM size
- Pedestal Pressure Varies with shape squareness as expected from stability analysis
  - Increases confidence in stability models
  - Pedestal pressure dependencies on parameters such as shape, global beta, or pedestal width characteristics can be mapped out with model equilibria based upon experimental conditions

Discussion (cont.)

- Squareness, or triangularity, may not be best parameterization of shape for stability limit
  - Squareness may be capturing curvature (reduction of poloidal field) near top of plasma
  - Other possible options to explore; Average in/out curvature, average magnetic well depth of pedestal
- ELM size responds to squareness control
  - In general, ELM size decreases along with pedestal pressure at higher squareness
  - Squareness could prove valuable as a probe of ELM dynamics; preliminary observation of ELM conducted energy preferentially reduced at higher squareness