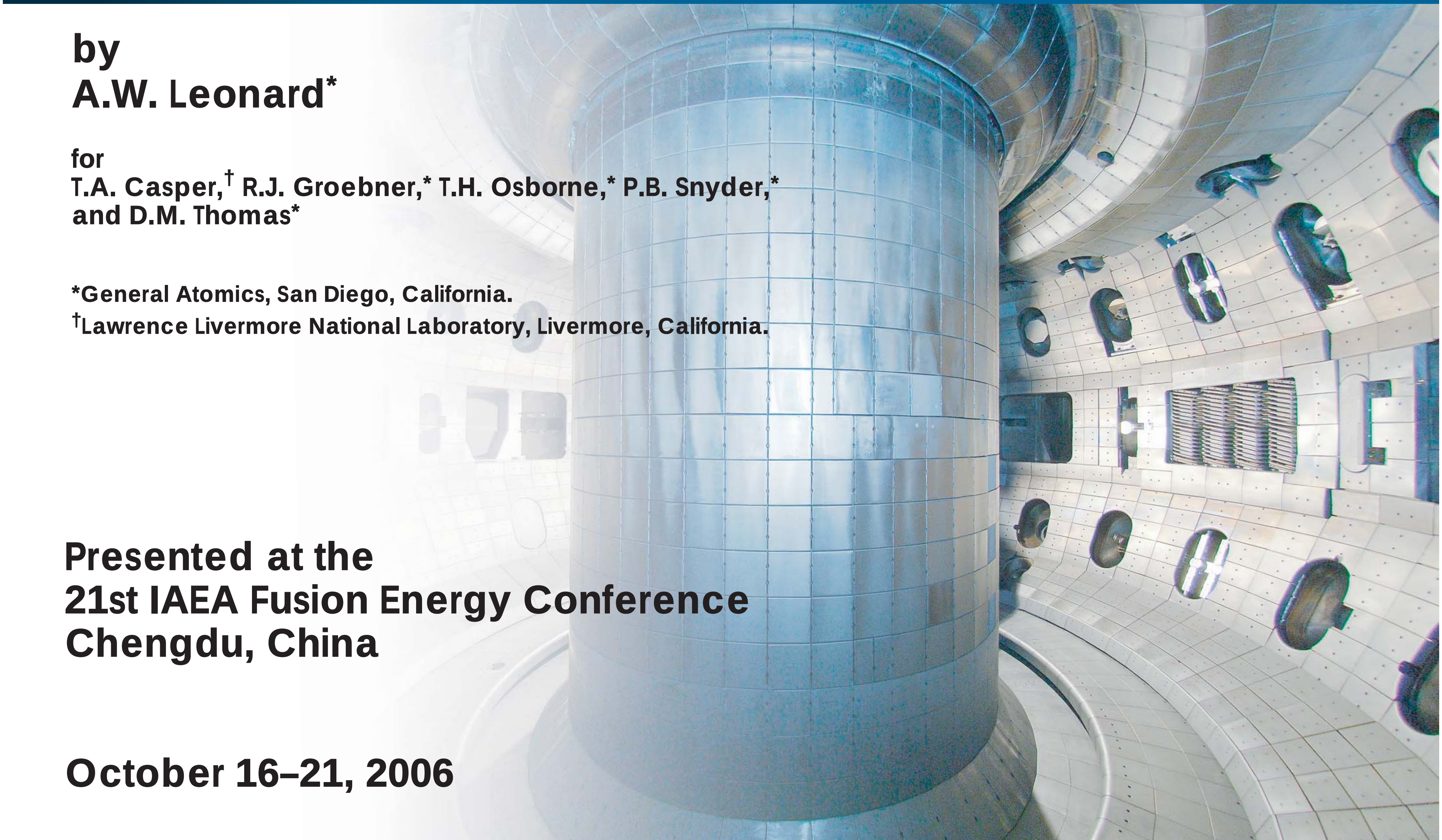
# Pedestal Performance Dependence Upon Plasma Shape



by
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**Presented at the**
**21st IAEA Fusion Energy Conference**
**Chengdu, China**

**October 16–21, 2006**

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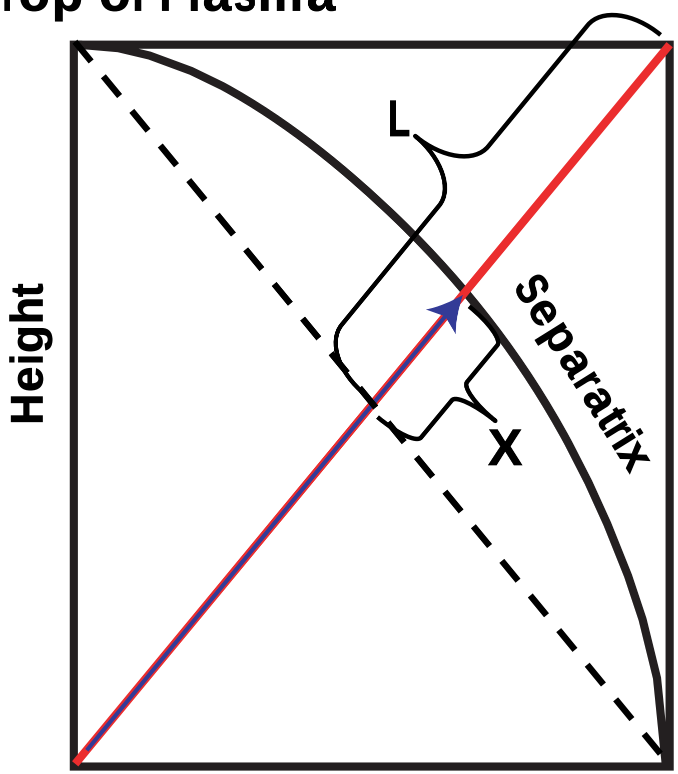
GENERAL ATOMICS

# 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)**
- **Squareness has advantages for controlling pedestal and ELM characteristics**
  - Pedestal and ELMs can be optimized while leaving the divertor configuration unchanged, including recycling, fueling and pumping
  - Optimize operation of existing coil geometry
  - A probe of pedestal transport and ELM dynamics
- **In ITER-like shape pedestal pressure can be increased by 50% by modifying the upper outer squareness**
- **Hybrid discharges utilize squareness to optimize pedestal and ELM characteristics to avoid deleterious NTMs for long pulse operation**
- **Advanced Tokamak discharges achieve higher performance through pedestal optimization**
- **Pedestal width is an important characteristic that is also affected by shape modification**

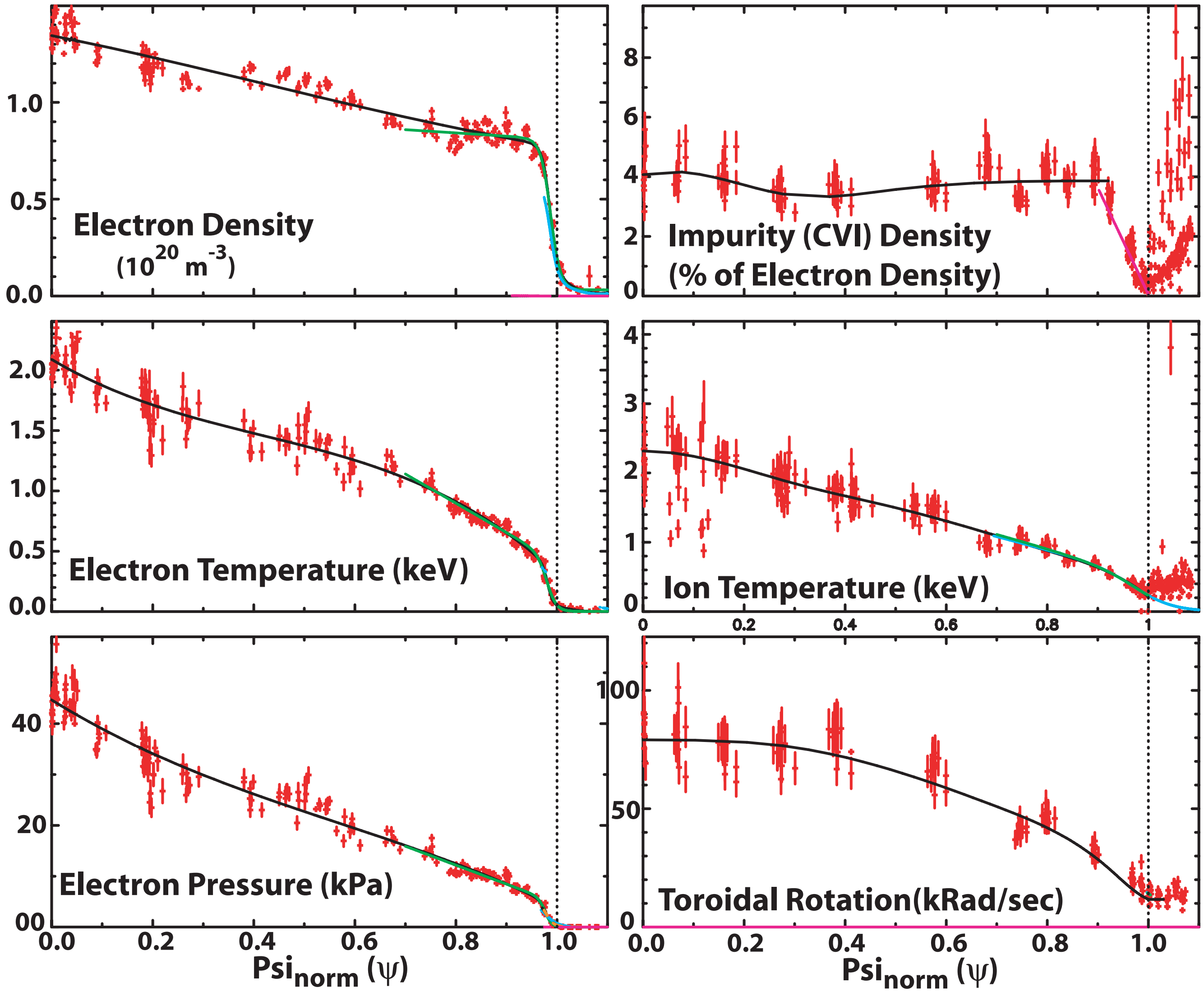
# Squareness is Used to Describe Outboard Plasma Shape




- **Outer upper (lower) quarter of boundary defined by Radial maximum and Vertical maximum (minimum)**
- **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 include integral moments of shape, or average curvature
  - While the stability limit is not inherently dependent on the shape parameters, triangularity, squareness, etc., capture aspects of physically relevant parameters such as average magnetic well depth and magnetic shear

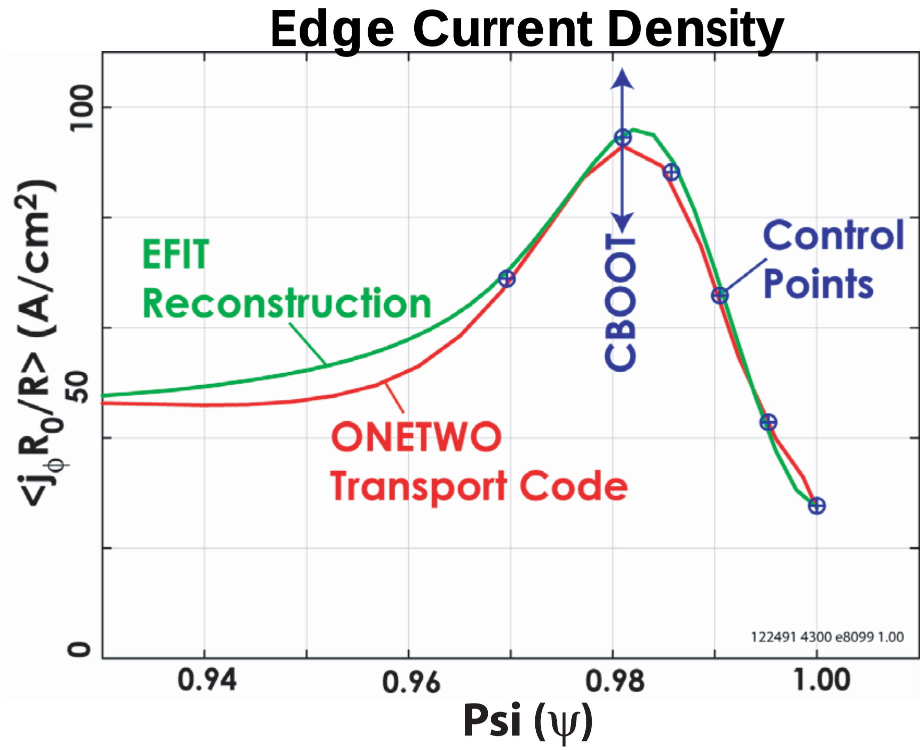
# Pedestal Profiles are Characterized Just Before an ELM for Stability Analysis

**Profiles 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 ($\psi$) with preliminary equilibrium
- Ion temperature and density profiles obtained from CER (CVI)
- Fast Ion pressure calculated by ONETWO analysis
- Total pressure and modeled bootstrap current constrain equilibrium reconstruction
- Profiles can be refit to constrained equilibrium, if warranted

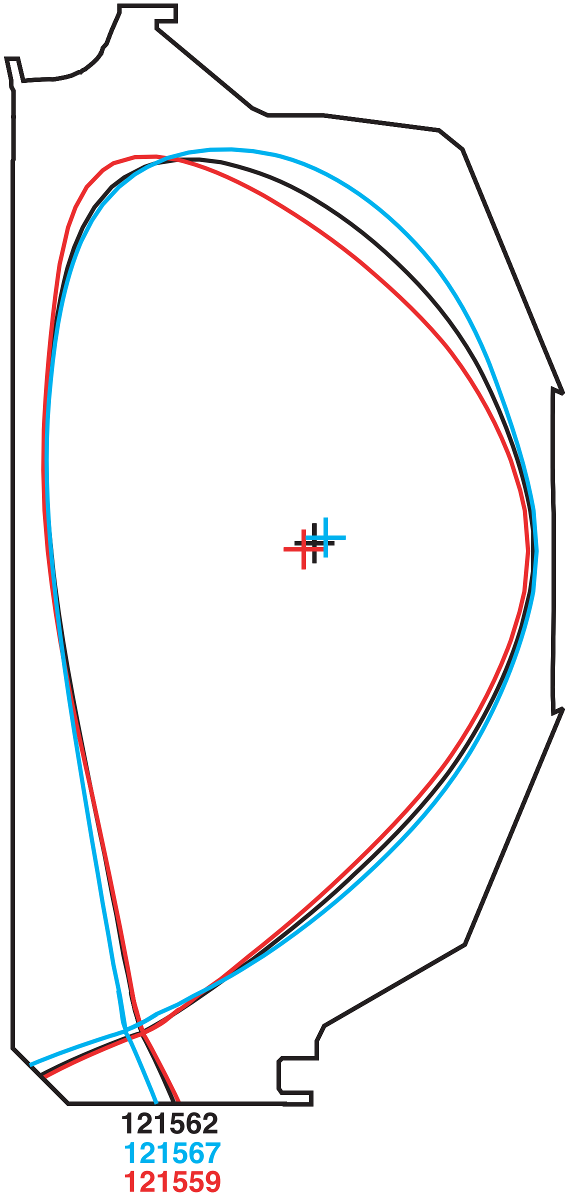
# Equilibrium Constrained by Measured Pressure and Bootstrap Model

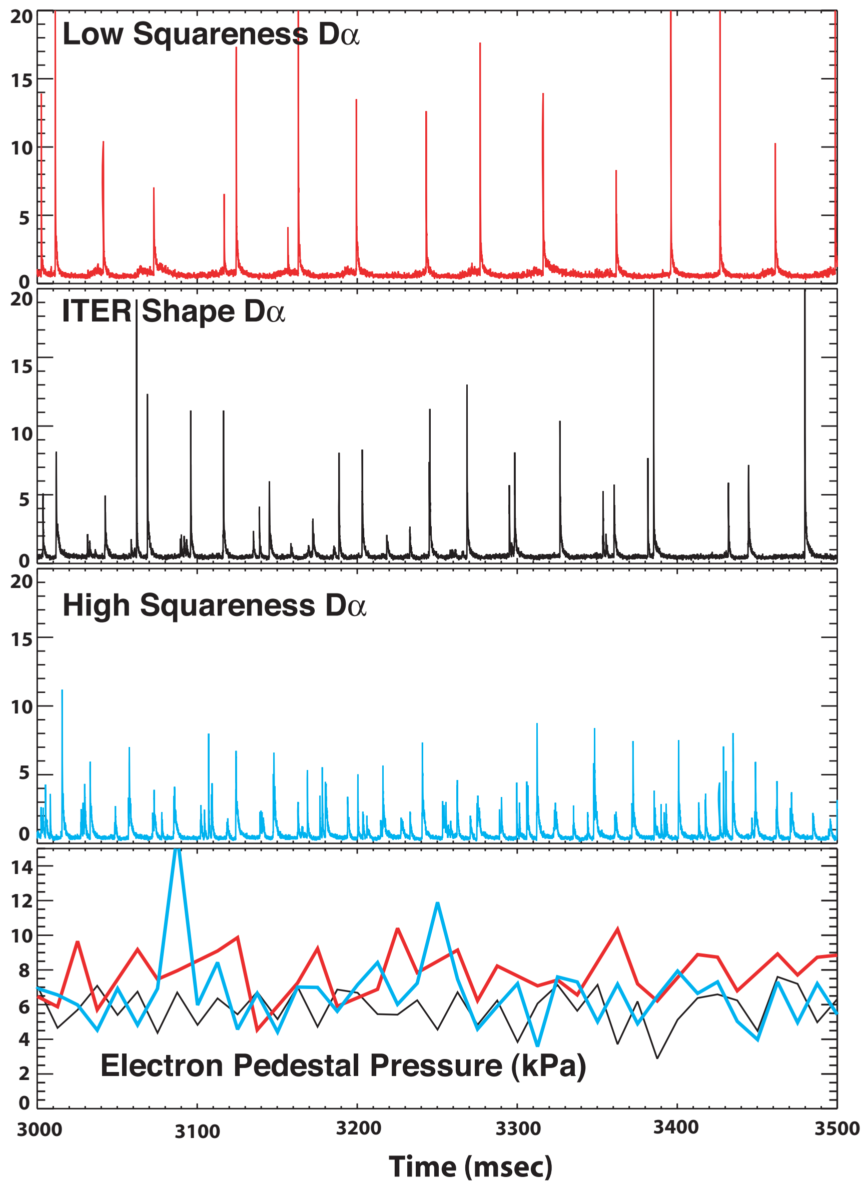



- **Edge current determined from ONETWO transport analysis using Sauter bootstrap model and fully relaxed current profile**
- **Equilibrium reconstruction constrained by measured pressure and modeled edge current**
  - Tight constraint on edge pressure
  - Edge current constrained by modeling while central current fit by magnetics and MSE
- **Sensitivity of edge stability to current and pressure gradients mapped by creating model equilibria about experimental point**
  - Edge pressure ($\psi \geq 0.8$) scaled while keeping total stored energy constant
  - Bootstrap current model applied for each pressure assuming constant collisionality
  - Bootstrap current multiplier scanned for each pressure scaling
  - Growth rate for n=5,10,20,25 and 30 calculated by ELITE for each equilibrium
  - Highest growth rate for each equilibrium is collected

# ITER-Shape Scan

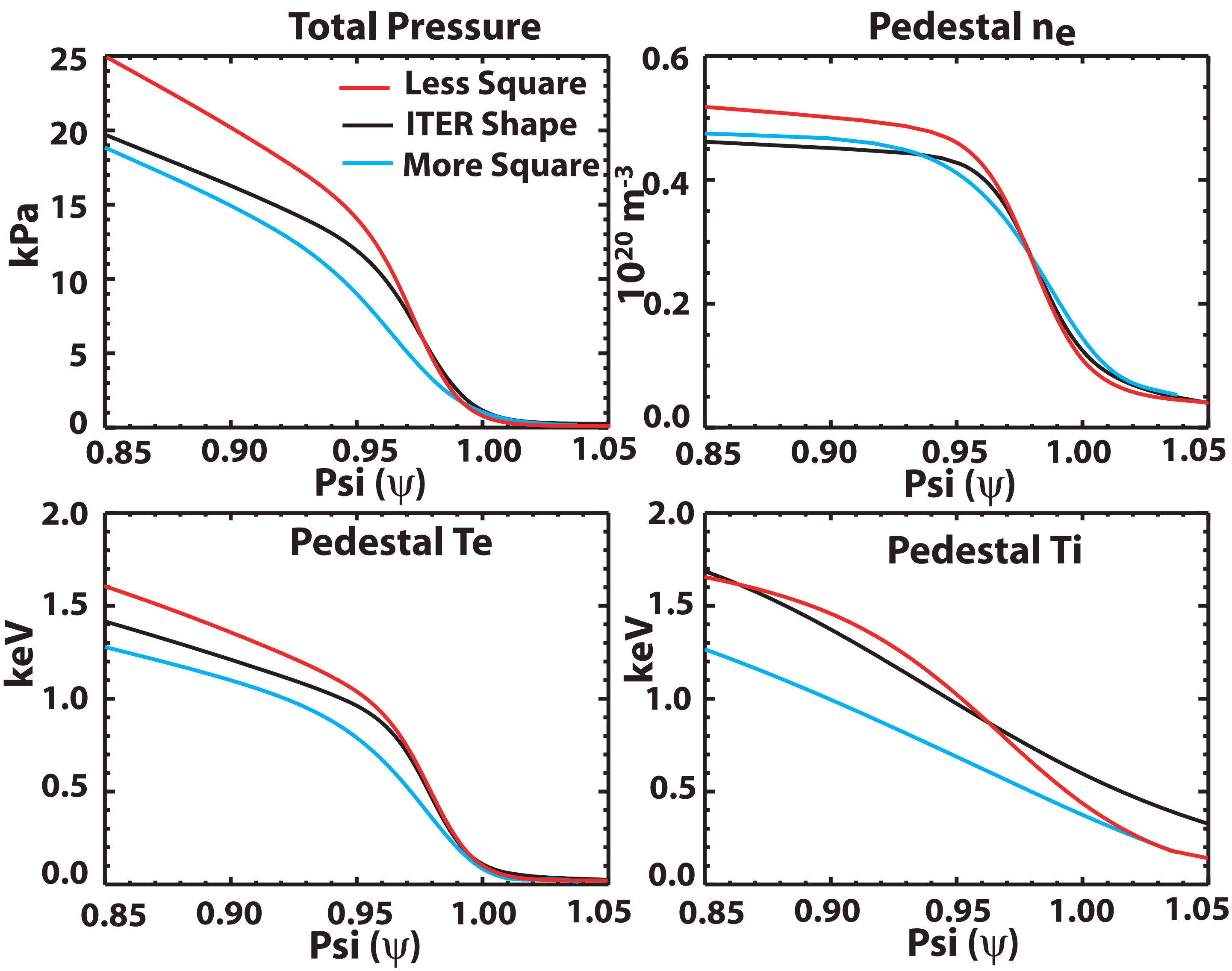
# Upper Outer Squareness Scanned about ITER Shape



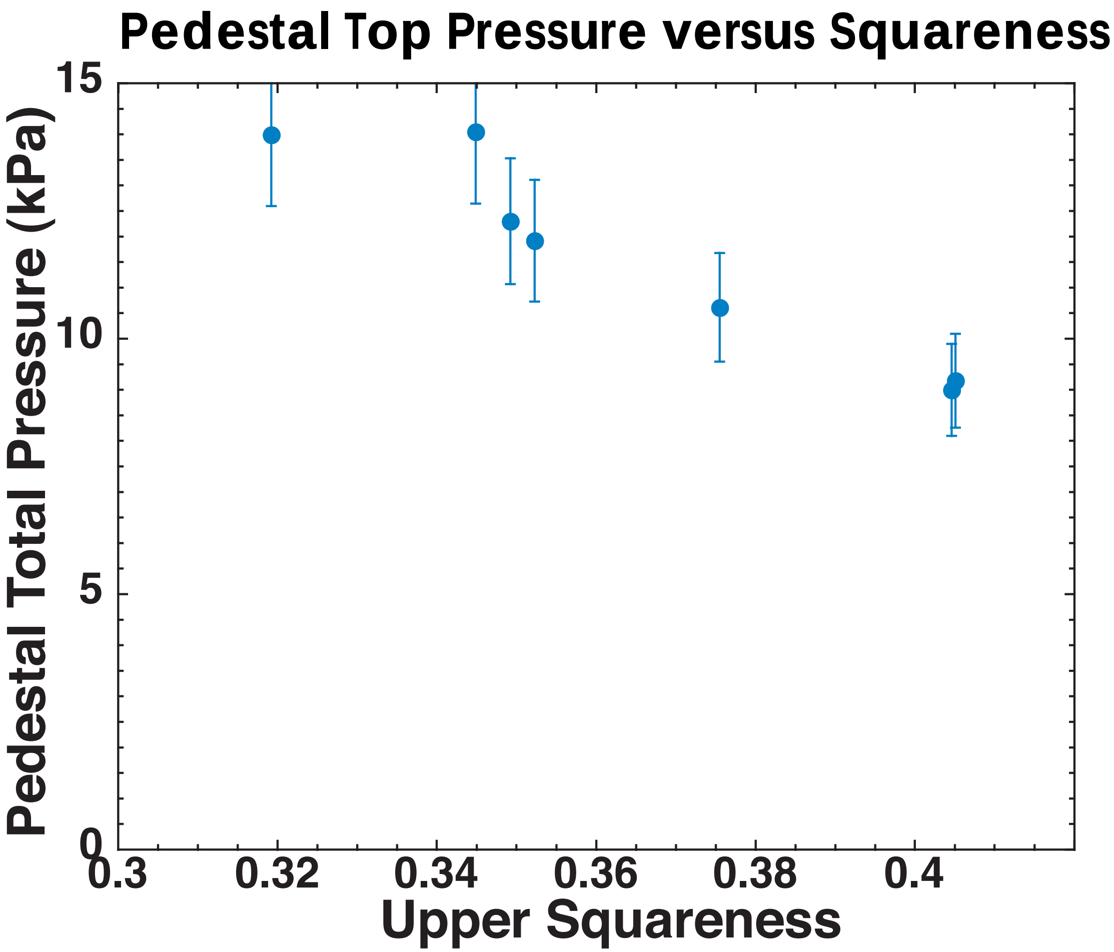

- Upper outer squareness was scanned about ITER shape, with modest changes to average triangularity
- Plasma Current; 1.5 MA, Toroidal field; 1.8 T
- $q_{95}$ ~3.7 somewhat higher than ITER target
- Constant injected power, 6.8 MW
- With increasing squareness ELM frequency increases and pedestal pressure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

# Pedestal Pressure Increases with Lower Squareness




- Pedestal pressure continuously increases with lower squareness
- Pressure increase due mostly to ion and electron temperature
- Total pressure includes fast ions from neutral beam heating, though typically negligible
- Profiles collected from last 20% of ELM cycle for stability analysis

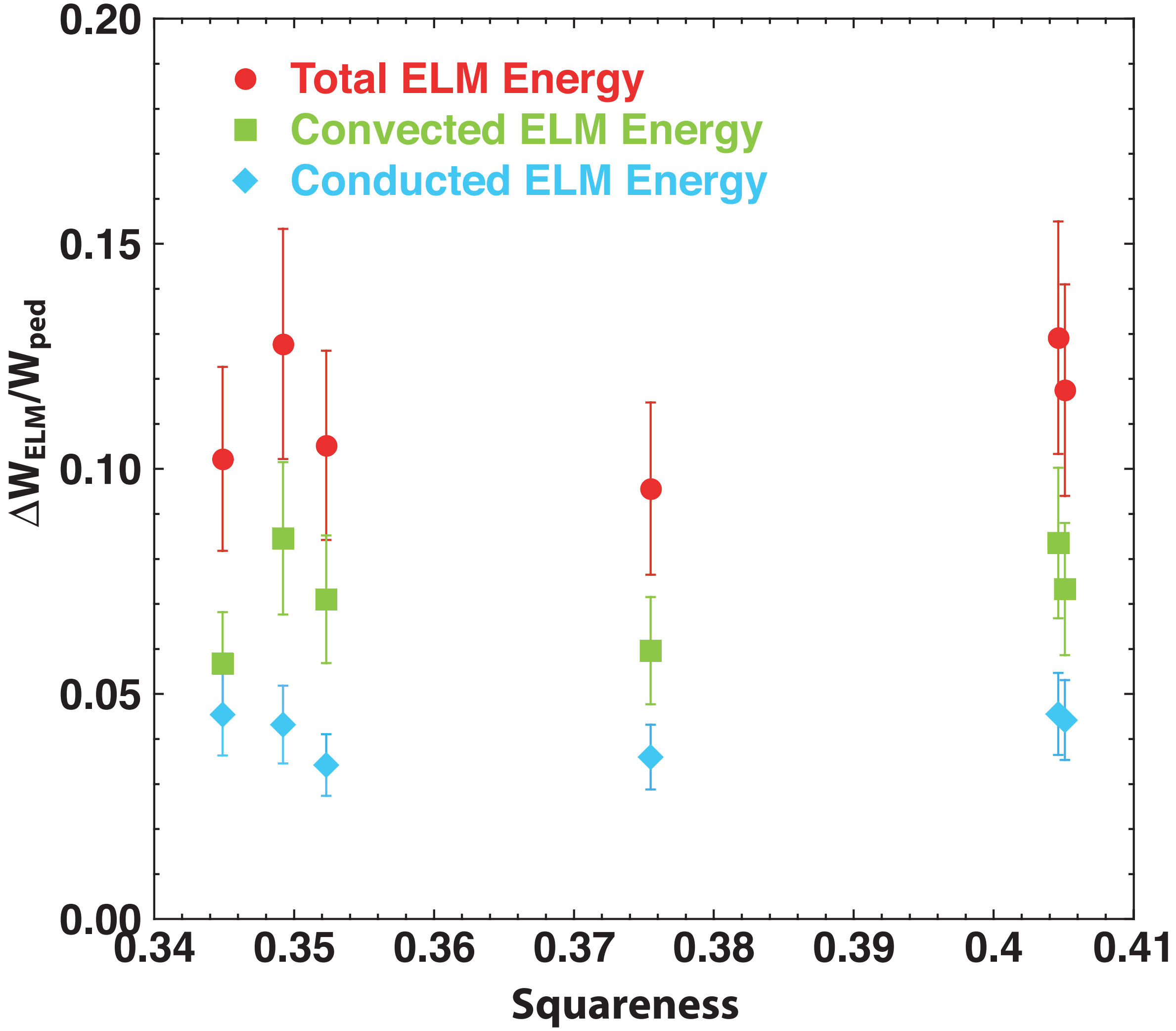
# Pedestal Pressure
# Varies Inversely with Squareness




- **Pedestal pressure increases ~50% from highest to lowest squareness**
- **ELM size decreases and ELM frequency increases with lower pedestal pressure**
- **Modest triangularity increase from <δ>=0.48 to <δ>=0.56 with scan to lower squareness not expected to significantly affect pressure[1]**

**[1] P.B. Snyder, PPCF 2004**

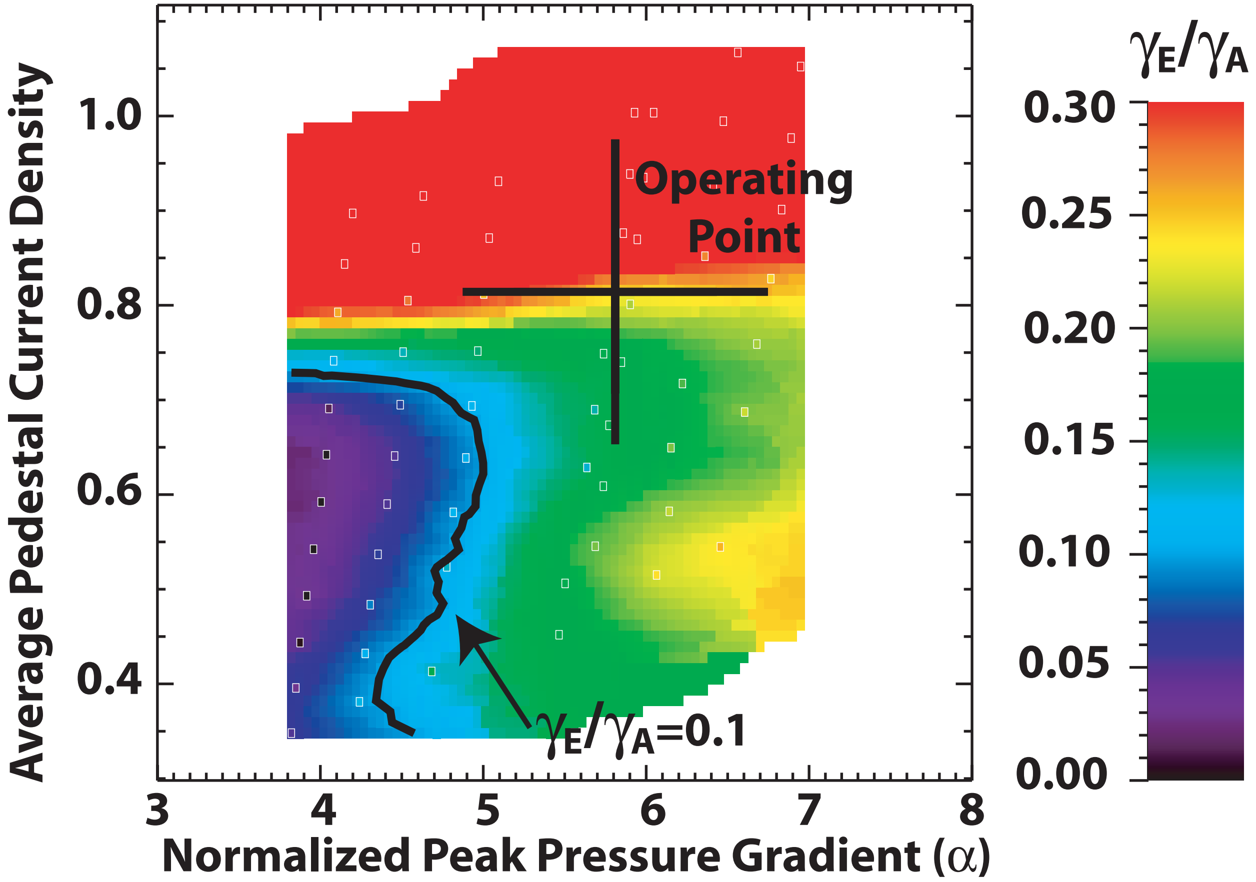
# ELM Size Remains Fixed Fraction of Pedestal Energy




- ELM energy from Thomson scattering analysis
- Convected energy-> Loss of density
- Conducted energy-> Loss of temperature
  - Assumption; $\Delta T_i = \Delta T_e$

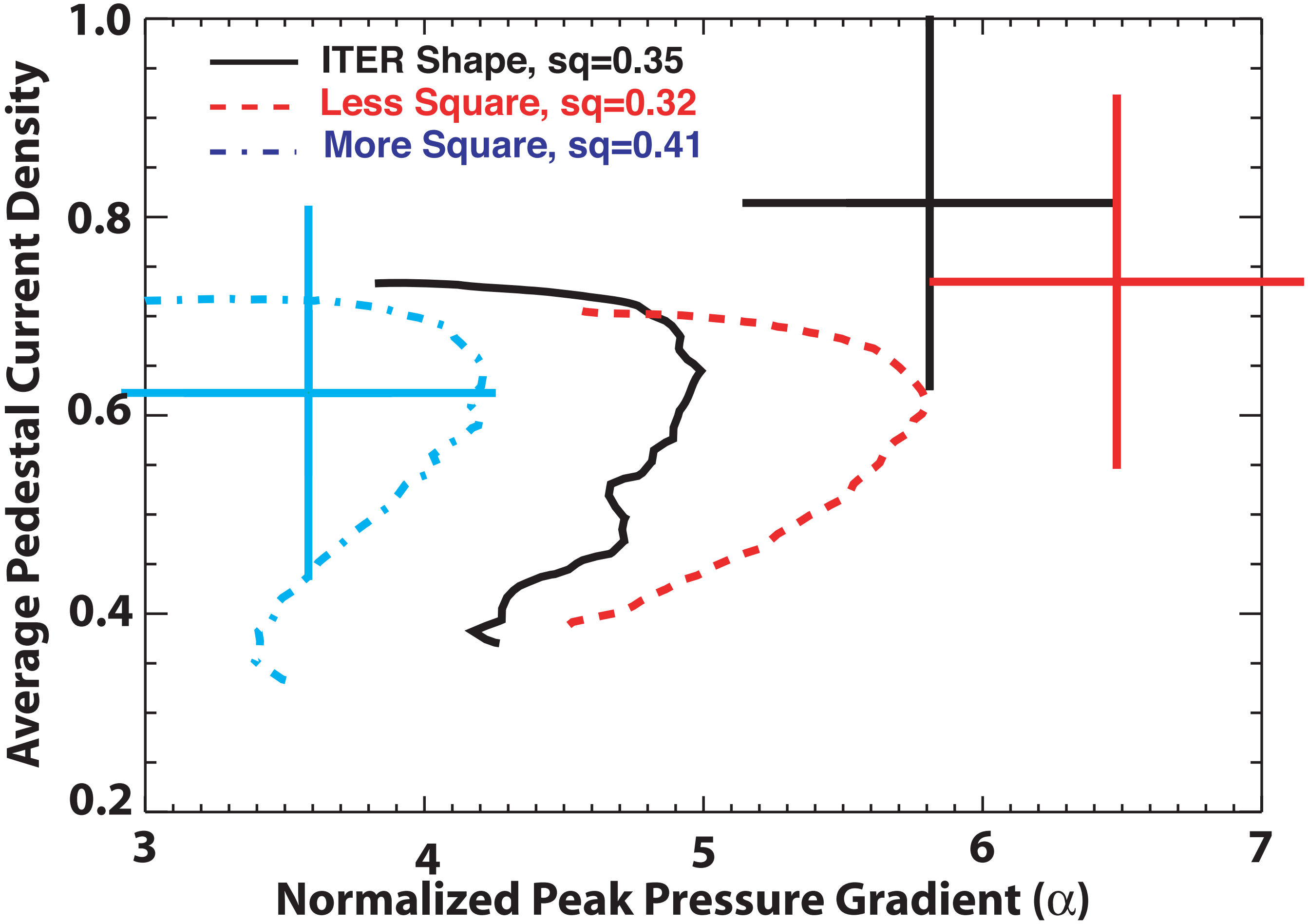
# Stability Analysis of Pedestal Exhibits Pressure and Current Limit

Stability Map for ITER Shape



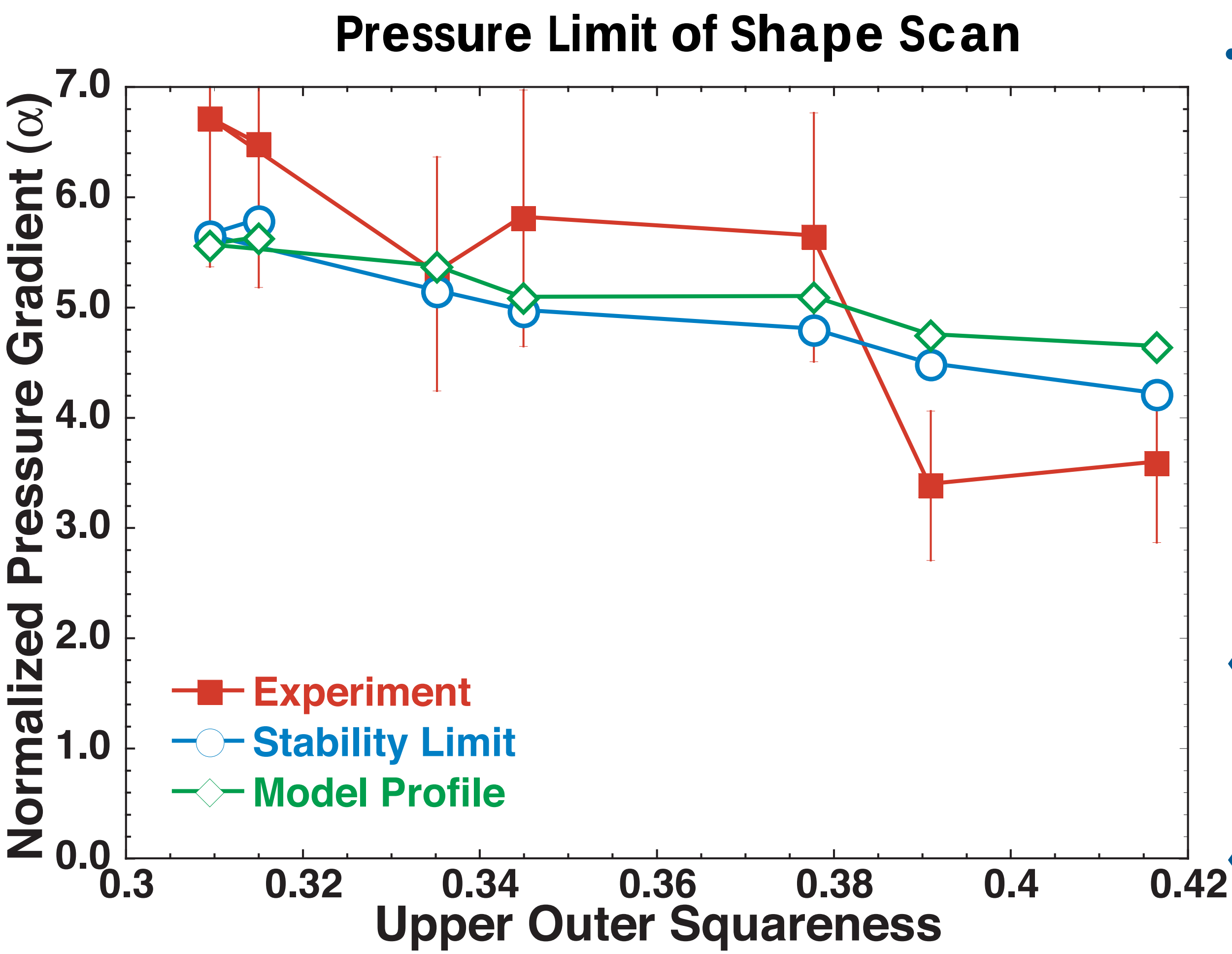

- Stability analysis of equilibria with variations of pedestal pressure and current about experimental point
- Growth rate normalized by Alfven time, $\gamma_A$
- Stability limit roughly $\gamma_E/\gamma_A$=0.1 for these conditions
- Stability map consistent with 20% uncertainty in measured gradient, pedestal total pressure uncertainty is less, ~10%

# Pressure Gradient Stability Limit Increases with Less Squareness



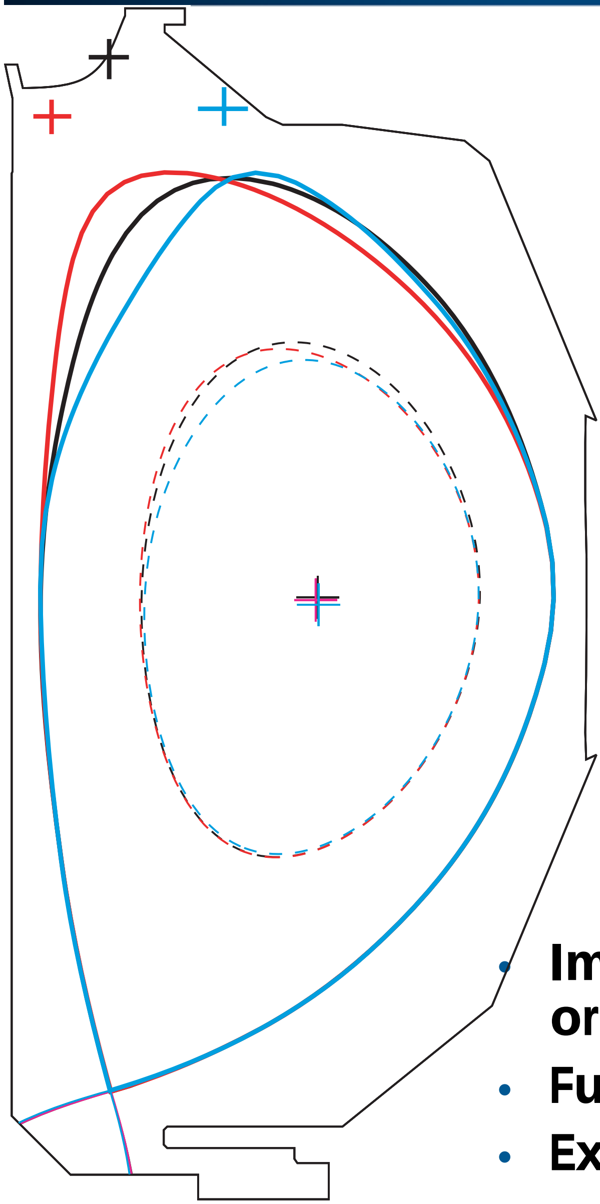

- **Stability analysis indicates maximum stable pressure increases for low squareness similar to observed pedestal total pressure increase**

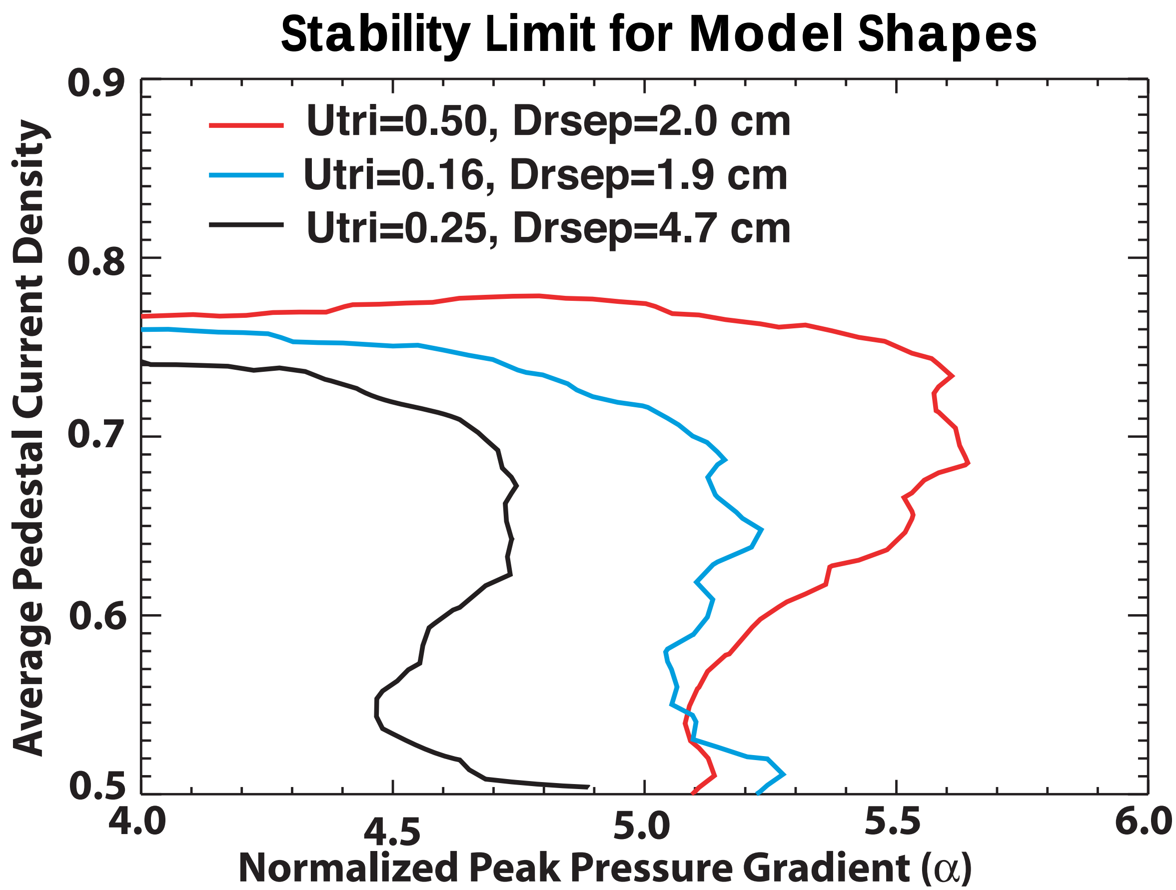
# Pedestal Stability Dependence on Shape Scales Similar to Experiment




- **Pedestal increases with lower squareness;**
  - 50% increase in experimental total pressure
  - 21% increase in pressure gradient stability limit, insensitive to profile details
  - 35% implied increase in width consistent with stability analysis and experimental measurement
- **"Model" pressure limit is stability analysis using fixed pedestal width**
- **Measured pedestal width uncertainty consistent with stability analysis**

# Shape Study Trades Off Triangularity for Squareness

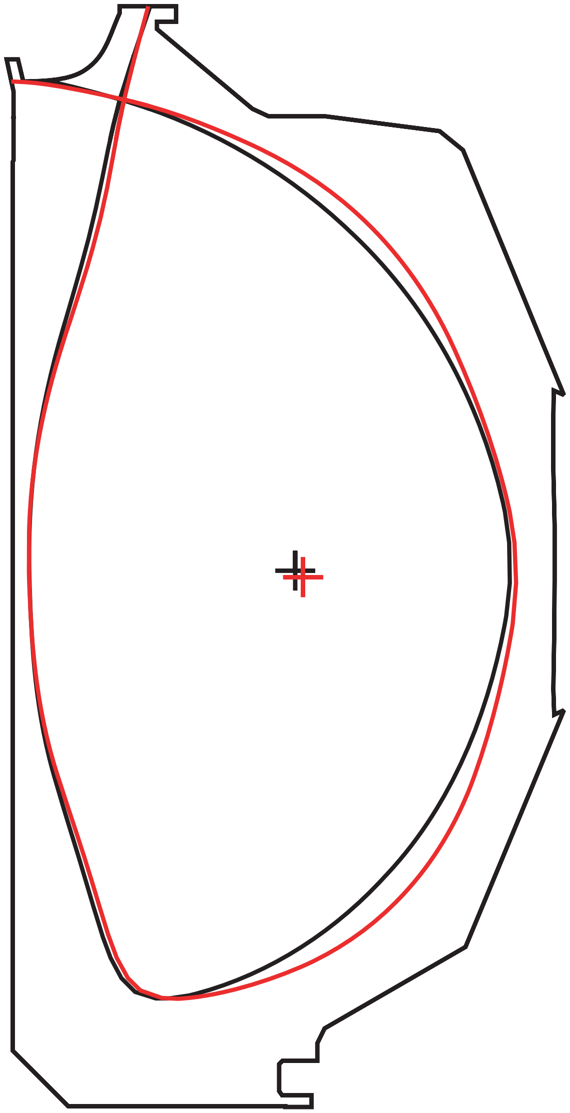


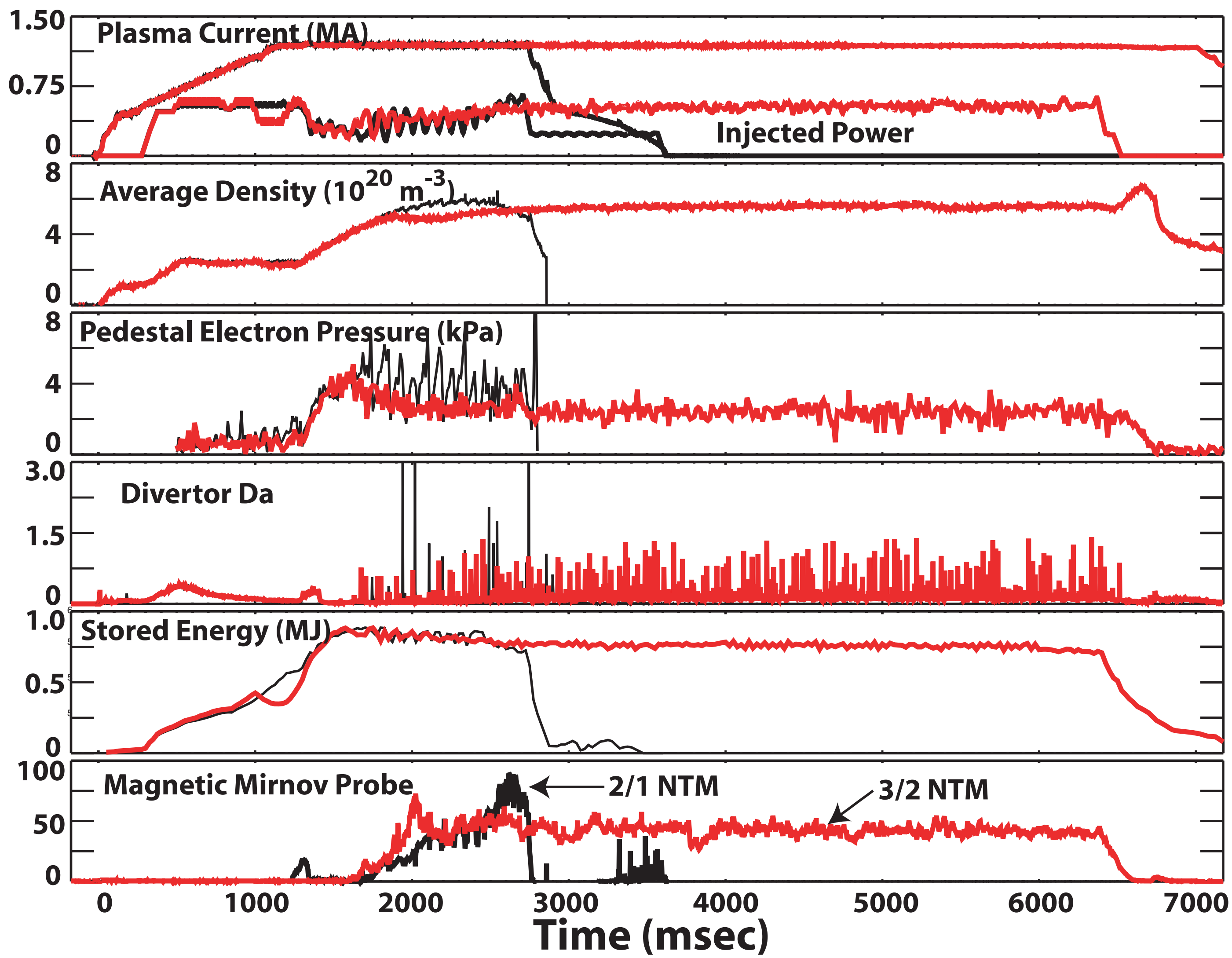



- **Improved stability can be obtained by lower squareness, or a closer secondary separatrix, even at low triangularity**
- **Further optimization at low triangularity is possible**
- **Experimental pedestal profile used for stability analysis**

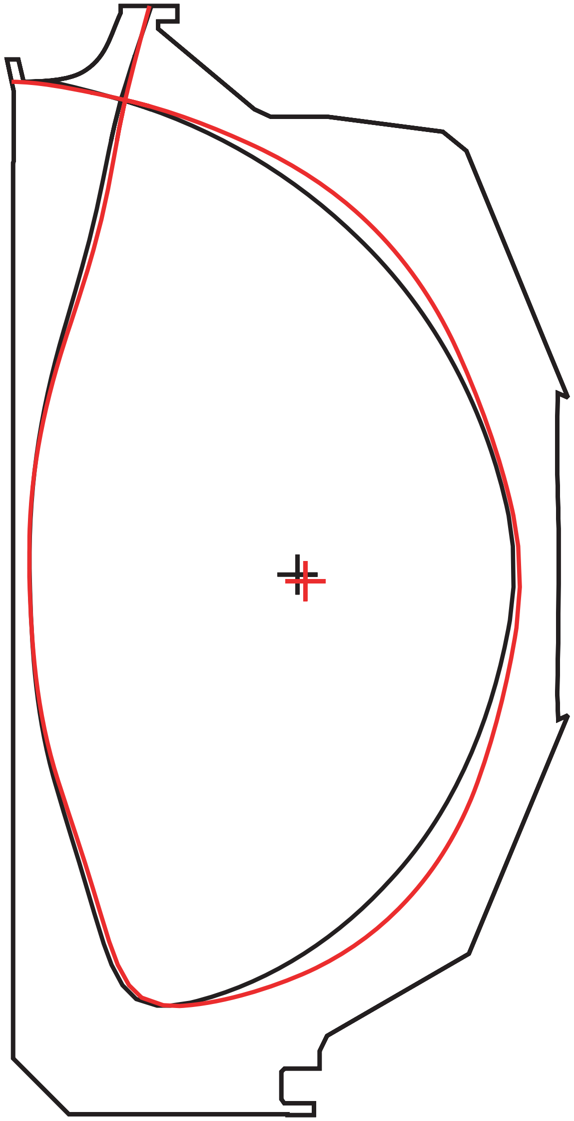
# Hybrid Optimization

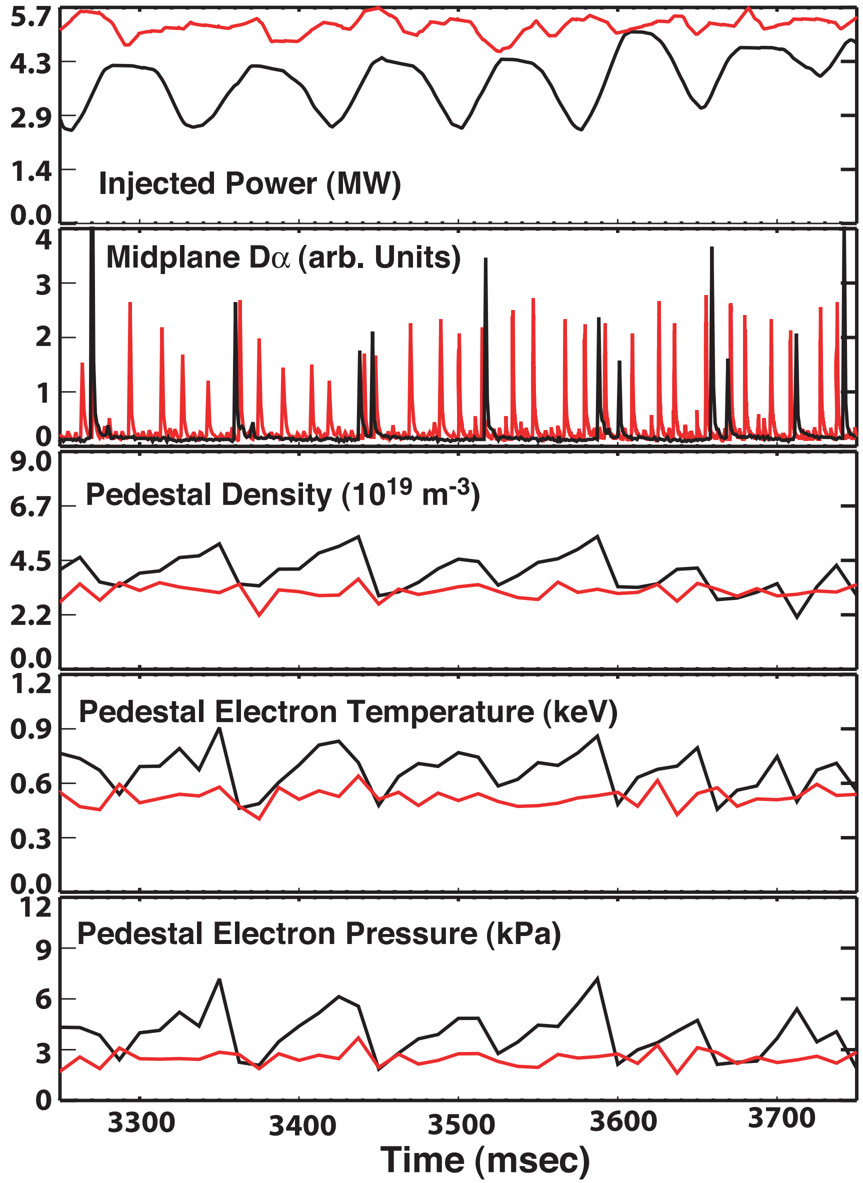
# Hybrid Discharges Optimized at Lower Pedestal, Higher Squareness



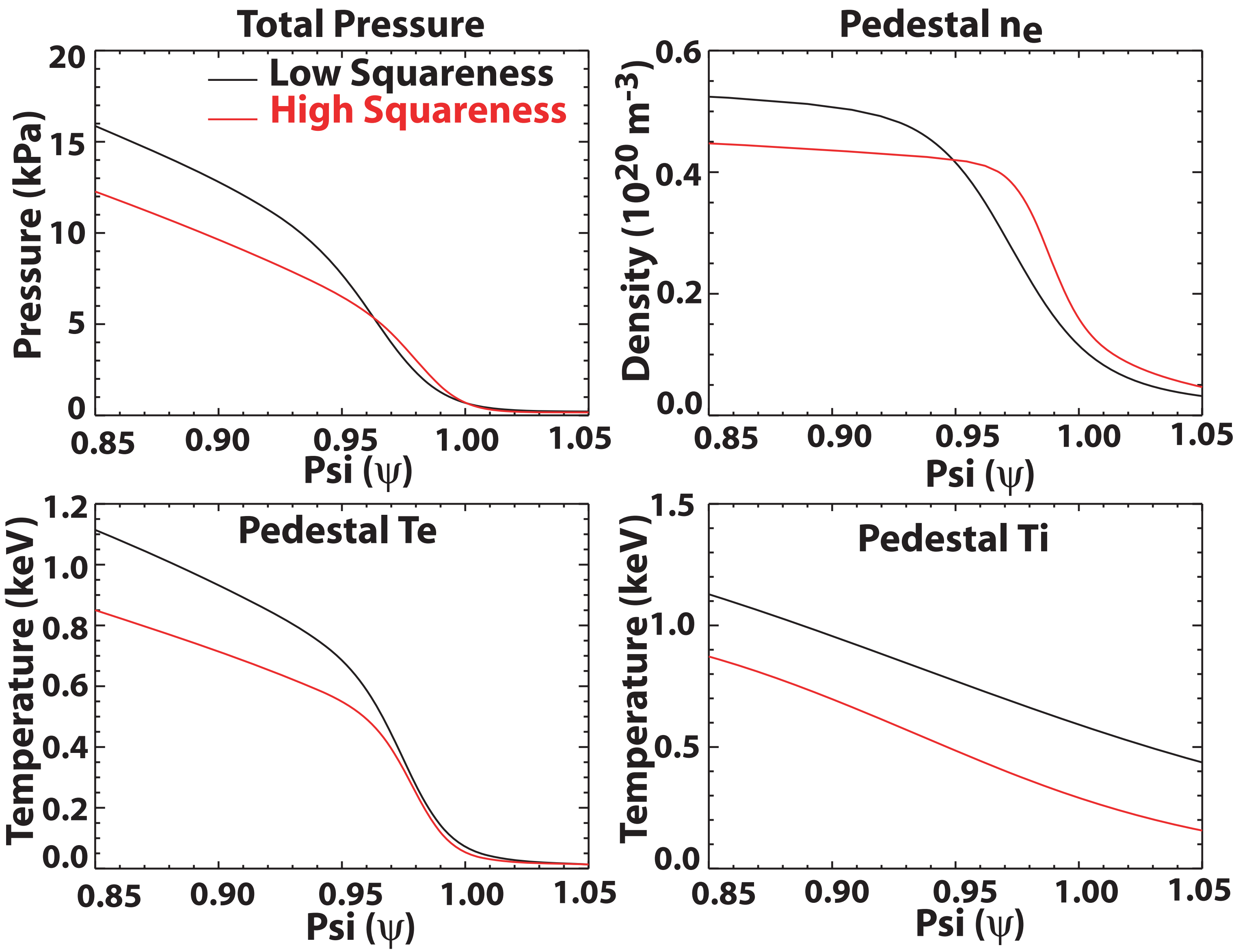
# Lower Squareness Produces Higher Pedestal in Hybrid Discharges



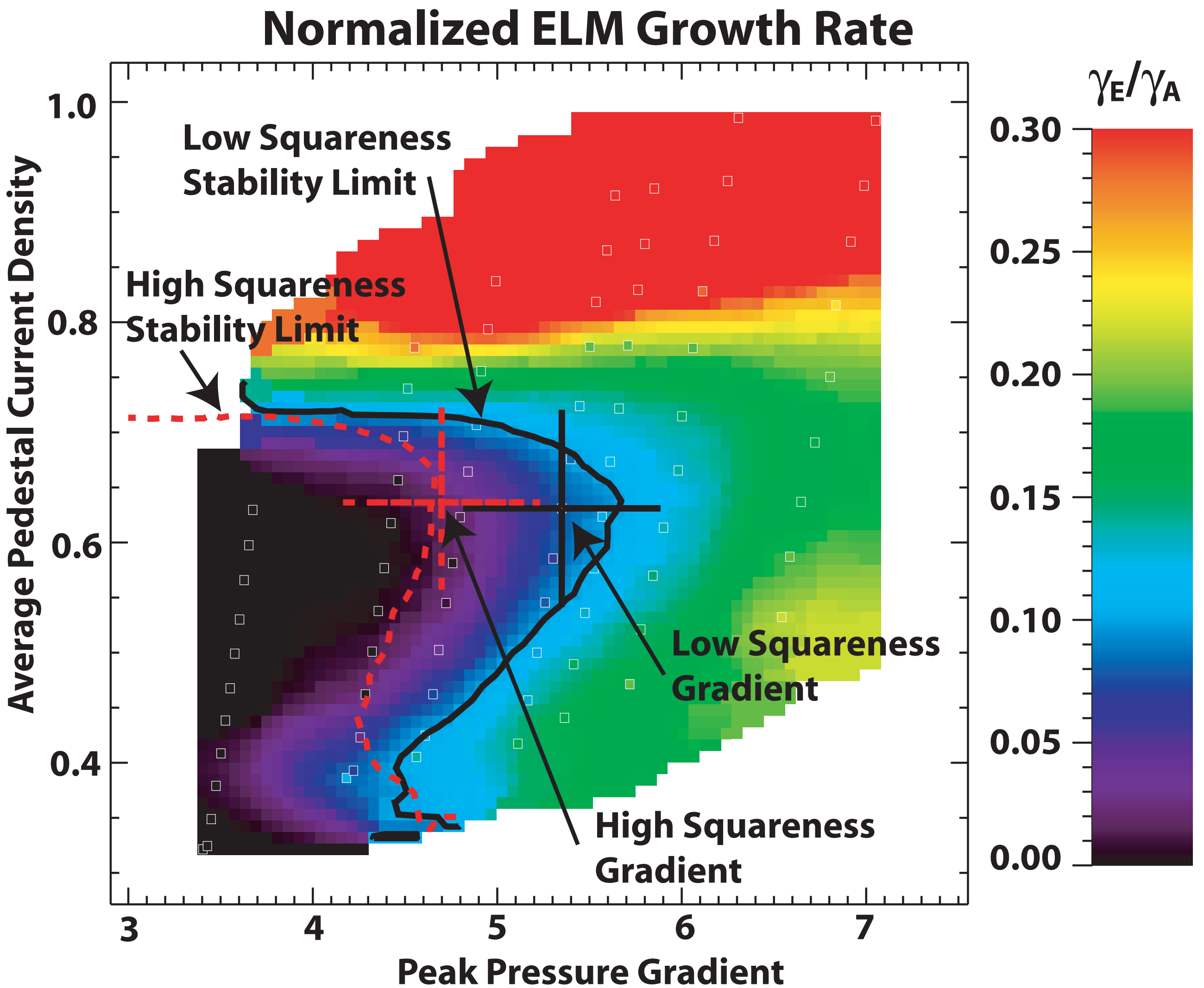

- **Higher pedestal density and temperature leads to higher pressure at low squareness**
- **Lower power at low squareness was unable to avoid eventual 2/1 NTM and disruption**
- **Both discharges; 1.2 MA, and 1.25 T**
- **Same average triangularity, <δ>~0.5**

# Higher Pedestal Pressure at Lower Squareness




- **Pedestal pressure increases ~70% at low squareness**
- **Higher electron and ion temperature with lower input power**
- **Wider $n_e$ and $T_e$ profiles at low squareness**

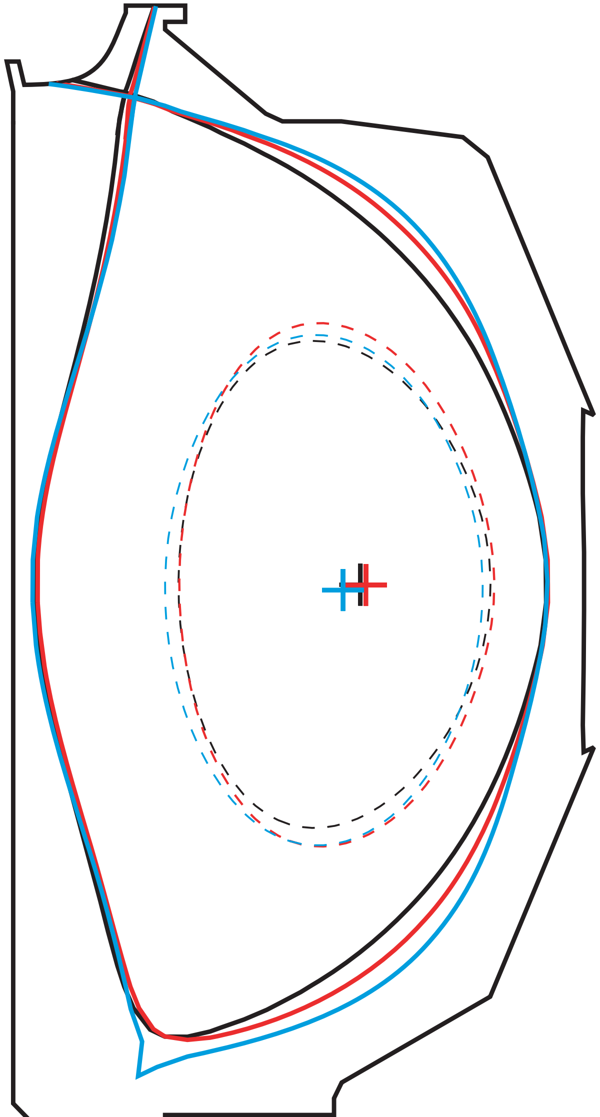
# Hybrid Pedestal Increases due to Stability Limit and Width

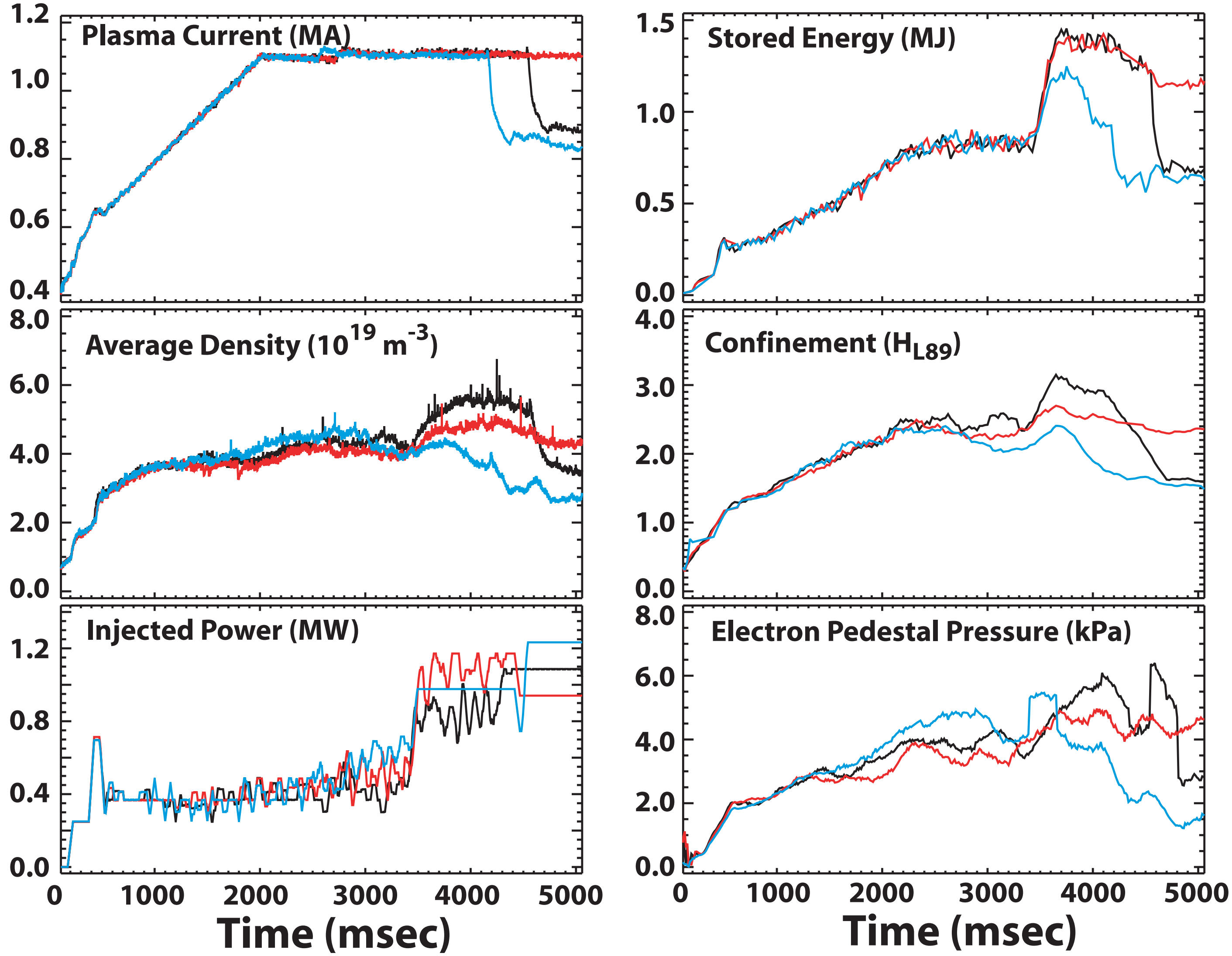



- **Increase in measured gradient similar to change in stability limit**
- **Pedestal total pressure increase ~70%**
- **Stability gradient limit increase ~25%**
- **Implied pedestal width increase ~35%**

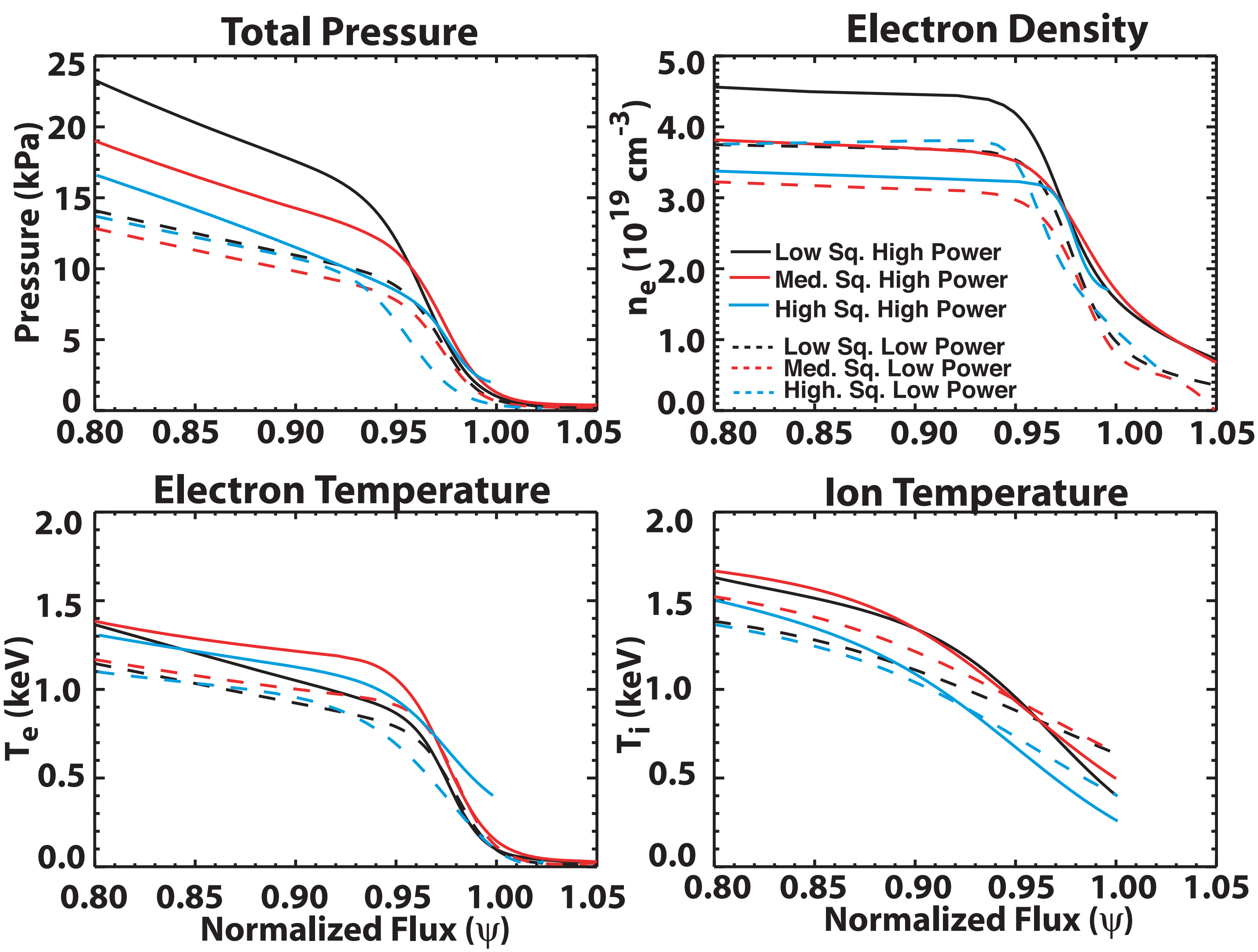
# Advanced Tokamak Optimization

# AT Discharge Improved Performance at Lower Squareness



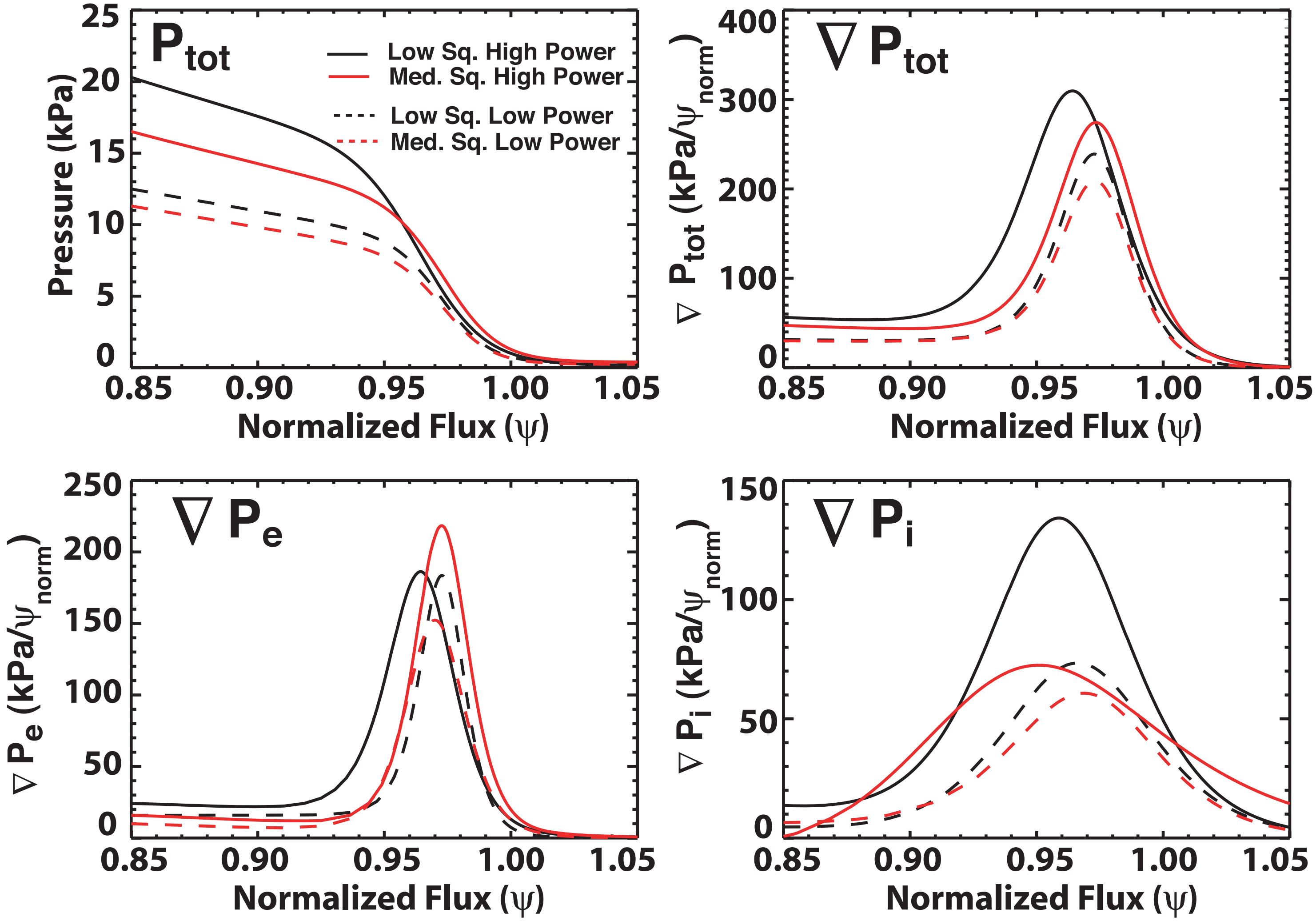



# Pedestal Pressure Increases with Lower Squareness at High Power




- **<u>Low Power Phase:</u>**
  - Pedestal pressure does not change significantly with shape
- **<u>High Power Phase:</u>**
  - Pedestal pressure increases with power.
  - Greater increase at lower squareness.
  - Both density and temperature increase
- **Profiles collected from last 20% of ELM cycle for stability analysis**

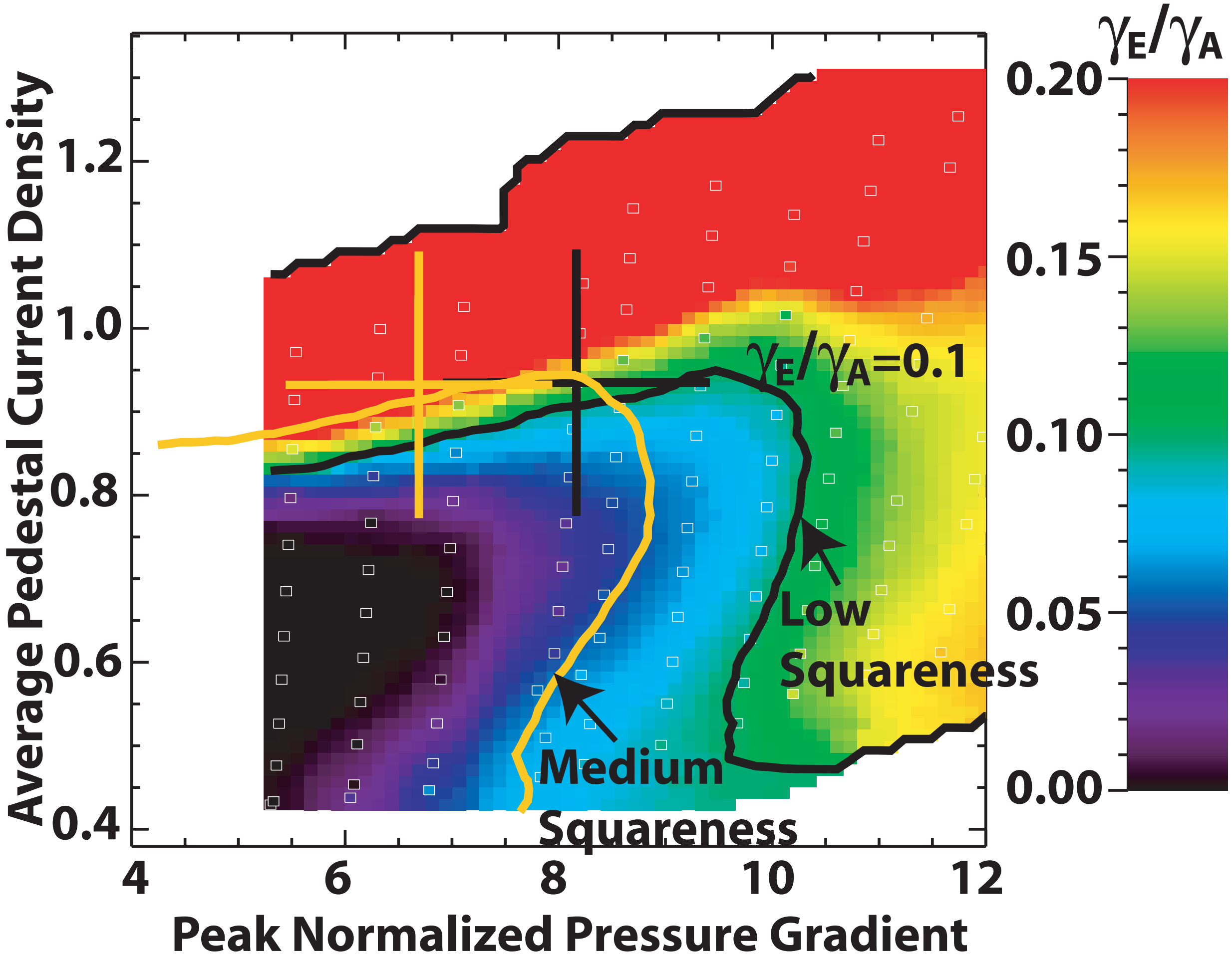
# Both Gradients and Widths Increase with Power




- Increase in ion pressure accounts for larger part of pedestal increase
- Ion pressure much wider than electron pressure
- Pedestal width increase largest for low squareness
- Pedestal height most accurate, some trade-off between measured gradient and width is possible

# Stability Map for Lower Squareness and Low Power

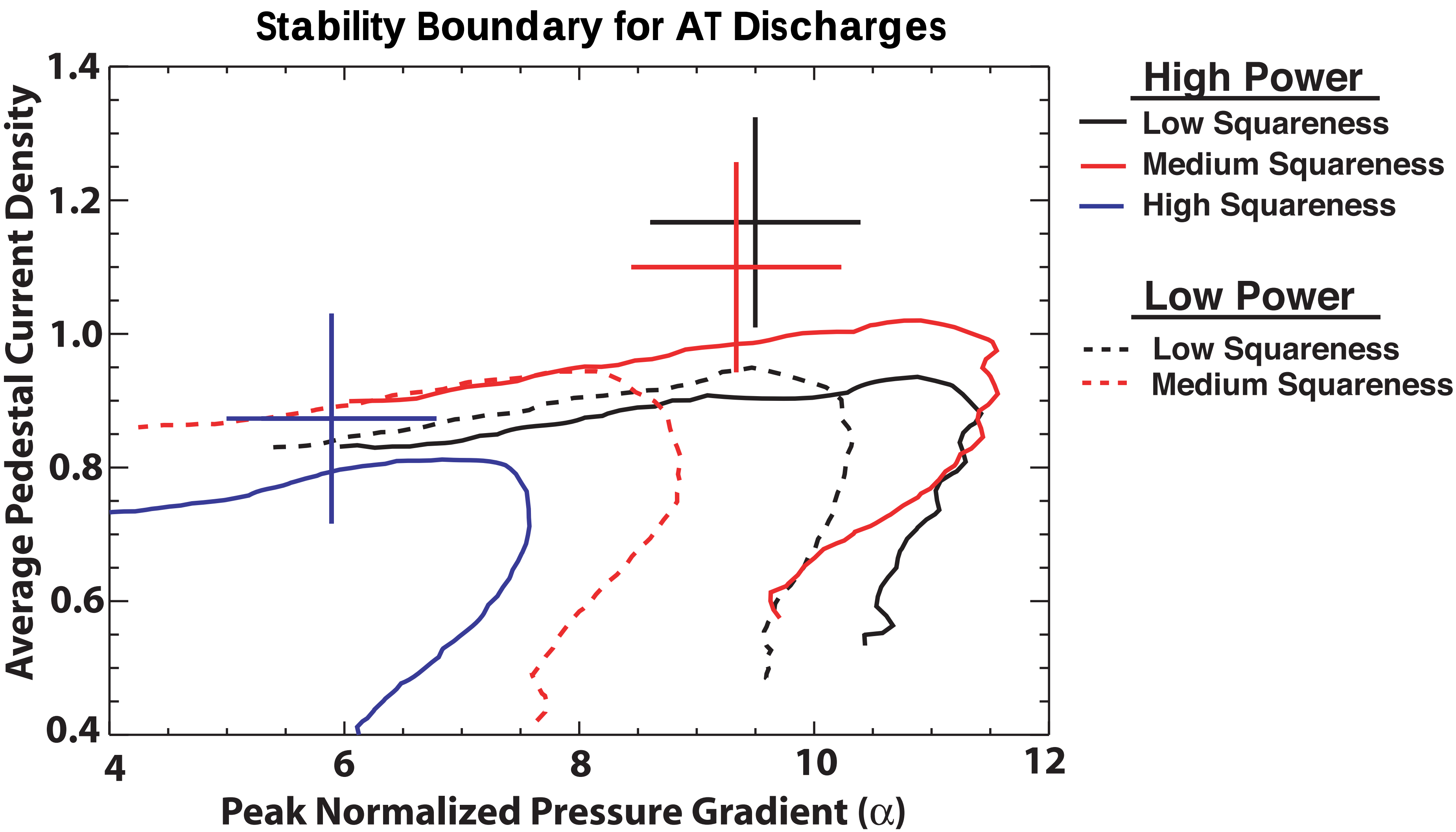
Stability Limit for Low and Medium Squareness at Low Power




## Low Power

- Experimental point at current limit, but still within uncertainty of pressure limit
- Measured gradient increases at low squareness similar to pressure gradient limit
- High normalized pressure limit for AT shape, $\alpha$~10, compared to ITER shape, $\alpha$~5
- Pressure limit has high sensitivity to details; shape, $\beta_p$, pedestal width

# Pressure Stability Limit Increases At High Power



# Pedestal Stability Consistent with Increased Pressure in AT Discharges

- **Stability limit increases with power as higher $\beta_p$ adds stabilizing poloidal field to outboard bad curvature side**
  - Low squareness increase; Total Pressure 75%, gradient 15%, width 50%
  - Medium squareness increase; Total Pressure 50%, gradient 40%, width 10%
  - Total pressure is more accurate, some tradeoff between gradient and width is possible
- **Operating point at current limit, but also within measurement uncertainty of pressure limit**
- **Pedestal height increases more than expected from shape change with fixed pedestal profile**
  - Low and high squareness have similar gradients at high power, but low squareness has 30% higher pedestal and width
  - Stability gradient limit should be ~10% greater for low squareness compared to medium squareness for the same pedestal width
  - For constant shape, total pressure scales ~ $width^{0.7}$ [Snyder, PPCF 2004]

# Summary

- Higher moments of the shape, such as squareness, can optimize pedestal performance
- Significant pedestal modification can be achieved with fixed divertor geometry
- Highest pedestal pressure is not always optimum. Hybrid operation is optimized at a reduced pedestal
- Pedestal pressure limit in advanced tokamak regimes is very high due to shaping, high $\beta_p$ stabilization and wider pedestals
- An increase in pedestal stability limit can be leveraged to even higher pressure for increased pedestal width

# Future Work

- **Shaping study of ITER's coil geometry to expand pedestal operational space**
- **Use model shapes and profiles to separate effects**
  - Shape
  - High $\beta_p$ stabilization
  - Pedestal profile shape
  - Edge current
- **Examine pedestal profile time dependence**
  - If pedestal width grows in time between ELMs then the pedestal height may greatly benefit from a modest increase in gradient stability limit