Influence of Beta, Shape and Rotation on the H-mode Pedestal Height

by

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with

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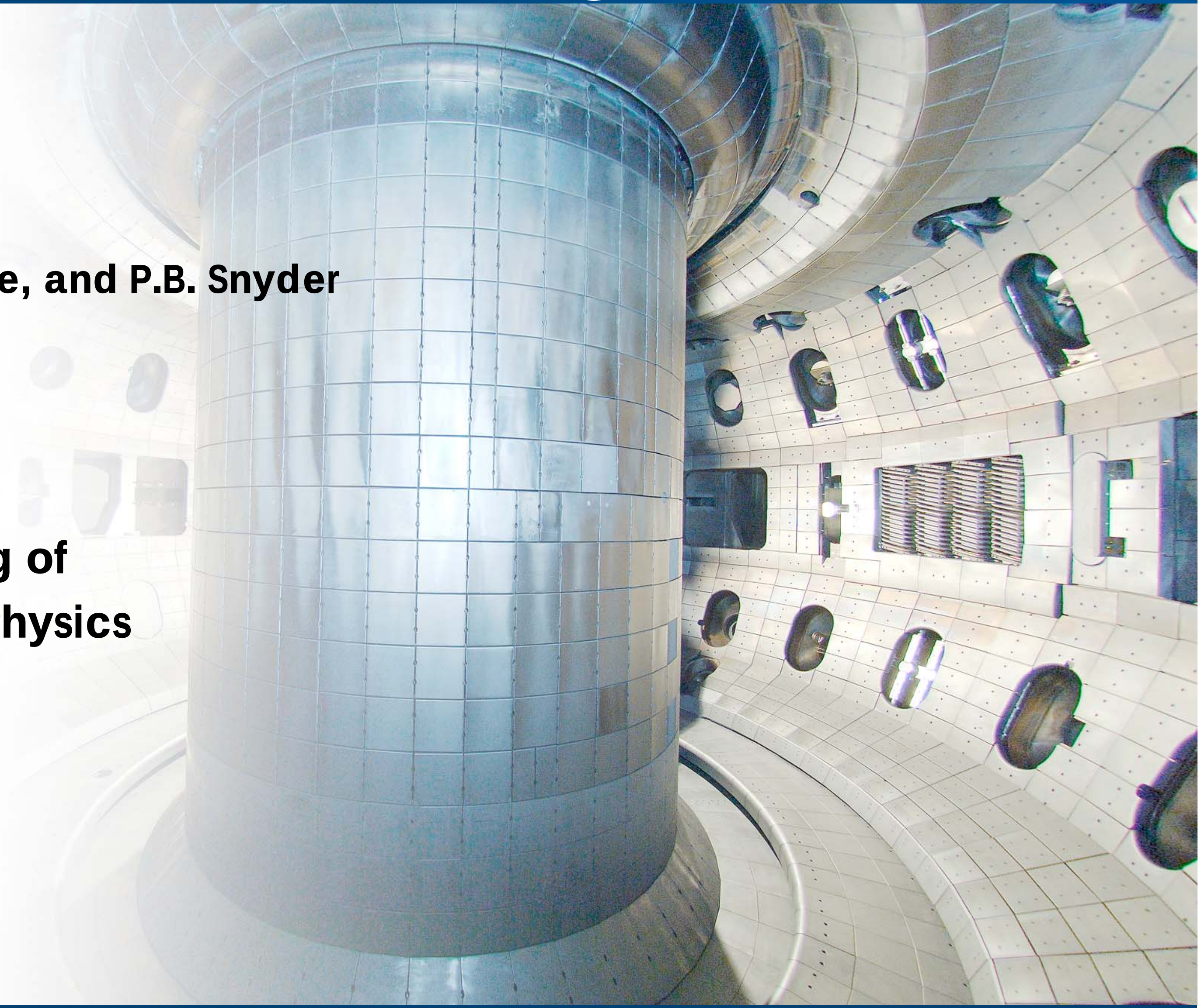

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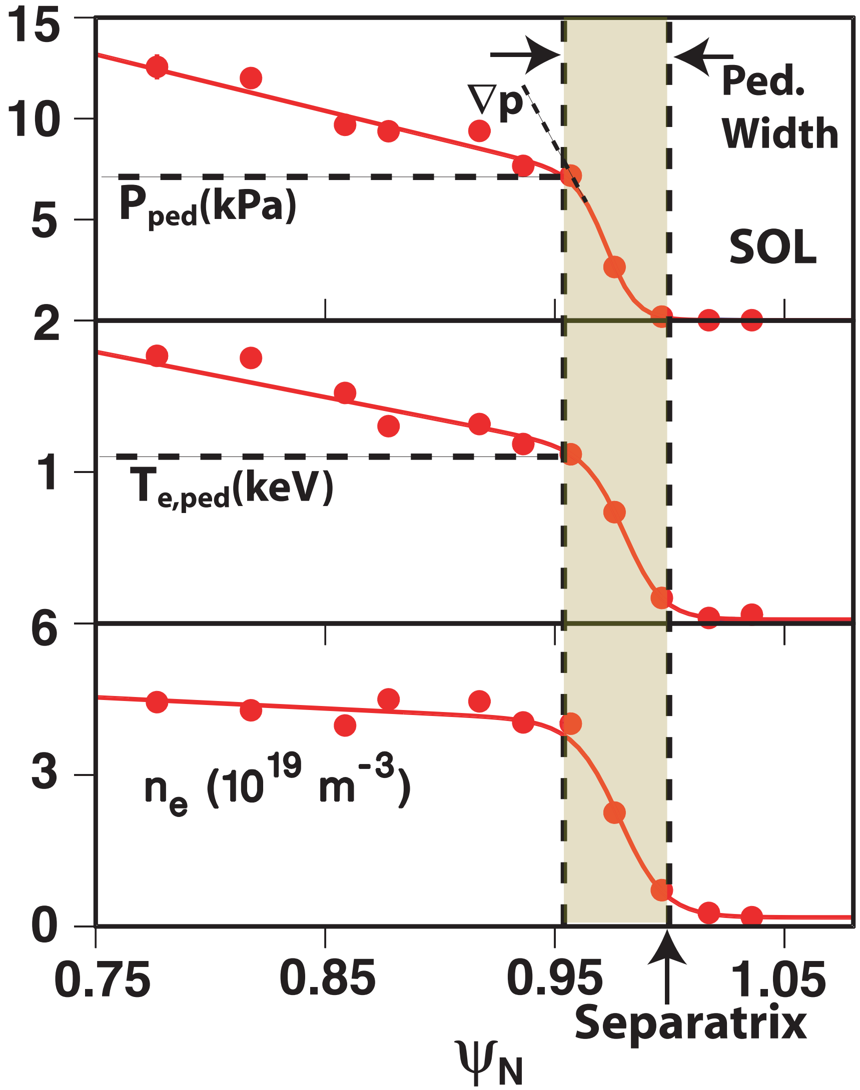
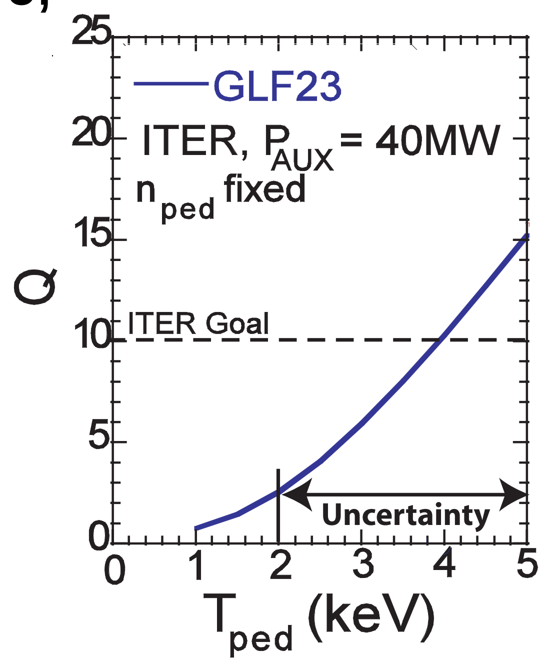
Pedestal Height is Greatest Uncertainty in Predicting Tokamak Performance



- Pedestal sets boundary condition for core transport
- For stiff transport, core profiles strongly dependent on pedestal
- Pedestal uncertainty for ITER corresponds to a wide range of performance; **Q=2-15**

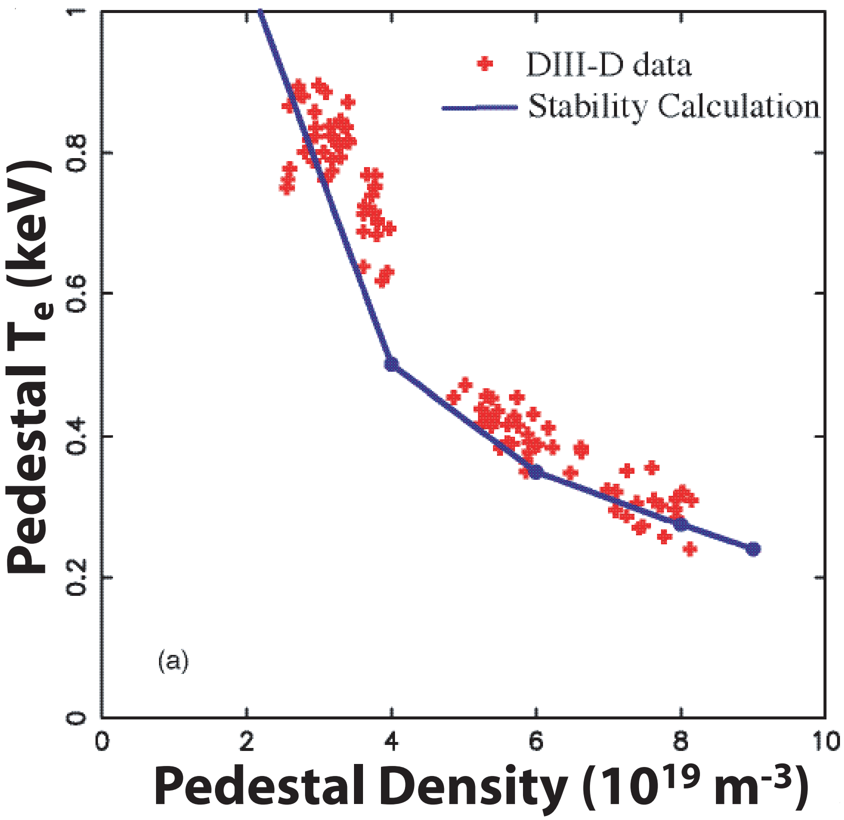


Pedestal Width is key to Pedestal Height Scaling

- **Validated edge stability model can predict pedestal top pressure if width is known**
- **Pedestal pressure height increases with improved edge stability**
  - Pedestal pressure increase with global β and stronger shaping
  - No change with toroidal rotation
- **Stability model utilized to extract pedestal width**
  - Greater accuracy than directly measured width
  - Pedestal width increases with higher pedestal pressure
  - Pedestal pressure rise double expected from stability with fixed width
- **Pedestal models predict an ion gyro-radius, ρ^*, width scaling, yet**
  - Width correlated with pressure ($\Delta \propto \beta_{ped}^{1/2}$)
  - No T_i (ρ^*) dependence

Validated MHD Stability Model a Tool for Extracting Pedestal Width from Pedestal Pressure

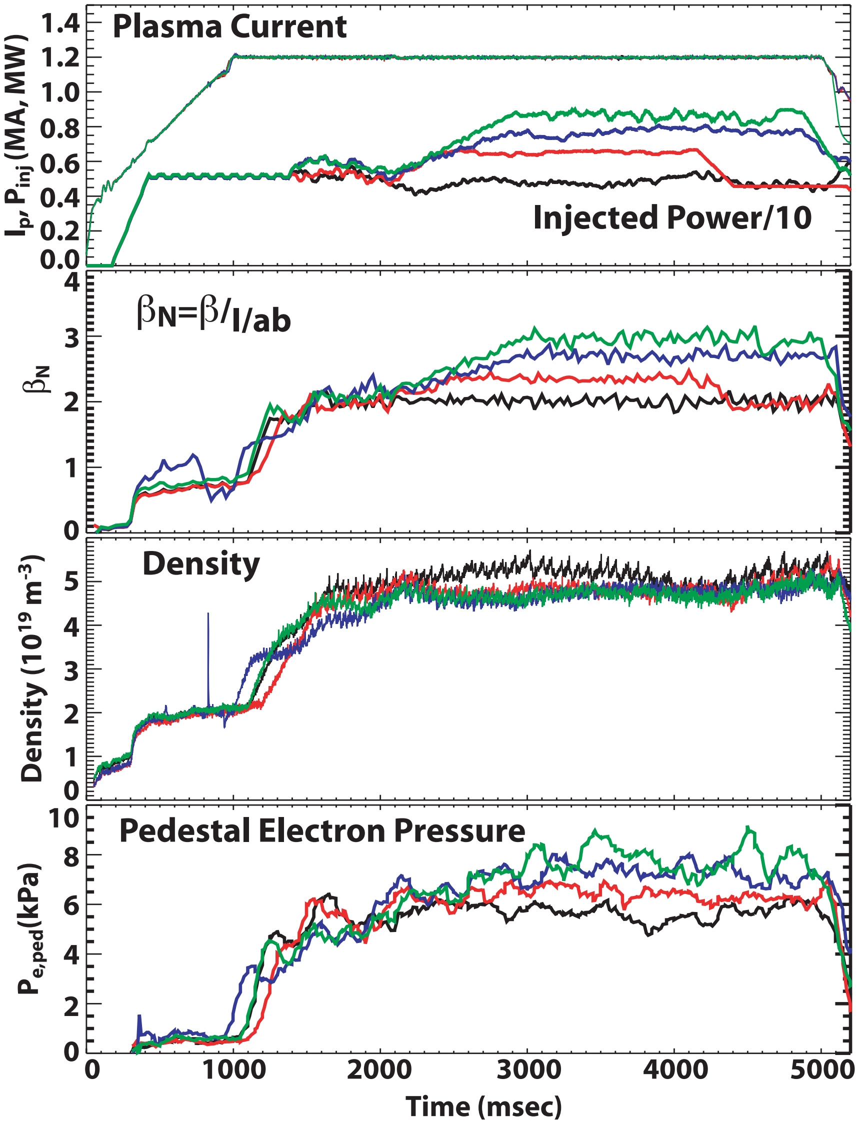
DIII-D Stability Study:
Fixed parameters; I_p, B_t, Shape, pedestal width, etc.

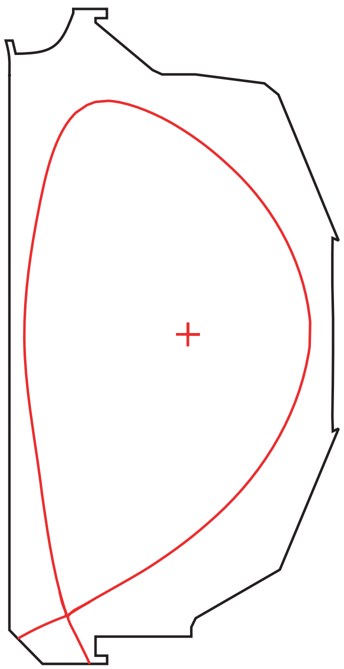


*[P.B. Snyder, H.R. Wilson, et al., PPCF **46** (2004) A131]*

- **The peeling-ballooning model has been validated over a range of conditions**
- **Stability model predicts pedestal pressure for a given width**
- **Stability model can extract width from a measured pedestal pressure**
  - Pedestal top more accurately measured than gradient and width

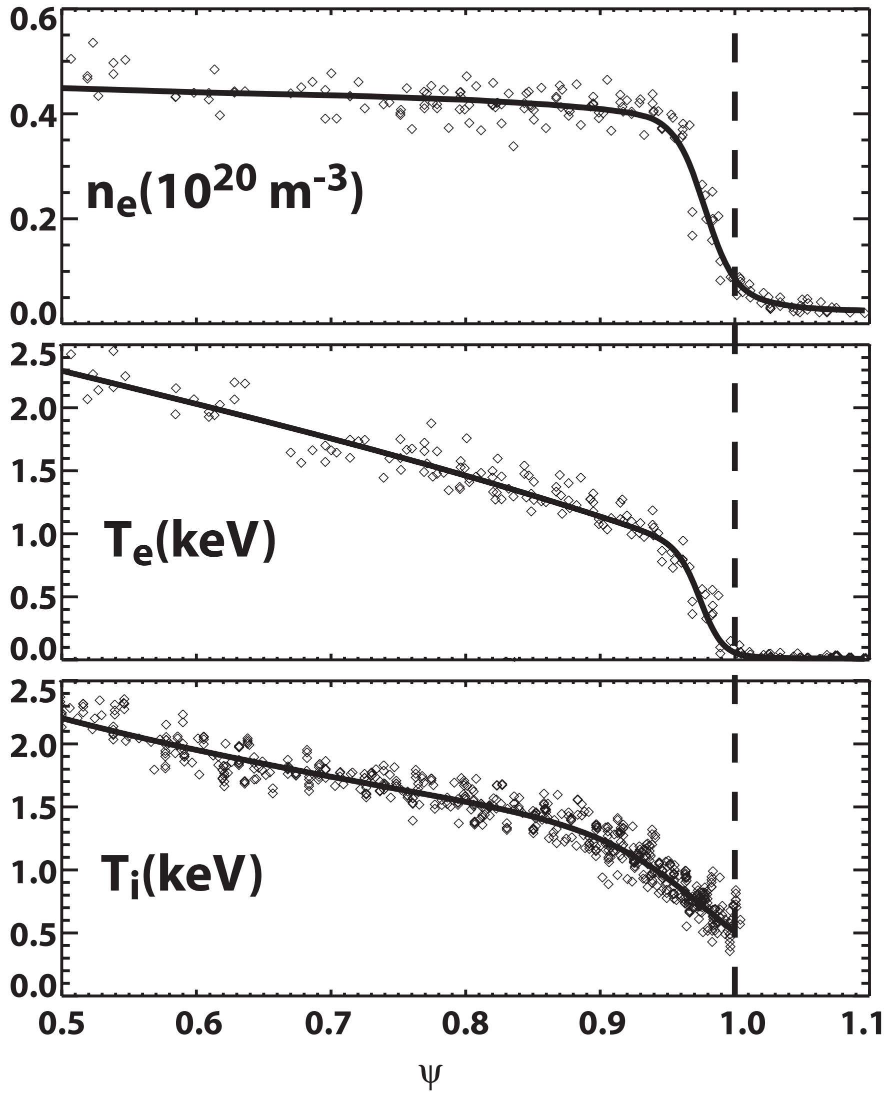
Pedestal Pressure Increases with Global Beta





- Power scan for β_N=2.0 to β_N=3.0
- Other parameters fixed; shape, q_{95}, density, etc.
- Pedestal pressure increases with β_N

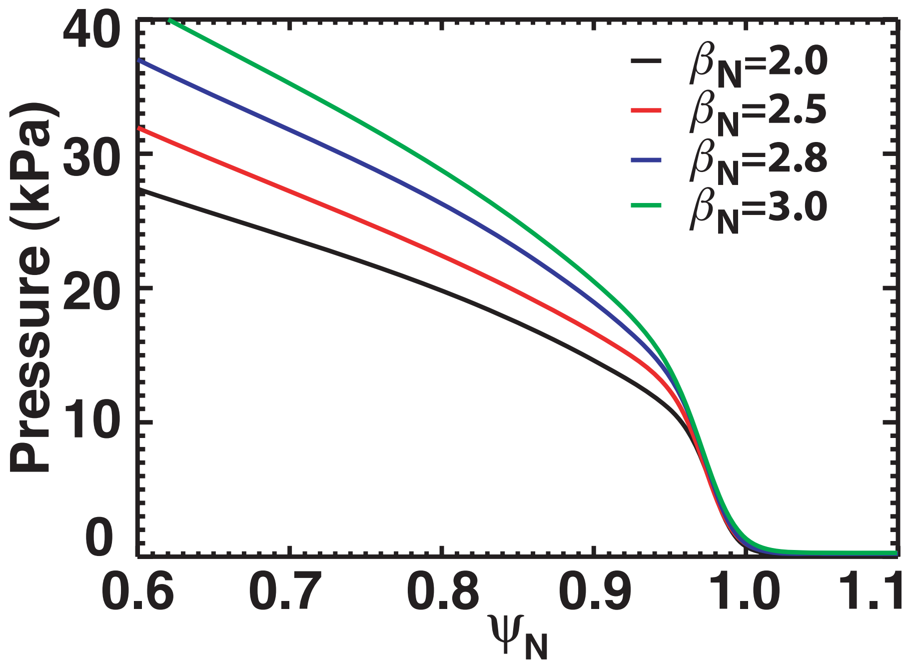
Pedestal Profiles Fit Just Prior to an ELM



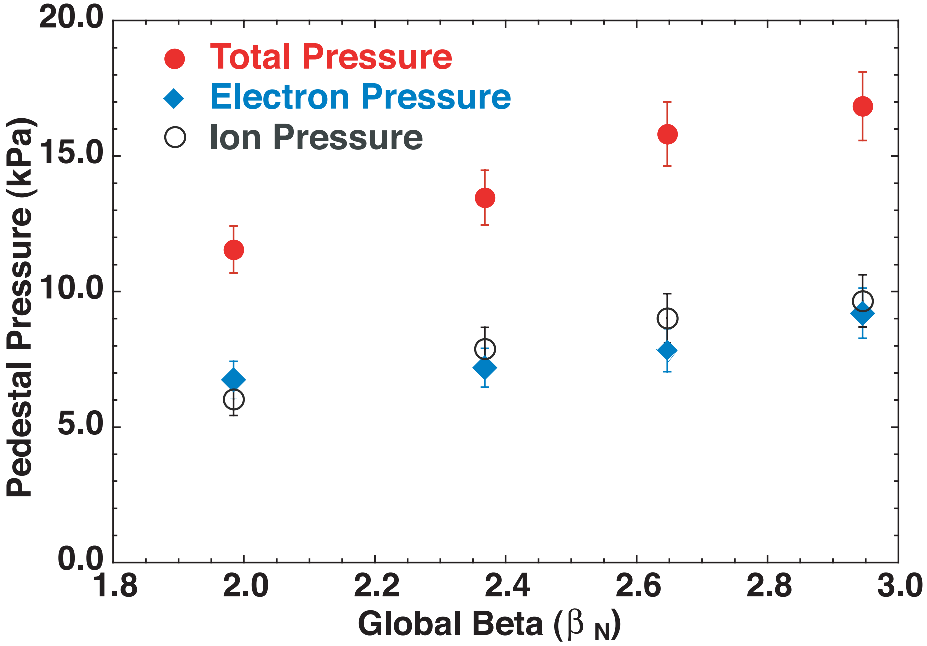
- **Profiles fit to data combined from the last 20% of many ELM cycles**
- **Hyperbolic tangent fit to profiles**
  - Pedestal height more certain, 5-10%
  - Width/gradient less certain, ~20%
- **T_i pedestal is usually significantly wider than T_e or n_e**
  - Ion pressure width set by density width
- **Pedestal pressure characterizes pedestal height for comparison with stability analysis**

Pedestal Pressure Increases with β_N

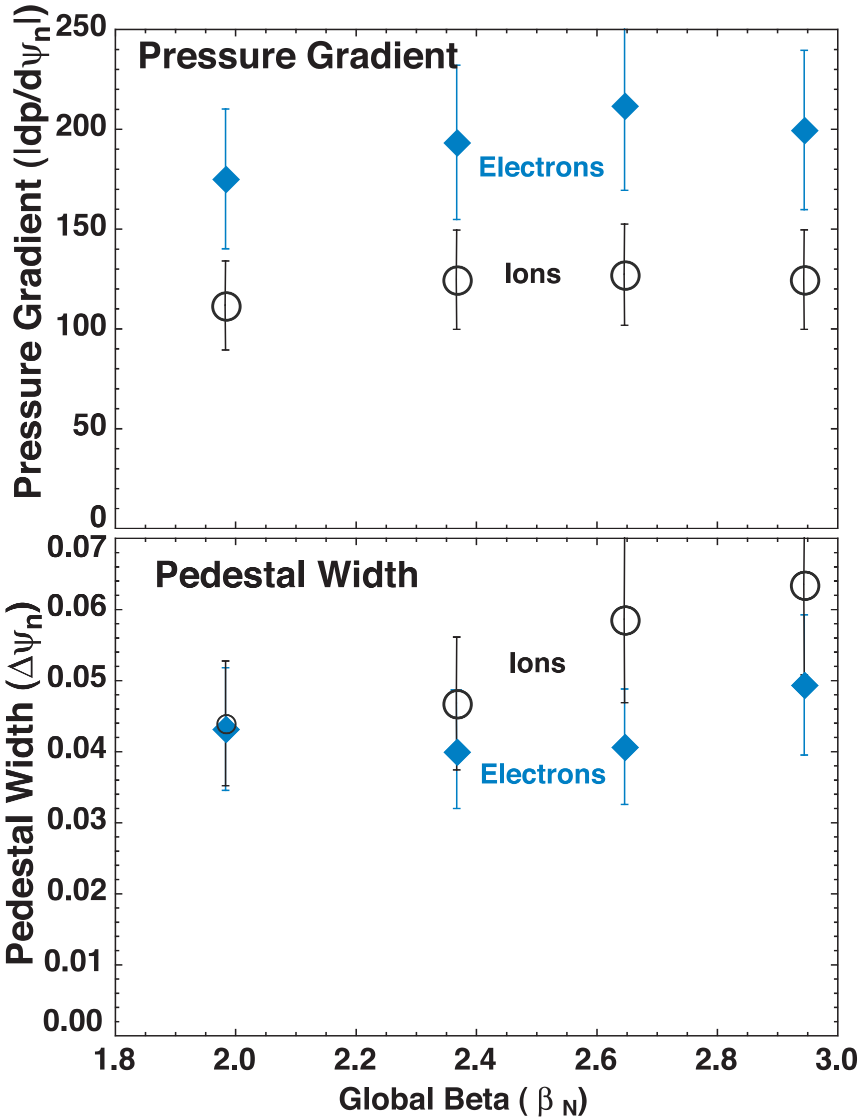
Total pedestal pressure increases ~50% as β_N increases from 2.0-3.0



Both electron and ion pedestal pressure increase

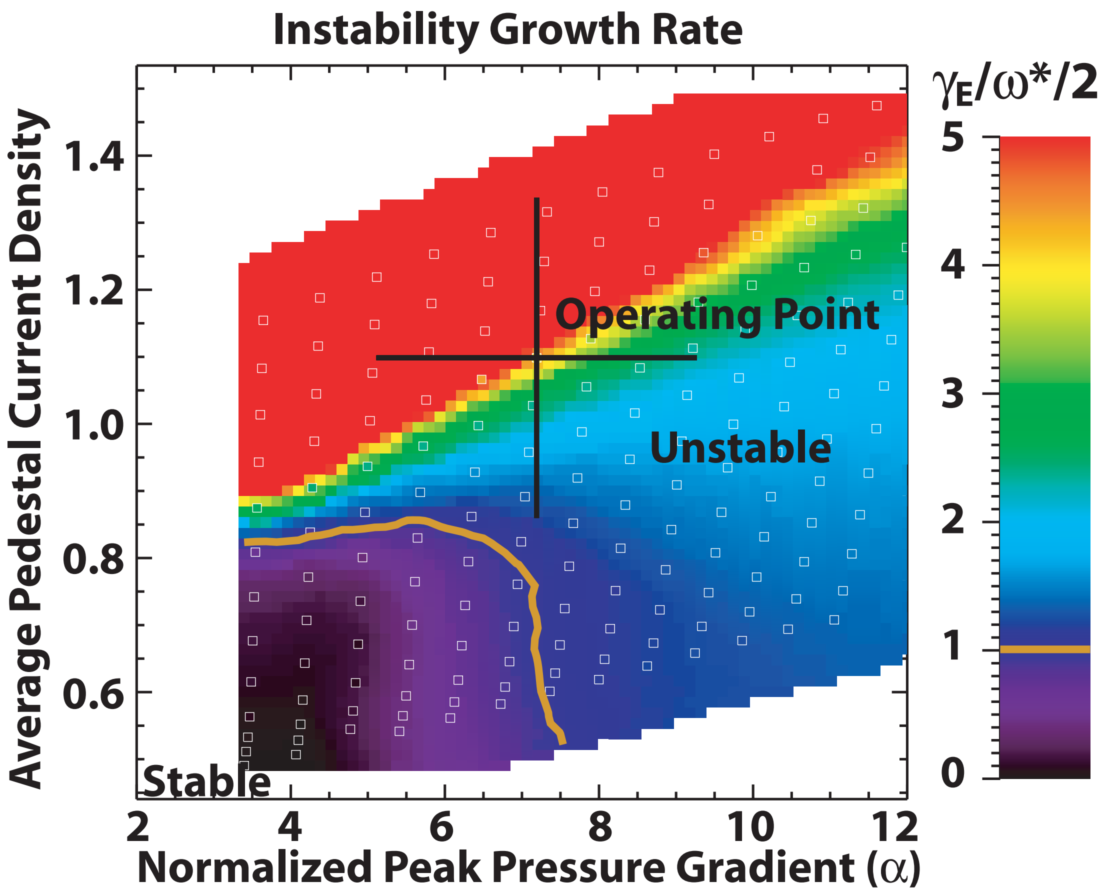


Both Pressure Gradient and Width Increase with β_N



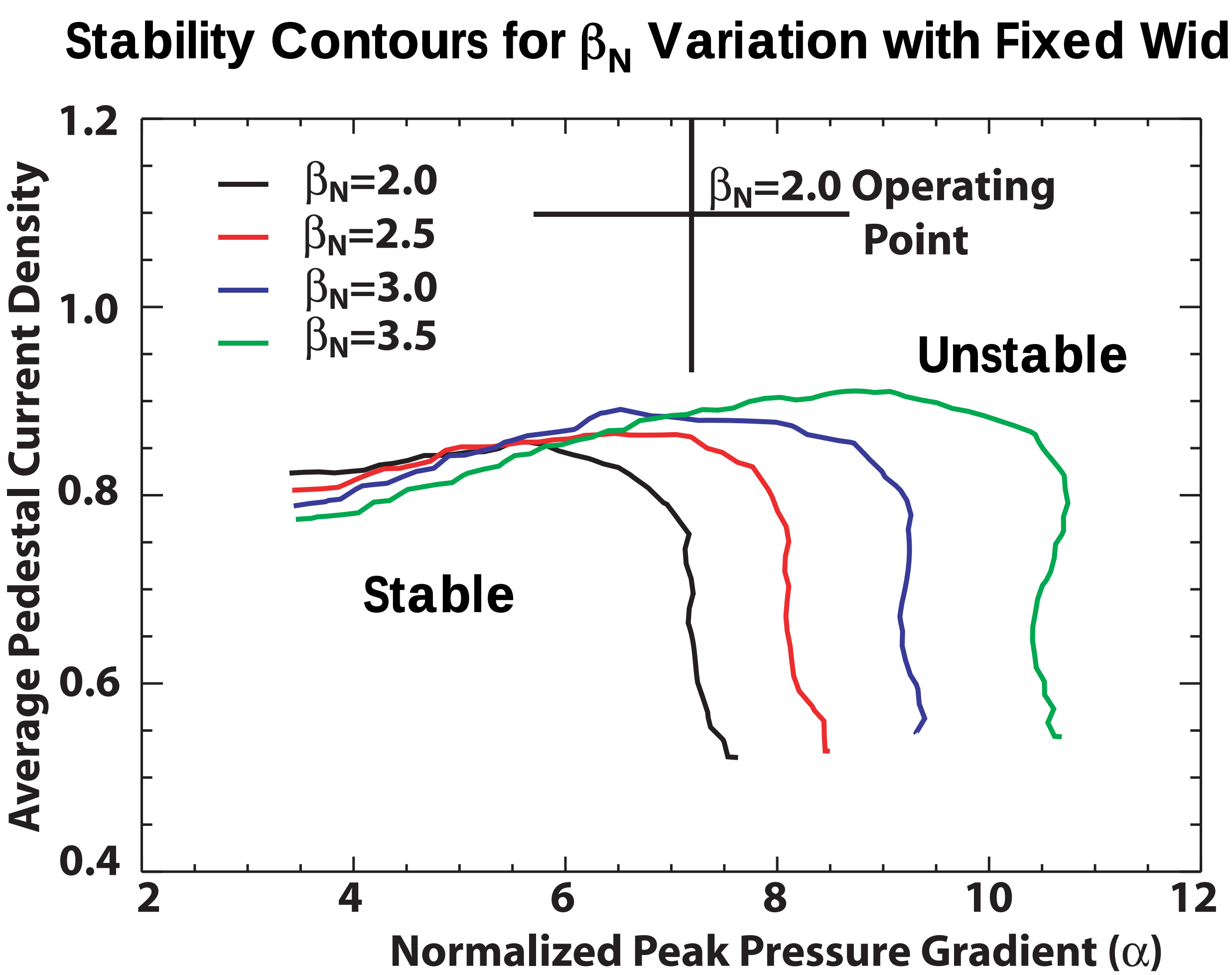
- Both gradients and widths increase with β_N
- Larger uncertainty, ~20%, for gradient and width measurements
- Stability constraint applied to pressure can reduce uncertainty in pedestal width scaling

Stability Space is Mapped for Each Configuration



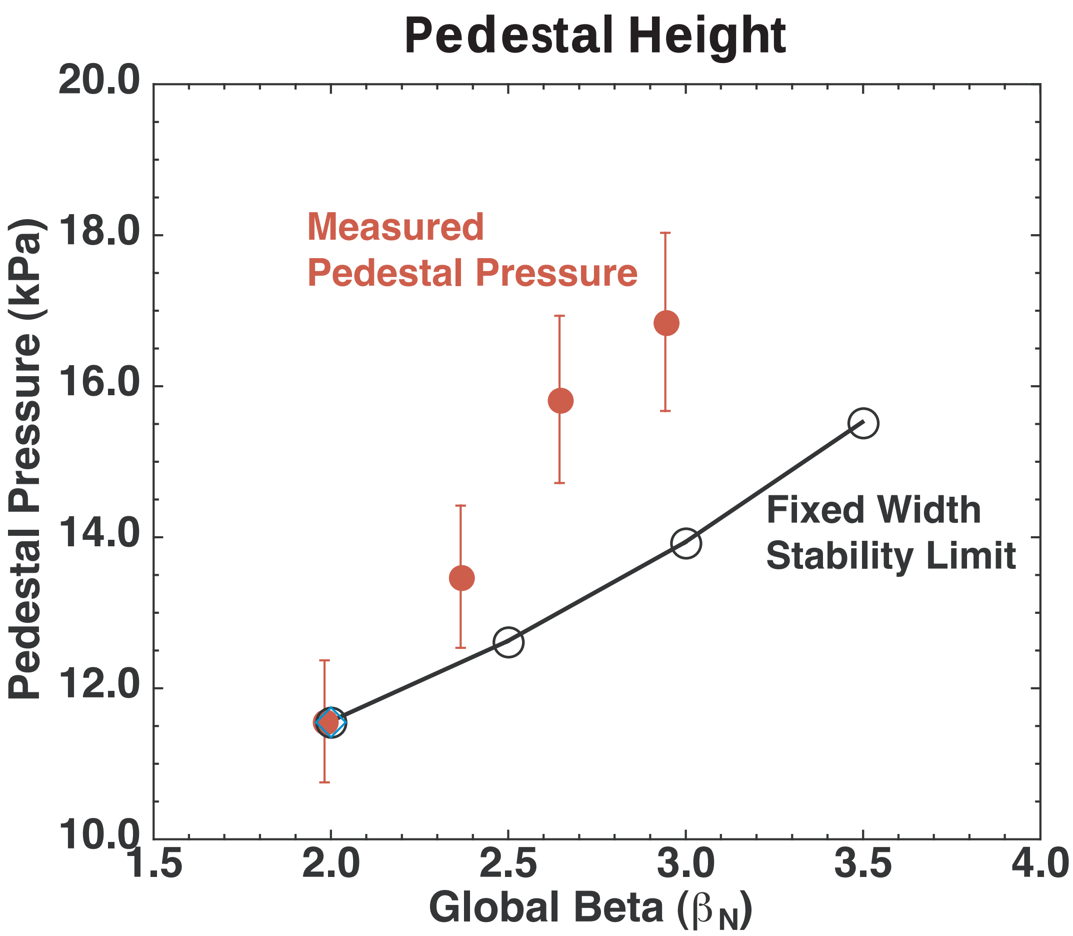
- **MHD equilibria constructed by measured pressure profile and Sauter bootstrap model for edge current**
- **Create 2D array of equilibria with varying pedestal current and pressure**
  - Fixed pedestal width
  - Fixed total stored energy
- **Stability analysis of each equilibrium using ELITE, n=5-25**
  - Stability threshold: $\gamma_E \leq \omega^*/2$
- **Variation in stability threshold analyzed for varying global β, shape, etc.**

Pressure Gradient Limit for Fixed Width Increases with Global β



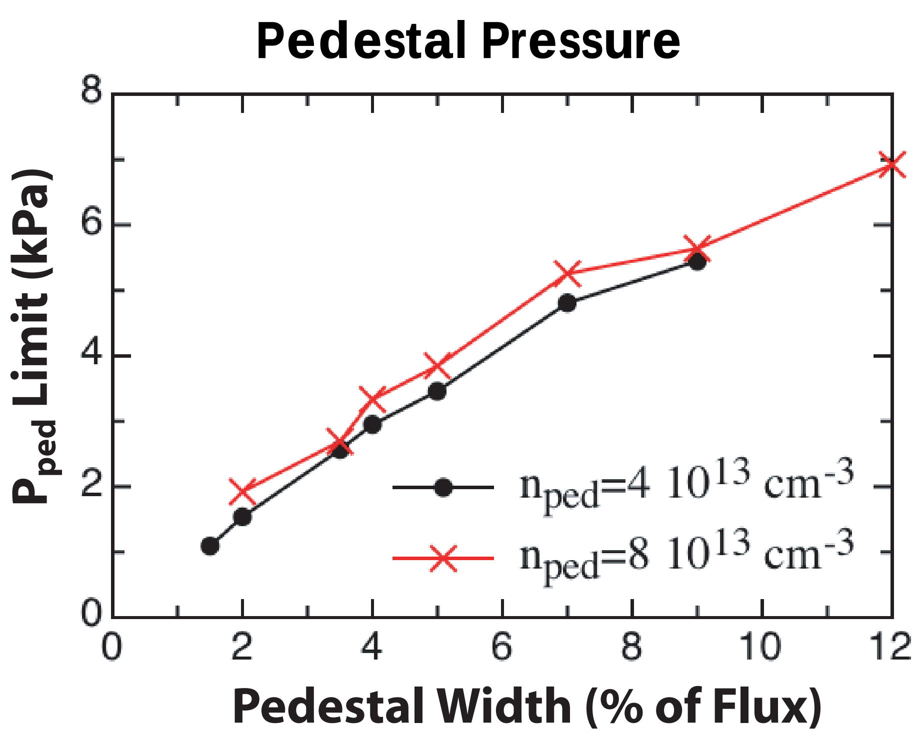
- **Stability dependence on β calculated using fixed pedestal width but varying total stored energy**
- **Calculated gradient limit increases with β due to Shafranov shift**

Improved Stability at Fixed Pedestal Width Can Account for Half of Pedestal Pressure Rise with β_N



- **Measured pedestal pressure proportional to global β_N**
- **Increase in stability limit at fixed pedestal width accounts for only half of observed increase in P_{ped} with β_N**
- **Width must increase with β to account for pedestal pressure increase**

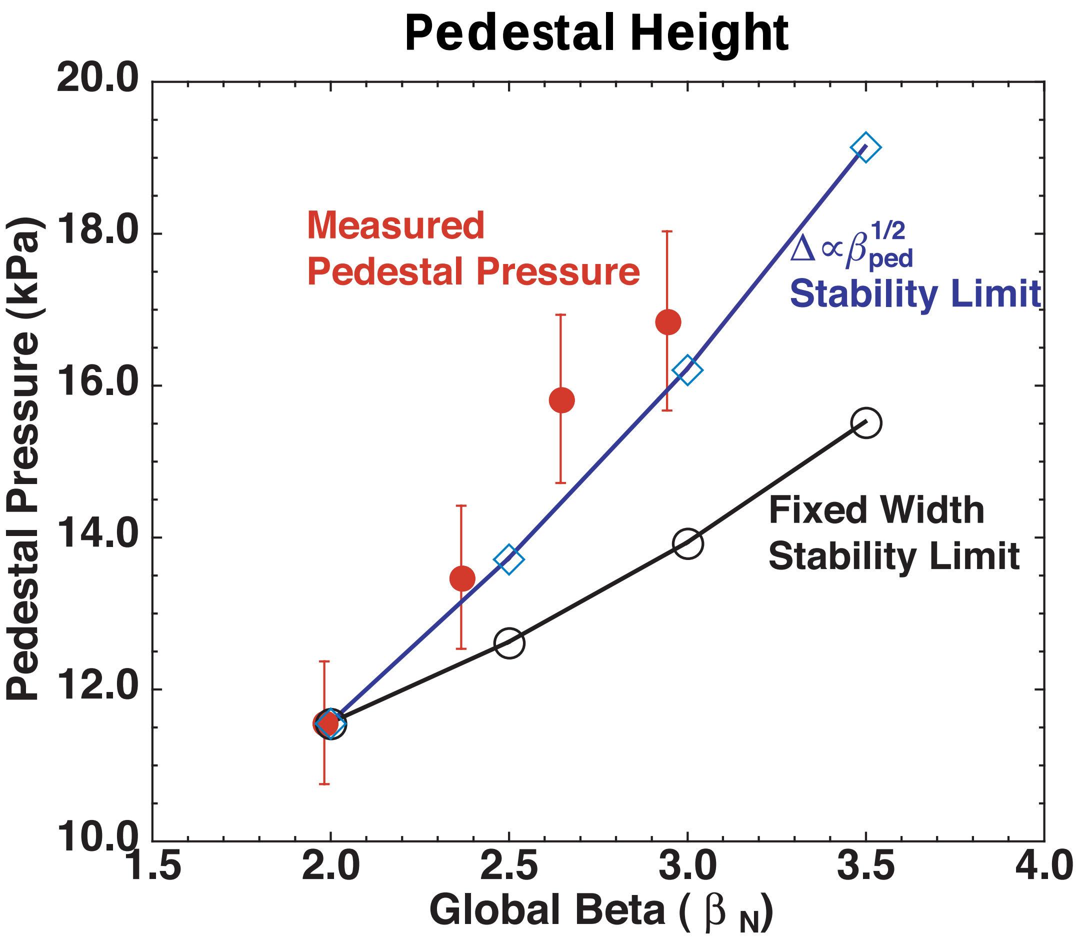
Pedestal Gradient Expected to be Weakly Reduced with Increasing Width



[P.B. Snyder, H.R. Wilson, et al., PPCF ***46*** *(2004) A131]*

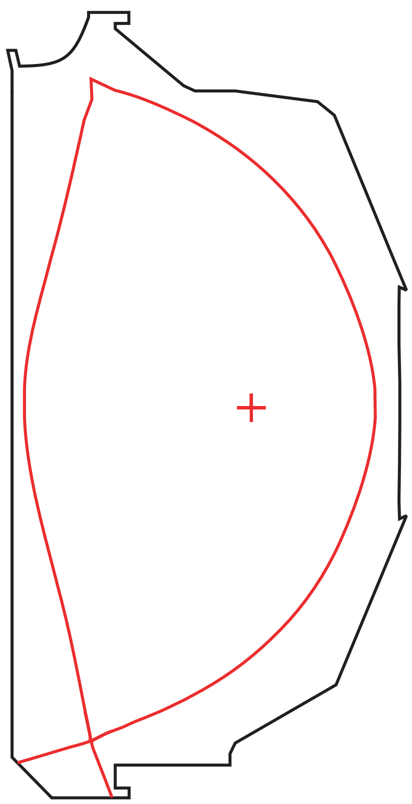
- **Previous numerical studies indicate width (Δ) scaling of stability limit:**
  - $\nabla p_{crit} \propto \Delta^{-1/4}$ or $P_{ped} \propto \Delta^{3/4}$
  - All other parameters fixed; Shape, β, etc.
  - Width variation of ∇p due to radial extent of finite *n* modes

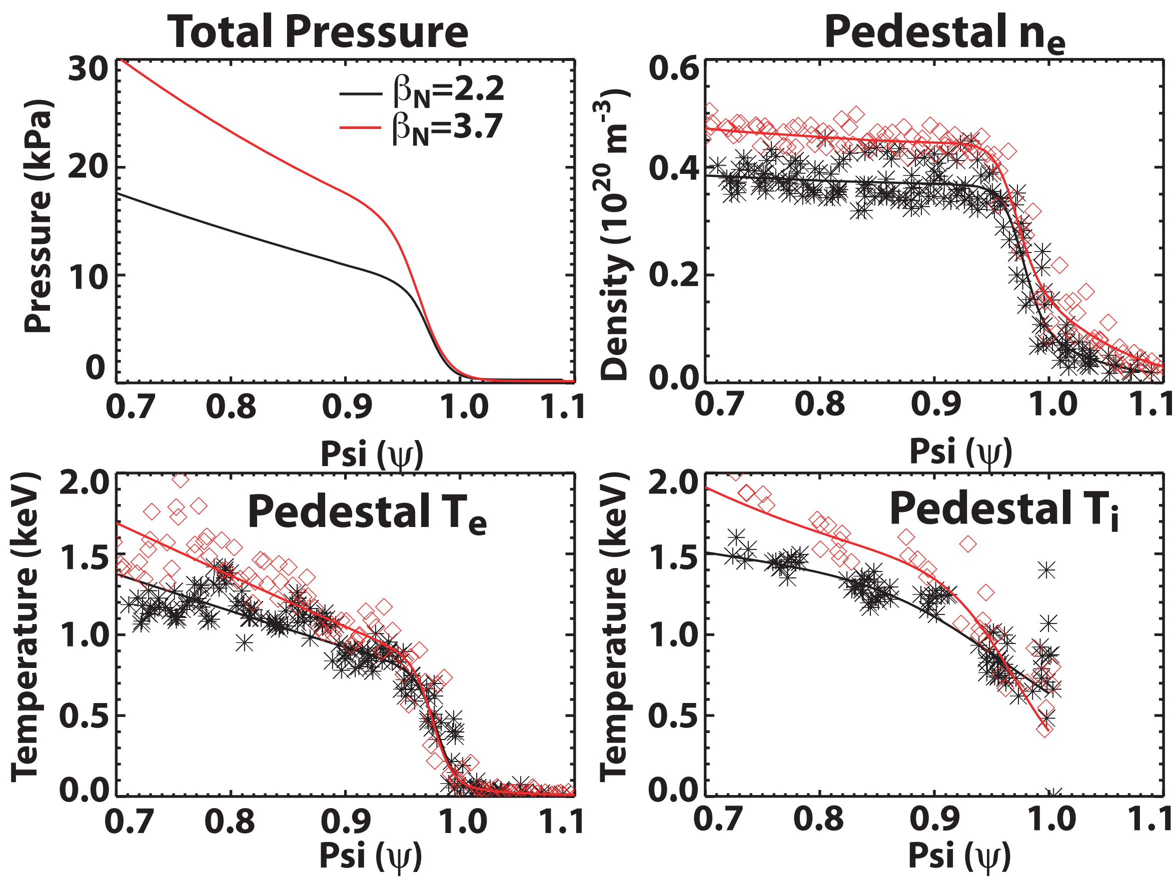
Stability Analysis Implies Pedestal Width Increase with β



- **Pedestal pressure proportional to global β_N**
- **Width must increase with β to account for measured pressure increase**
- **Width scaling consistent with previous statistical study**
  - $\Delta \propto \beta_{ped}^{1/2}$
  - T.H. Osborne, et. al., Jour. Nucl. Mater.,266-269, 131 (1999)

Similar Dependence of P_{ped} on global β_N Observed in High β Advanced Tokamak Regime



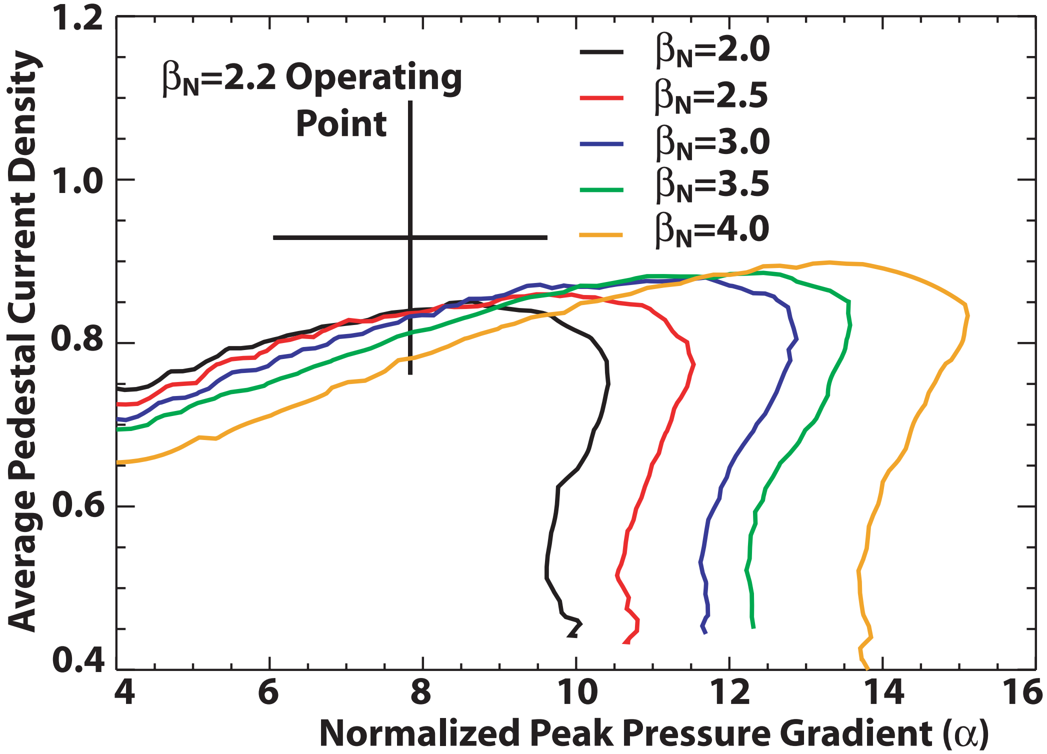


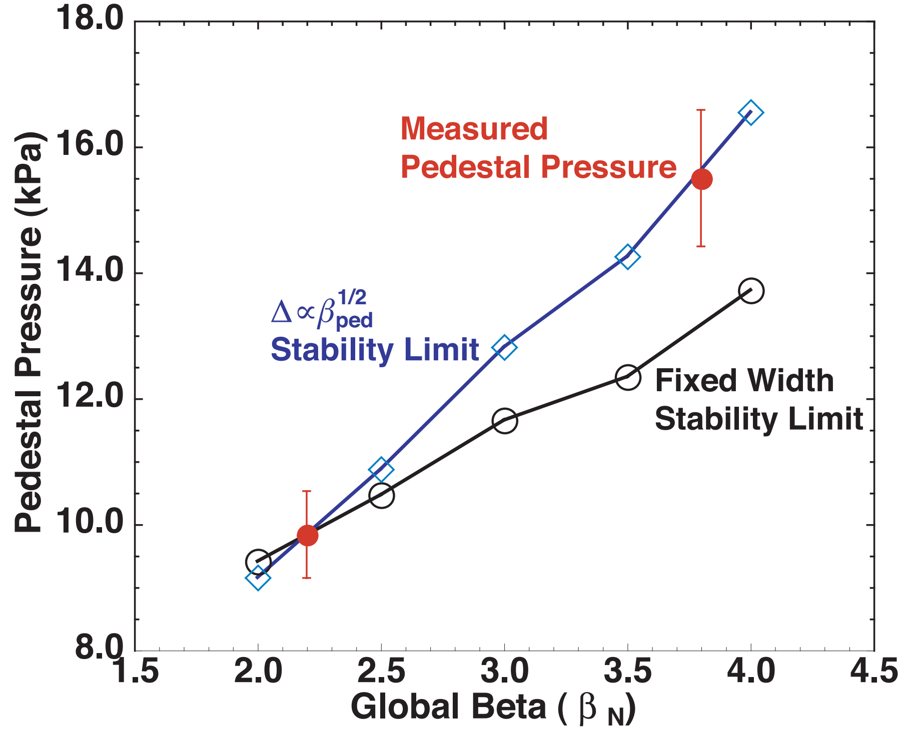
- **High β scenario with early heating**
- **Increase in β_N from 2.2 to 3.7, ~68%**
- **Pedestal pressure rises from 9.8 kPa to 15.5 kPa, ~58%**

DIII-D NATIONAL FUSION FACILITY

233-07/AWL/rs

Pedestal Width Scales with β in Advanced Regimes



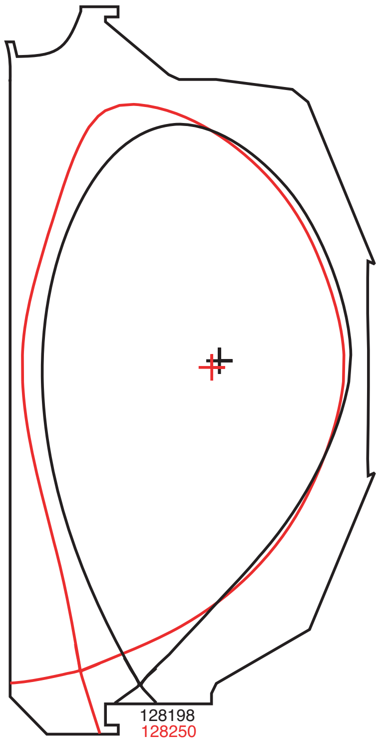


- **Pedestal stability continues to improve over wide range of β**
- **Pedestal width scaling, $\Delta \propto \beta_{ped}^{1/2}$, consistent with pressure increase**

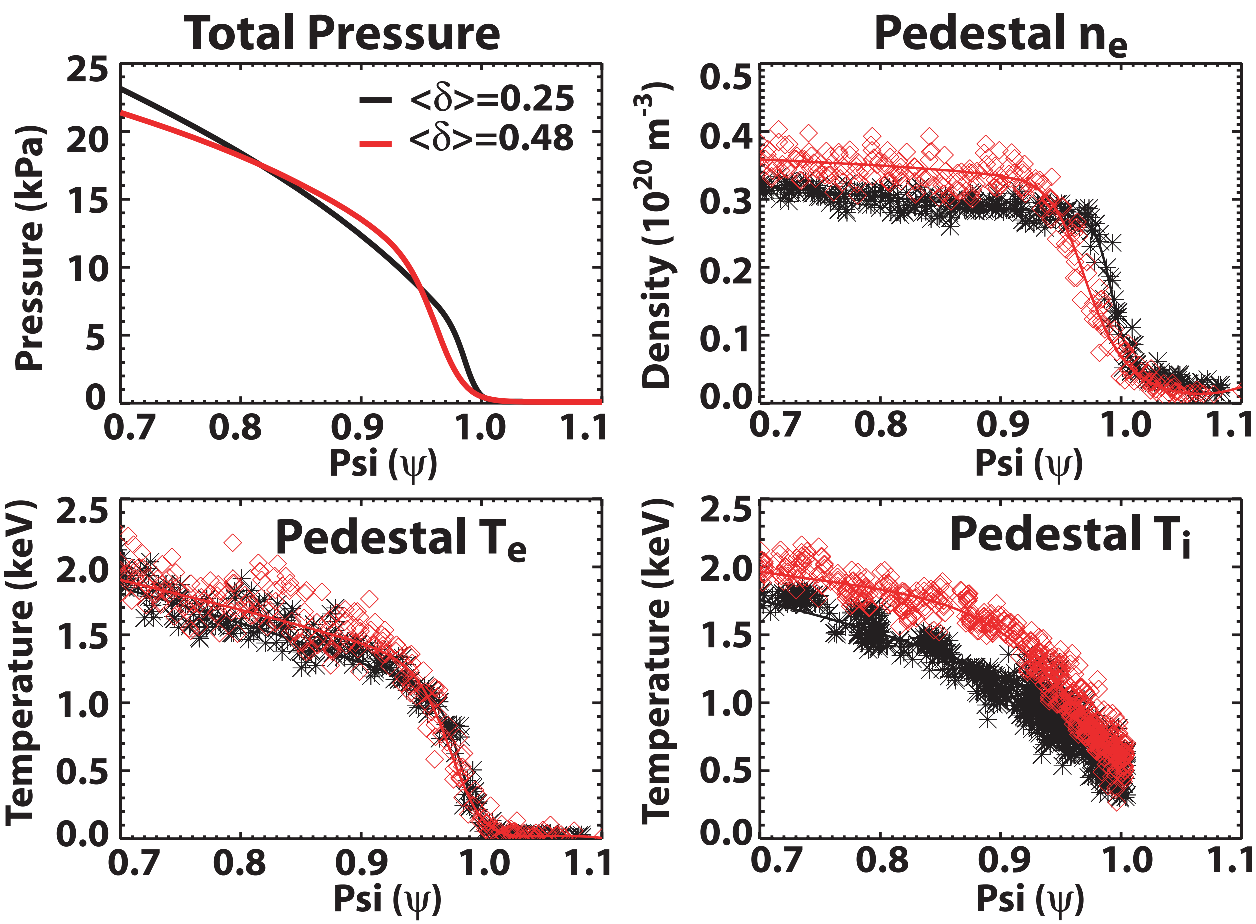
Shape an Important Factor for Pedestal Height

- **Shape dependence for pedestal and core confinement long observed**
- **Stronger shaping improves edge stability**
  - Elongation, triangularity, squareness, second separatrix, etc.
- **Contribution of stability to increased pedestal for stronger shaping not generally quantified**
- **Stronger shaping leads to higher stability limit and wider pedestal**

Shaping Can Produce Wide Range of Pedestal Heights



- **Constant conditions**
  - –ELMing H-mode
  - – β_N=2.0
  - –q_{95}=4.6
  - –Ip=1.1 MA
  - –Bt= 1.9T, ±10% to match q95



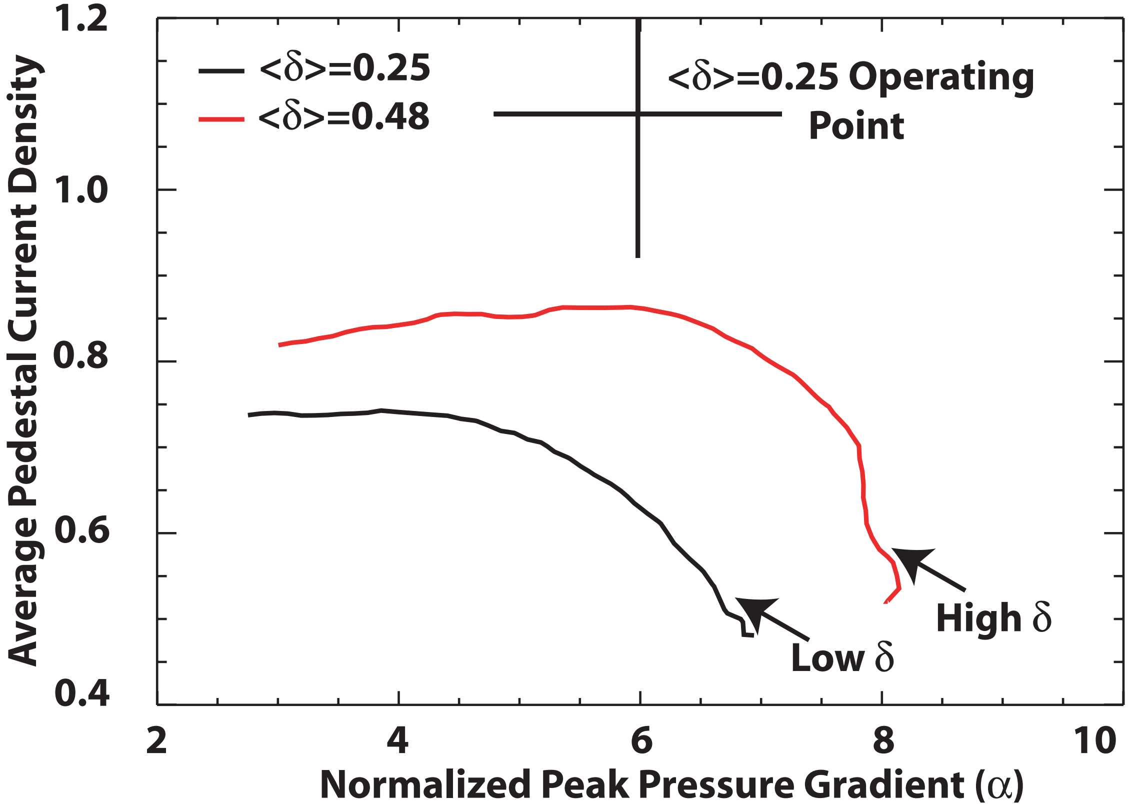
<δ >=0.25 : P_{ped}=8.1 kPa

<δ >=0.48 : P_{ped}=14.0 kPa

Global Energy Confinement: ~50% higher

Pedestal Width Increases with Stronger Shaping

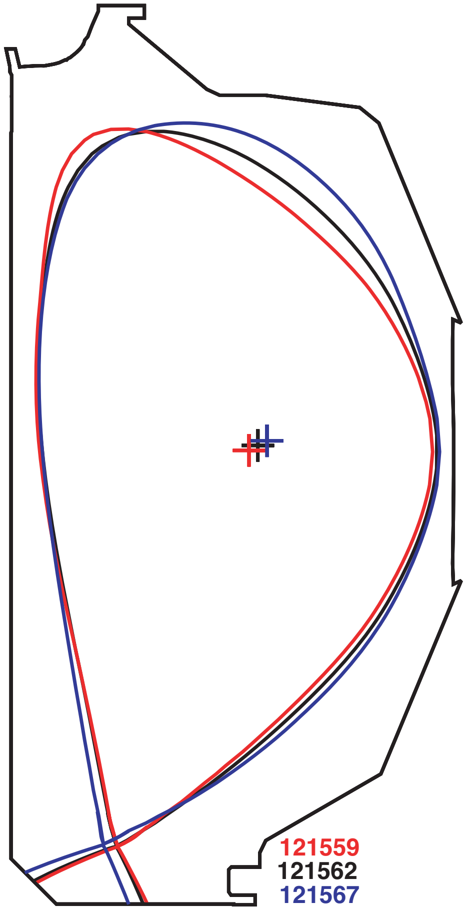
Stability Contours for Fixed Width



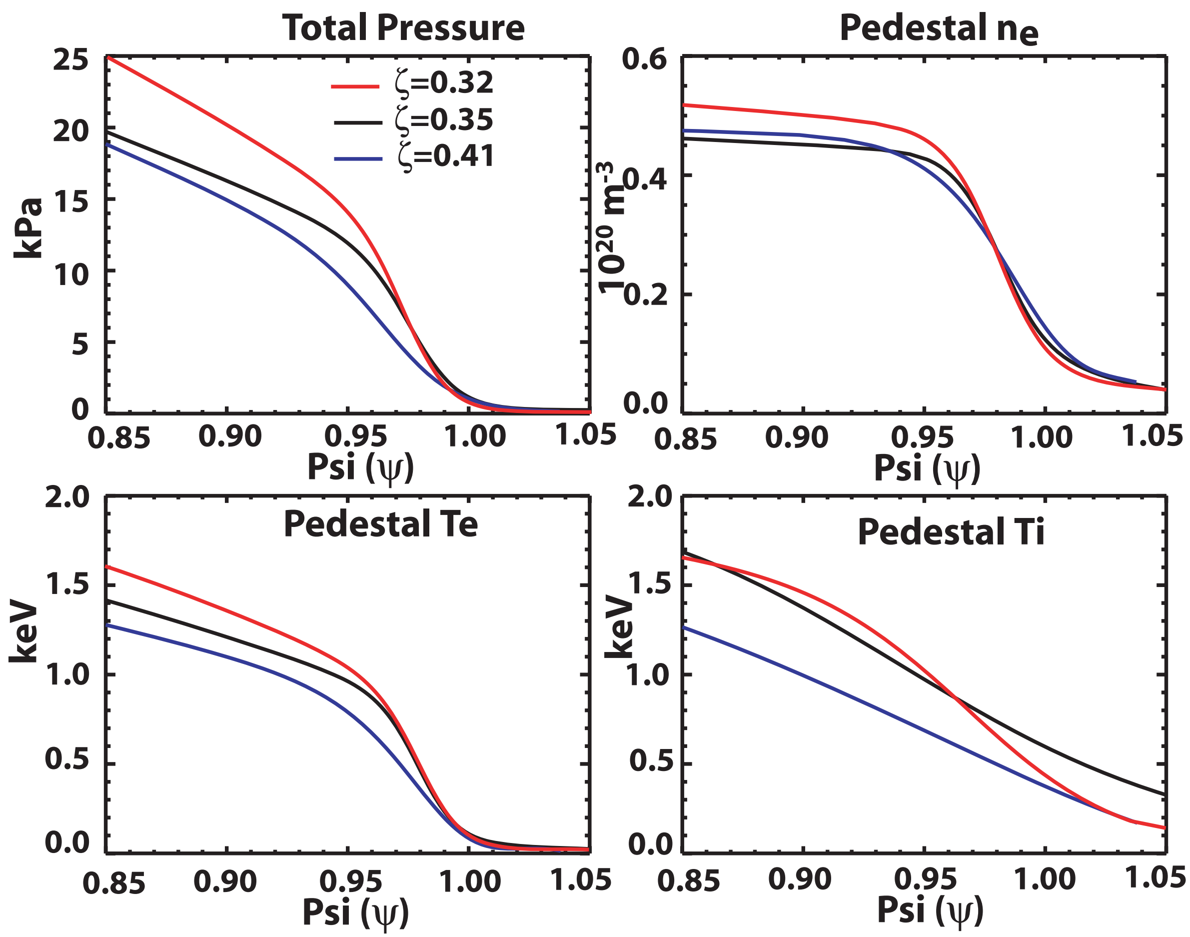
- **Stronger shaping raises pedestal pressure 72%**
- **Stability limit increases ~33% assuming fixed width**
- **Width increase of 31% for $\Delta \propto \beta_{ped}^{1/2}$ scaling yields**
  - Expected increase in P_{ped} of 75%, in agreement with experiment

Moderate Changes to ITER Shape Can Significantly Affect Pedestal

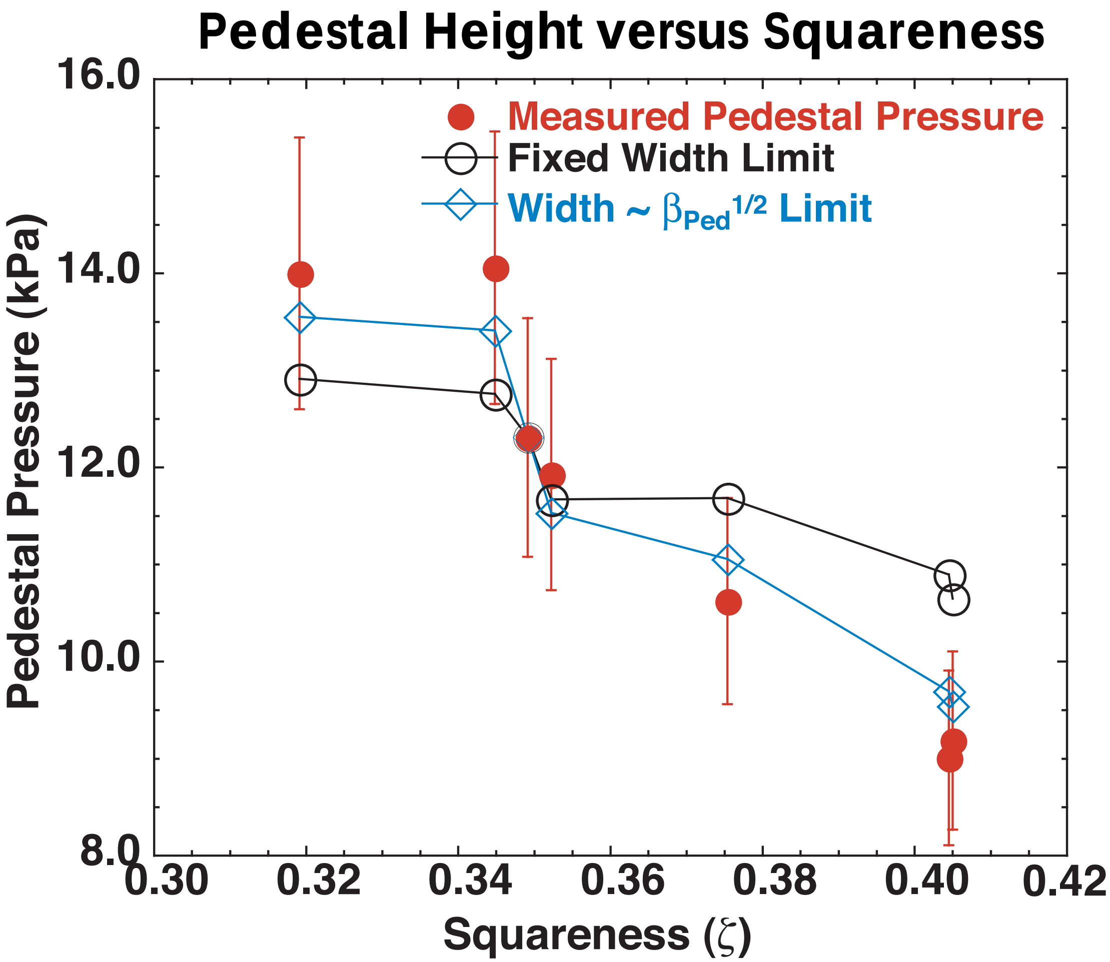
Squareness scan about the proposed ITER shape



Measured Pedestal Profiles in ELMing H-mode



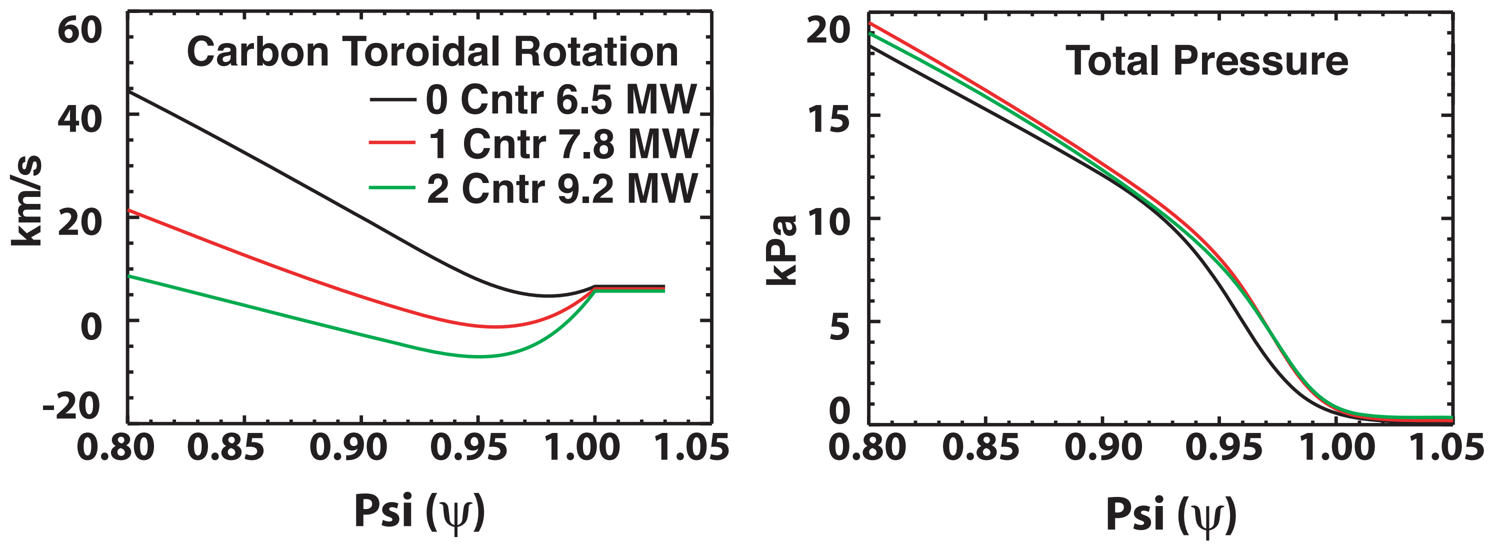
Pedestal Width Decreases with Squareness



- Pedestal pressure increases ~50% from highest to lowest squareness
- Improved stability for fixed width can account for half of pedestal pressure increase
- Pedestal width $\Delta \propto \beta_{ped}^{1/2}$ consistent with pressure variation

Toroidal Rotation does not Significantly Affect Pedestal Height

Rotation Scan in Hybrid Configuration



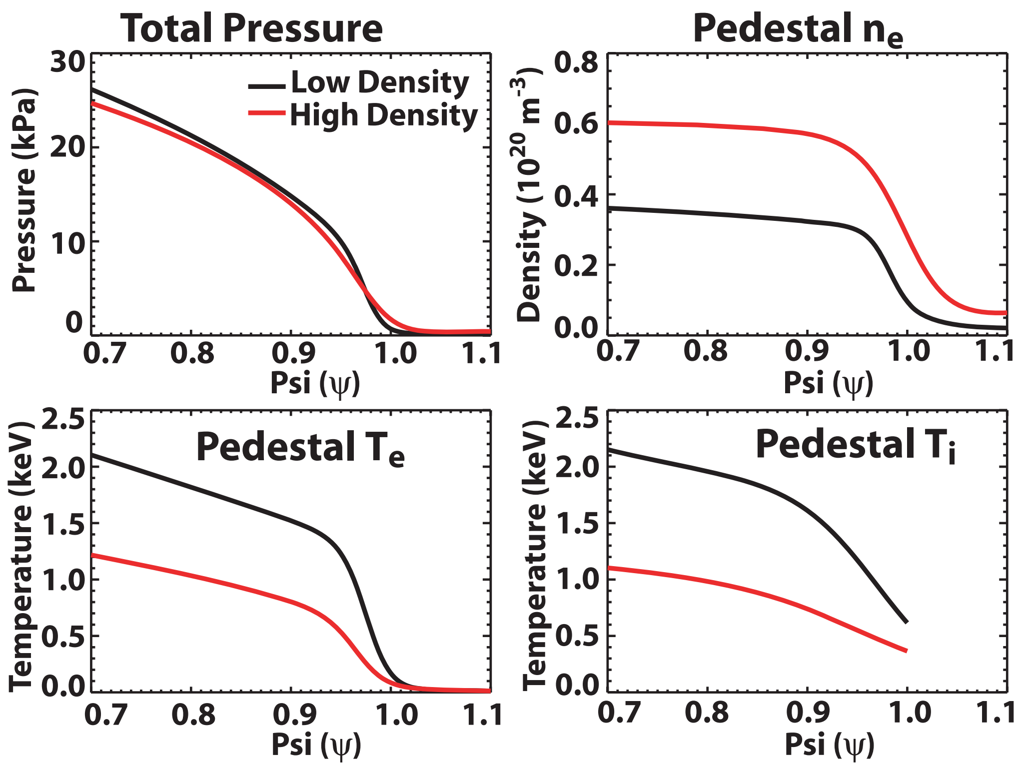
- Ratio of co to counter NBI to control rotation
- While central confinement degraded with counter injection pedestal pressure not significantly affected
- Previous stability studies in this parameter regime indicate edge stability limit not modified by toroidal rotation

*[P.B. Snyder, et al., Nucl. Fusion **47** (2007) 961]*

Implications for Pedestal Width Scaling

- **Significant gyro-radius dependence expected if width set where ExB velocity shearing exceeds driftwave growth rate**
  - $\Delta \propto \rho^{0.5-2.0}\left[f(S,\alpha,q)g(Z_{eff})h(\nu^{*})\right]$
  - Complicated dependence on other dimensionless parameters
- **Possible $\Delta \propto \beta_{ped}^{1/2}$ pedestal width scaling mechanisms:**
  - β_{ped} correlation with ρ^*: Improved stability leads to higher T_i
  - β_{ped} correlation with other parameters: S, α, etc.

Gyro-Radius Scaling Not Yet Observed



- **ρ* reduced, but pedestal not narrower**
- **Other dimensionless parameters change; collisionality, shear, etc.**

- **The ρ* pedestal width scaling is critical**
  - If Δ∝ρ*, ITER likely not to achieve its mission
  - Current experiments cannot match ITER ρ*
  - Experiments in DIII-D, JT-60U and C-Mod have not found significant ρ* scaling
- **A $\Delta \propto \beta_{ped}^{1/2}$ pedestal scaling consistent with single parameter scans in DIII-D and JT-60U**

T.H. Osborne, et. al., Jour. Nucl. Mater.,266-269, 131 (1999)

Summary

- **Pedestal pressure increases with improved edge stability**
  - Increase twice that expected for fixed pedestal width
  - Pedestal width increase, $\Delta \propto \beta_{ped}^{1/2}$, consistent with stability analysis and observed pressure variation
- **Pedestal height and width not dependent on toroidal rotation**
  - Consistent with stability analysis
- **Future work to isolate underlying physics of width scaling**
  - Universality of $\beta_{ped}^{1/2}$ scaling for pedestal width
  - Ion gyro-radius, ρ^*
  - Other dimensionless parameters; S, α, q, etc.