Progress Towards a Predictive Model for Pedestal Height in DIII-D

by
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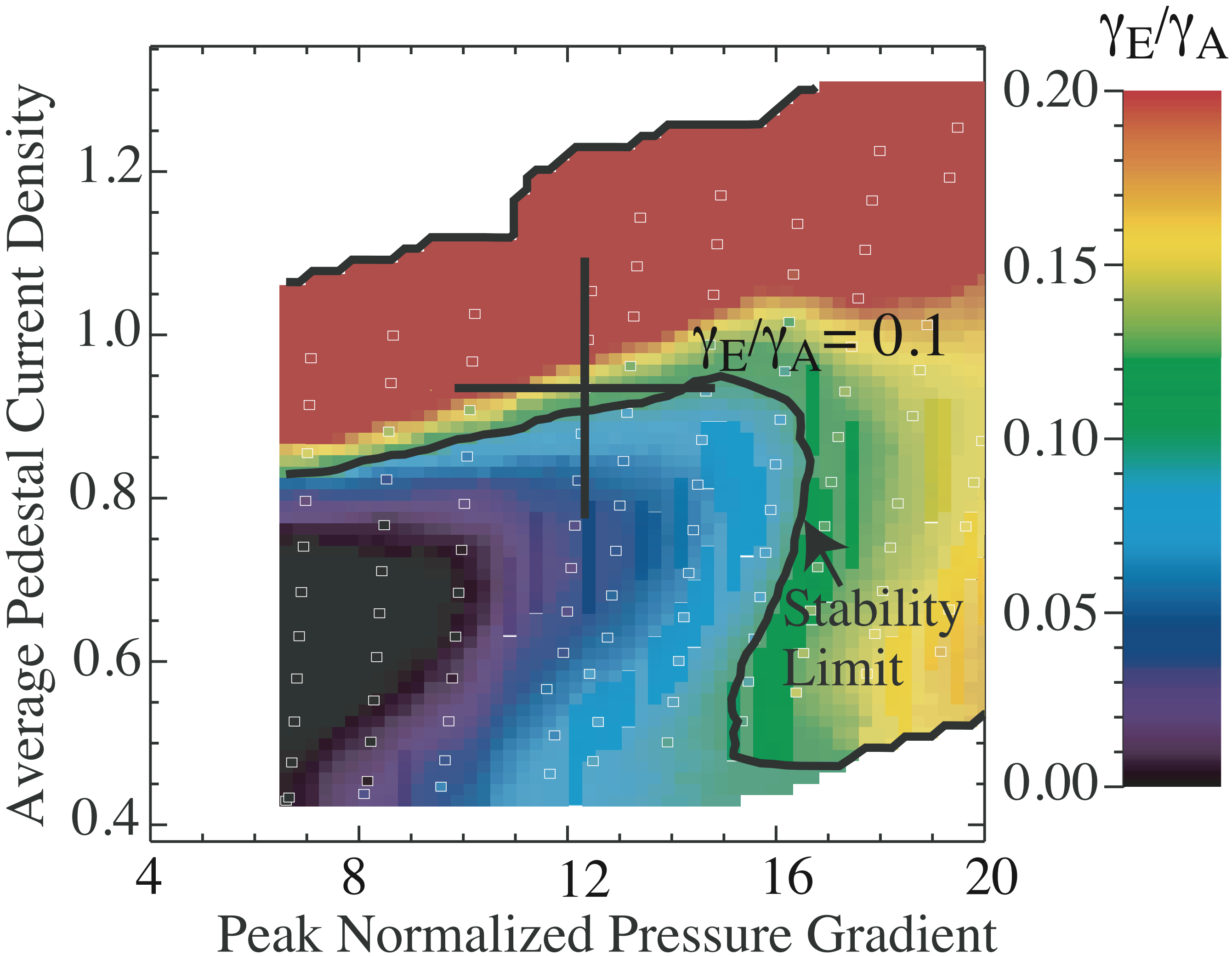
Overview

- **Best pedestal width scaling in DIII-D** is $\Delta = 0.076\ (\beta_\theta^{ped})^{1/2}$
  - Supported by an H/D mass scaling experiment
- **A new model predicts qualitative and quantitative trends in DIII-D pedestal width and height** (Snyder, IT/P6-14)
  - Model uses the best empirical width scaling
  - Peeling-ballooning MHD theory used to predict limiting pressure profile
- **Model predicts DIII-D pedestal height over more than an order of magnitude**
- **Pedestals from ITER demonstration discharges are described by the model**
- **Trends observed for pedestal width and height to increase together during ELM-free and inter-ELM phases**

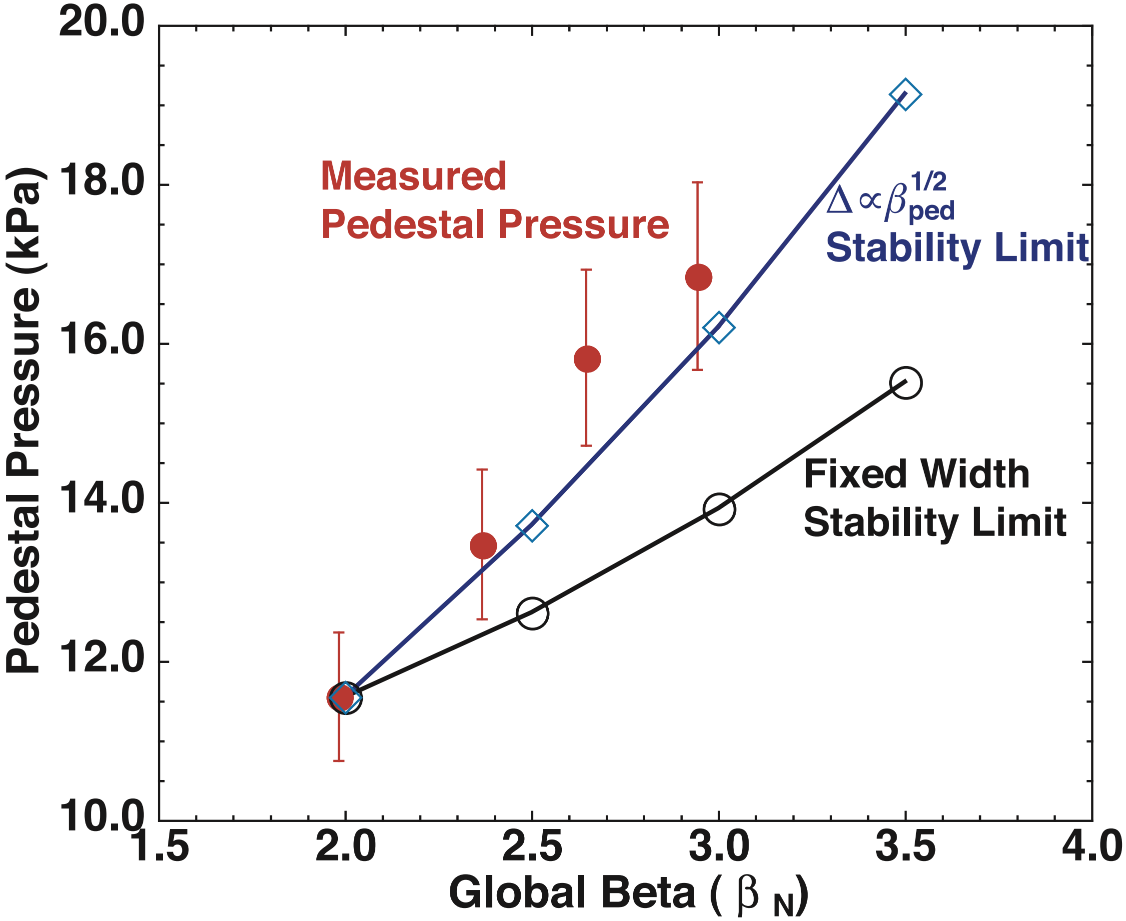
MHD Stability Limits to Pedestal

Peeling-ballooning MHD theory describes limits to pedestal pressure gradient observed in DIII-D



- Peeling-ballooning theory describes pedestal stability in terms of current density and pressure gradient
- Theory successfully describes pedestal conditions just before Type I ELM in DIII-D
- Pedestal typically achieves max pressure gradient just before ELM

Stability analysis, coupled with measured β^{ped}, can be used to study pedestal width scaling



Leonard et al., Phys Plasmas15 (2008) 056114

- **Previous numerical studies indicate width (Δ) scaling of stability limit:**

$$\nabla p_{crit} \propto \Delta^{-1/4} \longrightarrow P_{ped} \propto \Delta^{3/4}$$

  - All other parameters fixed shape, β, etc.
  - Width variation of ∇p due to radial extent of finite *n* modes
- **Calculate** β^{ped} **from** Δ_p x ∇p_{crit}
- **Constant** Δ_p **gives** β^{ped} **which is lower than measured values**
- Δ_p **scaling as** $(\beta^{ped})^{1/2}$ **gives** β^{ped} **which agrees with measured** β^{ped} **within experimental errors**

Pedestal Width Scaling in DIII-D

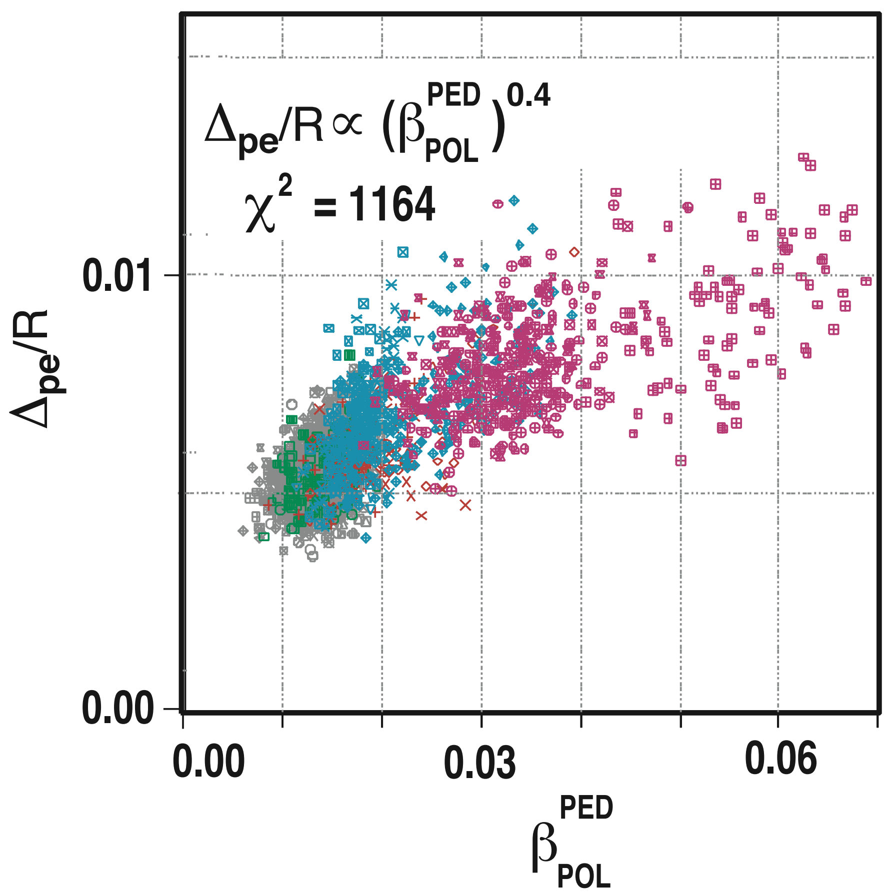
Several studies show that best pedestal width scaling in DIII-D is $\Delta \sim (\beta_\theta^{ped})^{1/2}$

- **Early database studies produced best width scalings: $\Delta_{pe} \sim (\beta_\theta^{ped})^{0.4}$ and $\Delta_{pe} \sim (\rho_{i\theta}^{ped})^{0.5}$**
  - Osborne et al., J. Nucl. Mater. **266-269** (1999) 131
- **Additional studies showed that Δ_{pe} did not change when $T_{i,ped}$ was modified at constant P_{ped} – this result inconsistent with ρ_i or $\rho_{i\theta}$ scaling of width**
  - Osborne et al., J. Nucl. Mater. **266-269** (1999) 131
- **Rho-star experiment showed that Δ_{Te} unchanged when ρ_{i*} was varied by factor of 1.6**
  - Fenstermacher et al., Nucl. Fusion 45 (2005) 1493
- **Beta scaling experiments indicate $\Delta \sim (\beta^{ped})^{0.5}$**
  - Leonard et al., Phys. Plasmas **15** (2008) 056114
- **New database analysis provides best scaling** $\Delta = 0.076\ (\beta_\theta^{ped})^{1/2}$ **in DIII-D**
  - Snyder et al., Bull. Amer. Phys. Soc. **52** (2007) 253
- **Mass scaling experiments in JT-60U support $(\beta_\theta^{ped})^{0.5}$ scaling and weak $\rho_{i\theta}^{ped}$ scaling**
  - Urano et al., Nucl. Fusion **48** (2008) 045008
- **Mass scaling in DIII-D is consistent with width scaling with β_θ^{ped} but not with $\rho_{i\theta}^{ped}$**

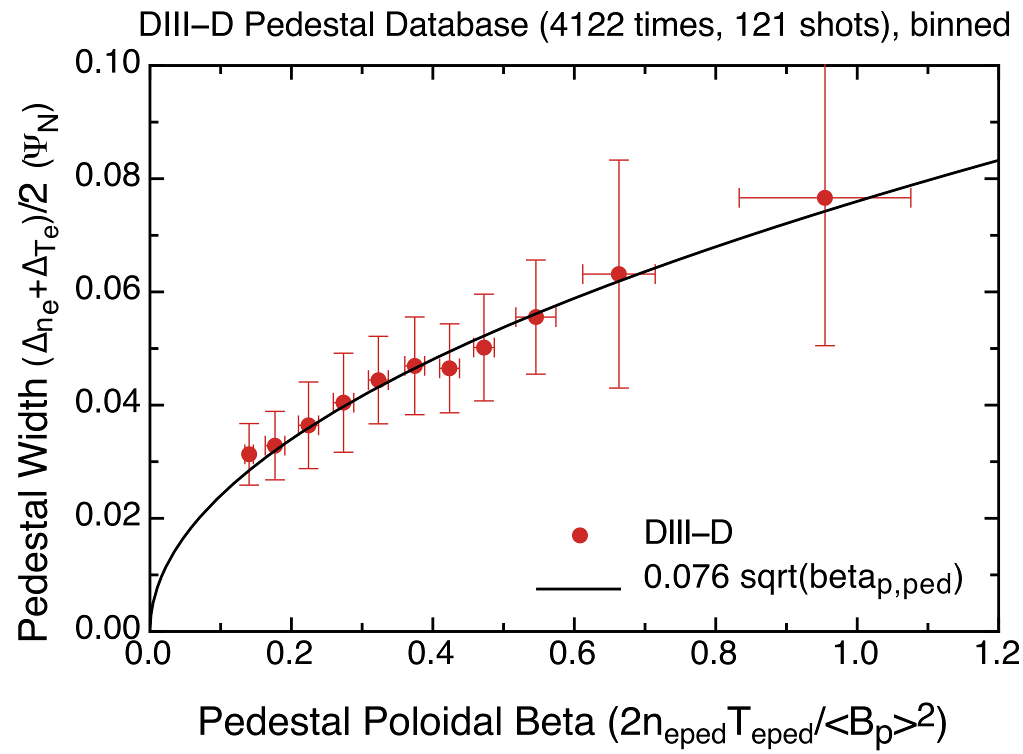
Empirical studies in DIII-D support pedestal width scaling with pedestal beta poloidal

- **Based on 1999 studies by Osborne and recent studies by Snyder**
- **Newest scaling is** $\Delta_{\psi_N} = 0.076\beta_{pped}^{1/2}$

Osborne et al., JNM 266–269 (1999) 131



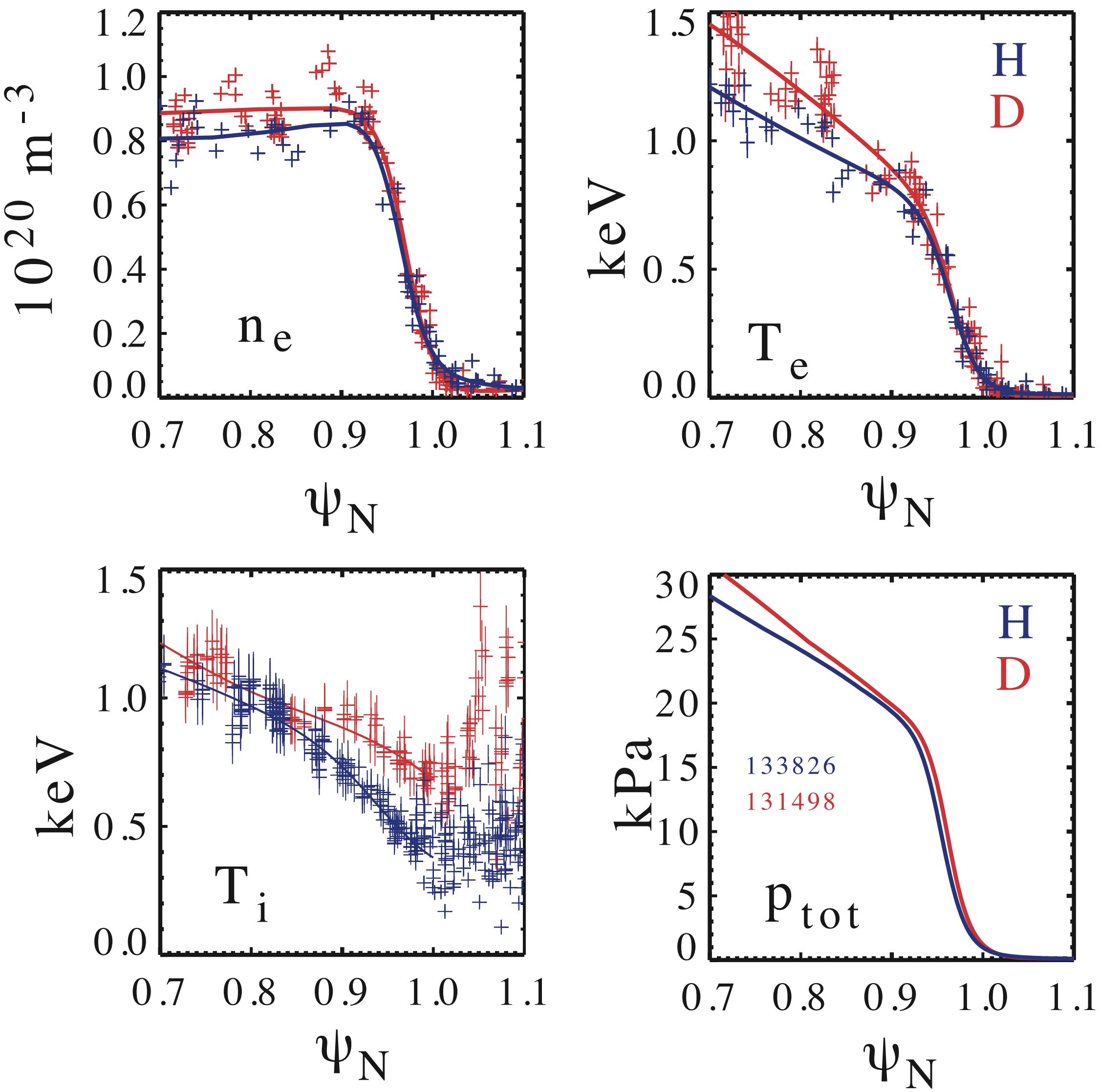
Snyder et al., BAPP 52 (2007) 253



Mass scaling experiment (H/D) shows correlation of pedestal width with β_θ as opposed to $\rho_{i\theta}$

- **Pedestal $\rho_{i\theta}$ and β_θ are correlated in most experiments and it is difficult to determine if Δ depends on one or the other**
- **Comparing pedestals in D vs H plasmas allows for a chance to break this degeneracy**
  - $\rho_{i\theta} \sim M_i^{1/2}$ whereas β_θ has no explicit mass dependence
  - [Urano et al., Nucl. Fusion 48 (2008) 045008]
- **Discharges were made in DIII-D in D and H with same shape, I_p, B_t, density profile and temperature profile**
  - ITER baseline demo shape used
- **In best match of pedestal height, the widths of the D and H pedestals were quite similar**
  - Results much more consistent with Δ being a function of β_θ than of $\rho_{i\theta}$

For best match of H and D pedestals, profiles of total pedestal pressure were very similar (ψ_N>0.9)



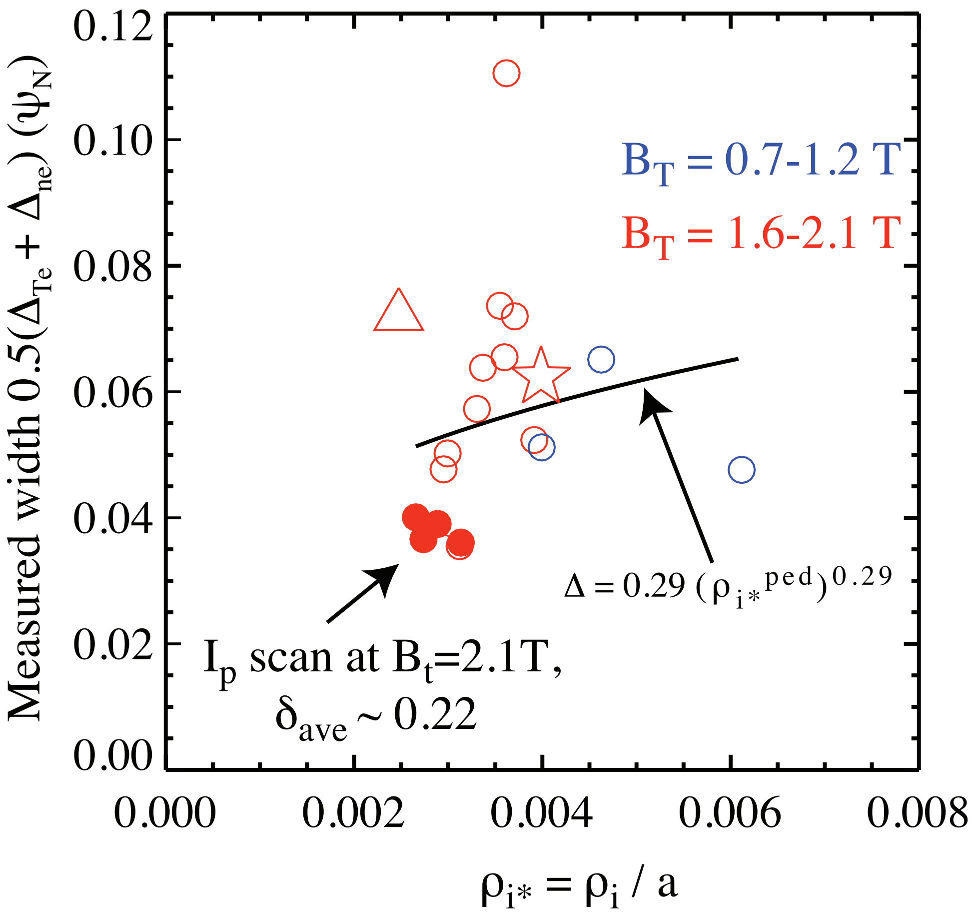
D and H discharges run with ITER baseline shape, q and β

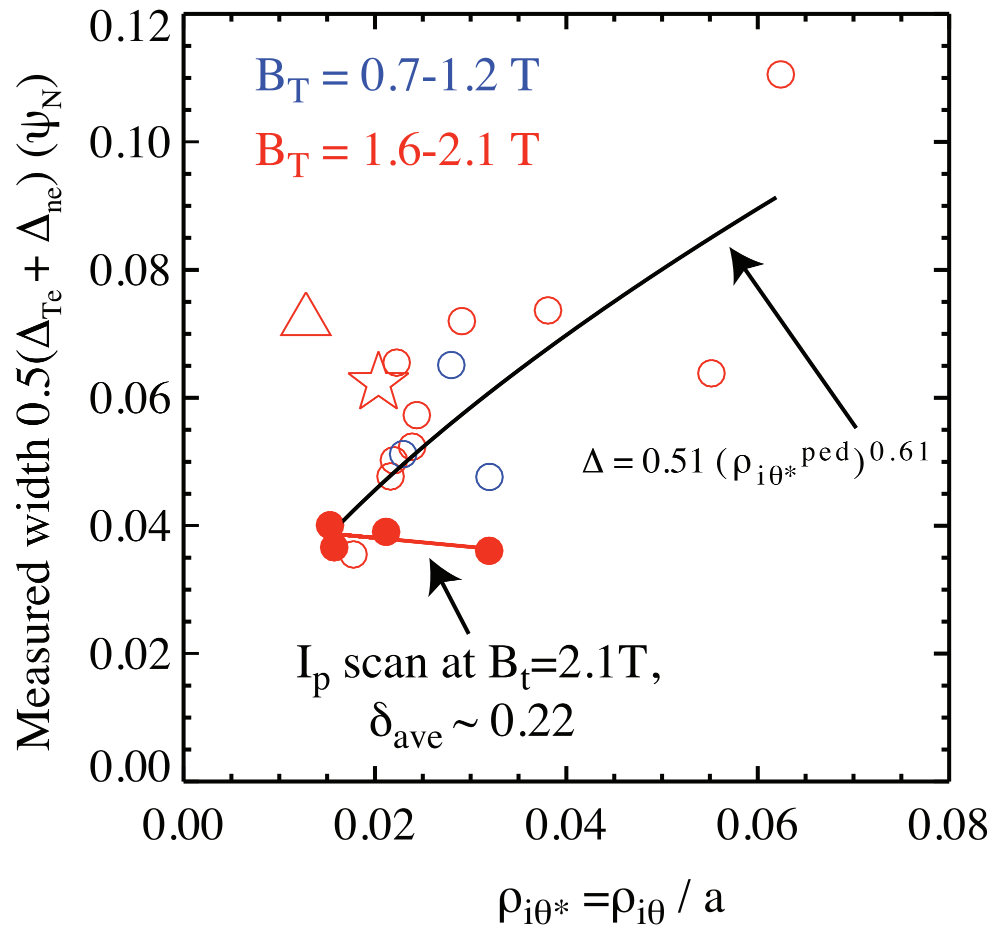
D and H discharges run at same I_p and B_t

Pedestal width scaling with $\rho_{i\theta}$ predicts that $\Delta_H = \Delta_D / \sqrt{2}$

Pedestal width scaling with β_θ^{ped} predicts that $\Delta_H = \Delta_D$

Ion toroidal or poloidal gyroradius scaling is not a good description of the measured widths





Circles from test of EPED1 (predictive pedestal model)
Star (triangle) from D (H) ITER baseline demo
Black lines are best power law fits to data

Predictive Pedestal Height Model

A new pedestal model has been developed to predict pedestal width and height

- **Model combines peeling-ballooning theory and empirical width model**
  - Peeling-ballooning theory computes limits of pedestal height
  - Width model is $\Delta = 0.076\ (\beta_\theta^{ped})^{1/2}$ where Δ is measured in ψ_N
- **Model is called EPED1**
  - Model self-consistently advances Δ and β_θ^{ped} until pedestal pressure reaches Type I ELM threshold
- **Current version of model assumes** $T_i=T_e$, $n_i=n_e$, $p_i=p_e$
- **Model evaluates width and height from**
  - $\Delta = 1/2(\Delta_{ne} + \Delta_{Te})$
  - $p^{ped} = 2\ n_e^{ped}\ T_e^{ped}$
  - These are most easily measured pedestal parameters

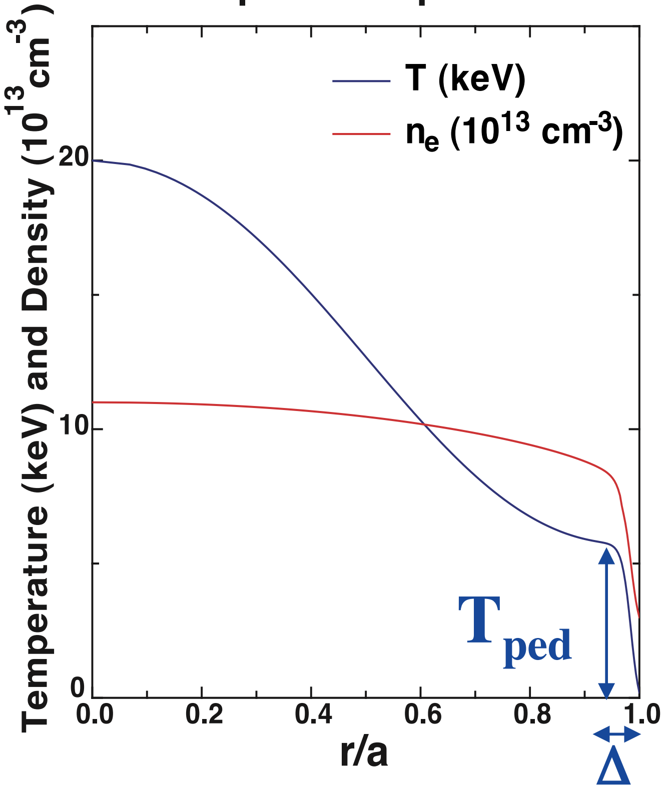
Pedestal model self-consistently increases ped width, gradient and height until MHD stability violated

Inputs to the model are B_t, I_p, R, a, κ, δ, n_e^{ped}, β_θ **(plus standard profile shapes)**

$$n_e(\psi) = n_{sep} + a_{n0}\{\tanh[2(1-\Psi_{mid})/\Delta] - \tanh[2(\Psi-\Psi_{mid})/\Delta]\} + a_{n1}[1-(\Psi/\Psi_{ped})^{\alpha_{n1}}]^{\alpha_{n2}}$$

$$T(\psi) = T_{sep} + a_{T0}\{\tanh[2(1-\Psi_{mid})/\Delta] - \tanh[2(\Psi-\Psi_{mid})/\Delta]\} + a_{T1}[1-(\Psi/\Psi_{ped})^{\alpha_{T1}}]^{\alpha_{T2}}$$

Sample ITER profiles



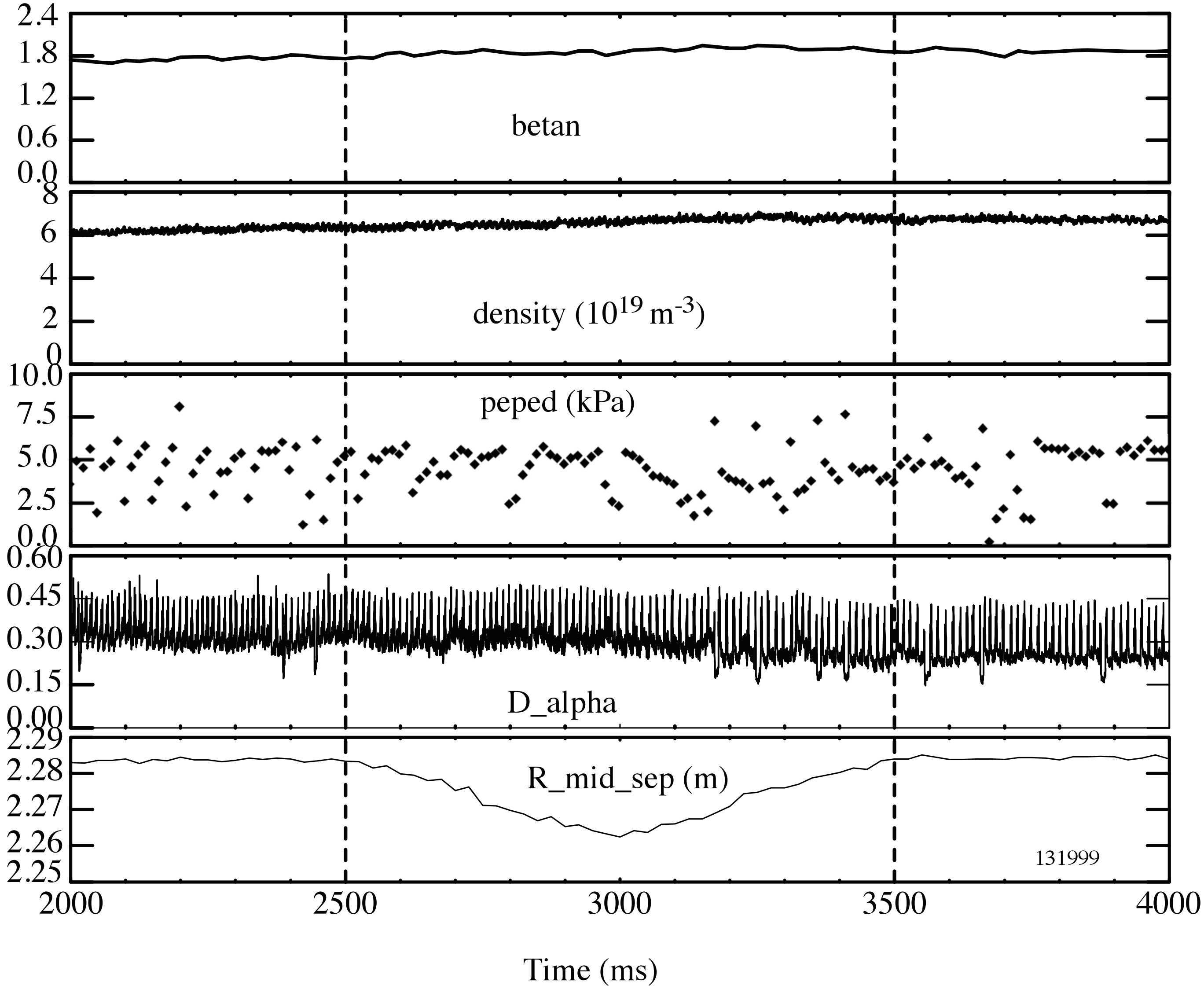
- **Machinery: Construct a series of TOQ equilibria with increasing pedestal height from inputs and width from**
  - $\Delta = 1/2(\Delta_{ne} + \Delta_{Te}) = 0.076\ (\beta_\theta^{ped})^{1/2}$
  - Current is assumed fully relaxed: includes Ohmic plus Sauter collisional bootstrap model
- **Evaluate n=5-30 stability with ELITE until stability boundary reached** $(\gamma > \omega_{*pi}/2)$
- **Outputs: pedestal height and width at threshold for Type I ELM**

Testing Pedestal Height Model

Experiment was performed to test the predictive pedestal height model

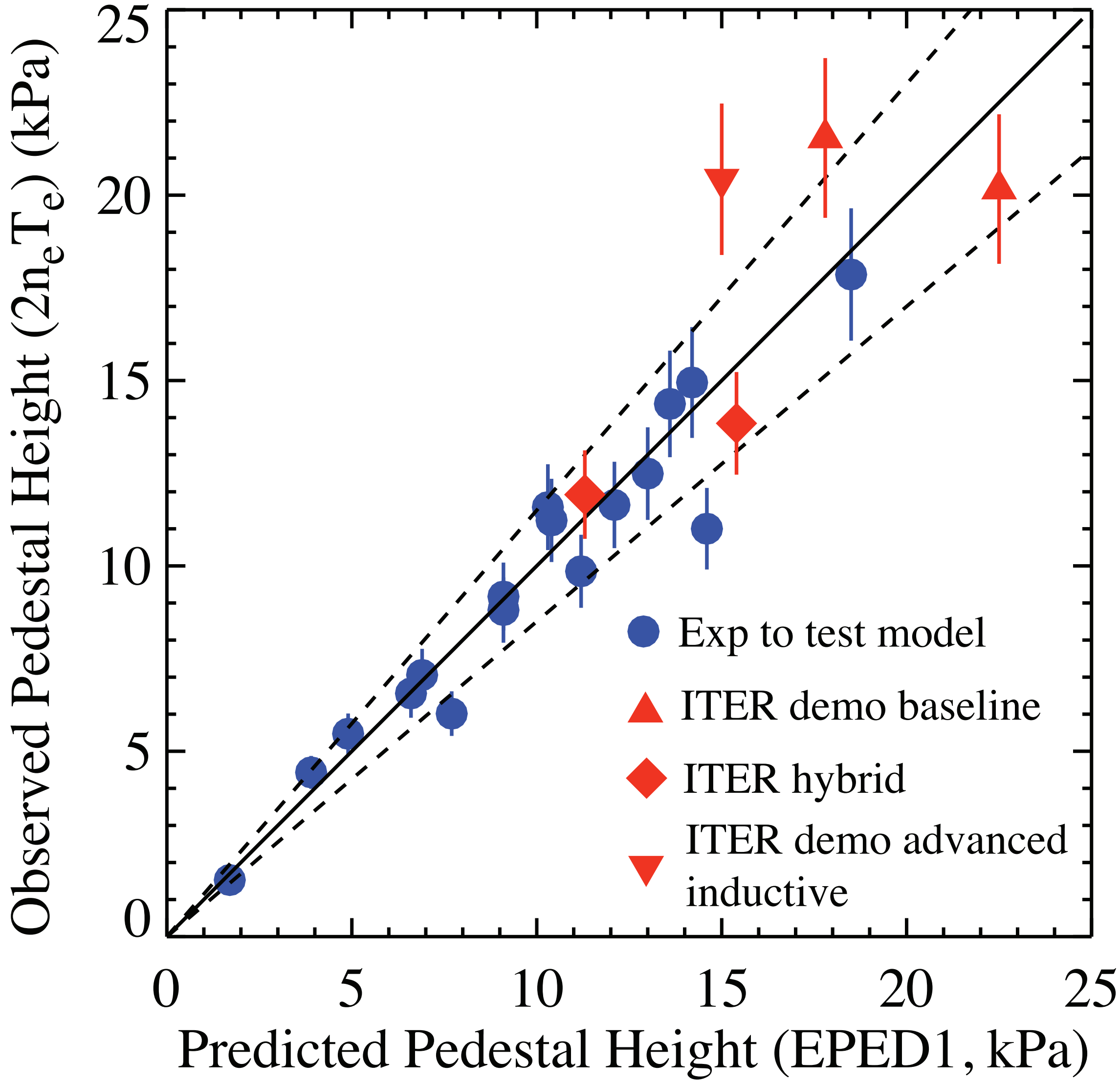
- **Experiment varied** I_p, B_t, δ_{ave} **by factor of 3 each**
  - I_p = 0.5-1.5 MA at B_t=2.1 T, δ_{ave} = 0.2
  - I_p /B_t = 0.5MA/0.7T - 1.5 MA/2.1T at δ_{ave} = 0.2
  - δ_{ave} = 0.2 = 0.55 at I_p/B_t= 1.16MA/2.1T
  - I_p = 0.5-1.5 MA at B_t=2.1 T, δ_{ave} = 0.55
  - I_p /B_t = 0.5MA/0.7T - 1.5 MA/2.1T at δ_{ave} = 0.55
- **Pedestal height was varied by more than a factor of 10 and width by more than a factor of 3**
- **Predictions of pedestal height and width were made with the model prior to the experiment**
  - Predictions were accurate to ~10-15%
- **Results are presented for model evaluated with actual values of** R, a, κ, δ, n_e^{ped}, β_θ **that were achieved**

Long steady stated discharges used to obtain high quality pedestal profiles



- Take data when global plasma parameters steady for ~ $3\tau_E$
- Pedestal data selected from times just before ELM crash
- Sweep of separatrix location used to improve pedestal resolution

Average ratio of predicted to observed pedestal pressure height in experiment was 1.03 +/-0.13



Widths evaluated just before Type I ELM crash

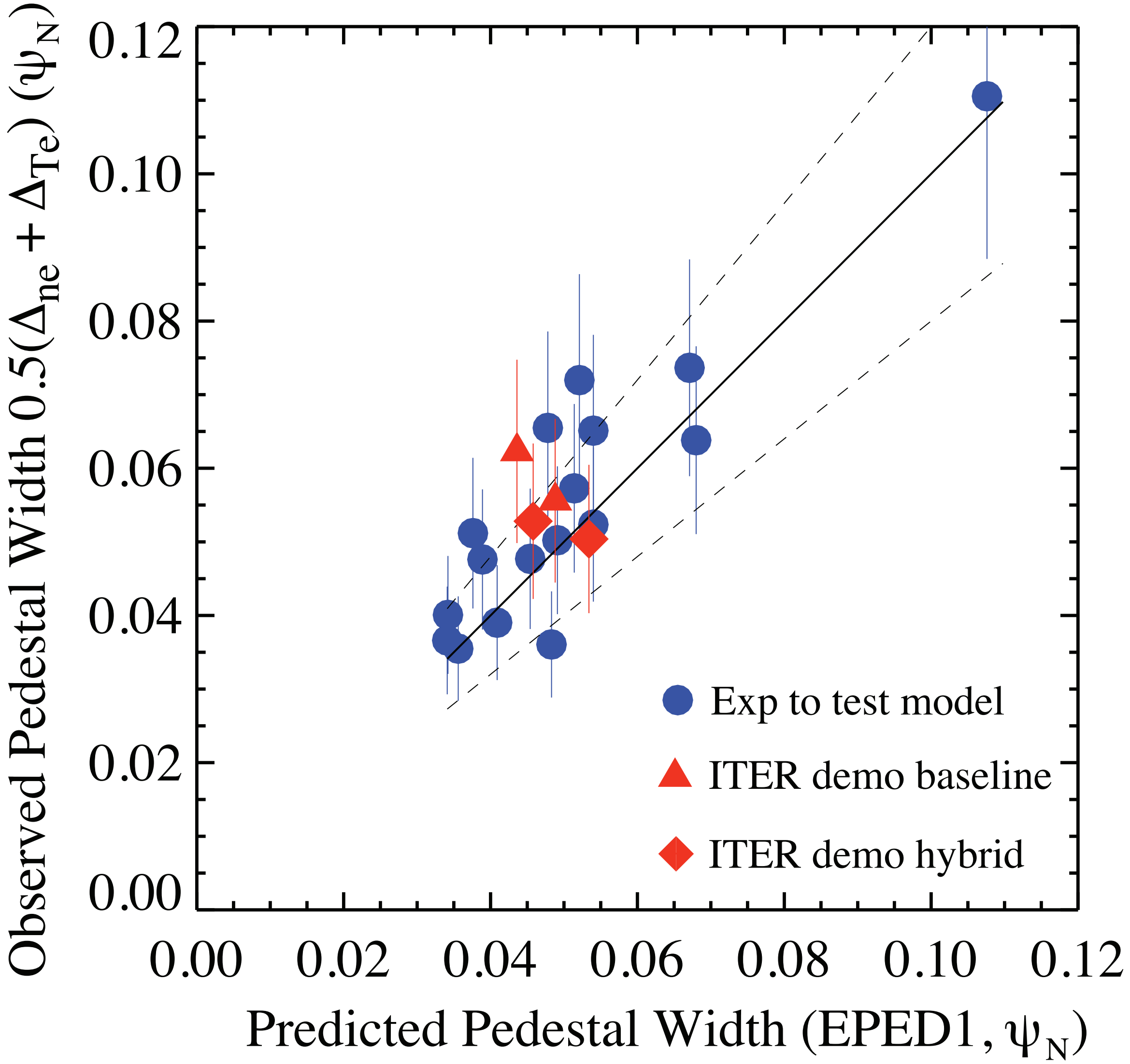
Blue circles are data from experiment in DIII-D to test EPED1

Red points are from ITER demo discharges performed in DIII-D

Solid line is unity line

Dashed lines are +/-15% from unity

Average ratio of predicted to observed pedestal width in experiment was 0.93 +/-0.15



Widths evaluated just before Type I ELM crash

Blue circles are data from experiment in DIII-D to test EPED1

Red points are from ITER demo discharges performed in DIII-D

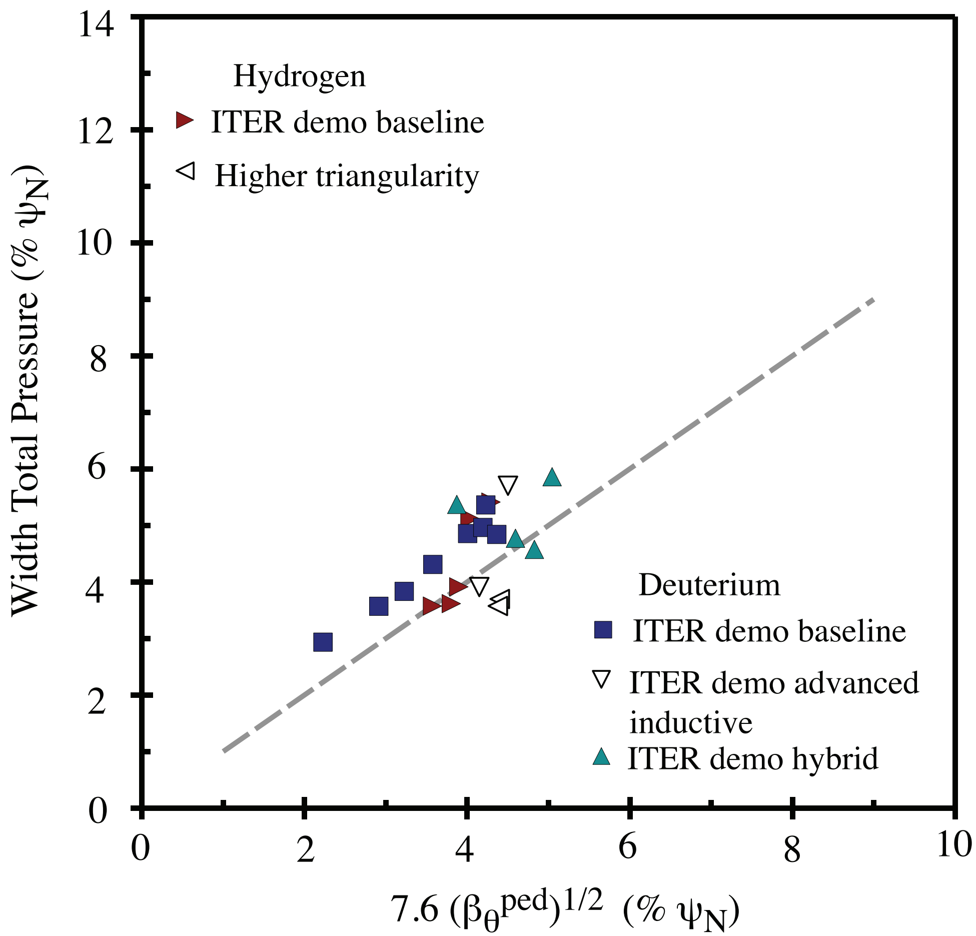
Solid line is unity line

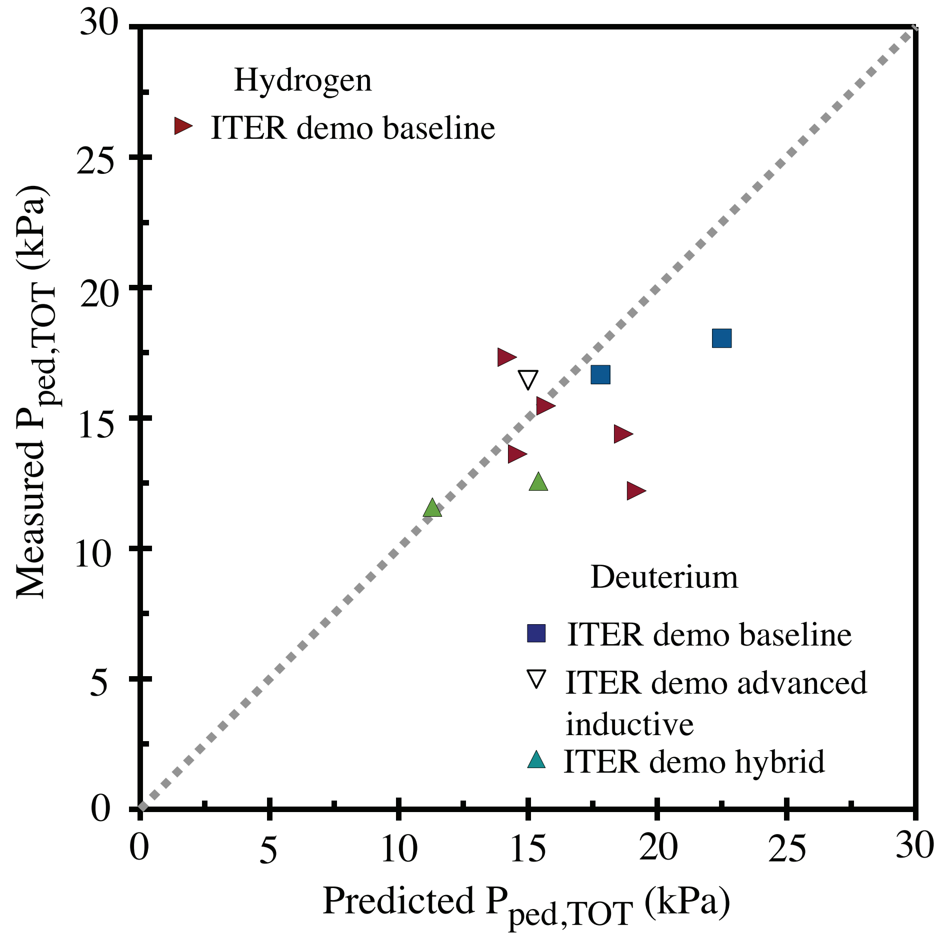
Dashed lines are +/-20% from unity

Pedestal characteristics in ITER demonstration discharges are described by model

- **Demonstration discharges have been made in DIII-D to study ITER baseline, advanced inductive, hybrid and steady state scenarios** (Doyle, EX/1-3)
  - Discharges run at planned ITER shape, q and β
- **Pedestal characteristics for ITER demo discharges are "normal" compared to other DIII-D H-mode data**
  - Widths are close to the scaling $\Delta = 0.076\ (\beta_\theta^{ped})^{1/2}$, where Δ_{ptot} and $\Delta = 1/2(\Delta_{ne} + \Delta_{Te})$ are used for width
  - EPED1 model predicts pedestal pressure for ITER demo discharges with about same accuracy as for model validation data

Widths and heights of ITER demo and Hydrogen discharges have been compared to EPED1 model



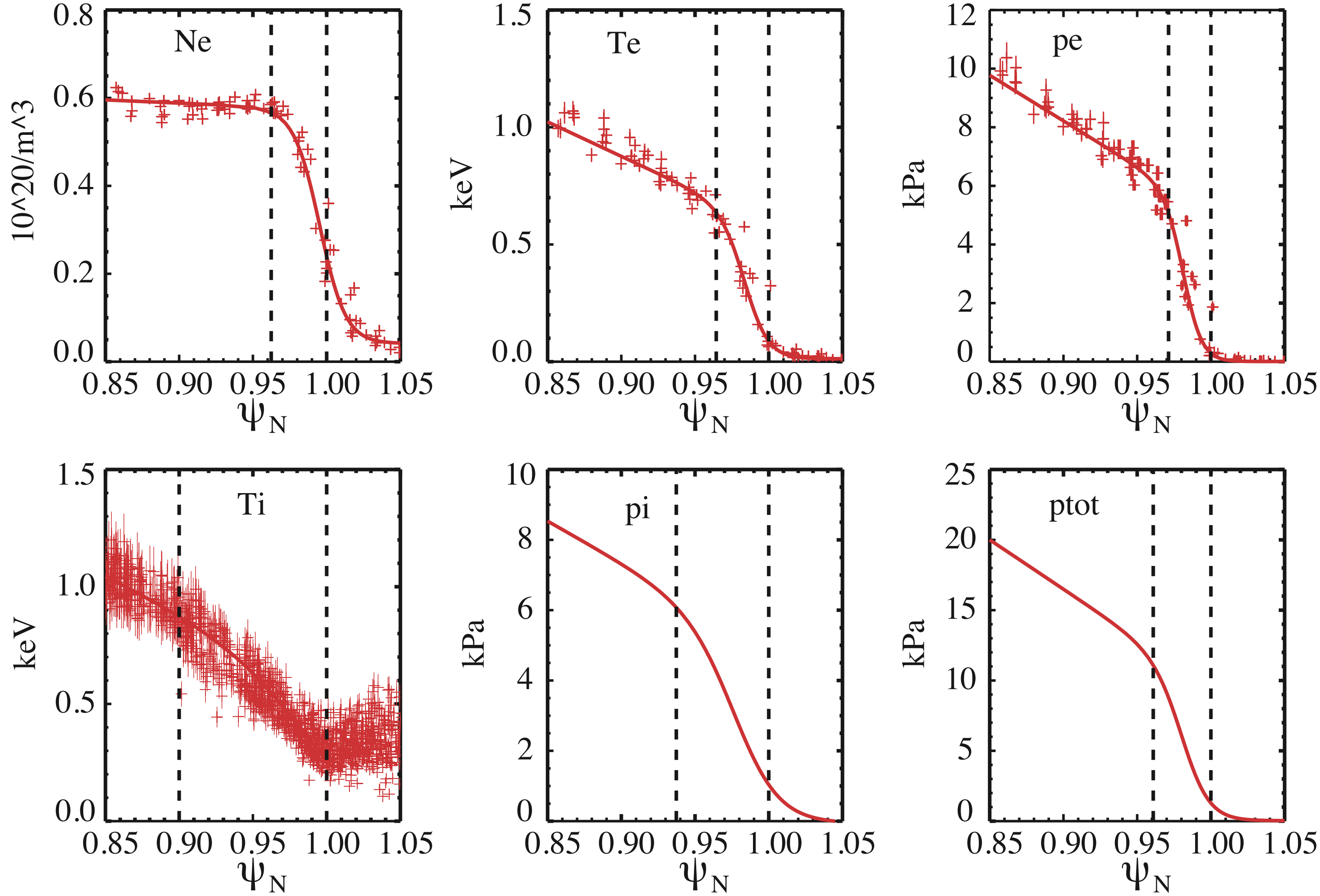


Sensitivity Studies

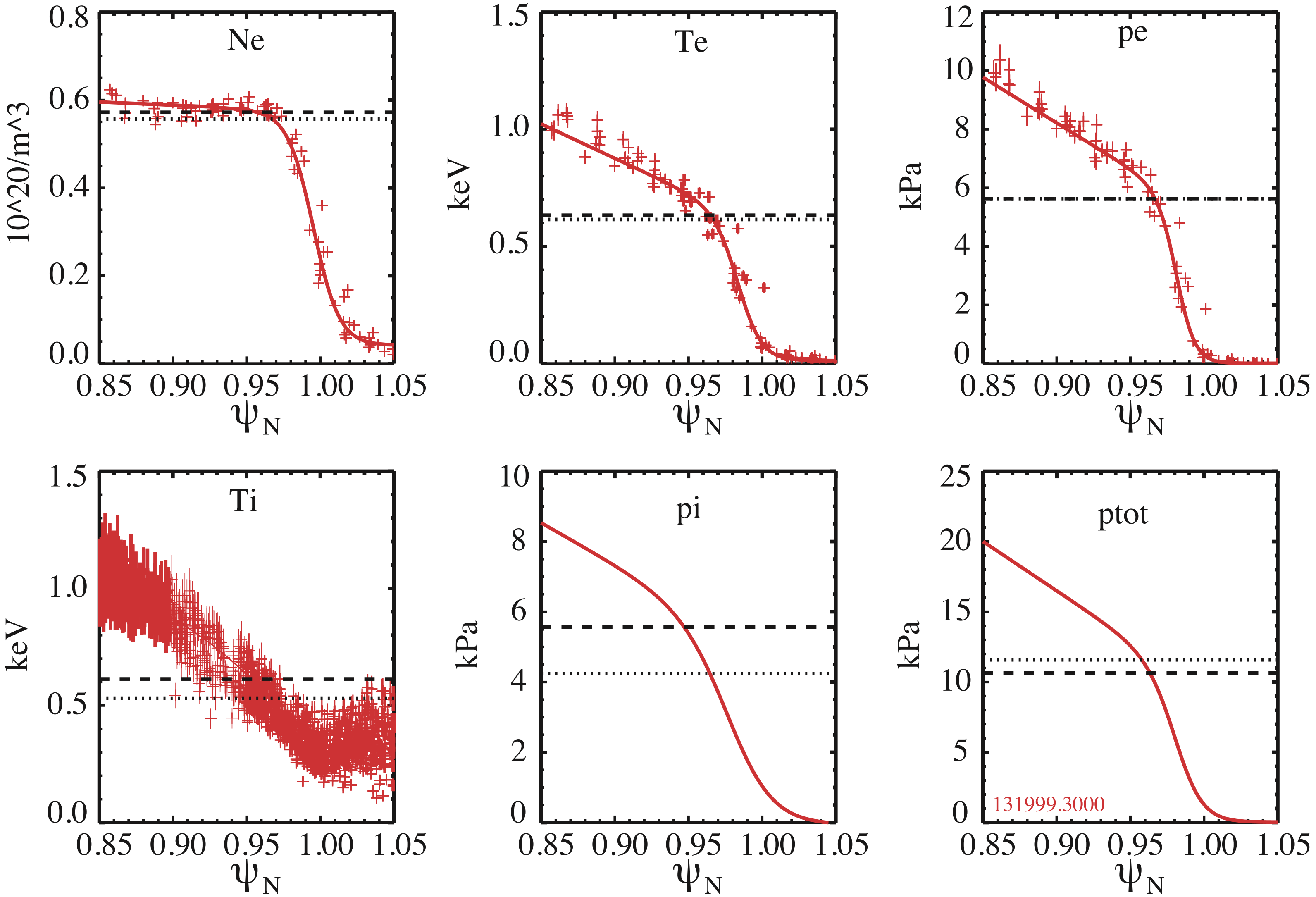
The model defines width and height in a specific way, but other definitions are possible

- **Model defines pedestal width as** $\Delta = 0.5(\Delta_{ne} + \Delta_{Te})$
  - Typically, different profiles have different widths; there is not a unique width which applies to all profiles
  - Some widths difficult to obtain from tanh because profiles do not exhibit sharp break in gradient expected from a tanh
  - Another measure of "pedestal width" would be total pressure width – this is more difficult to determine than Δ_{ne} or Δ_{Te}
- **Model defines pedestal pressure height as** $2\, n_e^{ped}\, T_e^{ped}$
  - There is an assumption that T_i=T_e, n_i=n_e
  - This definition is a robust way to obtain an approximate total pedestal pressure
  - Actual measurements of pedestal pressure tend to be lower than this estimate, mainly because $n_i < n_e$

Different pedestal parameters have different widths



Pedestal height defined either from tanhfit fit or from profile value at location of peped

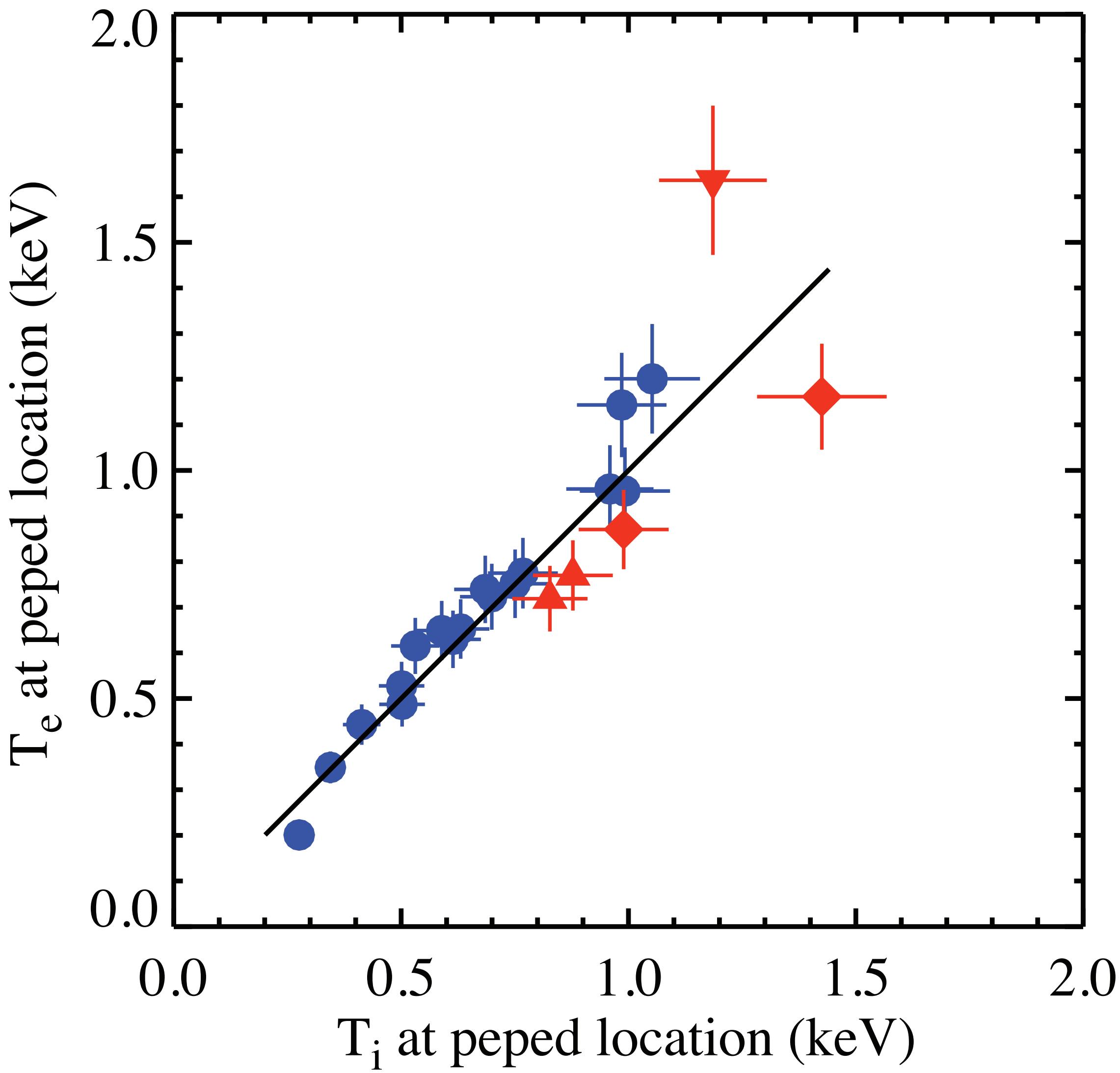


Dashed lines are heights from tanh fits to each profile

Dotted lines are heights from evaluating profile fit at location where

$p_e = p_e^{ped}$

Pedestal values of T_e and T_i are usually close, when they are evaluated at same location



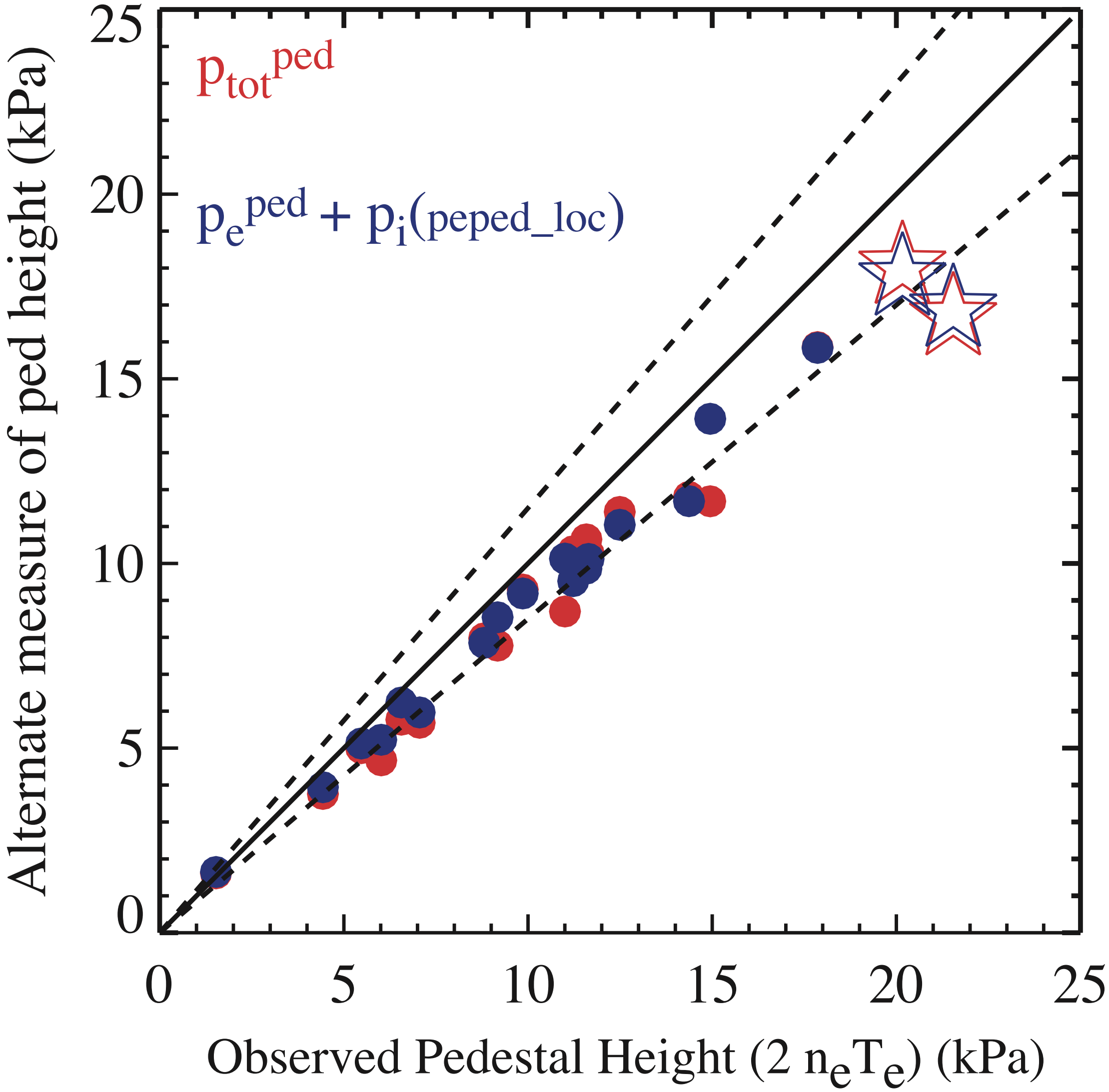
Data evaluated at location where $p_e = p_e^{ped}$

Circles from test of EPED1 in DIII-D

Stars from ITER demo discharges run in DIII-D

Solid line is unity line

Two definitions of pressure height give slightly lower numbers than 2 n_e^{ped} T_e^{ped}



p_{tot}^{ped} is ped height from tanh fit of total pressure

p_e^{ped} is ped height from tanh fit of electron pressure

p_i(peped_loc) is ion pressure where $p_e = p_e^{ped}$

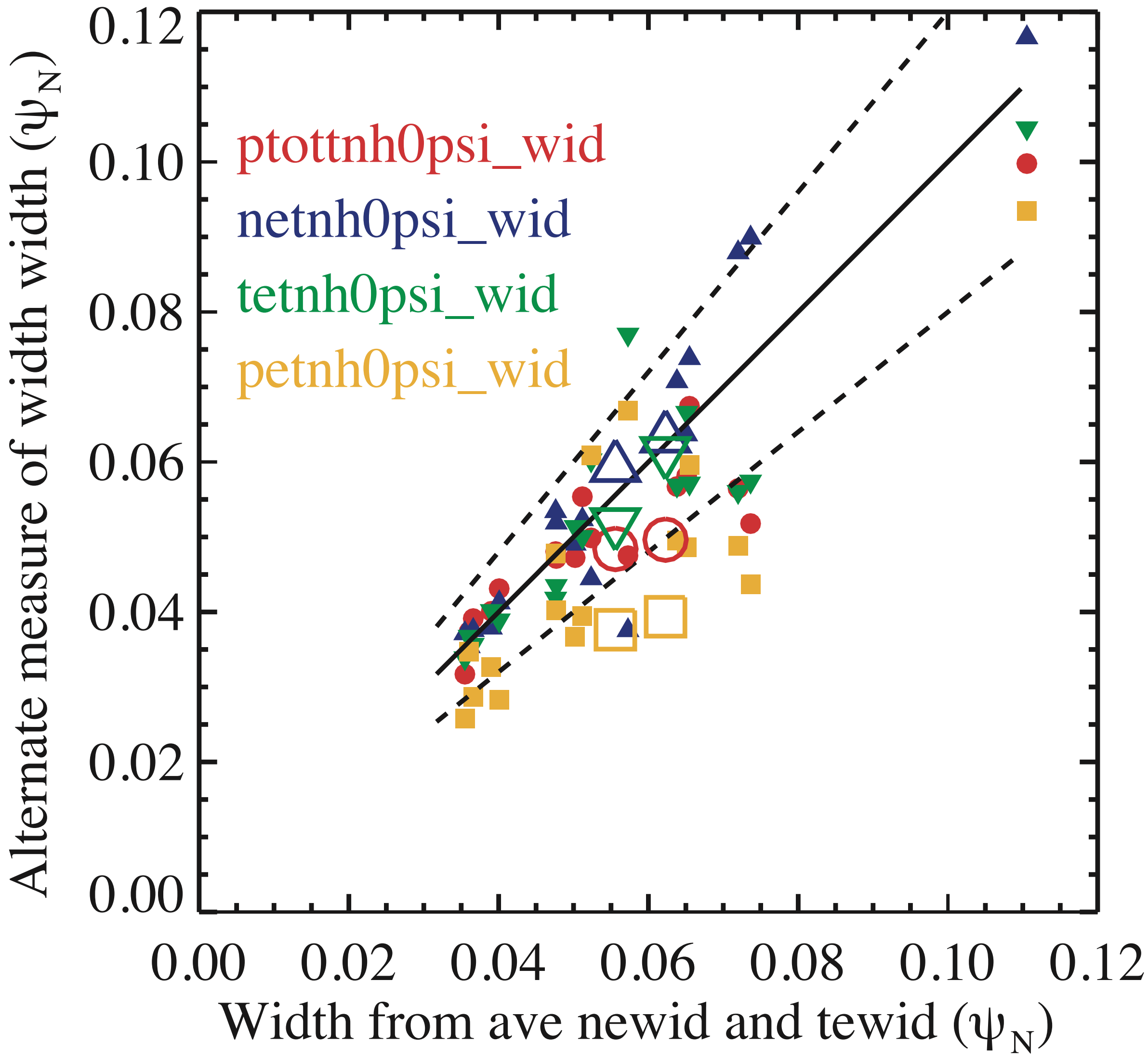
Circles from test of EPED1

Stars from ITER baseline demo

Solid line is unity line

Dashed line is +/- 10%

Different measures of width are typically within ~ 20% of one another



Filled symbols from test of EPED1

Open symbols from ITER baseline demo

Solid line is unity line

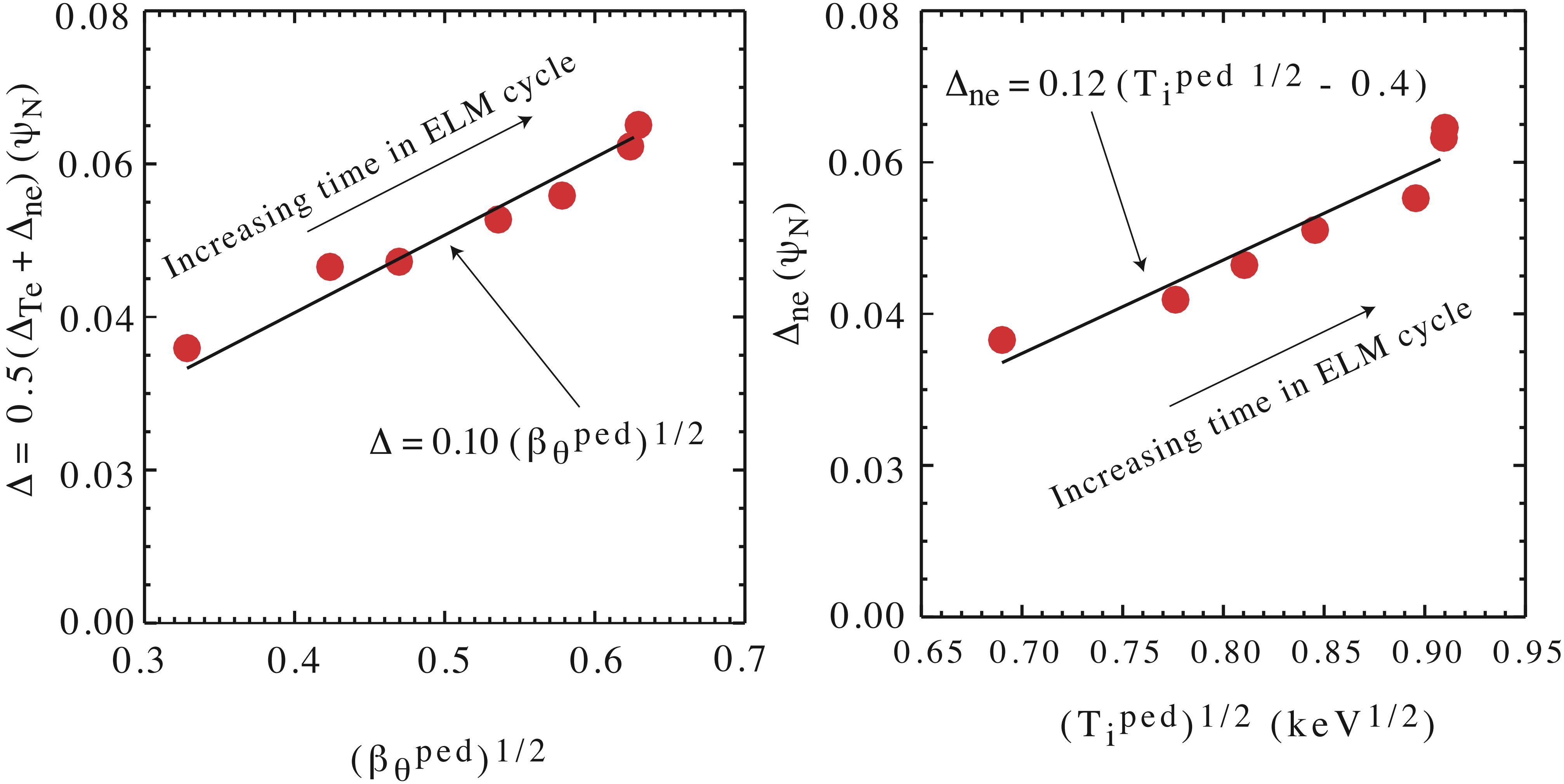
Dashed line is +/- 20%

Temporal Evolution of Pedestal

Pedestal increases in width and height during ELM cycle in many DIII-D discharges

- **Pedestal shows continual growth in width and height during ELM-free or inter-ELM periods in many discharges**
  - Effect is particularly noticeable in Δ_{ne}
- **The correlation** $\Delta = C\ (\beta_\theta^{ped})^{1/2}$ **has been observed, where** C **is close to** 0.076
  - The empirical scaling used in the EPED1 model
- **Also, the correlation** $\Delta_{ne} \sim (T_i^{ped})^{1/2}$ **has been observed**
  - A scaling from the XGC0 code - Chang, *et al.*, Bull. Am. Phys. Soc. 49, 314 (2004)
- **Thus, the width scaling observed just prior to an ELM crash** ($\Delta = 0.076\ (\beta_\theta^{ped})^{1/2}$) **might be a result of an inherent temporal growth of pedestal**
  - Growth is interrupted by an ELM

Growth of pedestal width observed during inter-ELM period



Summary and conclusions

- **Best pedestal scaling in DIII-D** is $\Delta = 0.076\ (\beta_\theta^{ped})^{1/2}$
  - Scalings based on ρ_i or $\rho_{i\theta}$ do not work well
  - Pedestal experiment in H and D plasmas supports these results
- **A model of pedestal height and width has been developed from the** $(\beta_\theta^{ped})^{1/2}$ **scaling and peeling-ballooning MHD theory**
  - This model predicts well the pedestal height and width in an experiment where p^{ped} was varied by more than 10X
  - Model predicts other discharges, including ITER demo plasmas
  - Model predicts T_i^{ped} = 4.6 keV in ITER (see Snyder IT/P6-14)
- **Growth of pedestal width and height has been observed in some inter-ELM phases**
  - Pedestal approximately follows $\Delta \sim (\beta_\theta^{ped})^{1/2}$ scaling
  - Thus, Δ scaling with $(\beta_\theta^{ped})^{1/2}$ at ELM crash might be a consequence of inter-ELM pedestal growth