Development and Validation of a Predictive Model for the Pedestal Height (EPED1)

P.B. Snyder[1] with R.J. Groebner[1], A.W. Leonard[1], T.H. Osborne[1], M. Beurskens[3], L.D. Horton[4], A.E. Hubbard[5], J.W. Hughes[5], Y. Kamada[2], A. Kirk[3], C. Konz[4], C.F. Maggi[4], N. Oyama[2], S. Saarelma[3], J.L. Terry[5], H. Urano[2], H.R. Wilson[6]

[1]*General Atomics, San Diego CA, USA*

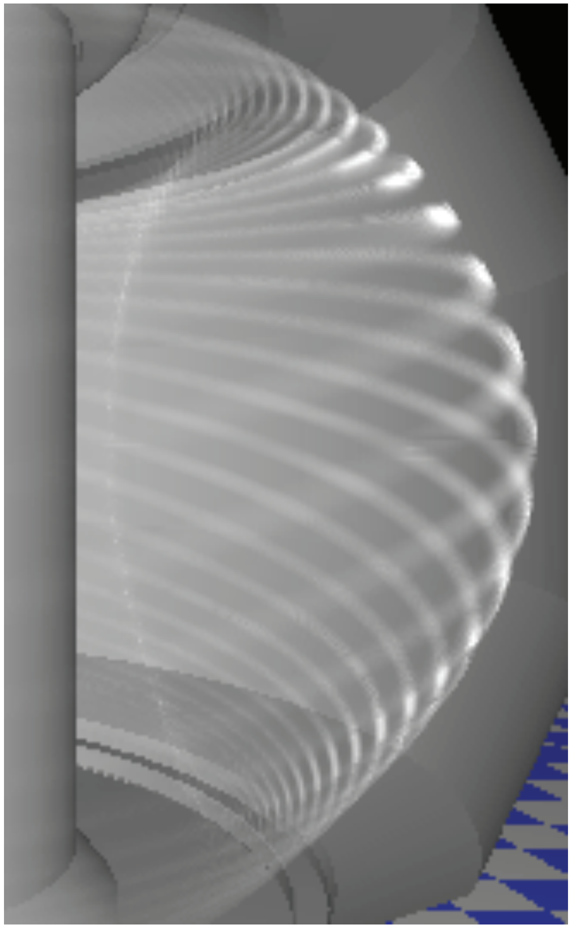
[2]*Fusion Research and Development Directorate, JAEA, Naka, Ibaraki, Japan*

[3]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK*

[4]*MPI für Plasmaphysik, EURATOM Association, Garching, Germany*

[5]*MIT Plasma Science and Fusion Center, Cambridge, Massachusetts, USA*

[6]*University of York, York, UK*



Presented at the
50th APS Annual Meeting of
the Division of Plasma Physics
Dallas, Texas

November 17–21, 2008

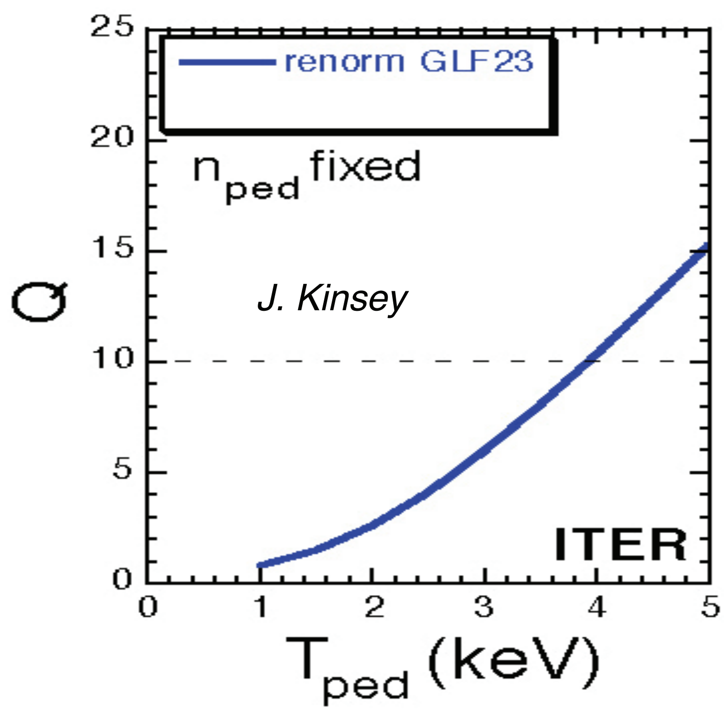
DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

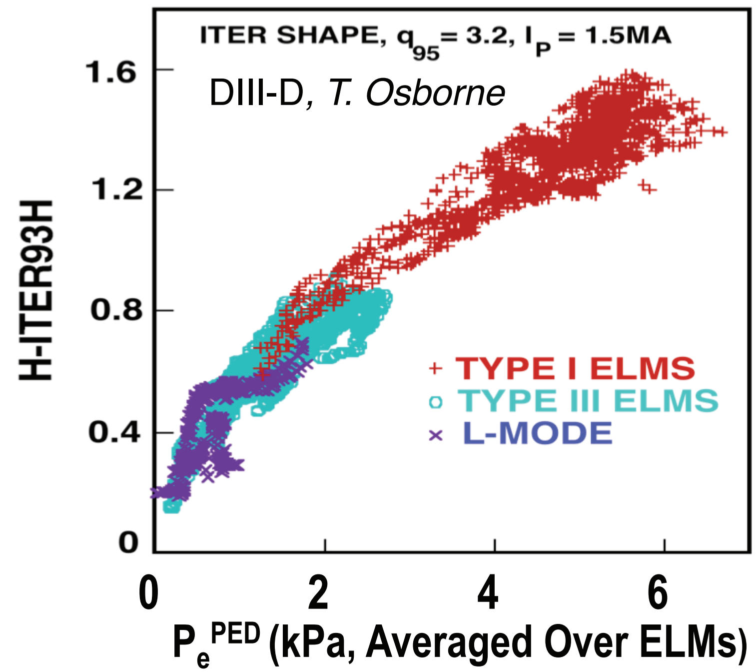
Motivation: Importance of the Pedestal Height and ELMs

- Fusion performance (Q) increases strongly with pedestal height (p_{ped}) due to stiff core transport
- Large Edge Localized Modes (>1MJ) can constrain material lifetimes on ITER
- Accurate prediction of both pedestal height and ELM behavior is essential to assess and optimize ITER performance

Predicted Impact of Pedestal Height



Observed Impact of Pedestal Height



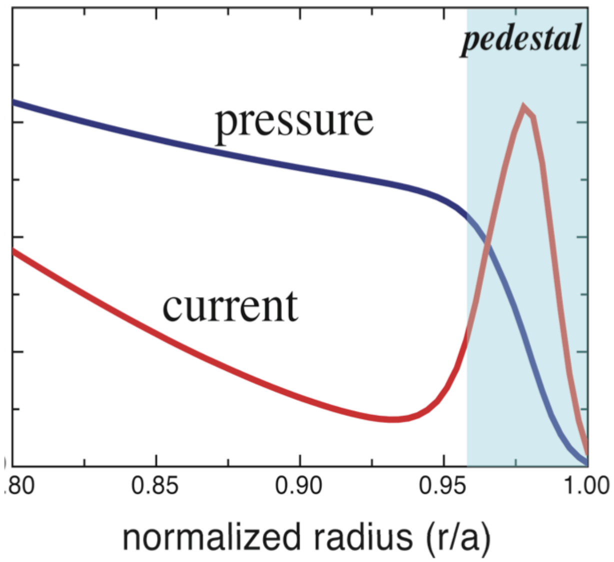
Combine Stability and Width Physics to Yield Predictive Model of the Pedestal

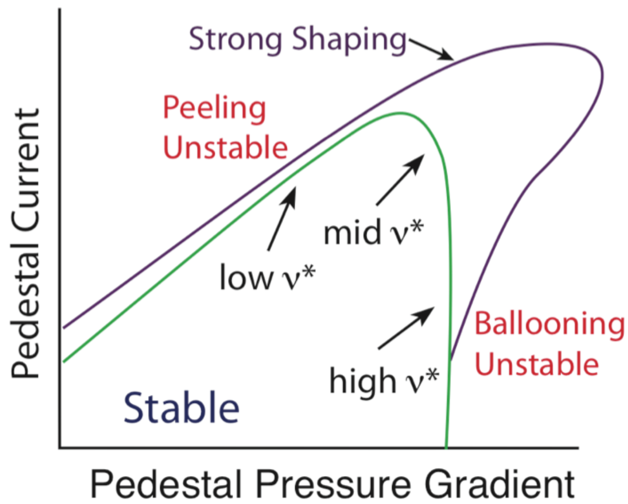
Develop a predictive pedestal model, incorporating what we know about width and stability physics, while remaining simple enough to be predictive and clear

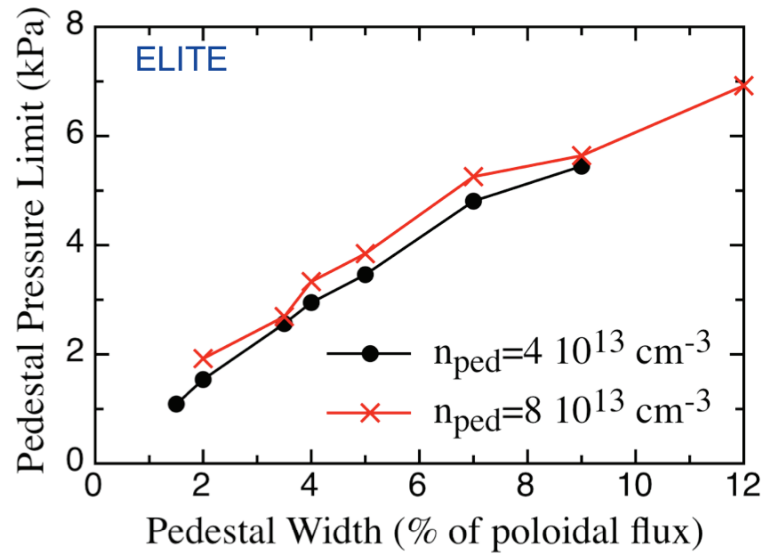
1. **Pedestal Stability and the Peeling-Ballooning Model**
   – Constraint on pedestal height as function of width
2. **Pedestal Width Models and Observations**
   – Second relation between width and height
3. **Development of the Predictive Model (EPED1)**
   – 2 "equations" for 2 unknowns: pedestal height and width
4. **Tests of EPED1 and Predictions for ITER**

Peeling-Ballooning Theory and Validation

The Peeling-Ballooning Model Explains ELM Onset and Pedestal Height Constraint



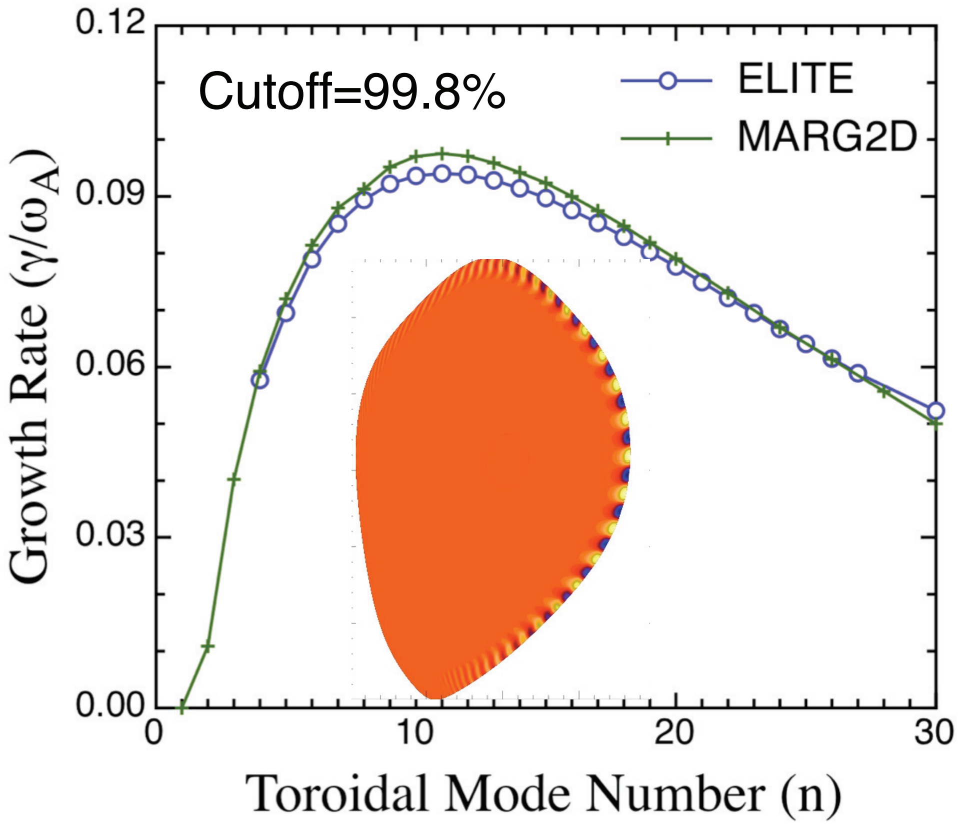




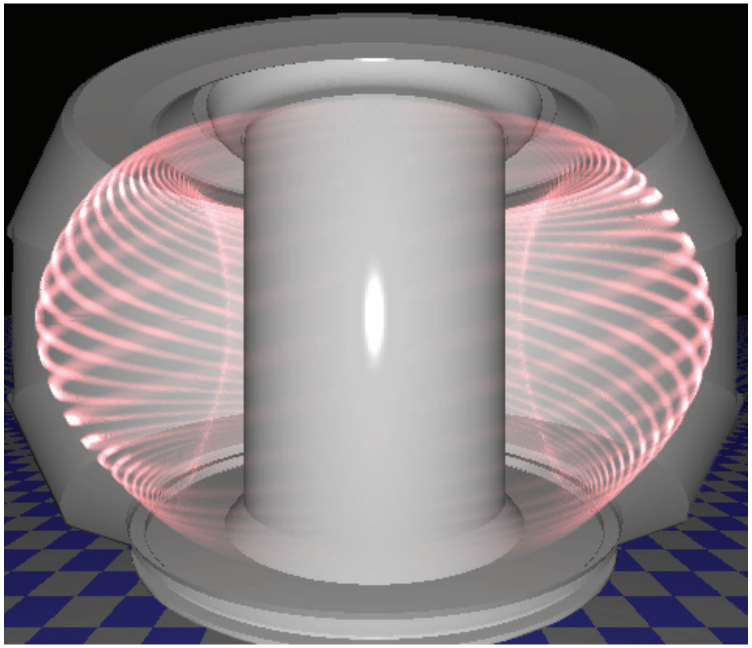
- **Standard ("Type I") ELMs caused by intermediate wavelength (n~3-30) MHD instabilities, which constrain the pedestal height**
  - Driven by sharp pressure gradient and bootstrap current in the edge barrier ("pedestal")
  - Complex dependencies on ν_*, shape etc. due to bootstrap current and "2nd stability"
  - P-B stability limit increases with pedestal width (Δ), but not linearly (roughly $\beta_{Nped} \sim \Delta^{3/4}$)

Efficient Codes Accurately Calculate Peeling-Ballooning Stability

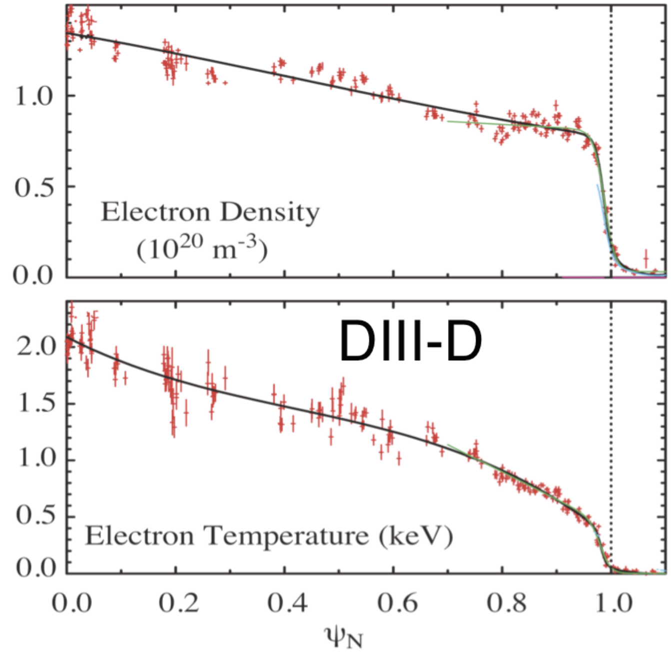
- **Range of complementary MHD codes available**
  - ELITE derived from an extension of high-n theory to incorporate intermediate-n modes
    - Will be used in EPED1
- **Extensive successful benchmarks have been carried out between codes**
  - Good agreement in both limiter and near-separatrix geometry

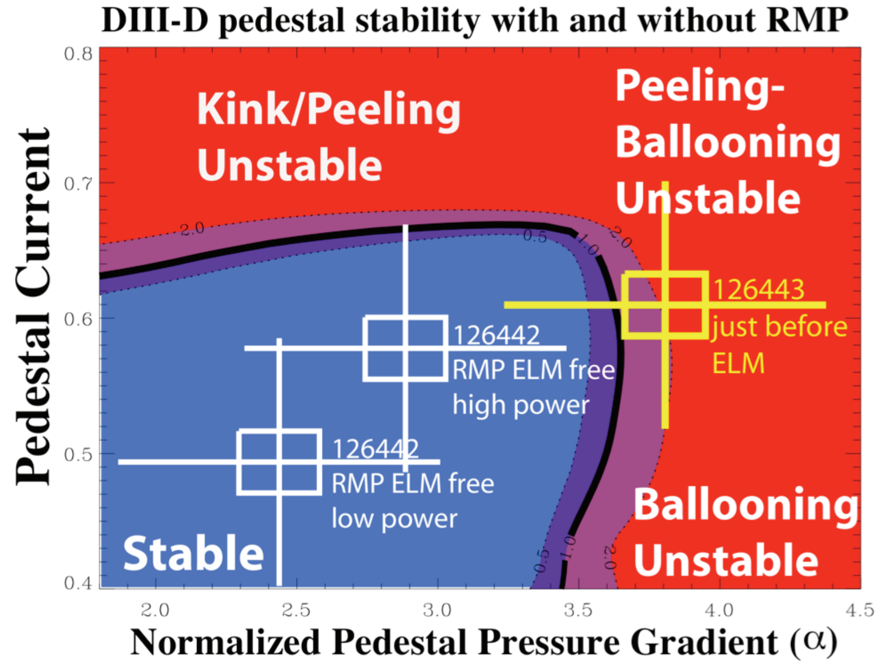


n=18 peeling-ballooning mode structure in DIII-D (ELITE)



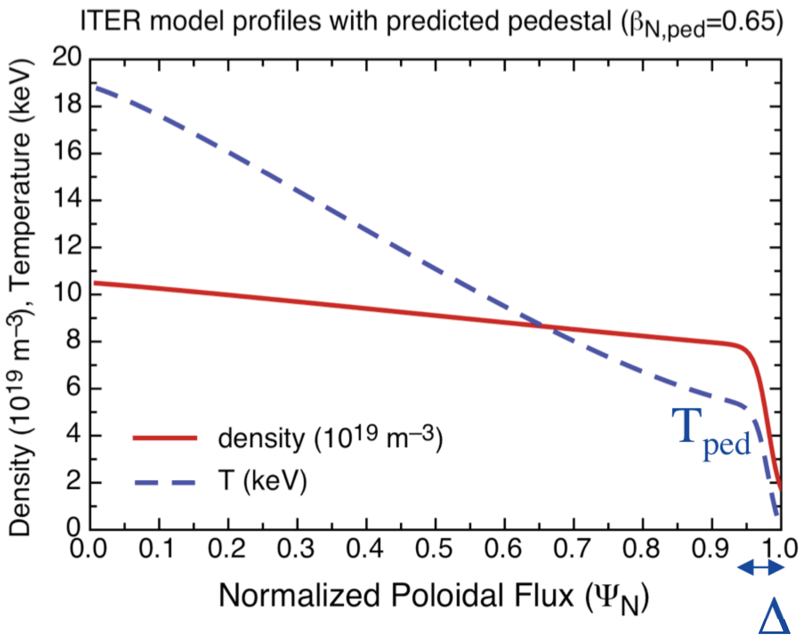
Peeling-Ballooning Model Extensively Validated Against Experiment

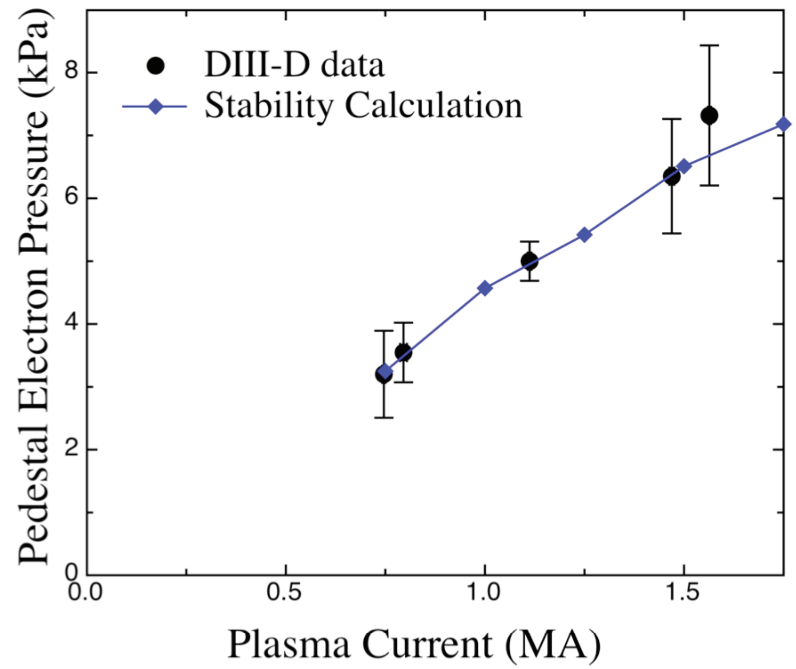




- **High resolution diagnostics allow routine, accurate profile measurements across the edge barrier**
  - Reconstruct accurate equilibrium with J_{bs}, perturb to find stability boundary
- **Onset of each (Type I) ELM consistently found to correlate to crossing the P-B stability boundary**
  - Pedestal height changes with changes in edge stability (shape, q, ν^*…)
  - Statistically validated in large studies (1.05 ±0.19 for 39 DIII-D discharges)
  - Provides upper limit for all types of H-Mode Operation (QH, RMP, TIII, EDA…)

Stability Studies Using Model Equilibria Useful for Predictions in Present and Future Devices





- **For predictions it is useful to conduct pedestal stability analysis on series of model equilibria**
  - Simplified shape and profiles, with tanh pedestal and Sauter bootstrap current
  - Predict pedestal height as a function of (Δ ,B_t, I_p, R, a, κ, δ, $n_{e,ped}$, β_p)
  - Calculations using pedestal width (Δ) as an input find good agreement with observation (model equilibria capturing important stability physics) *[Snyder04]*

Can accurately quantify stability constraint, but need model of the pedestal width for fully predictive pedestal model

Pedestal Width Models and Observations

Pedestal Width Theory Has Progressed Slowly

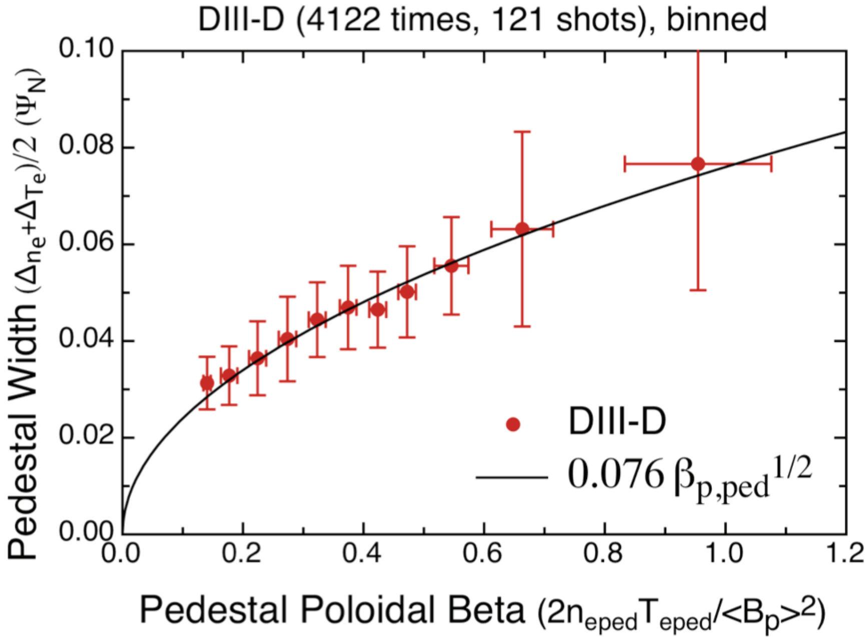
- **Long history of theories of the pedestal width**
  - Most based on ExB suppression of edge turbulence
    - Leads to gyro- and/or banana- radius scaling (not observed)
- **Problems with that approach:**
  - Tells us how barrier formation begins. Want to know what constrains the higher gradients after the barrier is formed
  - Stability constrains both height and width (no steady state)
    - Width generally grows up to ELM, can't calculate without ELM physics

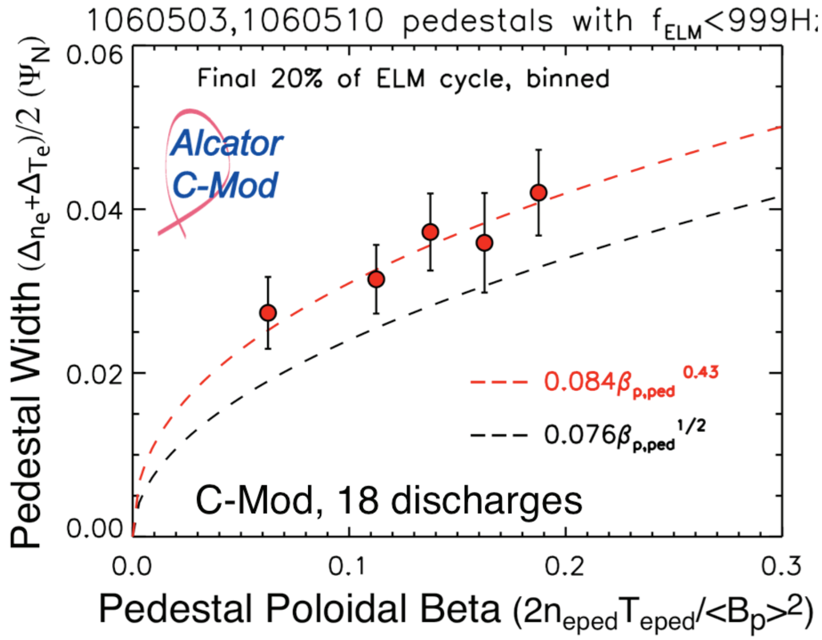
Propose Pedestal Constrained by EM Turbulence near ideal ballooning α_{crit}

- **GF and GK simulations find onset of strongly driven KBM turbulence near ballooning α_{crit}** *[Snyder99, Scott01, Jenko01, Candy05…]*
  - – kinetic effects drive onset slightly below ideal boundary
  - – ExB shear can impact onset somewhat but not suppress
  - – turbulence onset near nominal α_{crit} even with 2nd stability

- **Implies** $\alpha \propto \alpha_c \propto \beta_{p,ped} / \Delta$ $\boxed{\Delta \propto \beta_{p,ped} / \bar{\alpha}}$ (Δ is width in normalized poloidal flux)
  - **Strong dependence of pedestal width on $\beta_{p,ped}$**
  - **Weaker than linear due to ExB and magnetic shear effects, and finite scale effects**
  - **Simulations needed for full quantification not yet feasible, but expect dependence of Δ on $\beta_{p,ped}$ to persist**

A number of experiments find pedestal width scaling with pedestal poloidal beta





- **Scaling of $\Delta_{\psi_N} \propto \beta_{p,ped}^{1/2}$ first found by Osborne99: recent measurements find similar scaling across many machines**
- **DIII-D, C-Mod, MAST, AUG find $\Delta\sim\beta_{p,ped}^{1/2}$ dependence in T1 discharges**
  - Accounting for this dependence, weak dependence on other parameters (q, ν^*, ρ_i, ρ_θ, β)
  - Combining this with P-B stability explains beta (power) & shape observations *[Leonard08]*
- **Isotope variation expts on JT-60U** *[Urano08]*, **DIII-D** *[Groebner08]* **find no dependence of width on mass**
- **JET - DIII-D rhostar scan expts find no/weak rhostar dependence of the width**

Strong support for pursuing model based on $\Delta_{\psi_N} = 0.076\beta_{p,ped}^{1/2}$

A Predictive Pedestal Model (EPED1)

The EPED1 Model Predicts Pedestal Height and Width in Current and Future Experiments

- **Combine insight from theory and observation to develop and test a predictive model for the pedestal**
  - – Keep it simple and ***predictive*** but include essential physics
- **EPED1 consists of 2 hypotheses that together allow a predictive model of the height and width:**

A. *The pedestal height in high performance H-modes is constrained by intermediate-n edge stability*

- *Characterized via n=5-30 stability analysis on series of 2D model equilibria with fixed profile shapes, and a $\gamma > \omega_{*pi}/2$ threshold*

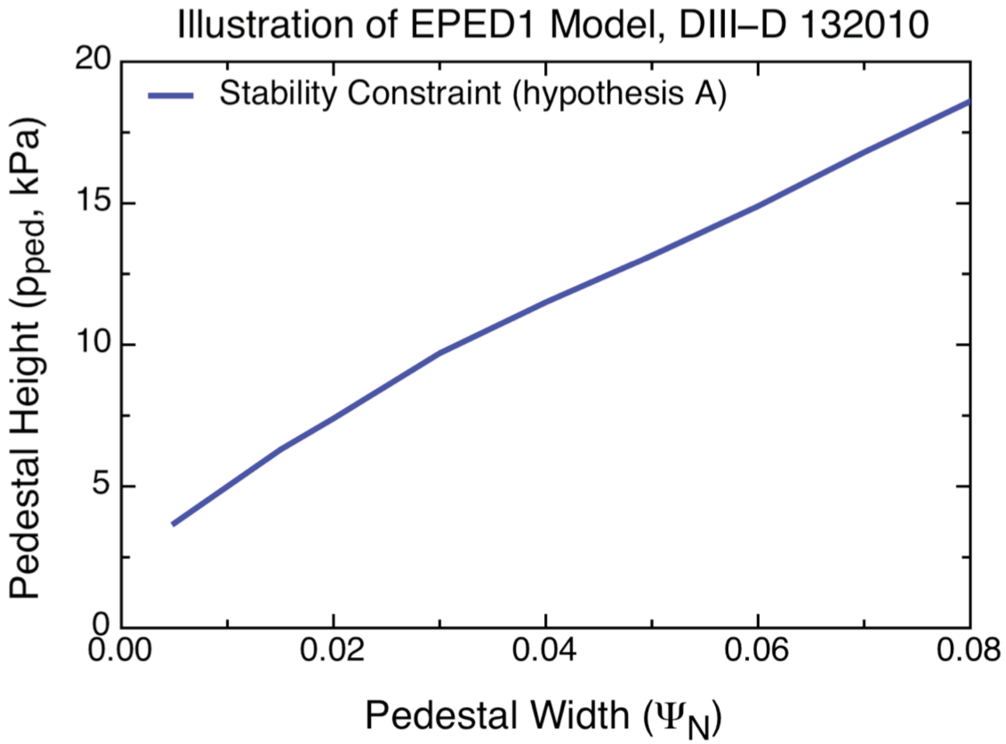
B. *The pedestal width can be characterized as* $\Delta_{\psi_N} = 0.076 \beta_{p,ped}^{1/2}$

- *0.076 constant fixed in EPED1*
- *Width Δ is defined as the average of the n_e and T_e pedestal widths, fit to tanh functions in normalized poloidal flux*

Mechanics of the EPED1 Predictive Model

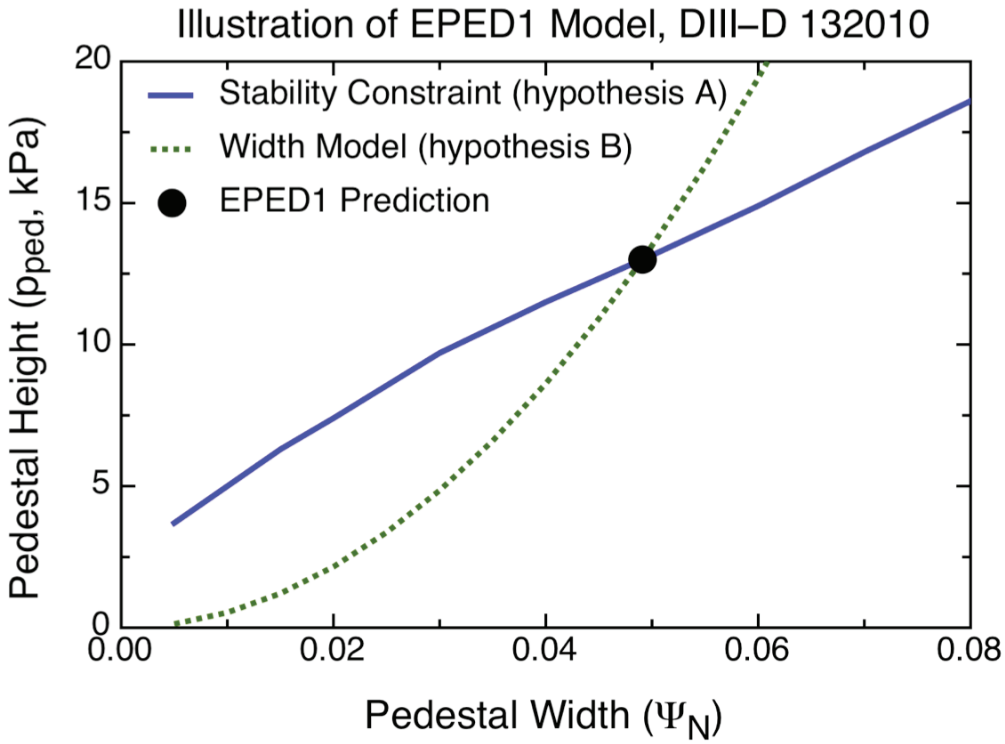
- Input: B_t, I_p, R, a, κ, δ, n_{ped}, β_{global}
- Output: Pedestal height and width

- Stability calculated via a series of model equilibria with increasing pedestal height
  - ELITE, n=5-30



Mechanics of the EPED1 Predictive Model

- Input: B_t, I_p, R, a, κ, δ, n_{ped}, β_{global}
- Output: Pedestal height and width

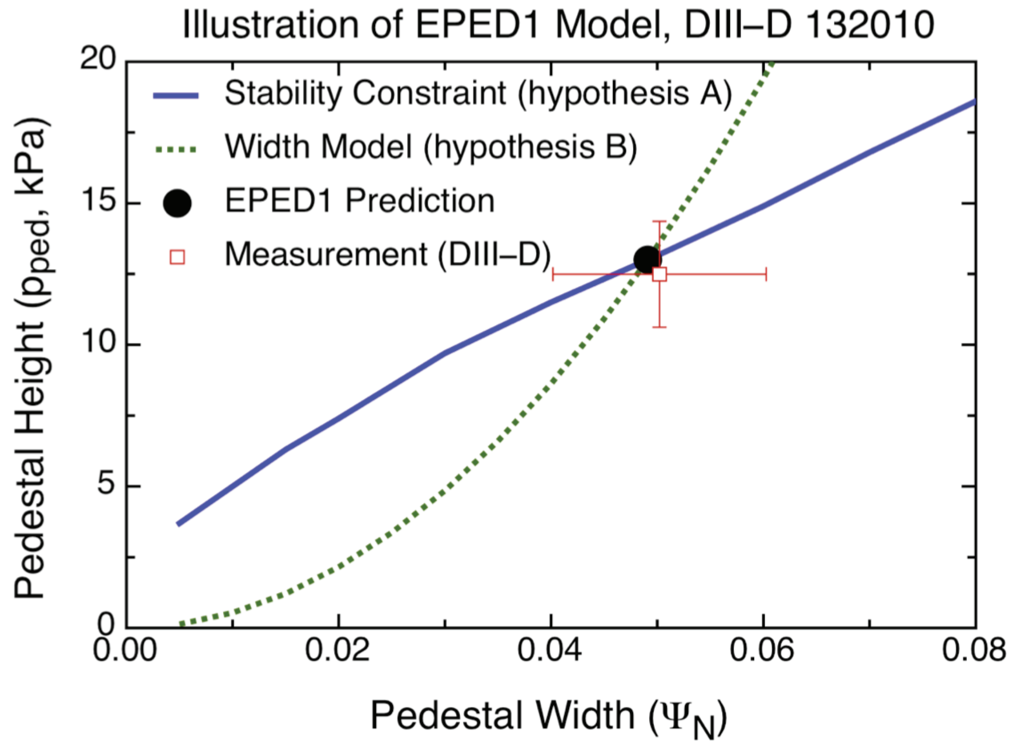


- Stability calculated via a series of model equilibria with increasing pedestal height
  - ELITE, n=5-30
- Width: $\Delta_{\psi_N} = 0.076\beta_{p,ped}^{1/2}$
- Different width dependence of stability (roughly $p_{ped} \sim \Delta^{3/4}$) and width model ($p_{ped} \sim \Delta^2$) ensure unique nontrivial solution, which is the EPED1 prediction (black circle)

Mechanics of the EPED1 Predictive Model

- Input: B_t, I_p, R, a, κ, δ, n_{ped}, β_{global}
- Output: Pedestal height and width

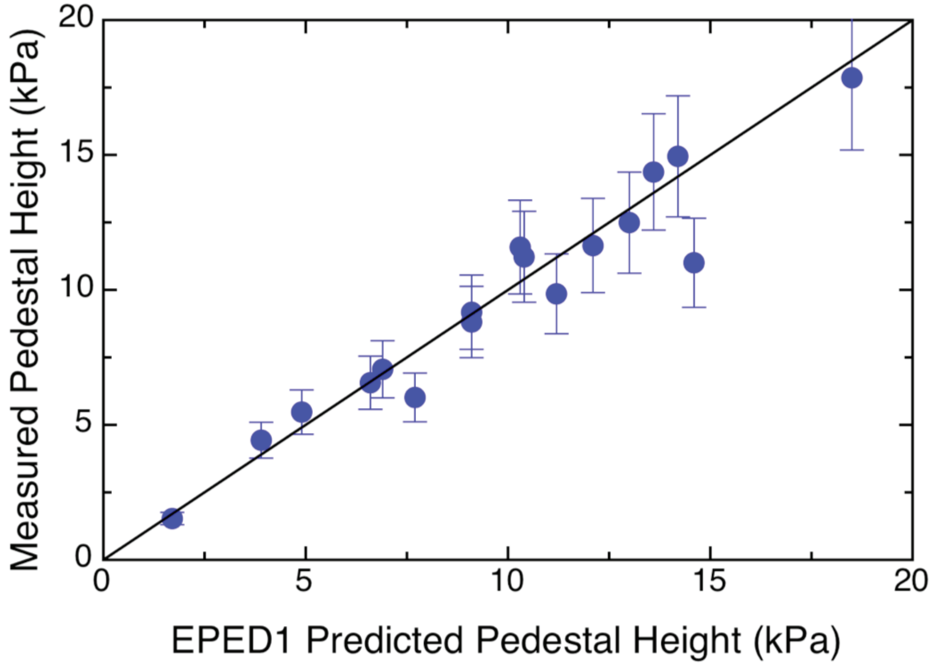
- **Stability calculated via a series of model equilibria with increasing pedestal height**
  - ELITE, n=5-30
- **Width:** $$\Delta_{\psi_N} = 0.076\beta_{p,ped}^{1/2}$$

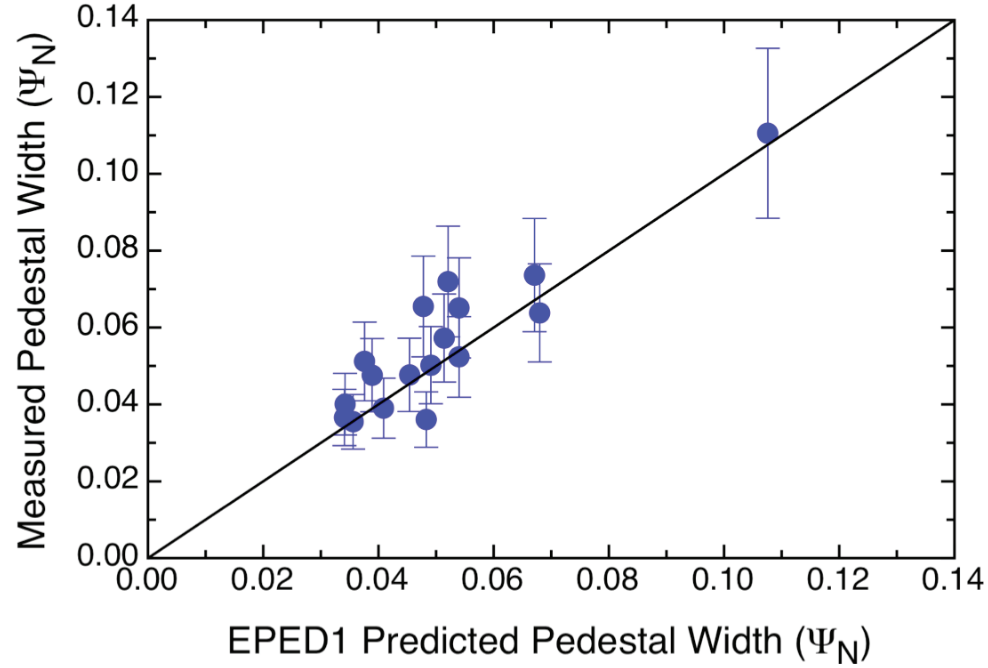


- **Different width dependence of stability (roughly p_{ped}~$\Delta^{3/4}$) and width model (p_{ped}~Δ^2) ensure unique nontrivial solution, which is the EPED1 prediction (black circle)**
  - Can be systematically compared to existing data or future experiments

Stability and width physics are tightly coupled: If either stability or width physics model is incorrect, predictions for both height and width will be systematically incorrect

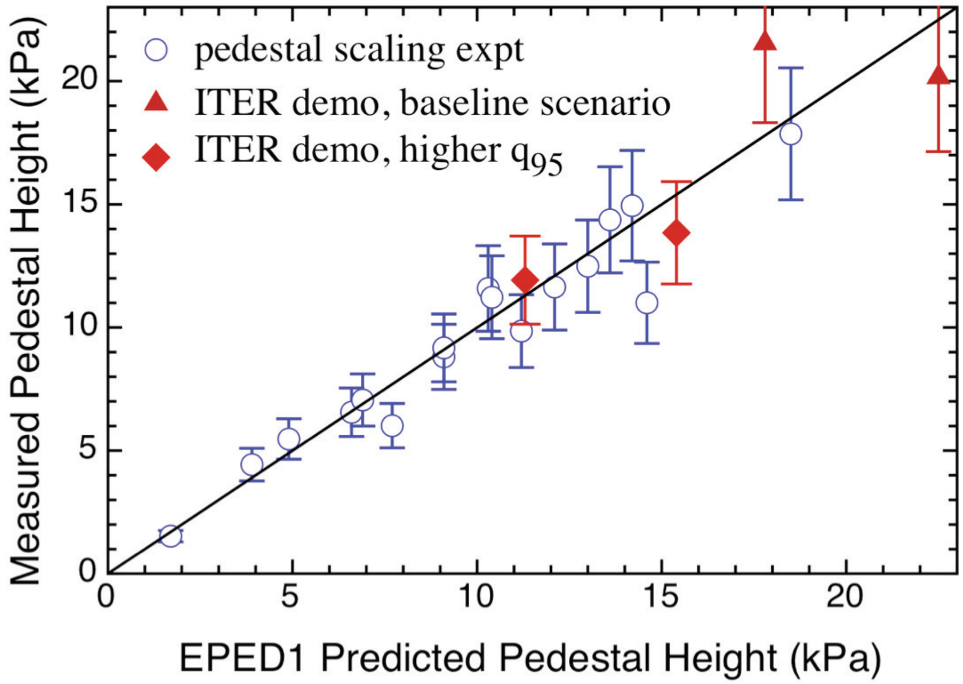
EPED1 Predictions in Good Agreement with Dedicated DIII-D Experiment





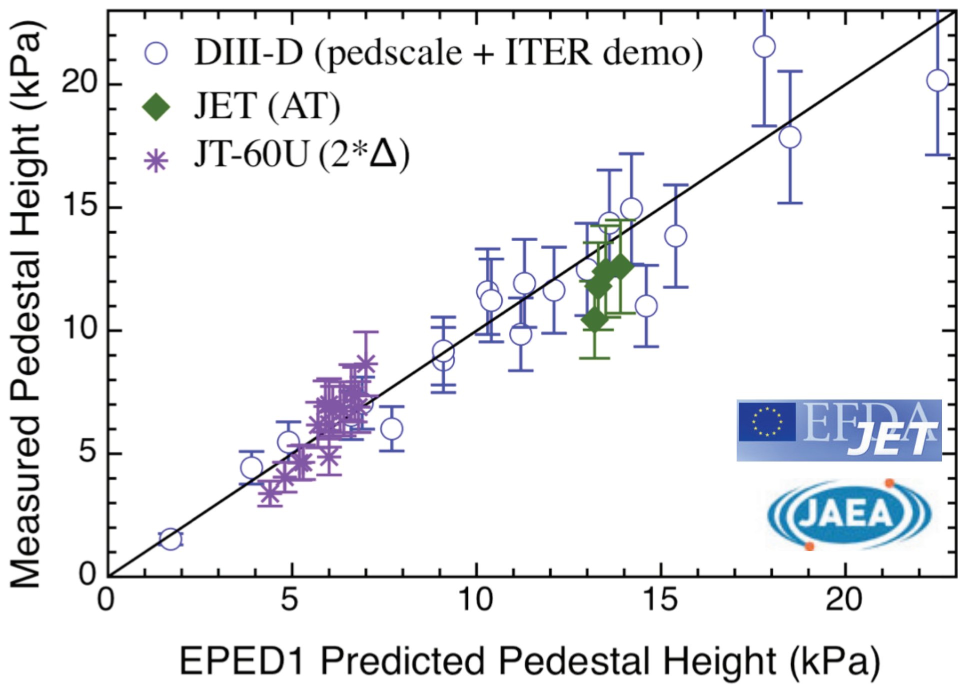
- **Experiment planned to yield large pedestal variation via scans in I_p, B_t and δ (~factor of 3 variations, 17 discharges) *[Groebner08]***
- **EPED1 predictions made before the experiment**
  - Good agreement, reproduces observed trends
- **Using achieved inputs, find very good agreement in predicted/ measured height 1.03 ±0.13 and width 0.93 ±0.15**
  - Height varied more than a factor of 10, width varied by factor of ~3

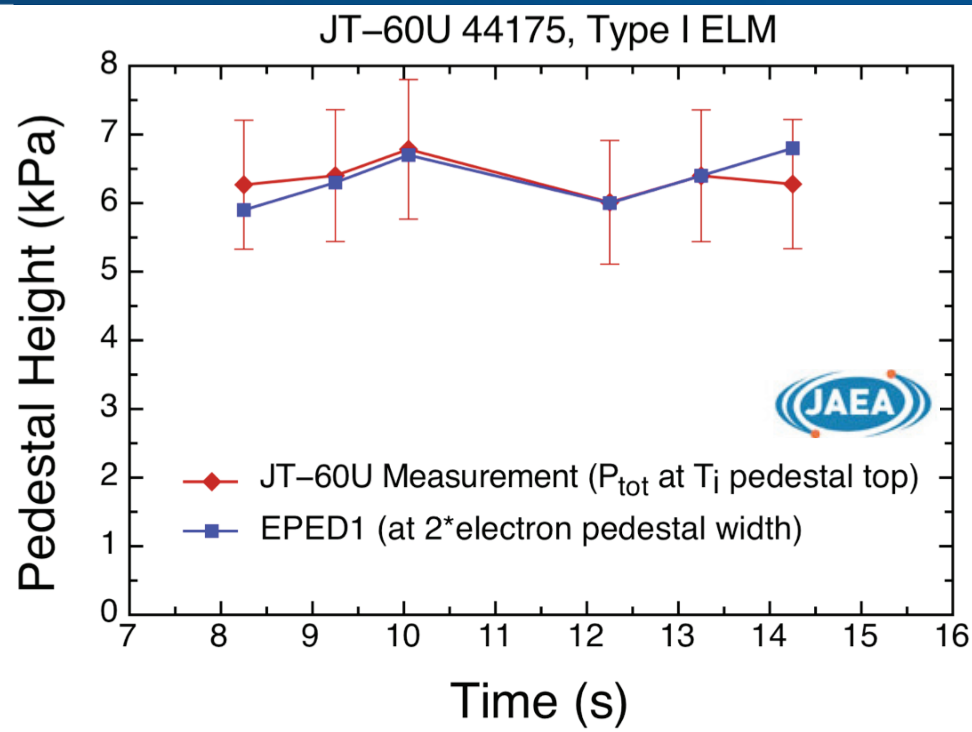
EPED1 Accurately Predicts Pedestal in DIII-D ITER Demonstration Discharges



- **Experiments conducted using DIII-D as 1/3.7 scale model of ITER** *[Doyle08]*
  - These discharges match ITER shape, beta, q, a/R
  - EPED1 predictions accurate (1.00 ±0.14) for 2 baseline and 2 higher q_{95} discharges
- **EPED1 also tested on randomly selected set of 20 discharges from DIII-D pedestal database (height: 0.97 ±0.23, width: 1.01 ±0.22)**
- **Overall agreement on 41 DIII-D discharges studied thus far: ratio of predicted to observed height 1.00 ±0.18, width 0.96 ±0.19**

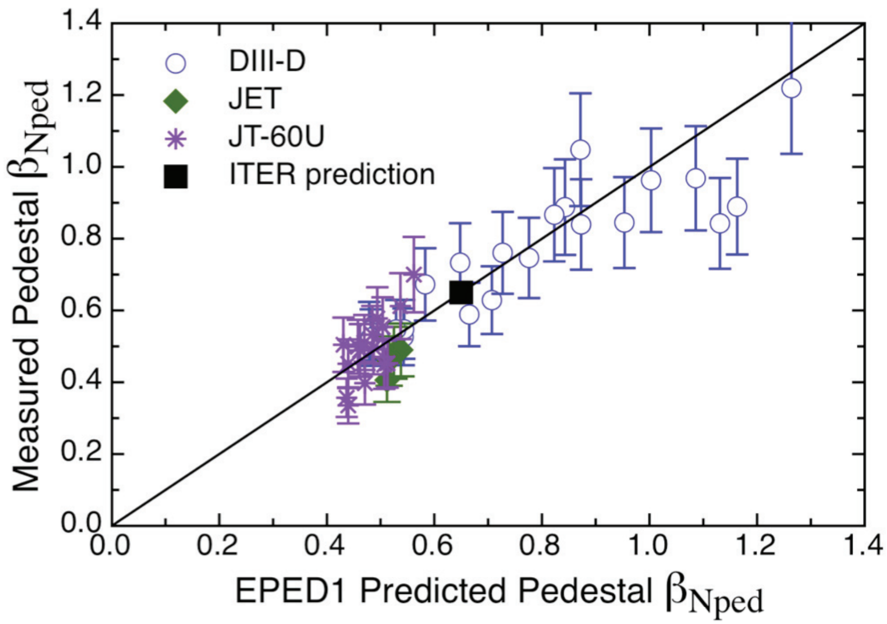
Successful Initial tests of EPED1 on JET and JT-60U

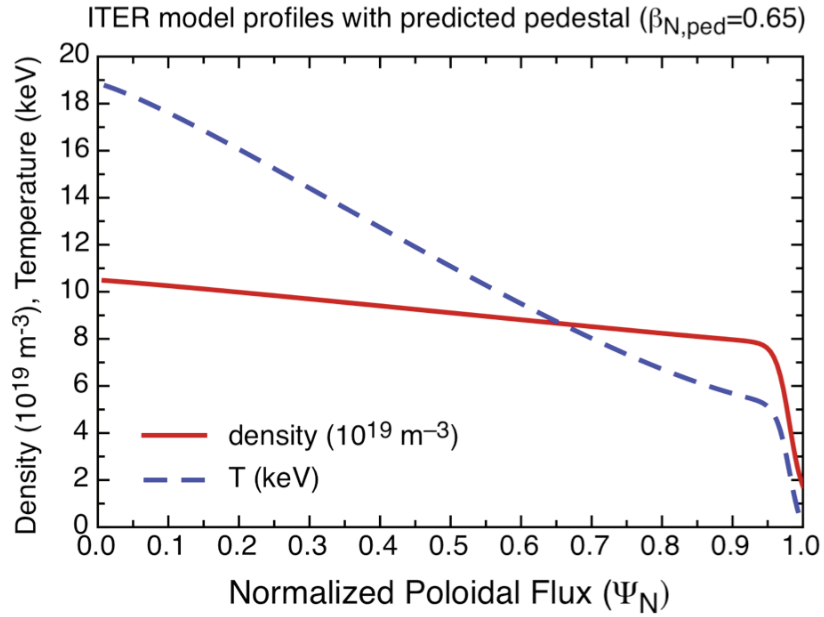




- **Initial test on 4 JET AT shots yields reasonable agreement**
- **Trends with time on JT-60U accurately reproduced**
  - Caveat: measurements at T_i pedestal top
  - Changes in time of pedestal explained by β_{global} and n_{ped} variation
- **Predicted/Measured pedestal height = 1.02 ±0.13** ***(21 DIII-D, 16 JT-60U, 4 JET)***

Pedestal Prediction for ITER





- **$\beta_{N,ped}$ useful metric for predictions**
- **For ITER baseline, EPED1 predicts a pedestal height of $\beta_{N,ped}$~0.65, and a width Δ_ψ~0.04 (~4.4cm)** [Small optimizations around base parameters allow $\beta_{N,ped}$~0.8-0.9]
- **At ITER reference density, and typical density peaking, one expects n_{ped}~7x10^{19} m^{-3}, at this density, $\beta_{N,ped}$=0.65 corresponds to T_{ped}=4.6 keV**
  - ***Note***: Predictions are for pedestal top (ψ~0.96, ρ~0.95). Core transport studies often use a BC further in (eg Kinsey ρ=0.86). Using model profiles, our prediction corresponds to roughly $\beta_{N,\rho=0.86}$~1, $T_{\rho=0.86}$~6 keV, $n_{e,\rho=0.86}$~8x10^{19} m^{-3}

Summary

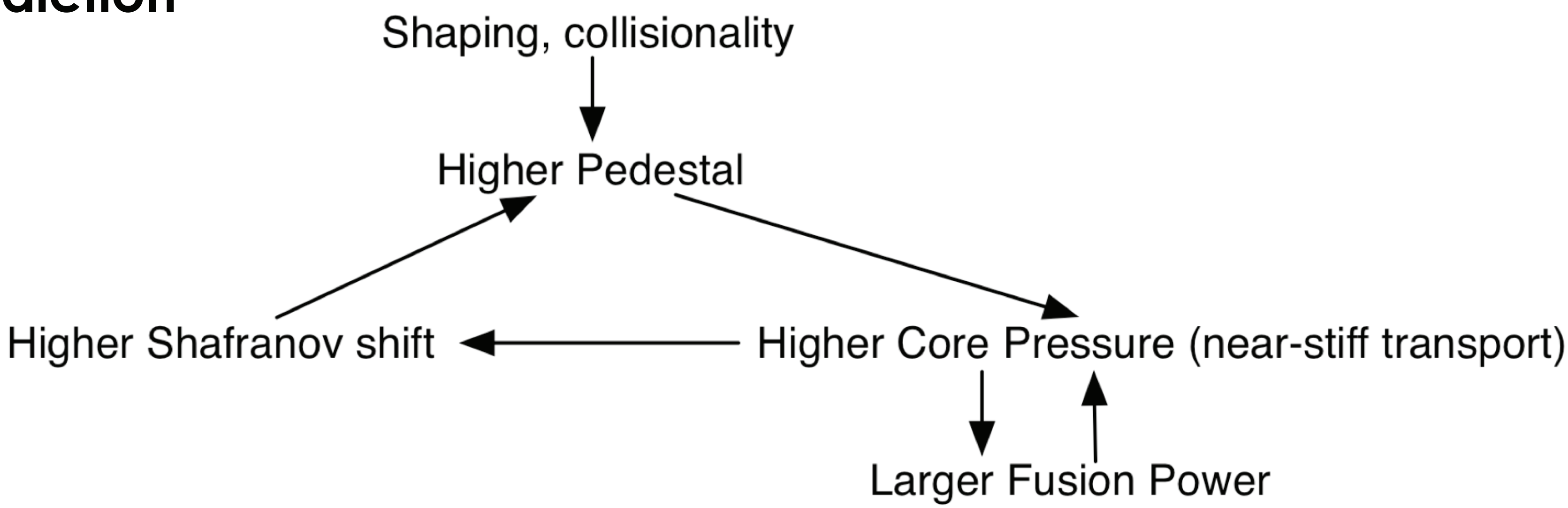
- **P-B stability constrains pedestal height, explains range of observations**
- **Observations and analysis suggest a pedestal width scaling** $\Delta_{\psi_N} \propto \beta_{p,ped}^{1/2}$
- **New predictive pedestal model developed, EPED1**
  - Combines stability calculations on model equilibria with simple width model

    $\Delta_{\psi_N} = 0.076\beta_{p,ped}^{1/2}$
    - Input: B, I_p, R, a, κ, δ, n_{ped}, β_{global} Output: Pedestal height and width
    - If any part is wrong, both height and width predictions wrong (test vs. height)
    - Width model acts as amplifier of stability physics: most complexity in stability
  - Good agreement in 41 DIII-D cases, including dedicated expt, ITER demo

    height 1.00 ±0.18, width 0.96 ±0.19
  - Encouraging initial tests for JET, JT-60U. Further tests in progress
- **EPED1 predicts ITER pedestal height of β_{Nped}~0.65**
  - For $n_{ped}=7\times10^{19}$ m^{-3}, corresponds to T_{ped}~4.6 keV
    - For connection to core, at ρ=.86: $\beta_{N,\rho=0.86}$~1, $T_{\rho=0.86}$~6 keV, $n_{e,\rho=0.86}$~8×10^{-19} m^{-3}

Future Work

- **Test and Improve upon EPED1**
  - Further systematic tests on multiple tokamaks
  - Extend physics model
    - Squareness, updown asymmetry, multiple widths… (tradeoffs)
    - Improved treatment of diamagnetic effects
  - Further dependencies of width (a/R, rhostar)
  - Determination of width coefficient from basic physics
- **Couple EPED1 to core transport (TGLF, MM etc) for global profile prediction**



References

[1] SNYDER, P.B. *et al*., Phys. Plasmas **12**, 056115 (2005).
[2] CONNOR, J.W. *et al*., Phys. Plasmas **5**, 2687 (1998).
[3] WILSON, H.R. *et al*., Phys. Plasmas **9**, 1277 (2002).
[4] SNYDER, P.B. *et al*., Phys. Plasmas **9**, 2037 (2002).
[5] MIKHAILOVSKII, A.B. *et al*., Plasma Phys. Rep. **23**, 844 (1997).
[6] HUYSMANS, G.T.A., Plasma Phys. Control. Fusion **47**, B165 (2005).
[7] TOKUDA, S. and WATANABE, T., Phys. Plasmas **6**, 3012 (1999); AIBA, N. *et al*., Comput. Phys. Commun. **175**, 269 (2006).
[8] AIBA, N. *et al*., Plasma Fusion Res. **2**, 010 (2007).
[9] MEDVEDEV, S. Yu., *et al*., Plasma Phys. Control. Fusion **48**, 927 (2006).
[10] KONZ, C., *et al*., EPS Conf. on Plasma Physics (2008).
[11] TURNBULL, A.D., *et al*., Plasma Phys. Control. Fusion **45**, 204 (2003).
[12] WILSON, H.R., *et al*., Plasma Phys. Control. Fusion **48**, A71 (2006).
[13] SNYDER, P.B., *et al*., Nucl. Fusion **47**, 961 (2007).
[14] SAARELMA, S., *et al*., Plasma Phys. Control. Fusion **49**, 31 (2007).
[15] HUYSMANS, G.T.A., and CZARNY, O., Nucl. Fusion **47**, 659 (2007).
[16] BEURSKENS, M., *et al*., Nucl. Fusion **48**, 095004 (2008).
[17] SAARELMA, S., *et al*., submitted to Plasma Phys. Control. Fusion (2008).
[18] SNYDER, P.B., *et al*., Plasma Phys. Control. Fusion **46**, A131 (2004).
[19] SAIBENE, G., et al., Nucl. Fusion **47**, 969 (2007).
[20] LEONARD, A.W., *et al*., Phys. Plasmas **15** 056114 (2008).
[21] OYAMA, N. et al, Nucl. Fusion **45**, 871 (2005).
[22] LÖNNROTH, J-S, *et al*., Plasma Phys. Control. Fusion **49**, 273 (2007).
[23] MOSSESSIAN, D.A., Phys. Plasmas **10**, 1720 (2003).
[24] MAGGI, C.F., *et al*., Nucl. Fusion **47**, 535 (2007); MAGGI, C.F., *et al*., EPS 2008.
[25] EVANS, T.E., *et al*., Nature Phys. **2**, 419 (2006).
[26] LIANG, Y., *et al*., Phys. Rev. Lett. **98**, 265004 (2007).
[27] LOARTE, A., *et al*., Phys. Plasmas **11**, 2668 (2004).
[28] BURRELL, K.H., *et al*., Fusion Energy 2008 (Proc 22 Int. Conf Geneva 2008, EX/8-4).
[29] ONJUN, T., *et al*., Phys. Plasmas **9**, 5018 (2002).
[30] OSBORNE, T.H., *et al*., J. Nucl. Mater. **266-269**, 131 (1999).
[31] URANO, H. , *et al*., Nucl. Fusion **48**, 045008 (2008).
[32] GROEBNER, R.J. , *et al*., Fusion Energy 2008 (Proc. 22nd Int. Conf. Geneva, EX/P3-5).
[33] SNYDER, P.B. , *et al*., to be submitted to Phys. Plasmas 2008; TTF, Boulder USA (2008).
[34] DOYLE, E.J. , *et al*., Fusion Energy 2008 (Proc 22nd Int. Conf. Geneva, EX/1-3).
[35] FENSTERMACHER, M.E., *et al*., Nucl. Fusion **48** 1493 (2005).