A First Principles Predictive Model of the Pedestal Height and Width

Development, Testing and ITER Optimization with the EPED Model

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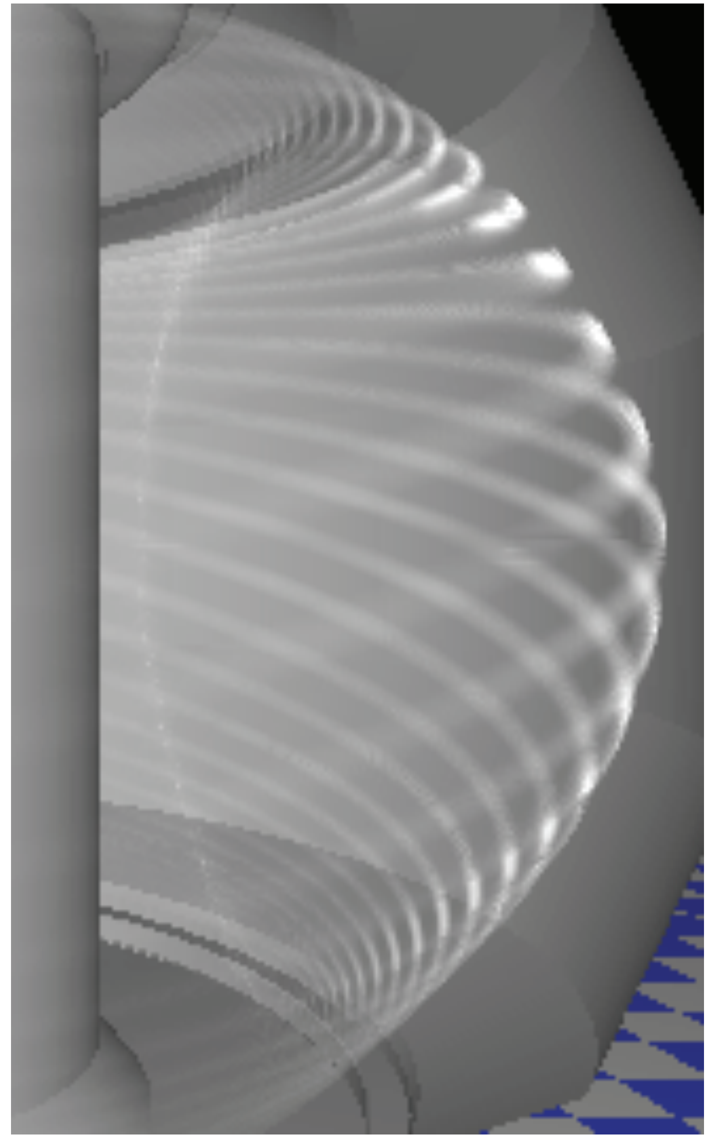

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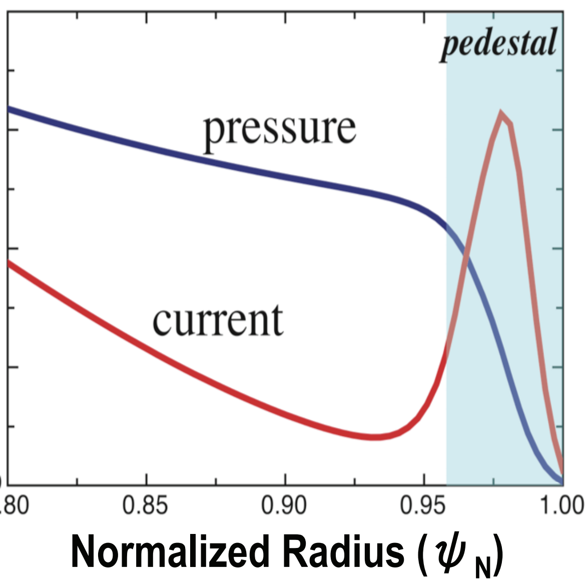
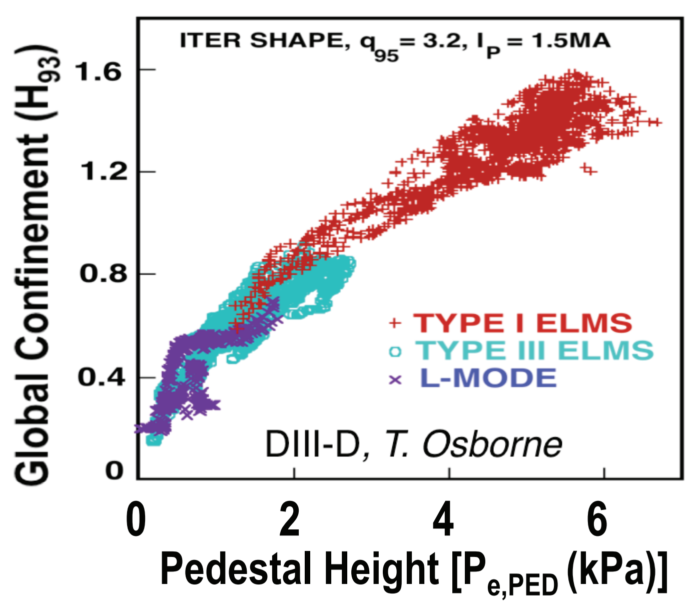
Motivation: Pedestal Height Critical for ITER Performance Prediction and Optimization

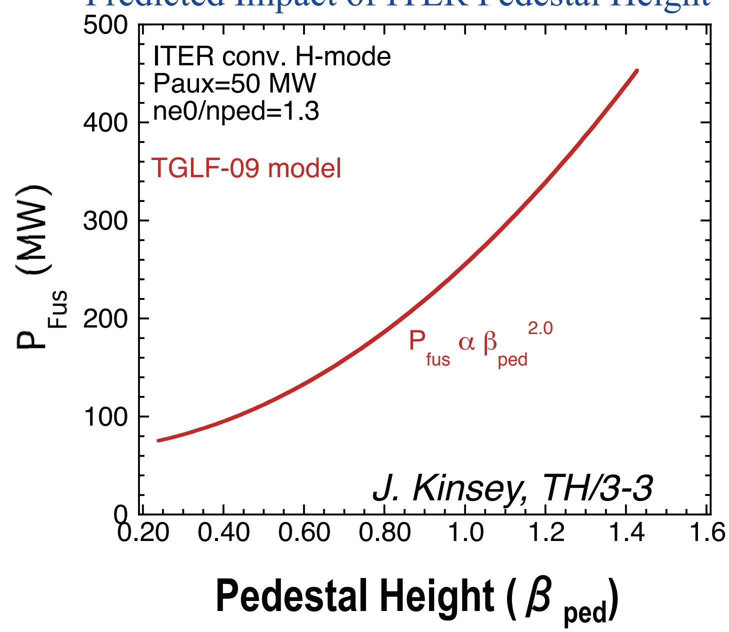
- **High performance ("H-mode") operation in tokamaks due to spontaneous formation of an edge barrier or "pedestal"**
- **Pedestal height has an enormous impact on fusion performance**
  - Dramatically improves both global confinement and stability (observed and predicted)
  - ***Fusion power on ITER predicted to scale with square of the pedestal pressure*** *[Kinsey, TH/3-3]*
- **Accurate prediction of the *pedestal height* is essential to assess and optimize ITER performance, and to optimize the tokamak concept for energy production**



Observed Impact of Pedestal Height

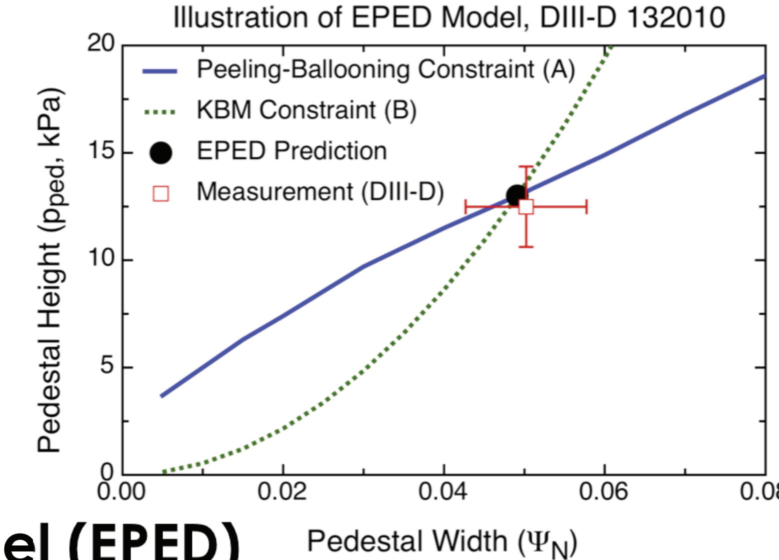


Predicted Impact of ITER Pedestal Height



EPED Model Combines Peeling-Ballooning and KBM Physics to Predict Pedestal Height and Width

Develop a model based on two fundamental physics constraints, which are directly calculable, but simple enough to be predictive and easily testable



A. The Peeling-Ballooning Model

- "Global" constraint on pedestal height vs width
- Successfully tested across wide range of cases

B. Kinetic Ballooning Mode Onset

- Local constraint from ballooning/GK theory
- Integrate to get 2nd relation on width vs height

C. Combine A&B to Develop Predictive Model (EPED)

- 2 "equations" for 2 unknowns: pedestal height and width
- EPED1.6: Both P-B and KBM constraints calculated directly for each case
  - ***First principles, no use of measurements in any part of model, but still simple & predictive***

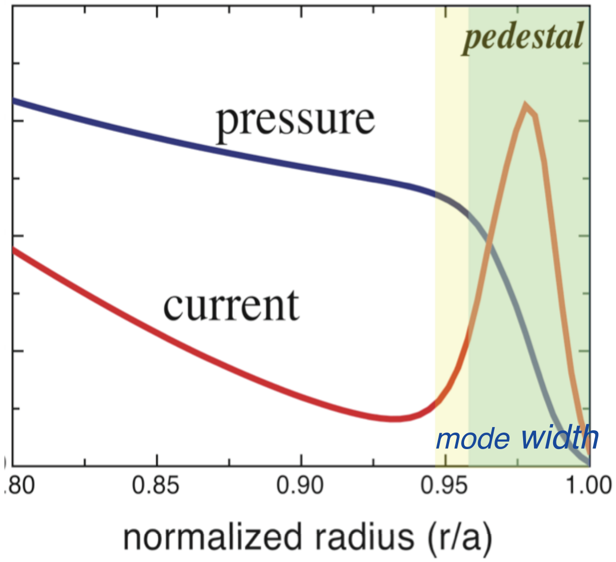
D. Validate Model Against Experiment

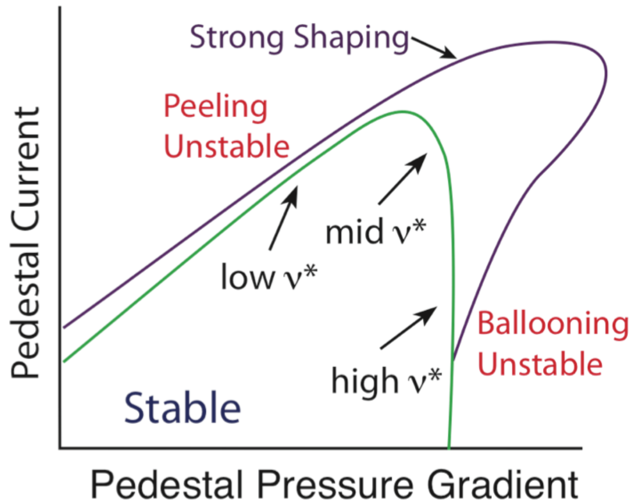
- Dedicated experiments on C-Mod and DIII-D, tests on JET and JT-60U
- *Good agreement across wide parameter range on multiple devices*

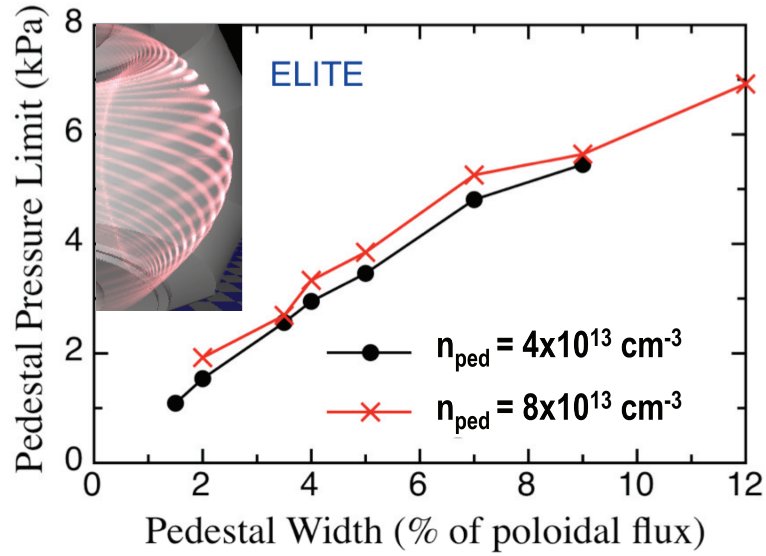
E. Predictions for ITER, ITER optimization

Peeling-Ballooning Model and Validation

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







- **Pedestal is constrained, and ("Type I") ELMs triggered by intermediate wavelength (n~3-30) MHD instabilities**
  - 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"

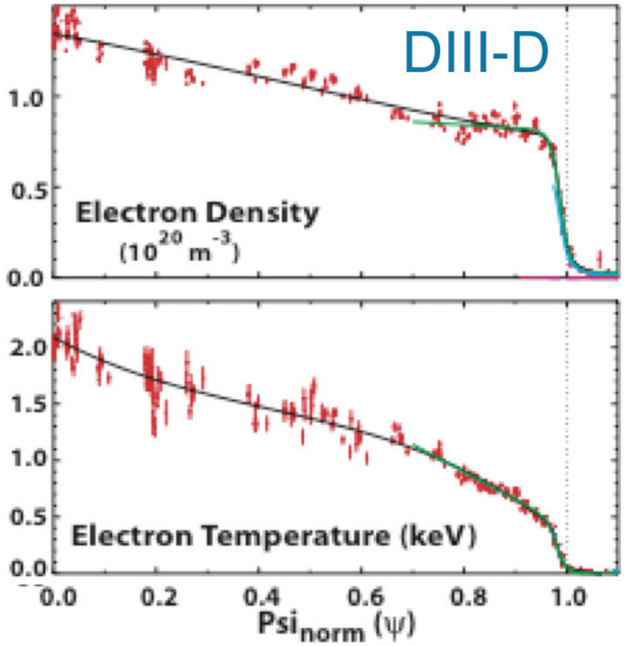
The P-B constraint is fundamentally non-local (effectively global on the scale of the barrier)

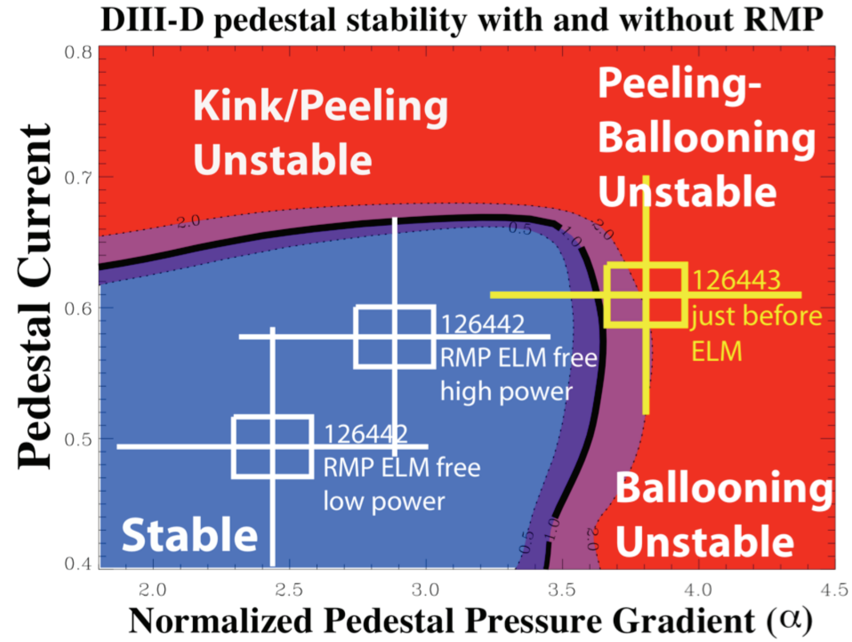
  - P-B limit increases with pedestal width (Δ_ψ), but not linearly (roughly $\beta_{Nped} \sim \Delta_\psi^{3/4}$)

- **ELITE code, based on extension of ballooning theory to higher order, allows efficient and accurate computation of the intermediate *n* peeling-ballooning stability boundary**

H.R. Wilson, P.B. Snyder et al PoP ***9*** *1277 (2002). P.B. Snyder, H.R. Wilson et al PoP* ***9*** *2037 (2002).*
P.B. Snyder, K.H. Burrell, H.R. Wilson et al Nucl Fusion ***47*** *961 (2007).*

Peeling-Ballooning Model Extensively Validated Against Observation





- **High resolution measurements allow accurate reconstructions and stringent tests of P-B pedestal constraint and ELM onset condition**
- **Pedestal constraint and ELM onset found to correlate to P-B stability boundary**
  (Multiple machines, >200 cases studied, ratio of 1.05 ± 0.19 in 39 discharges)
- **Model equilibrium technique used to apply P-B stability constraint predictively**

Can accurately quantify stability constraint [height=f(width)], but need second constraint for fully predictive model of pedestal height and width

Kinetic Ballooning Mode Onset Provides 2nd Constraint

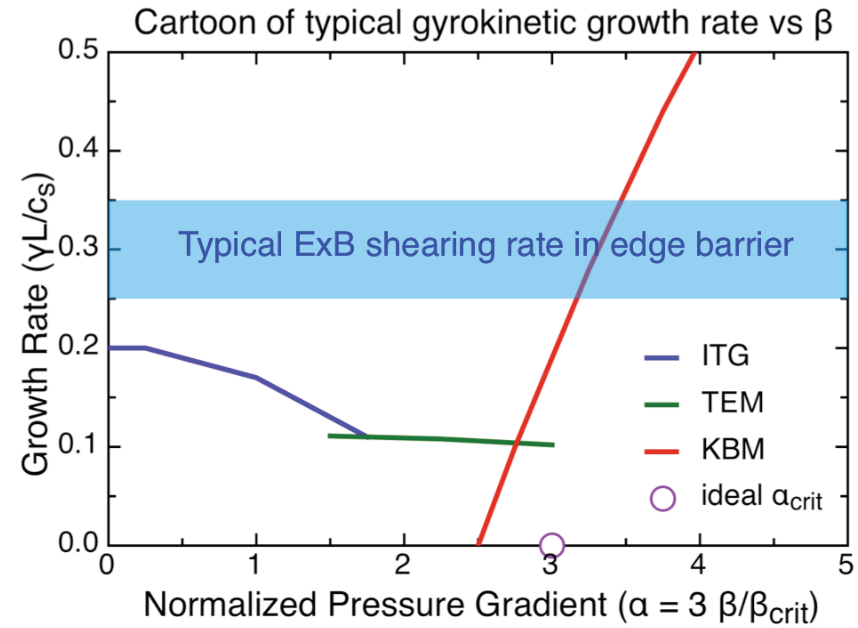
Many mechanisms drive transport across the edge barrier. We hypothesize that the KBM is the mechanism by which the gradients are finally constrained in the presence of strong ExB shear (in the regime of interest to ITER)

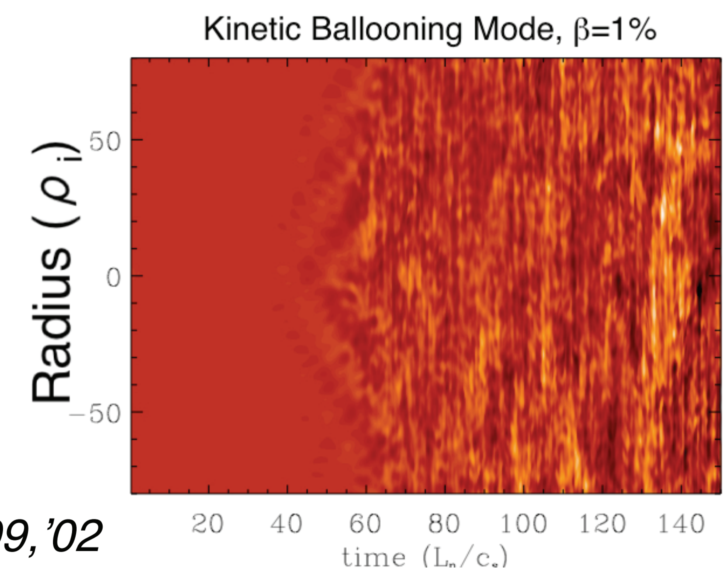
Propose Pedestal Constrained by KBM Onset Near Ideal Ballooning α_{crit}

- **Kinetic Ballooning Mode (KBM) is a pressure gradient driven mode**
  - Qualitatively similar to ideal ballooning mode
  - Kinetic effects essential for linear mode spectrum and nonlinear dynamics
- **Linear studies and electromagnetic KBM turbulence simulations find:**
  [Rewoldt87,Hong89,Snyder99,Scott01,Jenko01, Candy05…]
  - Abrupt linear onset, quickly overcomes ExB shearing rate, large QL transport
    - Linear onset near ideal ballooning critical gradient due to offsetting kinetic effects
  - Nonlinear: very large fluxes and short correlation times (highly stiff)
    - Flux will match source at gradient near critical

➢ **Simple model of the KBM can be quantitatively accurate**

- Stiff onset near MHD ballooning criticality





Snyder'99,'02

Calculate KBM Constraint in Terms of Measurable Parameters "ballooning critical pedestal"

"Ballooning critical pedestal" calculations to quantify KBM constraint

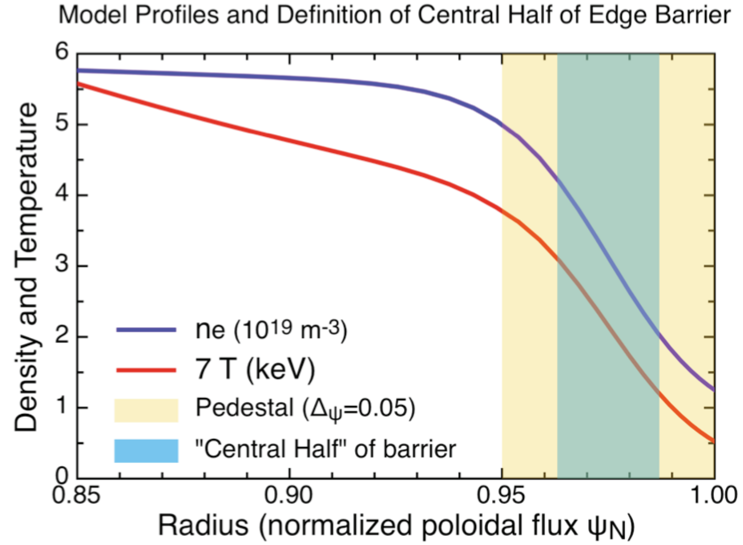
- **Model equilibria used to integrate local KBM constraint**
- **"ballooning critical" when central half of edge at or beyond MHD critical gradient** ***[baloo code, R.L. Miller]***
- **Find expected dominant dependence:**

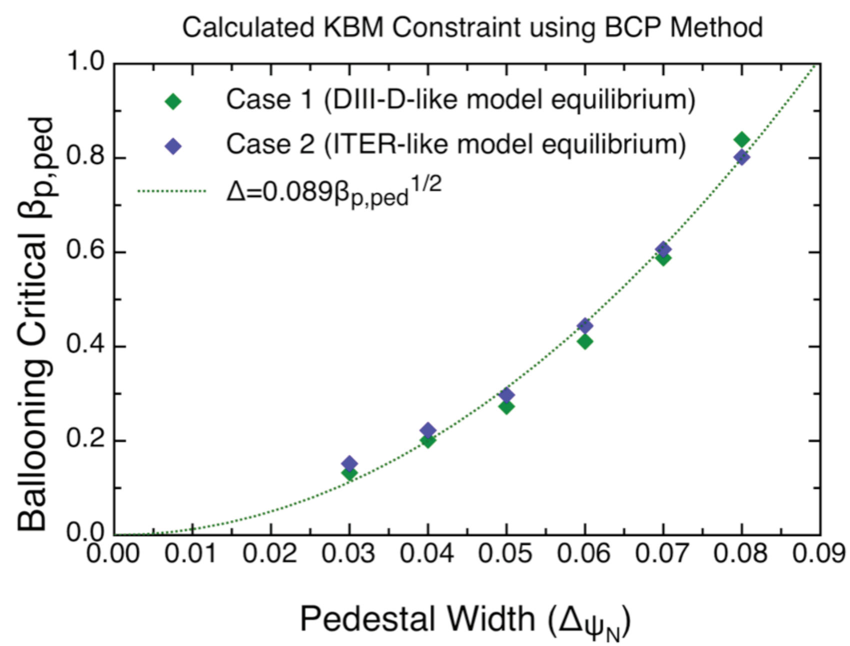
$$\beta_{p,ped} \sim \Delta_{\psi_N}^2 \Rightarrow \Delta_{\psi_N} \sim \beta_{p,ped}^{1/2}$$

- **Lump weak dependencies into G function, calculate <G>~0.07-0.1 for standard aspect ratio tokamaks (0.084 ± 0.10 for ensemble of 16 cases)**

$$\Delta_{\psi_N} = \beta_{p,ped}^{1/2} G(\nu_*, \varepsilon \ldots)$$

KBM constraint consistent with many observations, eg T Osborne, next talk, Z. Yan EXC/P3-05, Groebner10, Snyder09





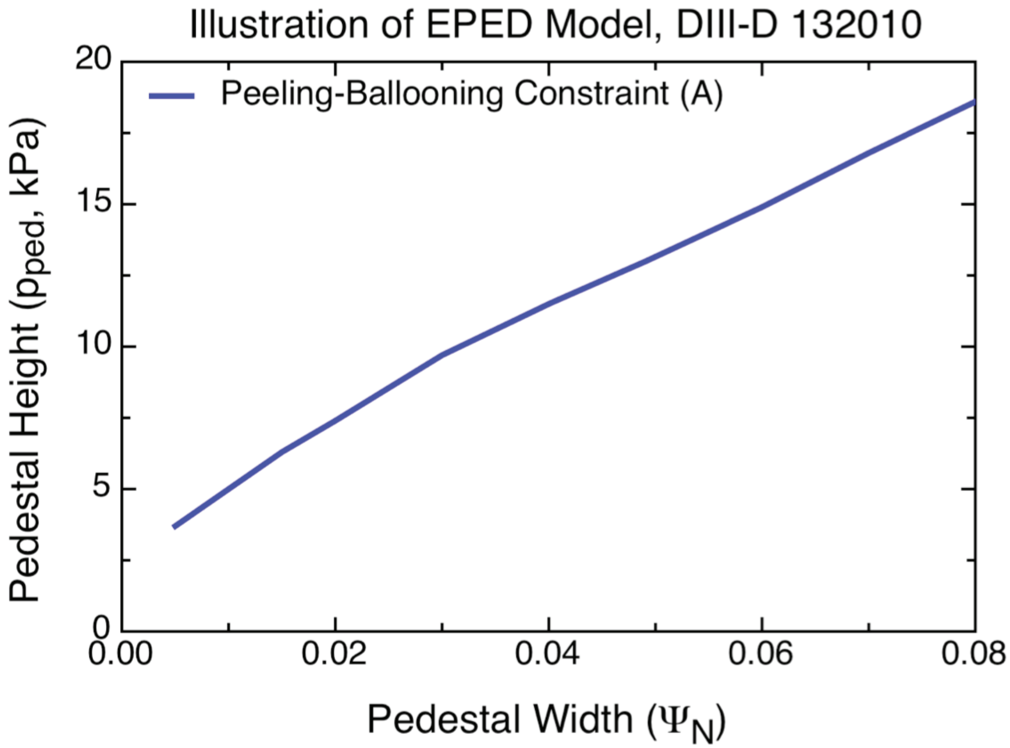
Implementing and Testing the EPED Model

Mechanics of the EPED Predictive Model

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

A. P-B stability calculated via a series of model equilibria with increasing pedestal height

- ELITE, n=5-30; non-local diamag model



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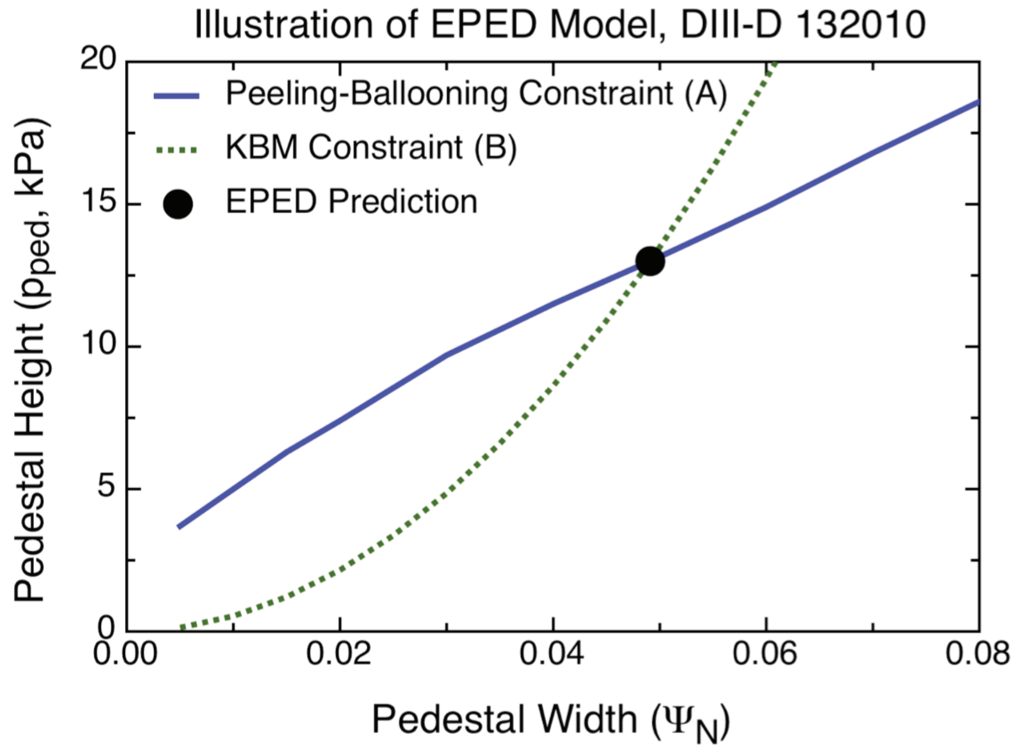
– Directly calculate with ballooning critical pedestal technique



- **Different width dependence of P-B stability (roughly $p_{ped} \sim \Delta_\psi^{3/4}$) and KBM onset ($p_{ped} \sim \Delta_\psi^2$) ensure unique solution, which is the EPED prediction (black circle)**

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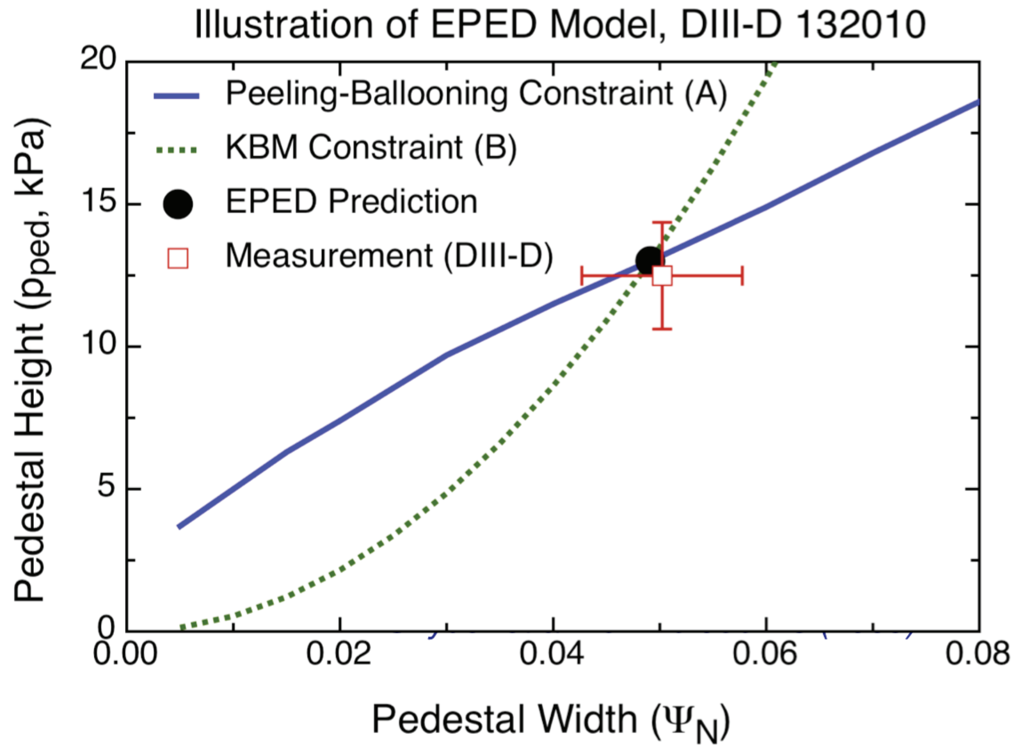

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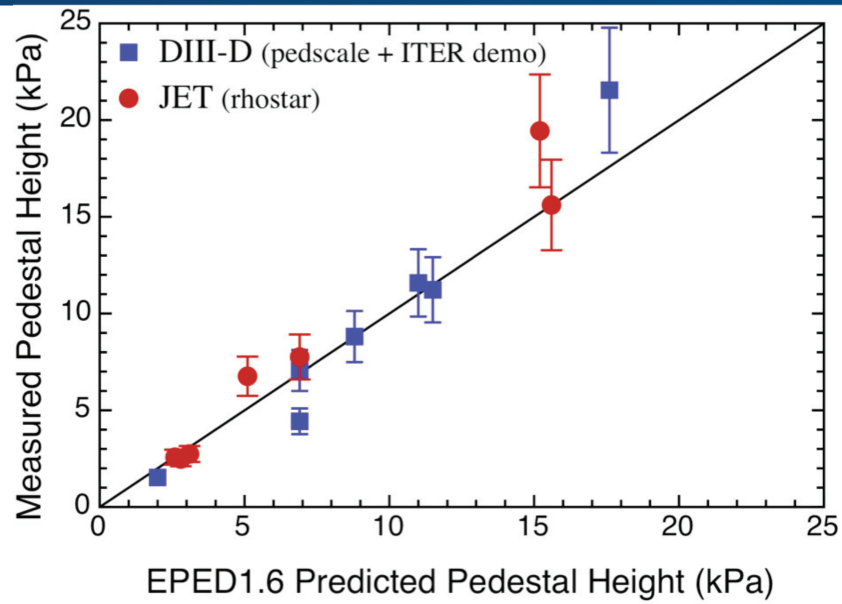
  - can then be systematically compared to existing data or future experiments

P-B stability and KBM constraints are tightly coupled: If either physics model (A or B) is incorrect, predictions for both height and width will be systematically incorrect

Effect of KBM constraint is counter-intuitive: Making KBM stability worse increases pedestal height and width

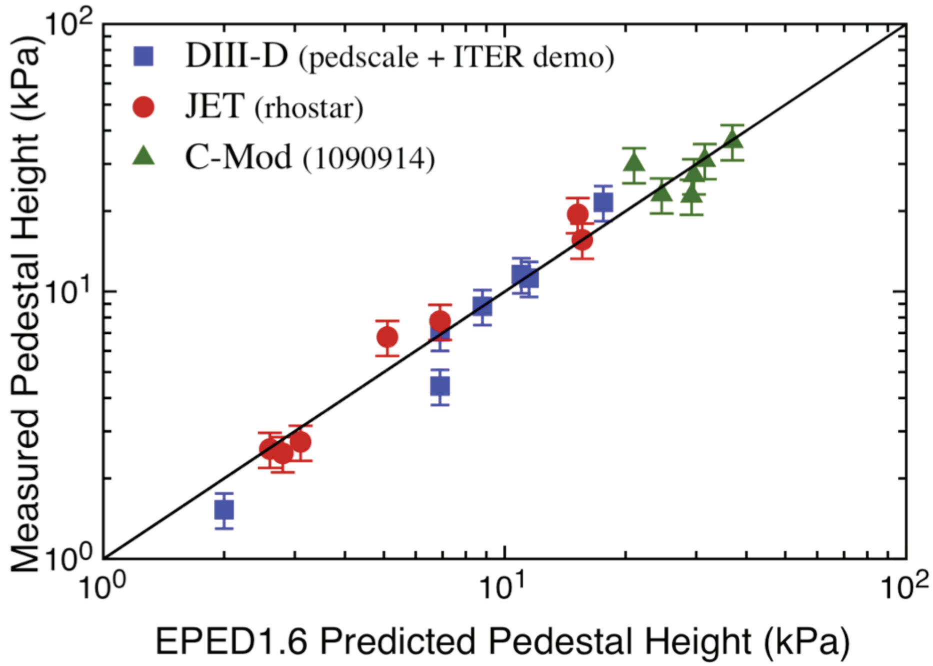
Experimental Tests of the Full EPED Model (EPED1.6)

Tests of Full Predictive EPED Model Successful



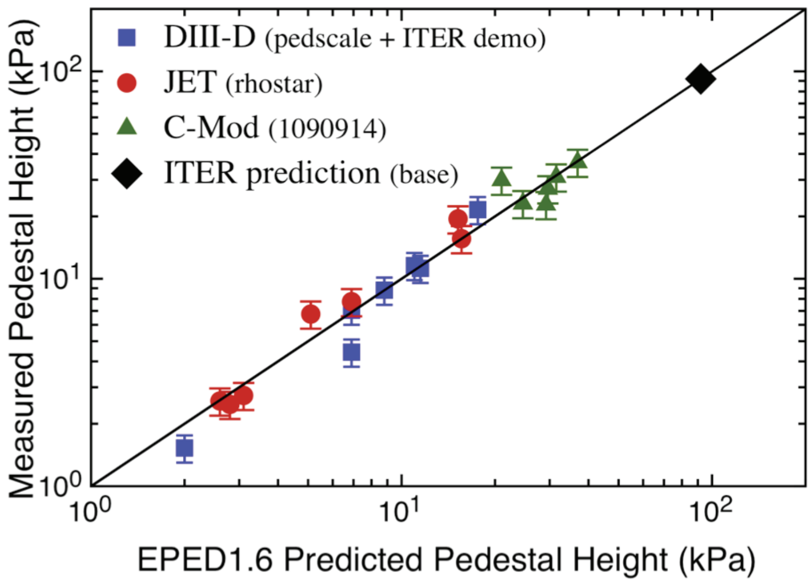
- **Previous version of model (EPED1) successfully tested on a wide range of cases on several tokamaks, including predictions before expt *[T. Osborne next talk, Groebner09&10, Snyder09, Beurskens09, Doyle10]***
- **EPED1.6 tested on initial set of 7 DIII-D and 7 JET discharges**
  - From pedscale *(Groebner09)* and ITERDEMO *(Doyle10)* expts on DIII-D, and ρ_* expt on JET *(Beurskens09, Osborne09&10)*
  - Large range of variation in pedestal height (1.6 - 22kPa), ρ_{*ped} (0.24 - 0.7), ν_{*ped} (0.3 - 5), β_{ped} (0.3 - 1.2%)
- **Good agreement in predicted/measured height: 1.02 ± 0.21**
  - Similar level of agreement in width (1.03 ± 0.29) *[no free parameters]*

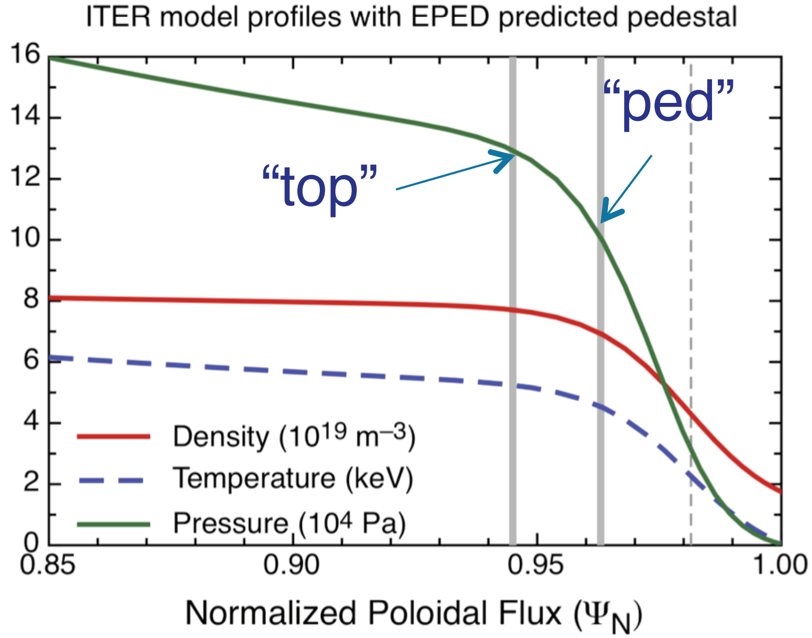
Dedicated Experiment on C-Mod Successfully Tests EPED Model in Plasma Current Scan



- **Collisionality and sophisticated diamagnetic stabilization physics are important for C-Mod regime**
- **Current scan expt on Alcator C-Mod, 9/09** *[Hughes, C-Mod team, Snyder, Groebner]*
  - Two values of current (I_p=940 & 680 kA, B_t=5.3T), ELMing discharges
- **Good agreement in predicted/measured height**
  - 6 C-Mod (1.03±0.19), 7 JET, 7 DIII-D discharges, factor of >20 in ped pressure
  - Ratio of 1.02 ± 0.20, correlation coefficient of 0.96 between prediction and observation

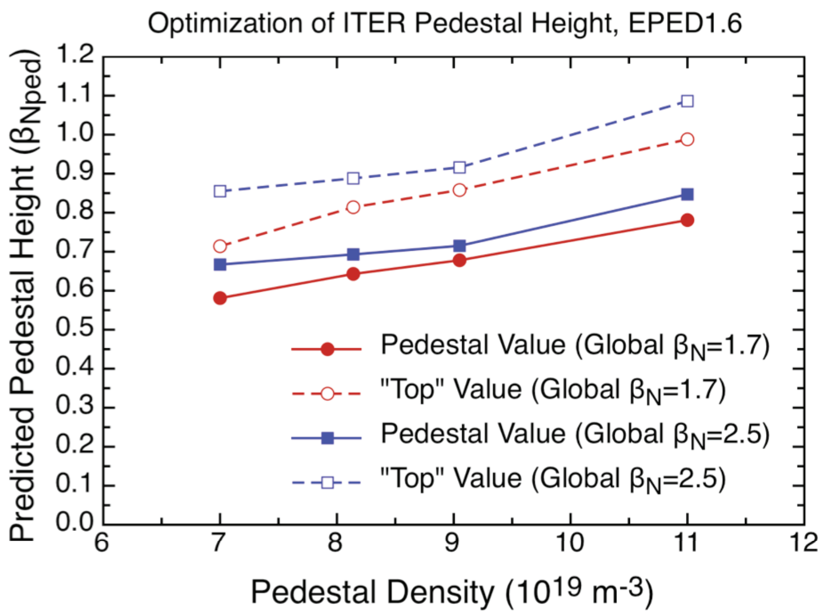
Pedestal Prediction for ITER

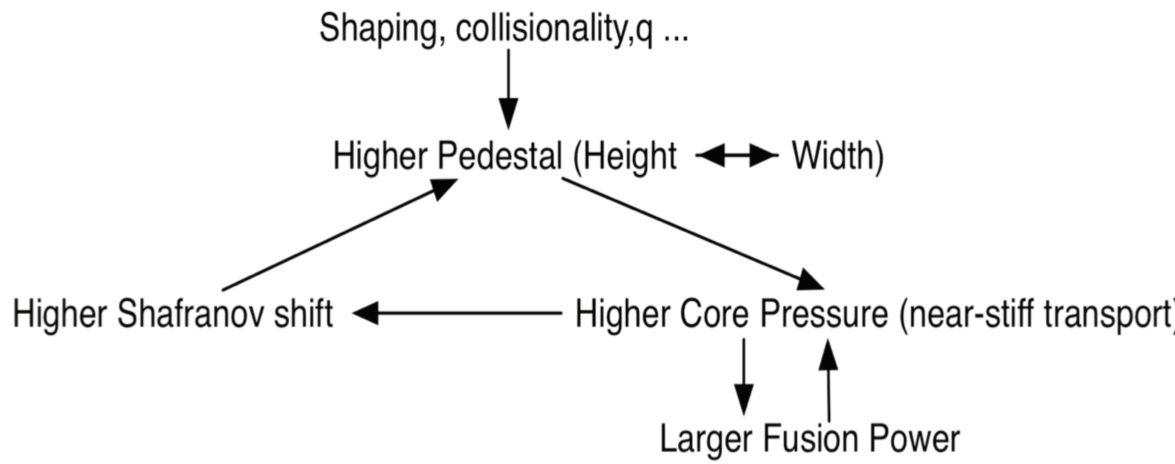




- **For ITER baseline, EPED1.6 predicts a pedestal height of $\beta_{N,ped}$~0.6 and a width Δ_ψ~0.04 (~4.4cm), for n_{ped}~7x10^{19} m^{-3}**
  - In normalized units, values similar to predictions and observations on existing devices
- **Predictions given for pedestal as defined by the tanh function half width ("ped")**
  - To connect to core simulations, we define a pedestal "top" that is another half-width in, inside the sharp gradient region
  - Reference EPED prediction is $\beta_{N,top}$~0.74 at the "top"

Understanding the Pedestal Allows ITER Performance Optimization





- **EPED predicted pedestal height increases with density and Shafranov shift (global β)**
  - Low density kink/peeling regime: *RMP ELM control and Quiescent H-Mode operate in this regime* (not sufficient condition – more research needed)
  - Virtuous cycle: Increasing core pressure improves pedestal height, which in turn increases core pressure **(P_{fus}~p_{ped}^2)**
  - Pedestal top values of $\beta_{N,top}$~0.9 can be achieved with optimization, which allows high predicted global performance in ITER *[Kinsey, TH/3-3]*

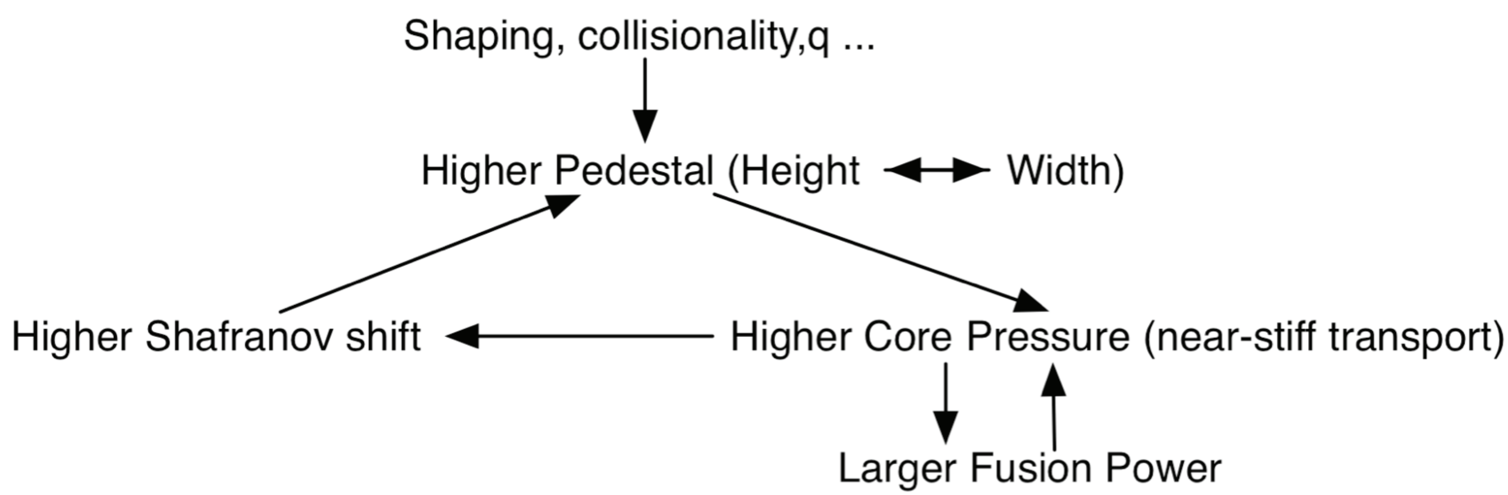
Summary: EPED Pedestal Model Developed and Successfully Tested

- **Predictive model combines non-local Peeling-Ballooning and near-local KBM physics**
  - Both constraints directly calculated, and each can be independently tested
  - No free parameters
- **Model successfully tested against existing machines over a wide range of parameters, including dedicated experiments**
  - Good quantitative agreement found (e.g. ratio of 1.02 ± 0.20, 0.96 correlation, in 20 cases on 3 tokamaks)
- **Model used to predict and optimize the pedestal in ITER**
- **Understanding and optimization of pedestal provides a powerful lever for ITER to achieve and exceed its performance goals** *($P_{fus} \sim p_{ped}^2$)*
  - *High performance in ITER achievable via coupled core-pedestal optimization*
  - *ITER operates in a stability regime where ELM control via RMP and QH-mode have been achieved, but further work is needed to quantify all requirements*

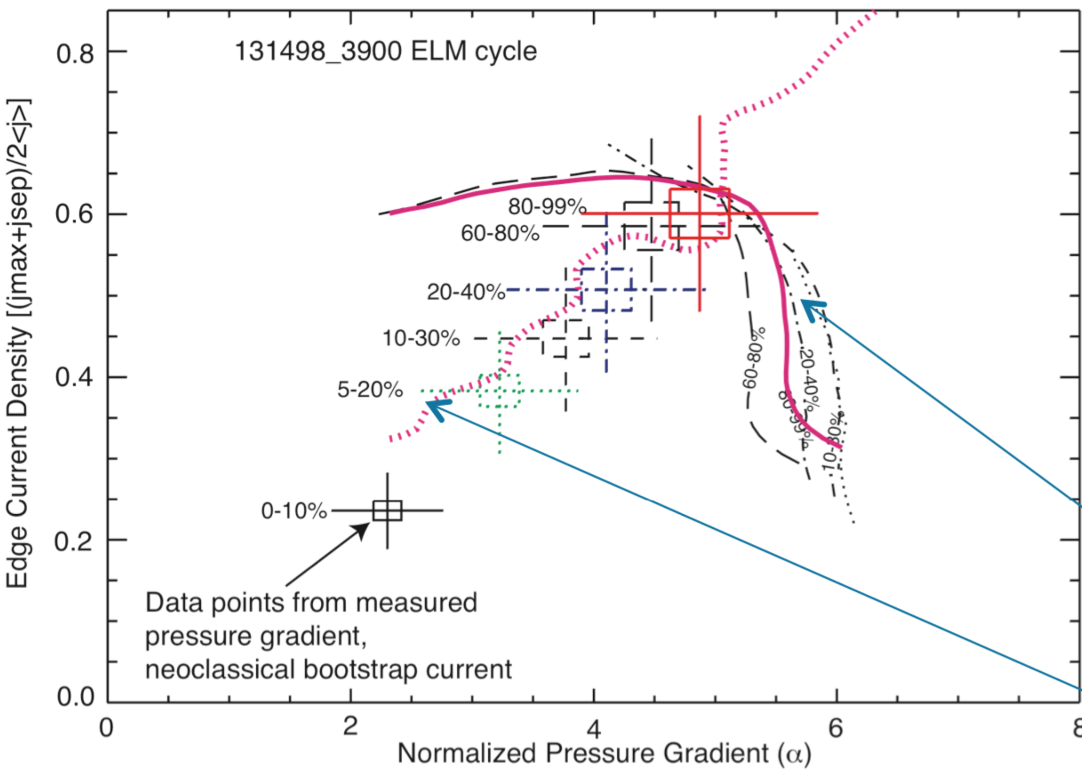
Backup Slides

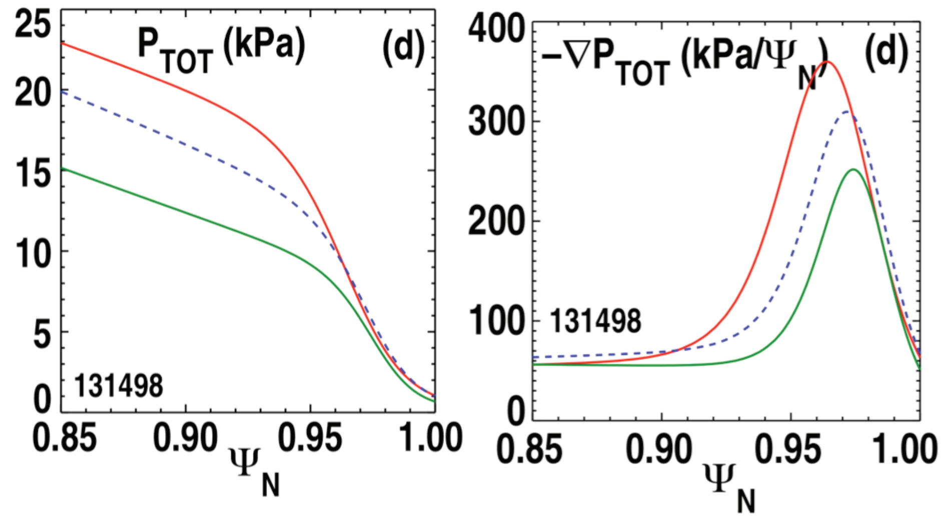
Future Work

- **Test and Improve upon EPED model**
  - Further tests of EPED on multiple tokamaks (including dedicated expts)
    - Systematic tests on C-Mod, DIII-D, NSTX for 2011 US Milestone
  - Extend physics of KBM model, and peeling-ballooning model (EPED2)
    - Improved treatment of diamagnetic effects in P-B
    - KBM from linear (eventually nonlinear) GK simulations, including weak dependencies of G (aspect ratio, collisionality…)
- **Couple EPED to core transport (TGLF, MM etc) for global profile prediction: global optimization, control**



Initial Tests of KBM Constraint in Slowly Evolving DIII-D Discharges



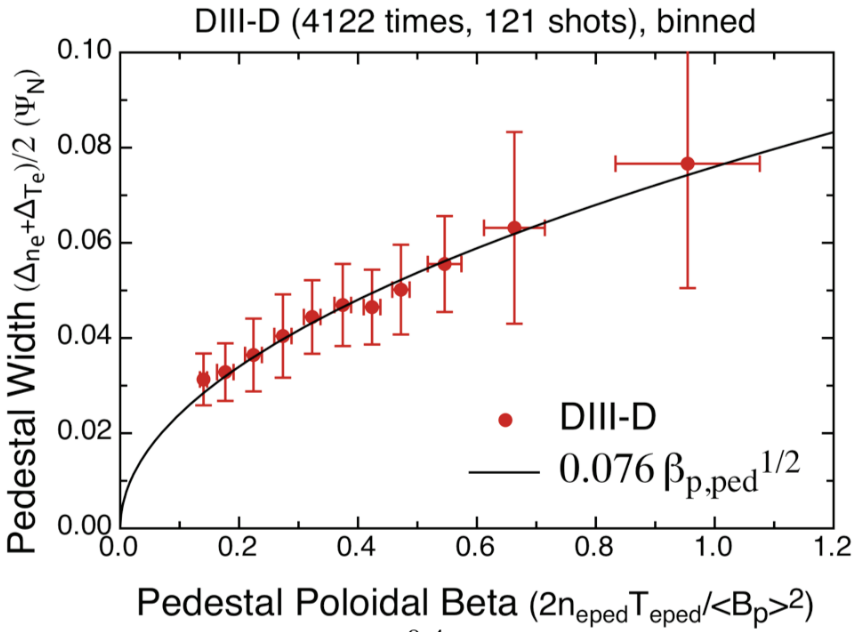


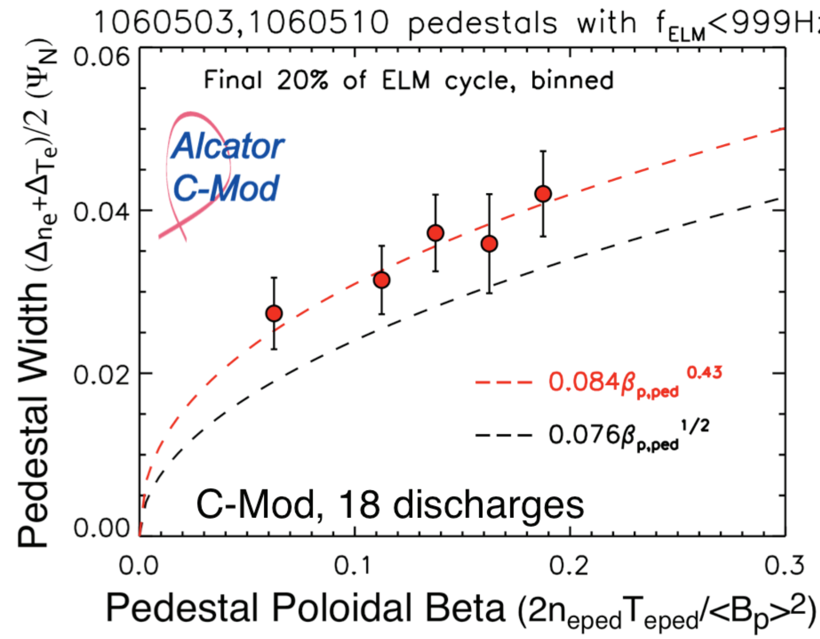
Peeling-ballooning modes limit pedestal height, boundary crossed ~ELM

Kinetic ballooning modes constrain "local" pressure gradient prior to ELM

- **Easy test: Integrate up critical KBM constraint and compare to observed relation between width and height (previous pages)**
- **Harder test: Look at dynamic evolution and contact with "local" KBM critical gradient (shown) –** challenging to diagnostic resolution
- **Harder yet: Look at dynamic evolution to find contact with KBM critical gradient and study resulting turbulence/bursts/~coherent mode** – challenging to sim/diagnostics

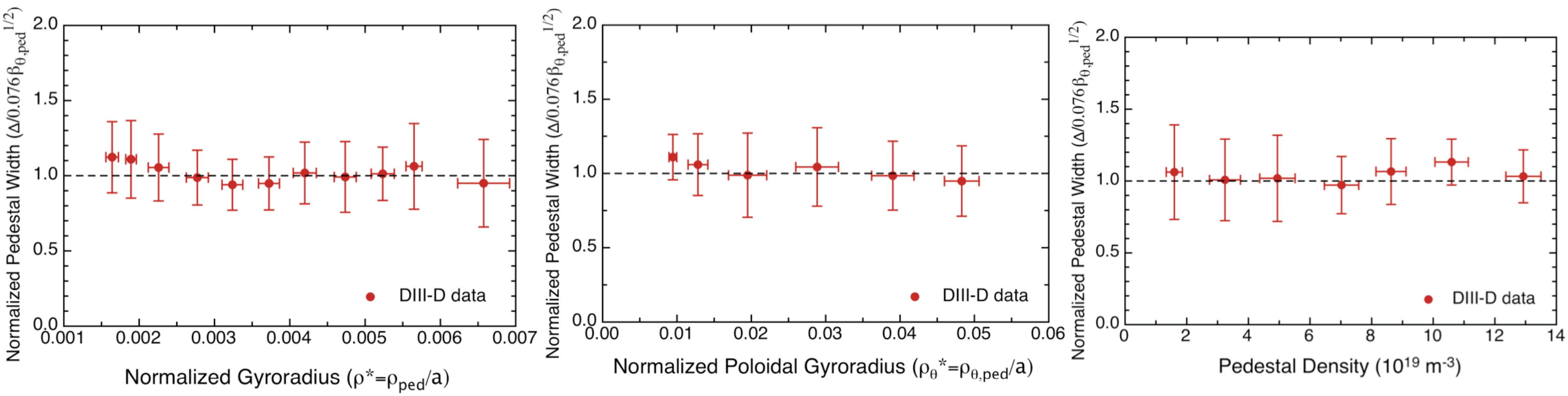
KBM Relationship Between Width and Height is Consistent with Observations





- **Scaling of** $\Delta / a \propto \beta_{p,ped}^{0.4}$ **first found by Osborne99: recent measurements find similar scaling across many machines**
- **DIII-D, C-Mod, MAST, AUG find Δ~$\beta_{p,ped}^{1/2}$ dependence in T1 discharges**
  - Accounting for this dependence, weak dependence on other parameters (q, ν*, ρ^*_i, ρ^*_θ, β)
  - KBM calculation: $\Delta_{\psi_N} = 0.09\beta_{p,ped}^{1/2} G(\nu_*, \varepsilon ...)$, <G>=1.0±0.2; data: <G>~0.84 (DIII-D), <G>~0.93 (C-Mod)
- **Isotope variation expts on JT-60U** *[Urano08]*, **DIII-D** *[Groebner08]* **find no dependence of width on mass** (consistent with KBM, inconsistent with gyro or banana radius models)
- **JET - DIII-D rhostar scan expts find no/weak rhostar dependence of the width** ***[Beurskens, Osborne'09]*** **(**consistent with KBM, inconsistent with gyro/banana radius)

$\Delta \sim \beta_{p,ped}^{1/2}$ Largely Accounts for Observed Variation in Observed DIII-D Pedestal Width



- **Define $F = \Delta_{\psi_N} / 0.076\beta_{p,ped}^{1/2}$ to look for any remaining width variation not accounted for by $\beta_{p,ped}^{1/2}$**
  - Particularly interested in gyroradius variation
    - If width scaled with ρ_θ rather than $\beta_{p,ped}^{1/2}$, F should scale with $1/n_e^{1/2}$
    - Appears to be ruled out in this dataset (apparent correlation of width to gyroradius is due to cross correlation of gyroradius and $\beta_{p,ped}^{1/2}$)
    - Also find weak or no correlation of F to q, beta, Greenwald fraction
  - Results consistent with expectations from KBM theory

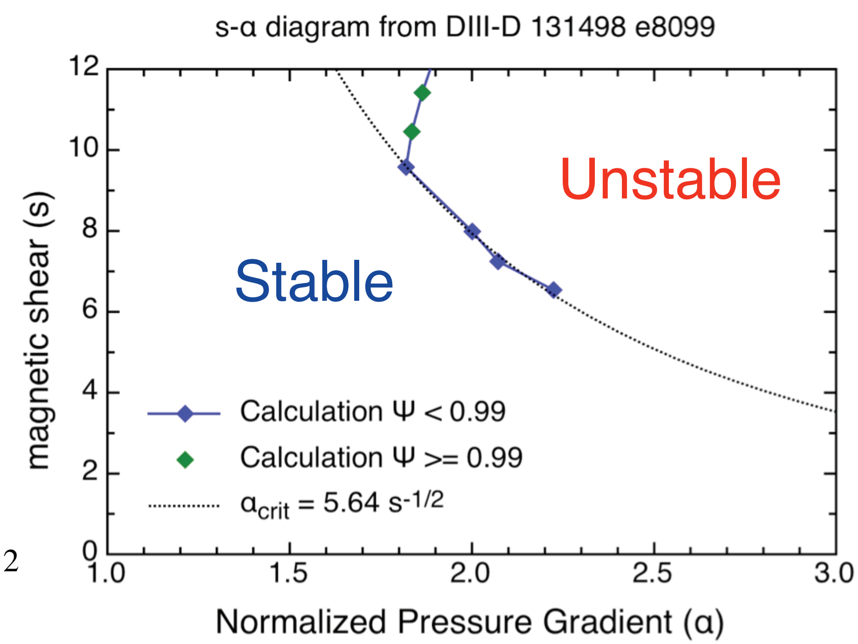
Magnetic Shear Dependence of KBM Onset Implies Approximately: $\Delta_\psi \sim \beta_{p,ped}^{1/2}$

- **Strong KBM onset implies:** $\alpha \propto \alpha_{crit}$
  - Integrating across edge barrier:

    $\overline{\alpha} \propto \overline{\alpha}_{crit} \propto \beta_{p,ped} / \Delta_\psi$ $\quad \boxed{\Delta_\psi \propto \beta_{p,ped} / \overline{\alpha}_{crit}}$

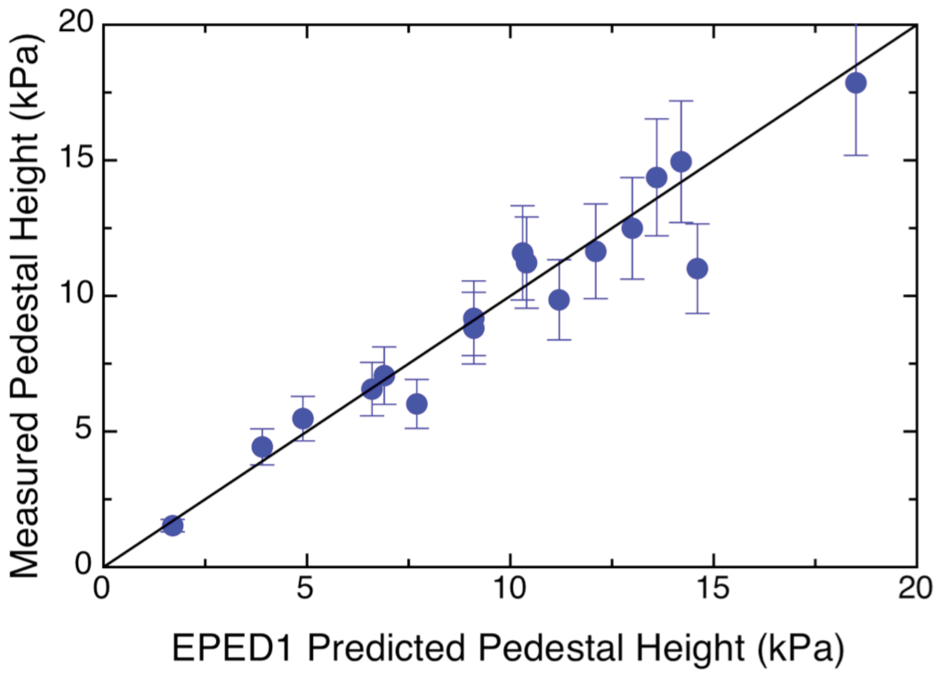
    (Δ_ψ is width in normalized poloidal flux, overbar represents average across barrier)
  - Strong dependence of Δ_ψ on $\beta_{p,ped}$, sub-linear due to s dependence of α_{crit}
  - Pedestal is predominantly in a low (local) magnetic shear region $\alpha_{crit} \sim 1/s^{1/2}$
  - Higher $J_{bs} \sim \beta_p$ reduces shear ($s \sim 1/J_{bs}$) and increases α_{crit}, expect approximately

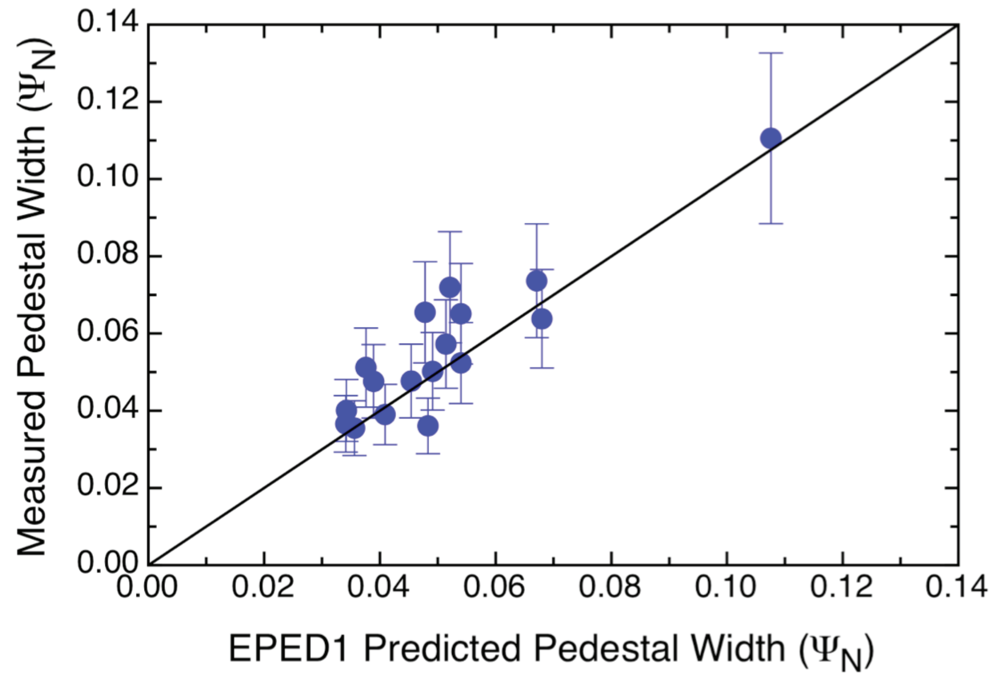
$$\overline{\alpha}_{crit} \propto \beta_{p,ped}^{1/2} \Rightarrow \Delta_\psi \propto \beta_{p,ped}^{1/2}$$



This is the leading order behavior, need to calculate quantitative details

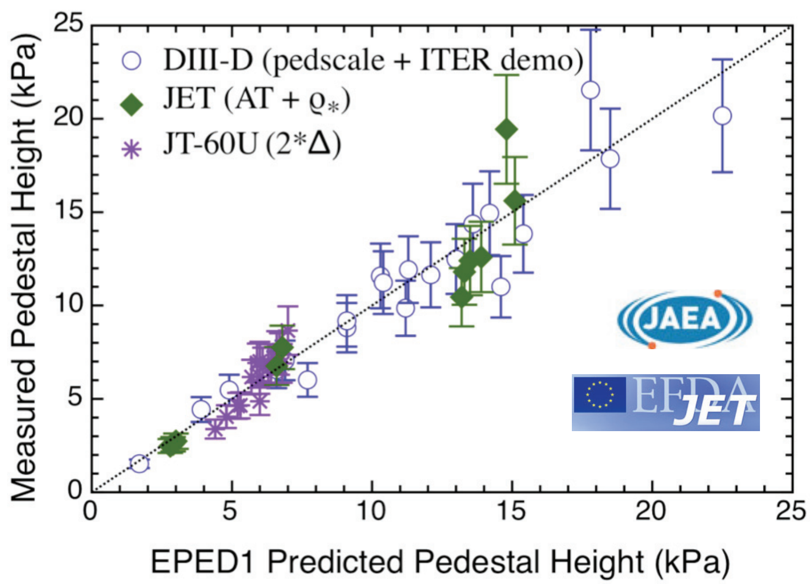
EPED Predictions in Good Agreement with Dedicated DIII-D Experiment (EPED1 Model)

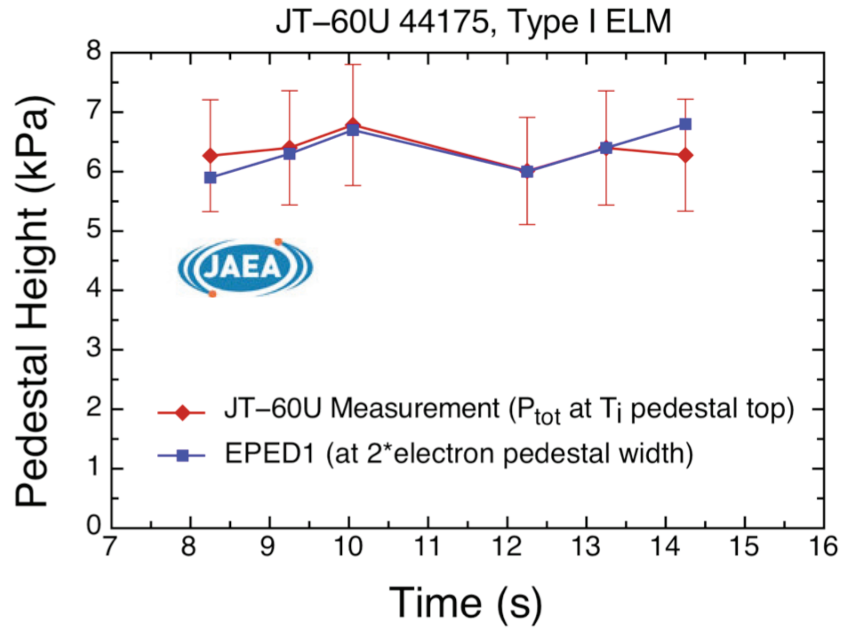




- **Experiment planned to yield large pedestal variation via scans in I_p, B_t and δ (~factor of 3 variations, 17 discharges)** *[Groebner08]*
- **EPED1 predictions made and presented before the experiment**
  - Good agreement, reproduce observed trends
- **Find very good agreement in predicted/measured 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

Tests of EPED on Multiple Devices (EPED1 Model)

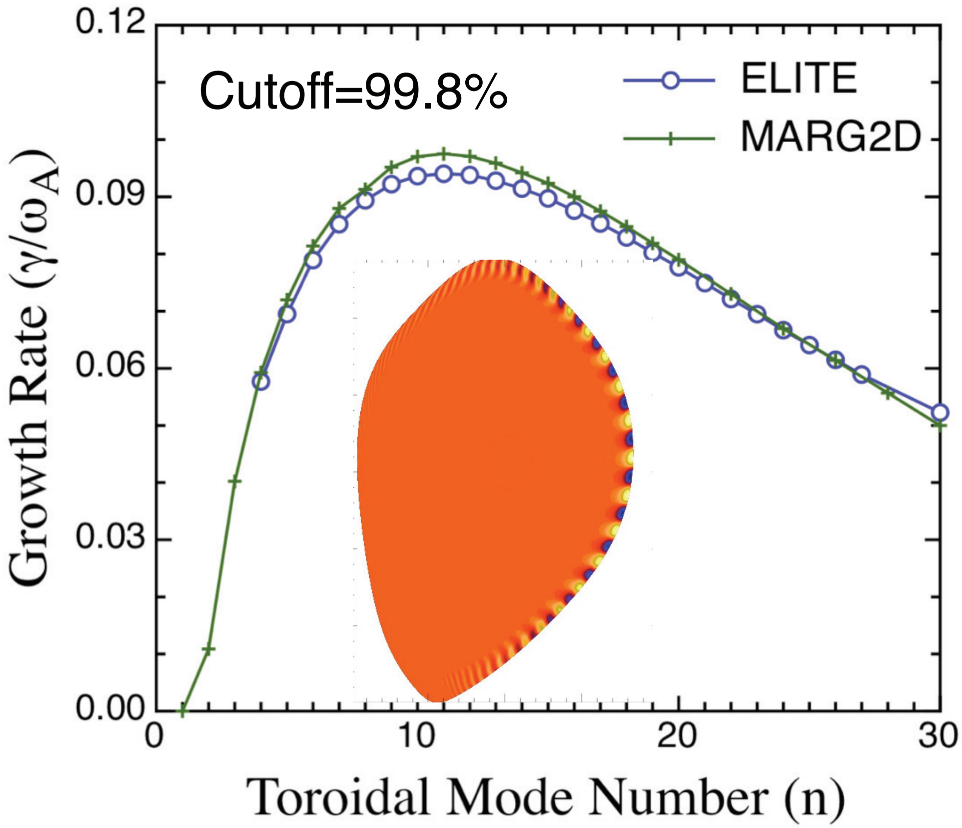


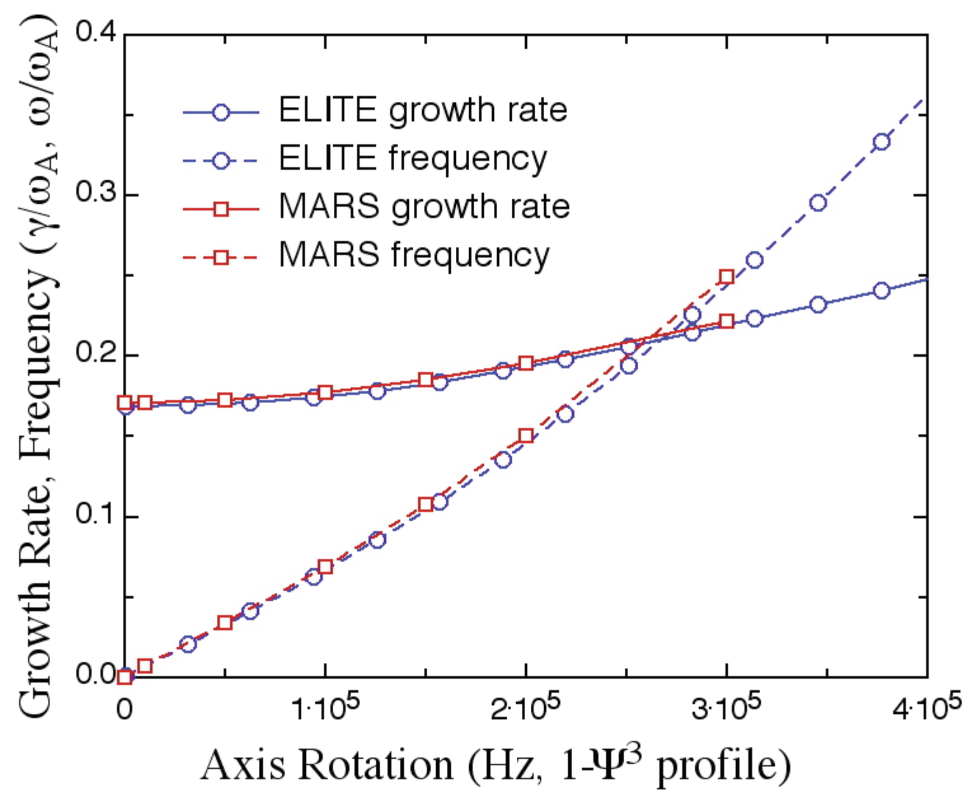


- **Initial test on 11 JET shots** *[Beurskens09]*, **1.05 ±0.14**
- **Trends with time on JT-60U** *[Urano08]* **accurately reproduced**
  - Changes in time of pedestal explained by β_{global} and n_{ped} variation
- **Predicted/Measured pedestal height= 1.02 ±0.14** ***(21 DIII-D, 16 JT-60U,11 JET)***
  - Good agreement in ITER demonstration discharges on DIII-D
- **Automation of EPED1 runs allows comparisons to large data sets**
  - *See T. Osborne, following talk*

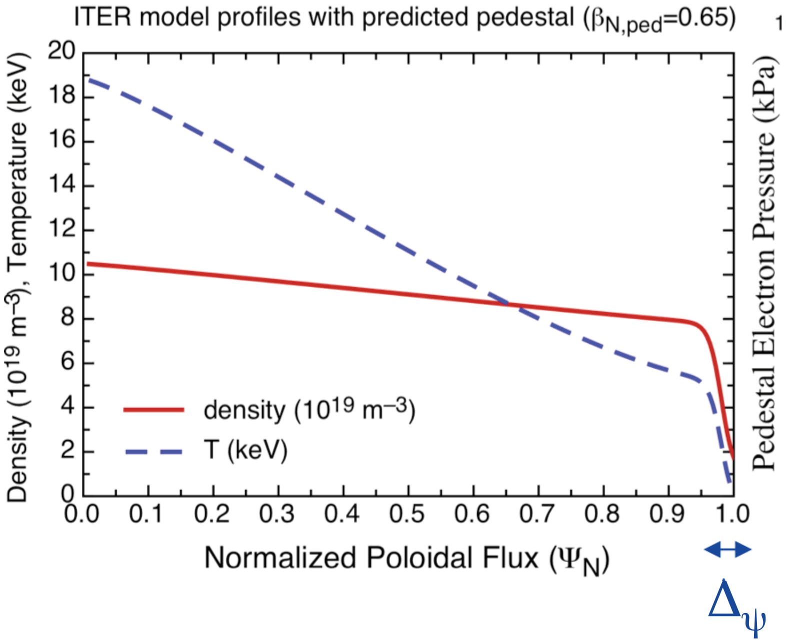
ELITE Code Extensively Verified

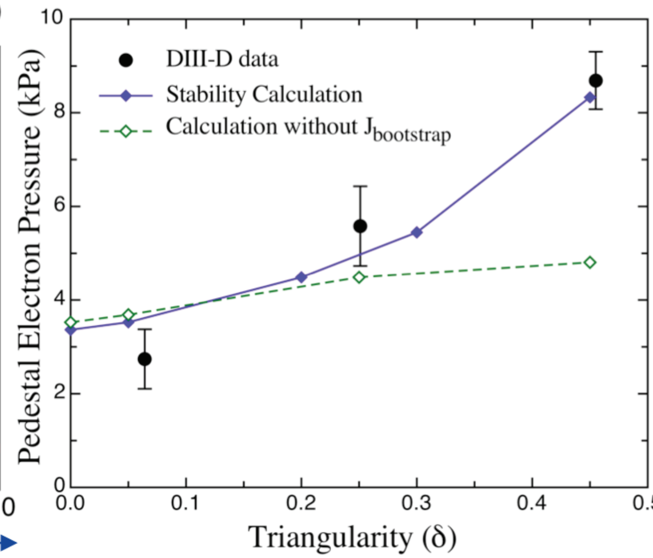
- **Extensive successful benchmarks have been carried out between codes (GATO, MARS, MARG2D, MISHKA, CASTOR, M3D, M3D-C1, NIMROD, BOUT++)**
  - Good agreement in both limiter and near-separatrix geometry
  - Good agreement both with and without flow shear (MARS and CASTOR)

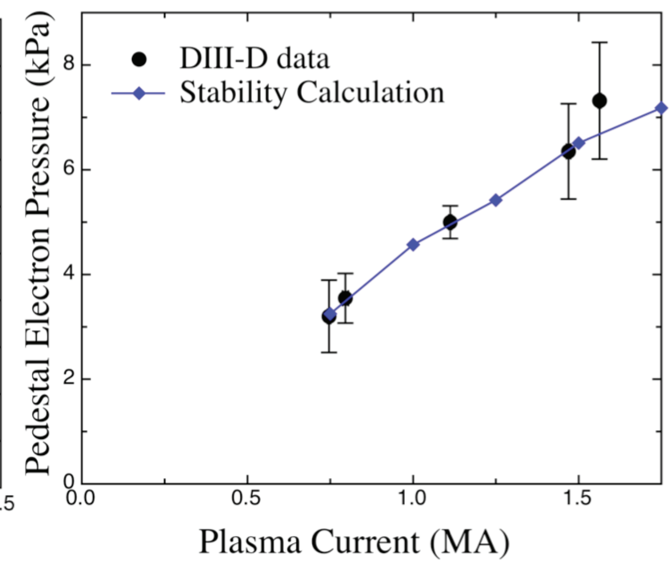




P-B Stability Studies Using Model Equilibria Useful for Predictions in Present and Future Devices







For predictions, 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_ψ, B_t, I_p, R, a, κ, δ, $n_{e,ped}$, $\beta_{N, global}$)
- Calculations using pedestal width (Δ_ψ) as an input find good agreement with observation (model equilibria capturing important stability physics) *[Snyder04]*
  - Δ_ψ *defined as the average of the electron density and temperature widths, fit to a tanh*

Can accurately quantify stability constraint [height=f(width)], but need second constraint for fully predictive model of pedestal height and width

A Hierarchy of Increasingly Sophisticated EPED (KBM&P-B) Models

- **Simplified (EPED1)**: Focus on the dominant dependence of Δ_ψ on $\beta_{p,ped}$
  - Neglect higher order dependencies of KBM constraint to allow model to be written in simple functional form (limited to standard aspect ratio tokamaks)
  - "Ballooning critical pedestal" calculations yield, $\Delta_{\psi_N} = 0.09\beta_{p,ped}^{1/2} G(\nu_*, \varepsilon ...)$ where G is a weakly varying function with <G>=1.0±0.2 for standard tokamaks
  - For definiteness, use value <G>=0.84 from large database *(DIII-D, T. Osborne)*
    - ***Observations consistent with theory***, find <G>~1, weakly varying in large expt database *[Groebner08, Snyder08]*
  - Yields simple EPED1 KBM Model:

$$\Delta_{\psi_N} = 0.076\beta_{p,ped}^{1/2}$$

- **Full EPED Model (EPED1.6)**: Direct calculation of both P-B and KBM (via "Ballooning critical pedestal") for each set of inputs
  - Incorporates higher order KBM dependencies (not just $\beta_{p,ped}$ dependence)
  - More sophisticated model of diamagnetic stabilization of P-B modes
  - Fully first principles model, nothing taken from observations

Pedestal Width Theory Has Progressed Slowly, Try New Approach

- **Long history of theories of the pedestal width**
  - Most based on ExB suppression of edge turbulence
    - Leads to gyro- and/or banana- radius scaling
- **Problems with that approach:**
  - ***Gyro- and banana- width scaling are not observed***
    - *More on this later…*
  - ExB suppression tells us how barrier formation begins. Want to know what constrains the higher gradients after the barrier is formed
  - P-B stability constrains both height and width (generally no transport steady state)
    - Width can grow up to ELM, can't calculate without ELM physics
  - Need a 2nd (local?) constraint, to accompany "global" P-B constraint
    - ***Many mechanisms cause transport in the pedestal (neo, turb etc), but we're looking the for one which stops the profiles from evolving***

      [focus on low collisionality, high power regime where QCM and TIII ELMs don't come in]