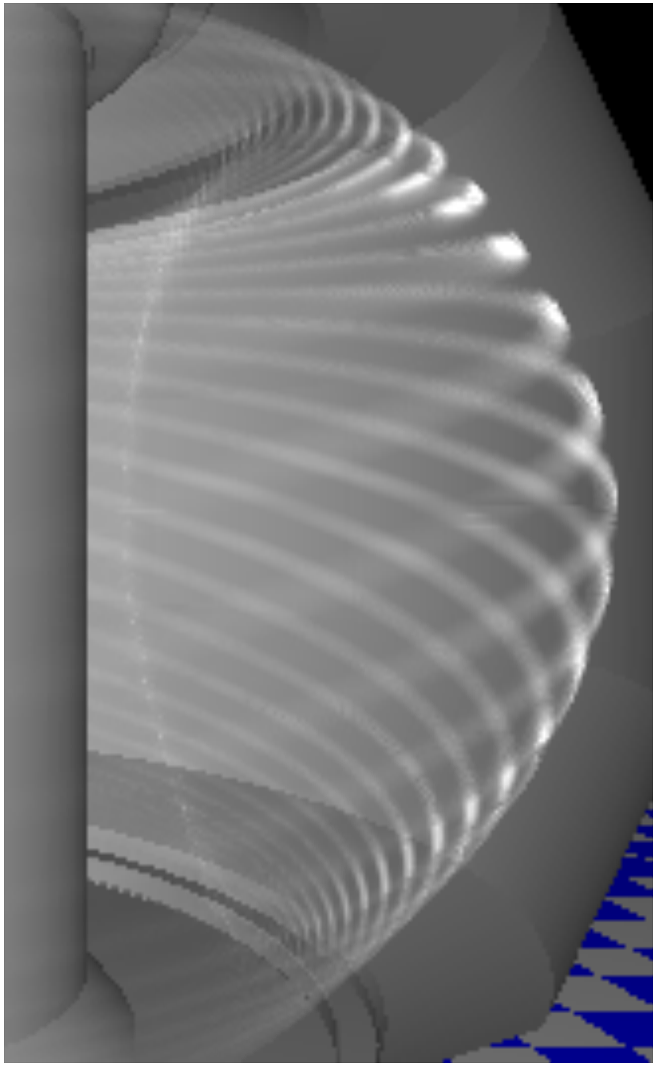
The EPED Pedestal Model: Extensions, Experimental Tests, and Application to ELM-suppressed Regimes

P.B. Snyder[1], M. Beurskens[2], R.J. Groebner[1], J.W. Hughes[3], R. Nazikian[4], D. Orlov[5], T.H. Osborne[1], O. Schmitz[6], M.R. Wade[1], J. Candy[1], L. Frassinetti[7], J.R. Walk[3], H.R. Wilson[8], X.Q. Xu[9]

[1]General Atomics, San Diego CA, USA
[2]EFDA/JET, Oxfordshire UK
[3]MIT/PSFC, Cambridge MA, USA
[4]PPPL, Princeton NJ, USA
[5]UCSD, San Diego CA, USA
[6]Forschungszentrum Jülich, Germany
[7]EURATOM-VR, Stockholm, Sweden
[8]University of York, York UK
[9]LLNL, Livermore CA, USA



Presented at the 53rd Annual Meeting of The APS Division of Plasma Physics Chicago, Illinois

November 8-12, 2010

EFDA JET

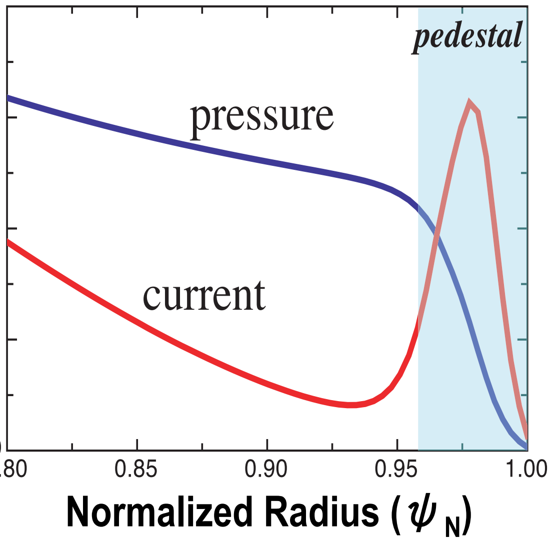
Alcator C-Mod

DIII-D NATIONAL FUSION FACILITY

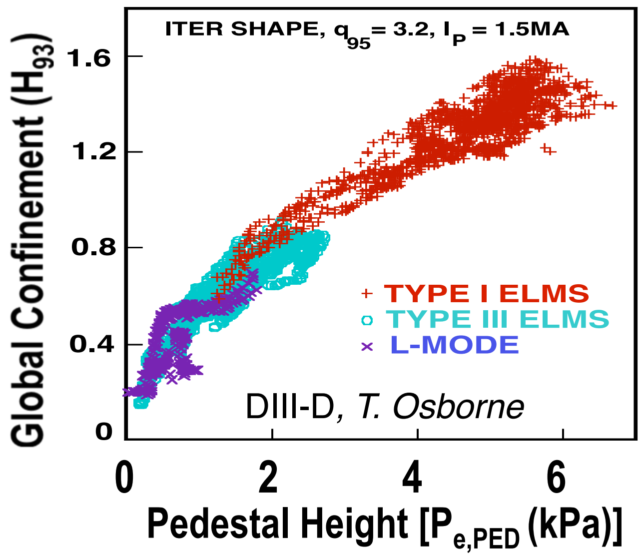
GENERAL ATOMICS

Motivation: Pedestal Height Critical for ITER Performance Prediction and Optimization

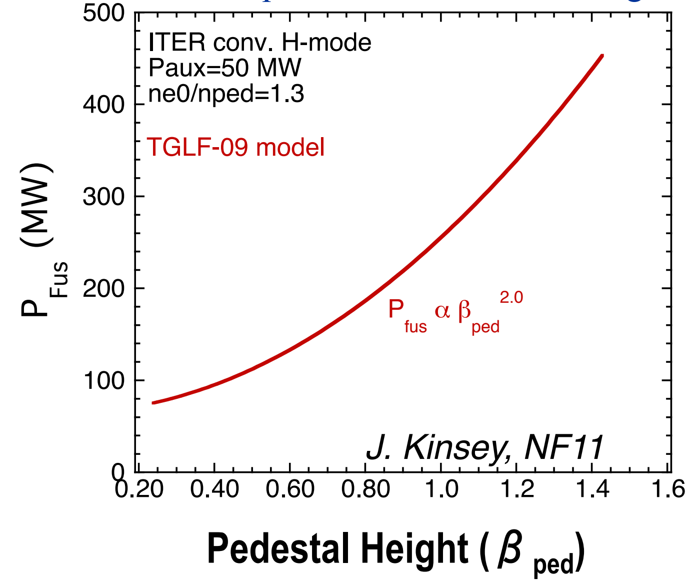
- **High performance ("H-mode") operation in tokamaks due to spontaneous formation of an edge barrier or "pedestal"**
- **Pedestal height has an enormous impact on fusion performance**
  - Dramatically improves both global confinement and stability (observed and predicted)
  - **Fusion power on ITER predicted to scale with square of the pedestal pressure**
    [Kinsey, Nucl. Fusion (2011)]
- **Accurate prediction of the *pedestal height* is essential to assess and optimize ITER performance, and to optimize the tokamak concept for energy production. Optimization must be done with *tolerable or controlled ELMs***



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

Developed based on two fundamental physics constraints, which are directly calculable, leading to a predictive and easily testable model

P.B. Snyder et al., *Phys. Plasmas* **16**, 056118 (2009); *Nucl. Fusion* **49**, 085035 (2009); *Nucl. Fusion* **51,** 103016 (2011)

A. Peeling-Ballooning Modes

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

B. Kinetic Ballooning Mode Onset

- Local constraint on pressure gradient 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 (EPED1 simplified KBM)
  - ***No fitting parameters in any part of model, straightforward & predictive***

D. Validate Model Against Several Devices, ELMing and QH Mode

- Comparisons on DIII-D, C-Mod, JET, JT-60U, AUG

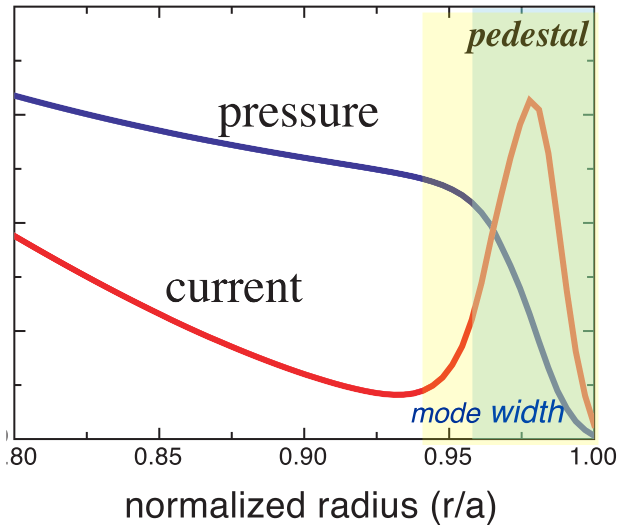
E. Application of the EPED Model to RMP ELM Suppression

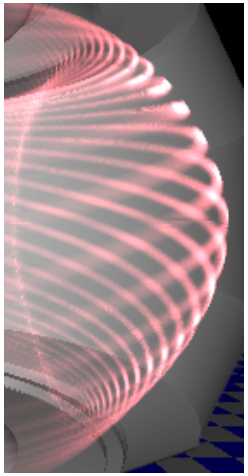
F. Summary, Including Pedestal Prediction and Optimization for ITER

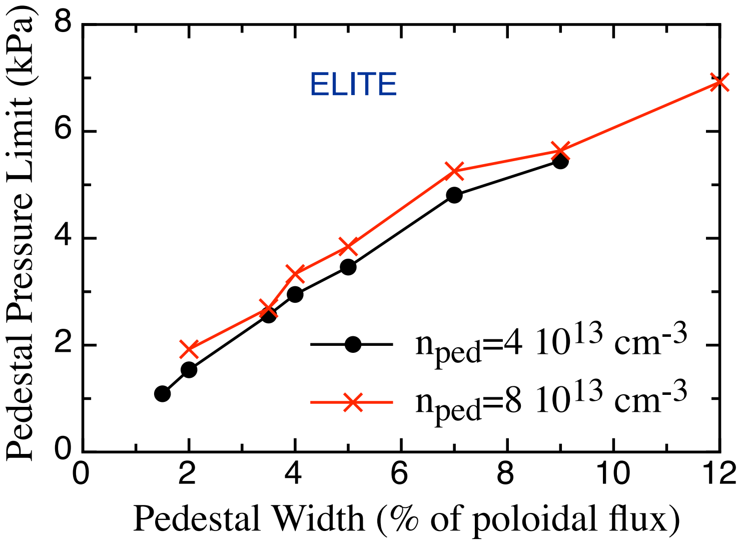
Peeling-Ballooning Modes

Provide a "global" constraint on the pedestal height as a function of the width

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., extensively tested against experiment

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

- *Can calculate P-B constraint predictively using sets of model equilibria* $\beta_{Nped}=f(\Delta_\psi)$
- 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

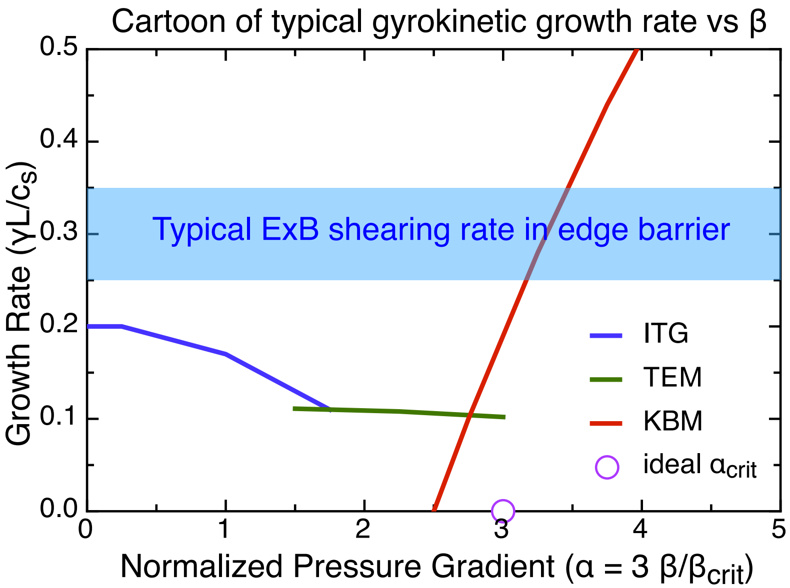
H.R. Wilson et al., *Phys. Plasmas* **9**, 1277 (2002); P.B. Snyder et al., *Phys. Plasmas* **9**, 2037 (2002);
P.B. Snyder et al., *Nucl Fusion* **47**, 961 (2007)

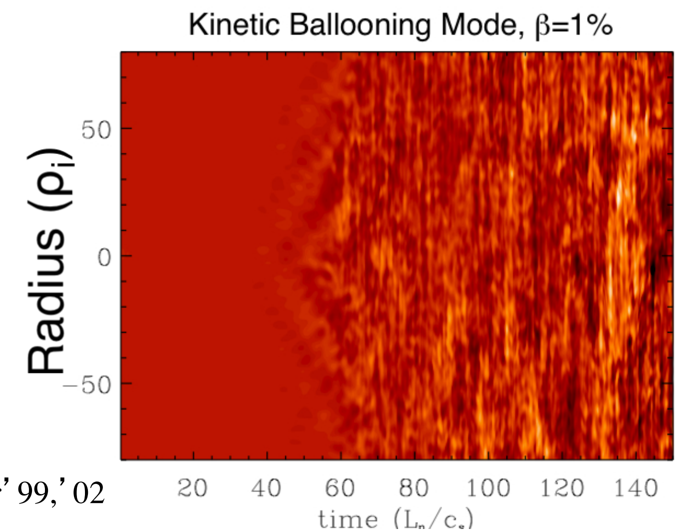
Kinetic Ballooning Mode Onset Provides 2nd Constraint

Many mechanisms drive transport across the edge barrier. We hypothesize that the KBM is the mechanism by which the pressure gradient is finally constrained in the presence of strong ExB shear (in the regime of interest to ITER – moderate to low collisionality and standard aspect ratio)

Propose Pedestal p' 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
    - Initial full EMGK calcs in full edge geometry with GYRO match expected onset
  - 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
  - Use model equilibria to "integrate" local constraint





Snyder'99,'02

GENERAL ATOMICS

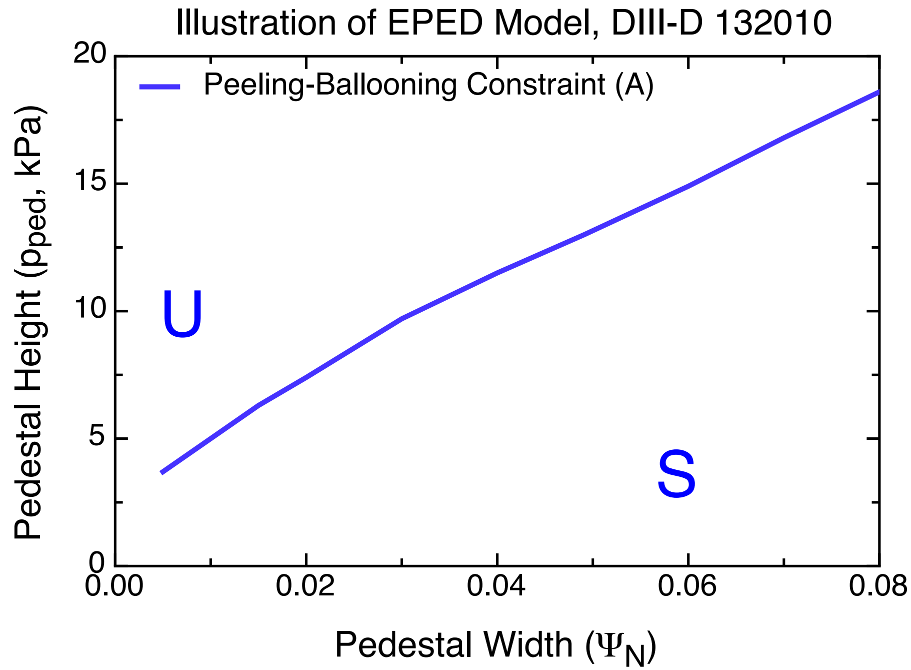
Implementing and Testing the EPED Model

Mechanics of the EPED Predictive Model

- **Input: B_t, I_p, R, a, κ, δ, n_{ped}, β_{global}, m_i**
- **Output: Pedestal height and width** ***(no free or fit parameters)***

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

  – ELITE, n=5-30; non-local diamag model from BOUT++ calculations



P.B. Snyder et al., *Phys.* 103016 (2011) *Plasmas* **16**, 056118 (2009); *Nucl. Fusion* **51**,

Mechanics of the EPED Predictive Model

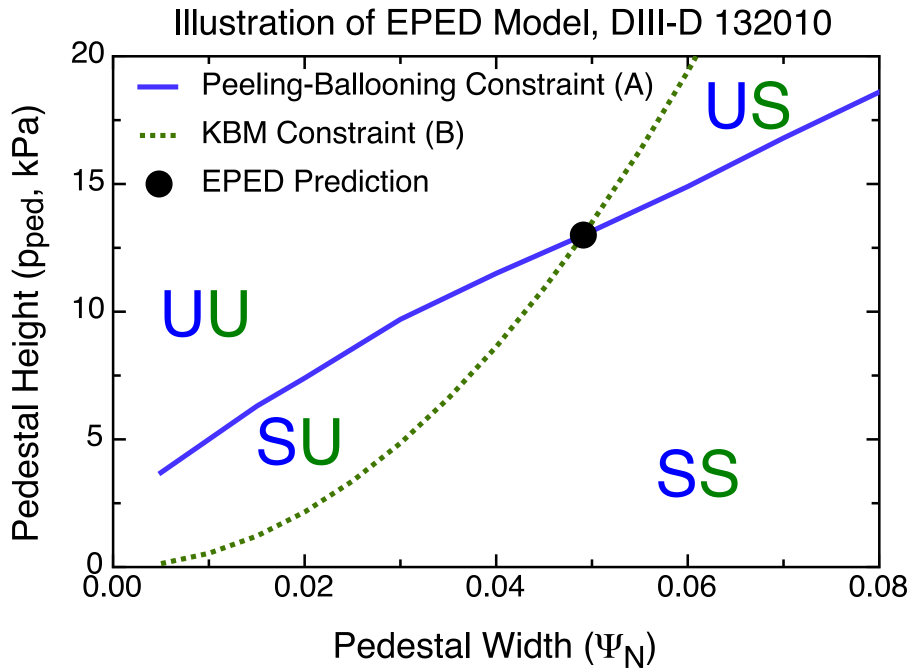
- **Input: B_t, I_p, R, a, κ, δ, n_{ped}, β_{global}, m_i**
- **Output: Pedestal height and width** ***(no free or fit parameters)***

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

- ELITE, n=5-30; non-local diamag model from BOUT++ calculations

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

- Directly calculate with ballooning critical pedestal technique



P.B. Snyder et al., *Phys.* 103016 (2011) *Plasmas* **16**, 056118 (2009); *Nucl. Fusion* **51**, 103016 (2011)

- **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)**

Mechanics of the EPED Predictive Model

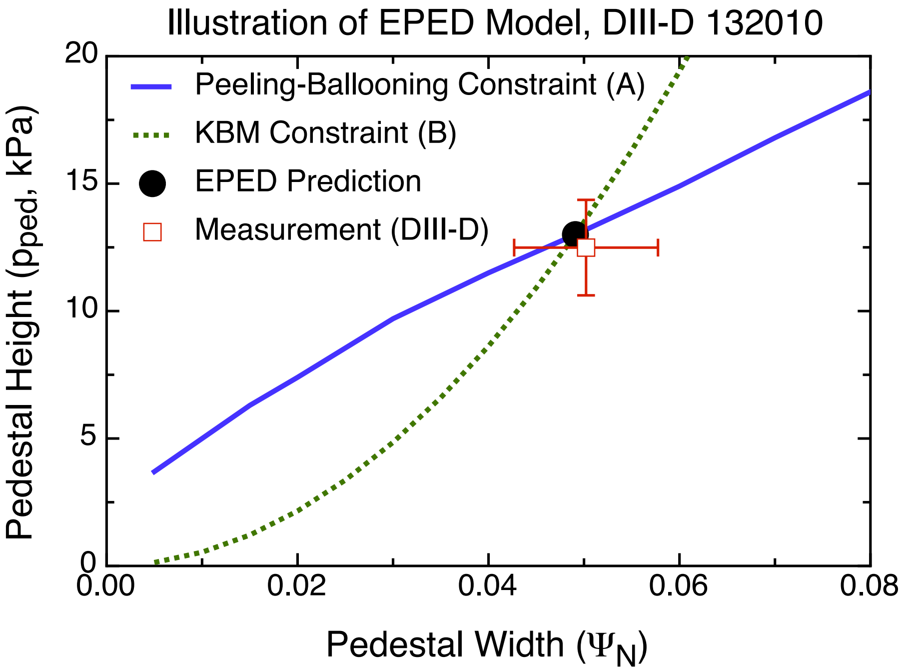
- **Input: B_t, I_p, R, a, κ, δ, n_{ped}, β_{global}, m_i**
- **Output: Pedestal height and width** *(no free or fit parameters)*

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

– ELITE, n=5-30; non-local diamag model from BOUT++ calculations

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

– Directly calculate with ballooning critical pedestal technique



P.B. Snyder et al., *Phys.* 103016 (2011) *Plasmas* **16**, 056118 (2009); *Nucl. Fusion* **51**, 103016 (2011)

- **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)**

– 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 <u>worse</u> increases pedestal height and width

Interaction of P-B and KBM Constraints Predicts Pedestal Height and Width Changes in I_p Scan

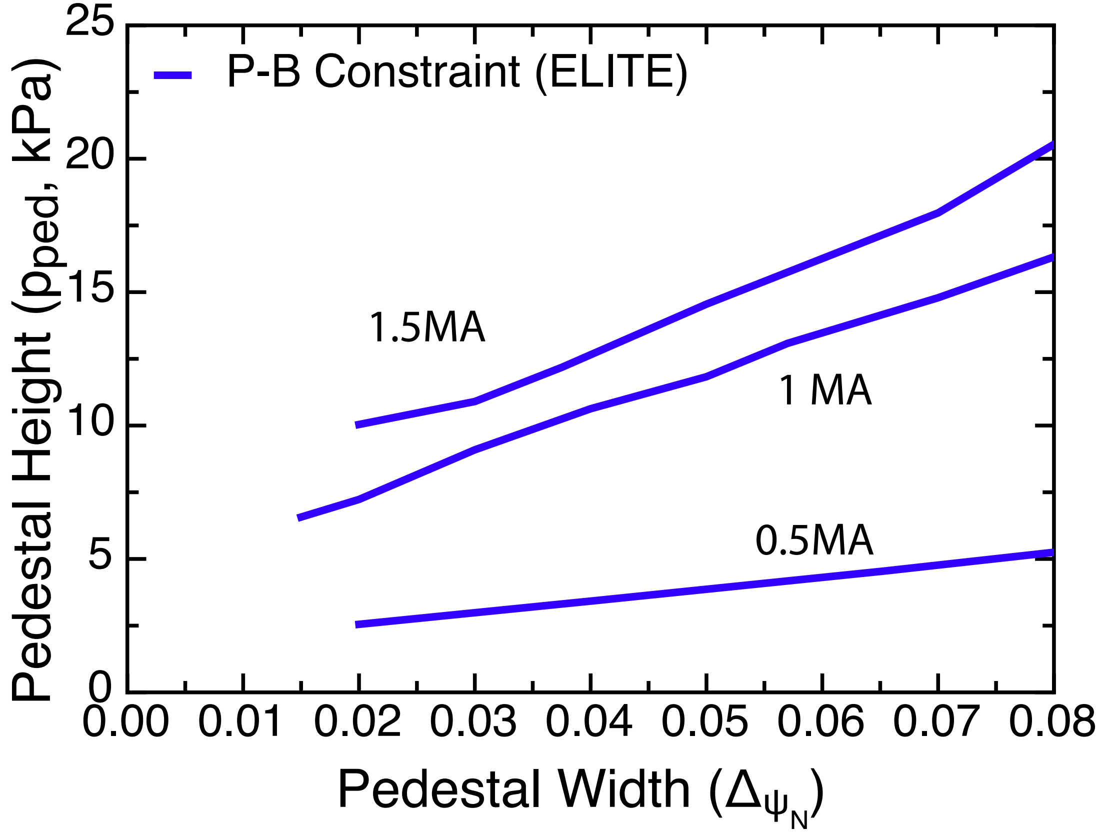
DIII-D: I_p varied by a factor of 3 (0.5, 1, 1.5 MA)

- B_t=2.1 T, κ=1.74, δ=0.3

  "Global" P-B stability increases roughly linearly with I_p

- β_N-like, dependence weakens as q gets low

EPED1 Model, DIII-D Current Scan (0.5, 1, 1.5MA)



Interaction of P-B and KBM Constraints Predicts Pedestal Height and Width Changes in I_p Scan

DIII-D: I_p varied by a factor of 3 (0.5, 1, 1.5 MA)

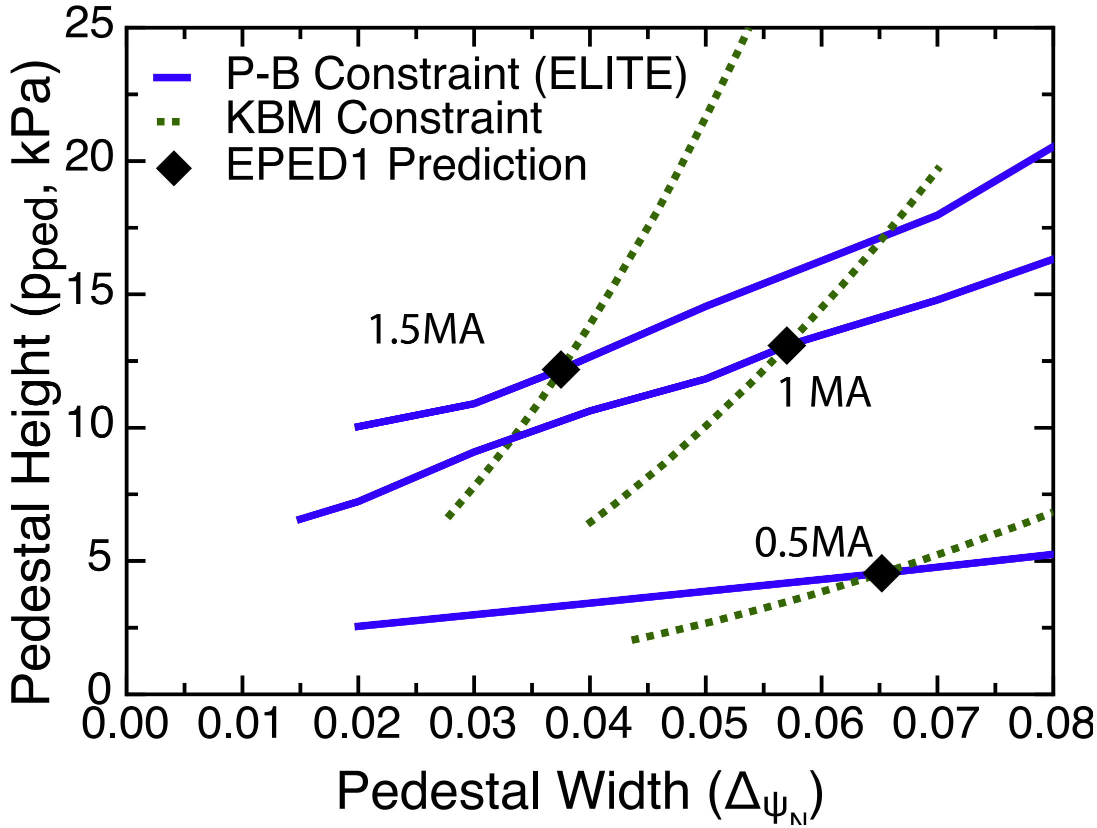
- B_t=2.1 T, κ=1.74, δ=0.3

  "Global" P-B stability increases roughly linearly with I_p
- β_N-like, dependence weakens as q gets low

  KBM increases with $\sim I_p^2$

Interaction of P-B and KBM leads to height that first rises strongly then stagnates, while width decreases with I_p

EPED1 Model, DIII-D Current Scan (0.5, 1, 1.5MA)



Interaction of P-B and KBM Constraints Predicts Pedestal Height and Width Changes in I_p Scan

DIII-D: I_p varied by a factor of 3 (0.5, 1, 1.5 MA)

- B_t=2.1 T, κ=1.74, δ=0.3

"Global" P-B stability increases roughly linearly with I_p

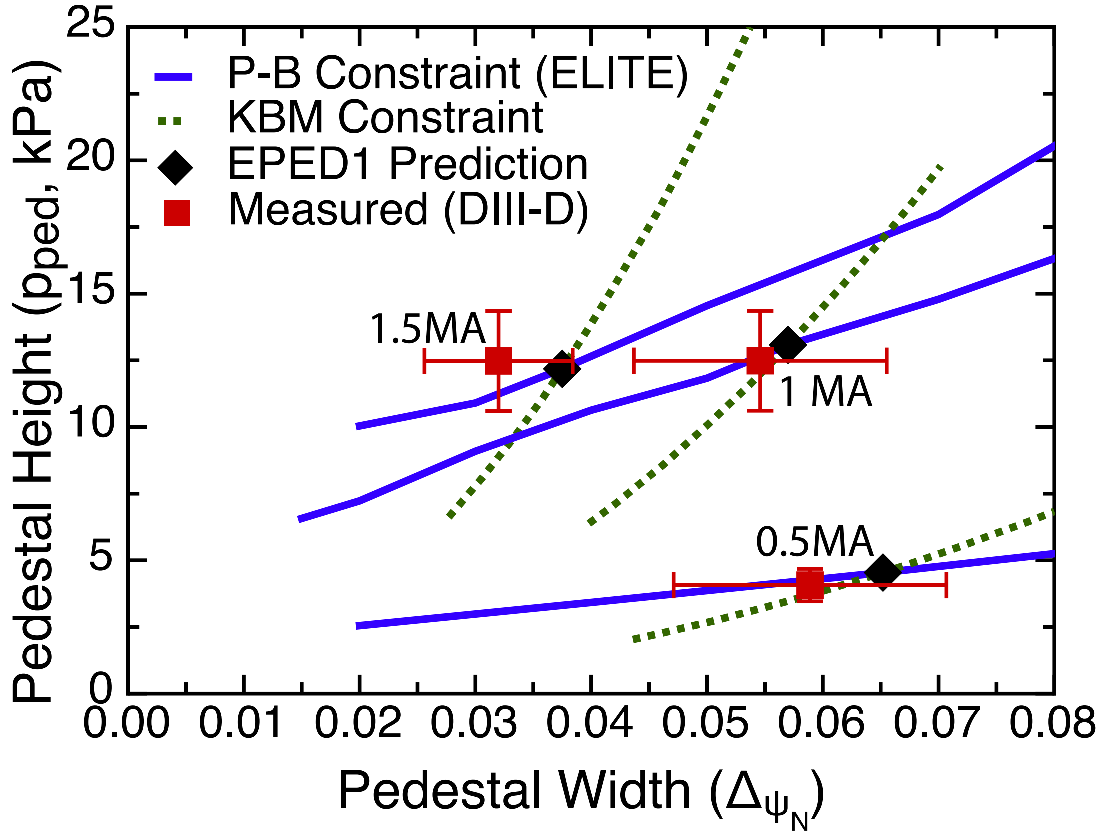
- β_N-like, dependence weakens as q gets low

KBM increases with $\sim I_p^2$

Interaction of P-B and KBM leads to height that first rises strongly then stagnates, while width decreases with I_p

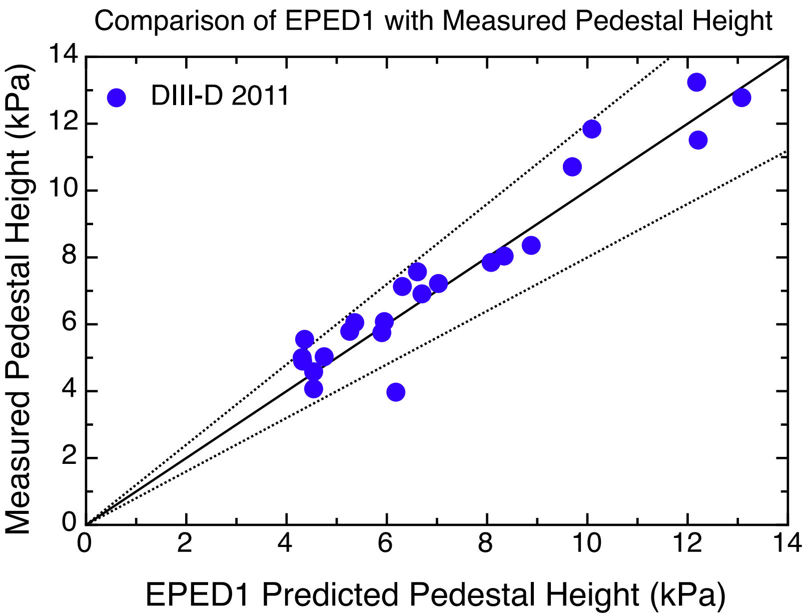
- Good agreement with observations at all I_p values

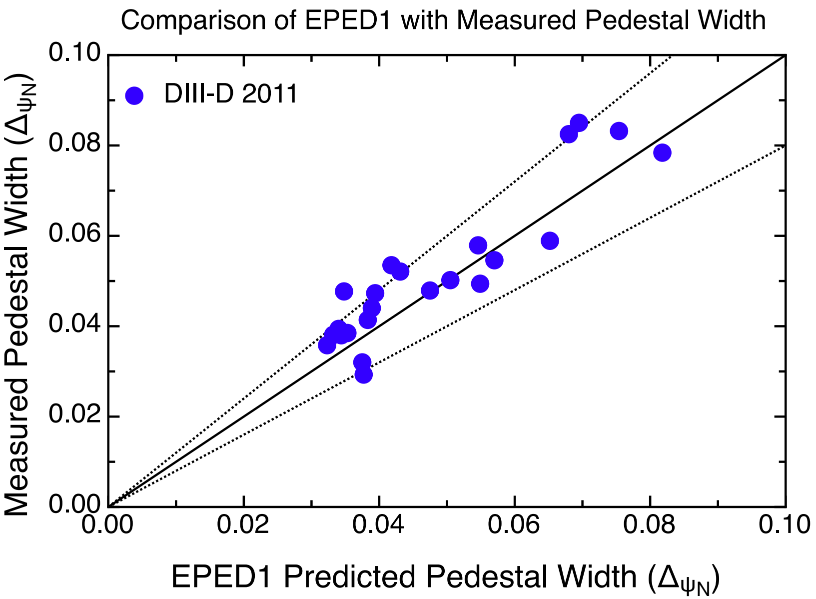
EPED1 Model, DIII-D Current Scan (0.5, 1, 1.5MA)



GENERAL ATOMICS

2011: DIII-D Upgrade to Thomson System Allows More Precise Height & Width Comparison





Major Thomson upgrade ~doubles resolution *(see D. Eldon UP9.069 & R. Groebner GO4.005)*

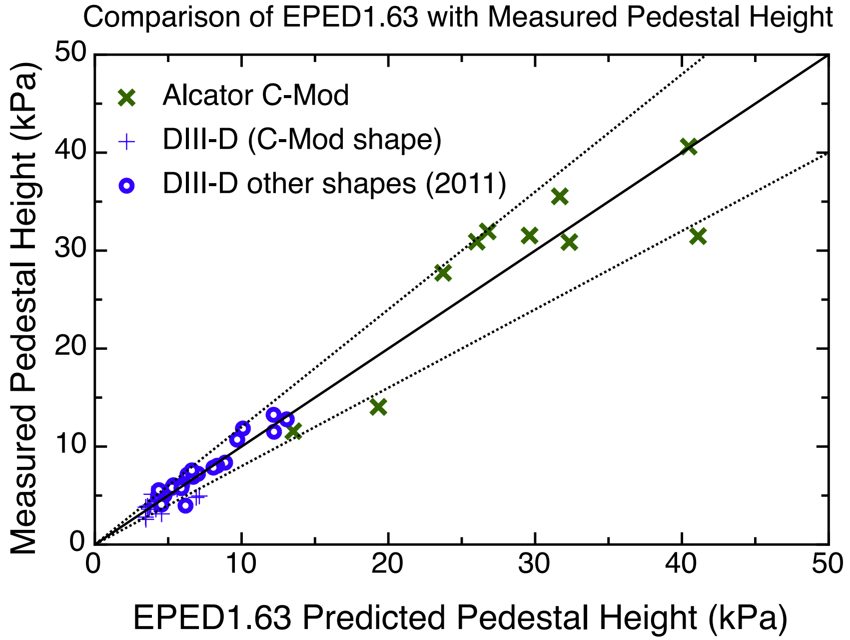
Dedicated expts to vary pedestal height and width (I_p scan) and compare to models

EPED1 model compared to measured height and width using both pre-expt predictions and post-experiment analysis. Wide range of widths and heights achieved

Good agreement with EPED1 model (24 cases, 14 shots):

- -Ratio of predicted to observed pedestal height: 0.98±0.15, corr *r*=0.96
- -Ratio of predicted to observed pedestal width: 0.94±0.13, corr *r*=0.91
- -Ratio of predicted to observed pedestal average pprime: 1.05±0.16, corr *r*=0.95

Test of the Full EPED1.63 Model on C-Mod/DIII-D Similarity Experiment



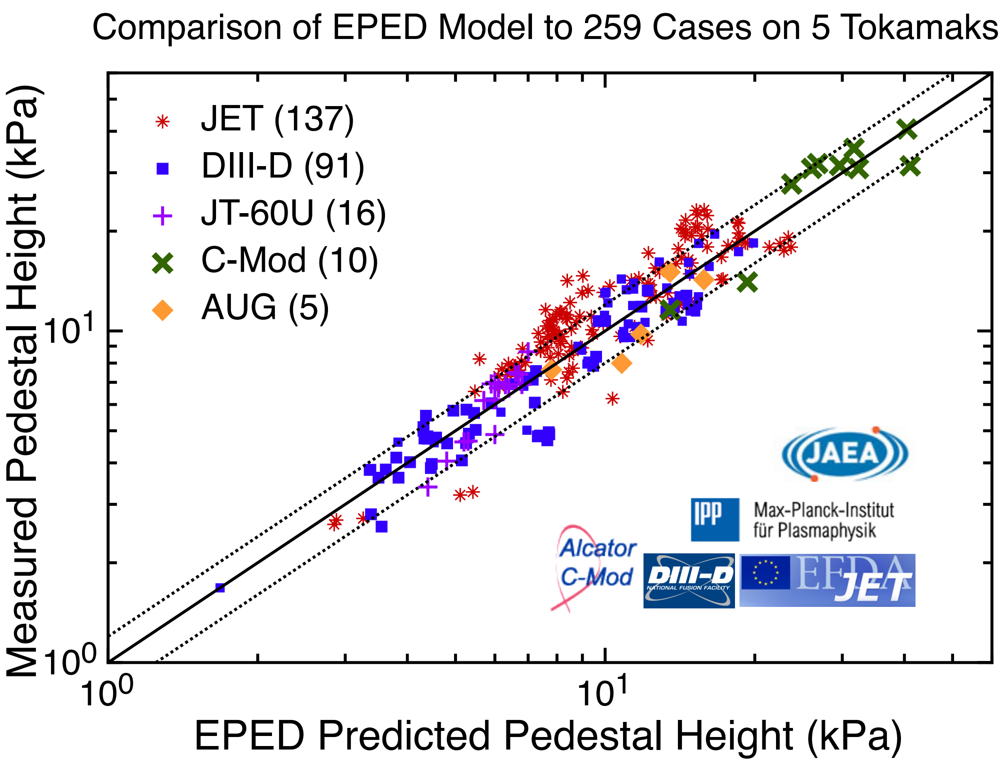
EPED1.63 model calculates both P-B and KBM constraints directly for each case – more time consuming, but more precise

- Advanced model of diamagnetic effects particularly important for comparisons with Alcator C-mod

Joint C-Mod/DIII-D similarity experiment

- Ratio of predicted to observed height 1.05 ± 0.19, corr *r*=0.98, 33 cases
- Good match in pedestal beta achieved by operating DIII-D in C-Mod shape

Test of EPED on 259 Cases on 5 Tokamaks Finds Agreement within ~20%



Combines new and published studies with both versions of the model (EPED1 and EPED1.63)

- 259 cases, factor of ~20 variation in pressure, ~10 in pedestal beta
  - Full set of 137 JET baseline and hybrid cases with HRTS (M. Beurskens, HMWS)
  - C-Mod and DIII-D data from JRT 2011 campaigns (EPED1.63)
  - Published studies on JT60-U, AUG, DIII-D

Ratio of predicted to observed height = 0.98±0.20 (corr *r*=0.92)

Consistent with ~10-15% measurement error and EPED accuracy to ~15-20%

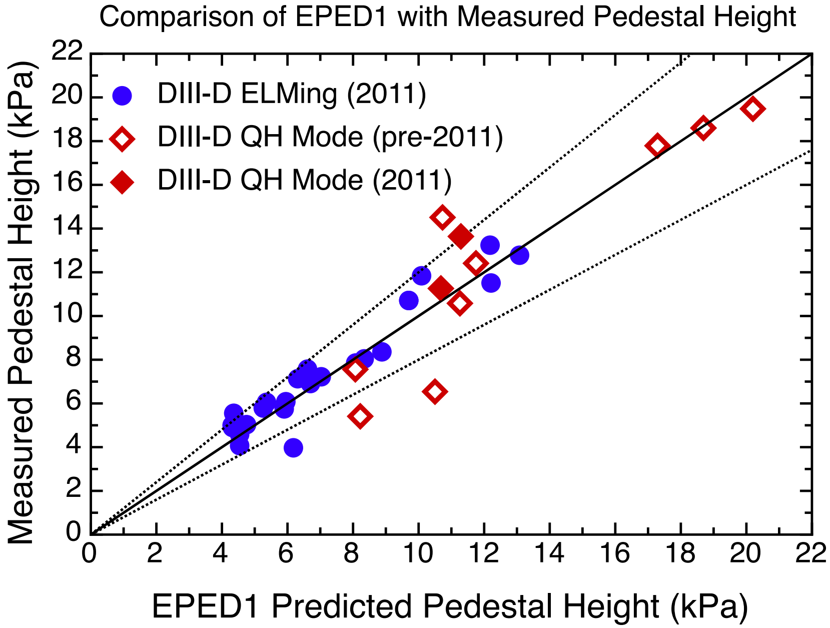
EPED1 model accurate to ~20% overall with strong correlation between predicted and observed pedestal height (no adjustable parameters)

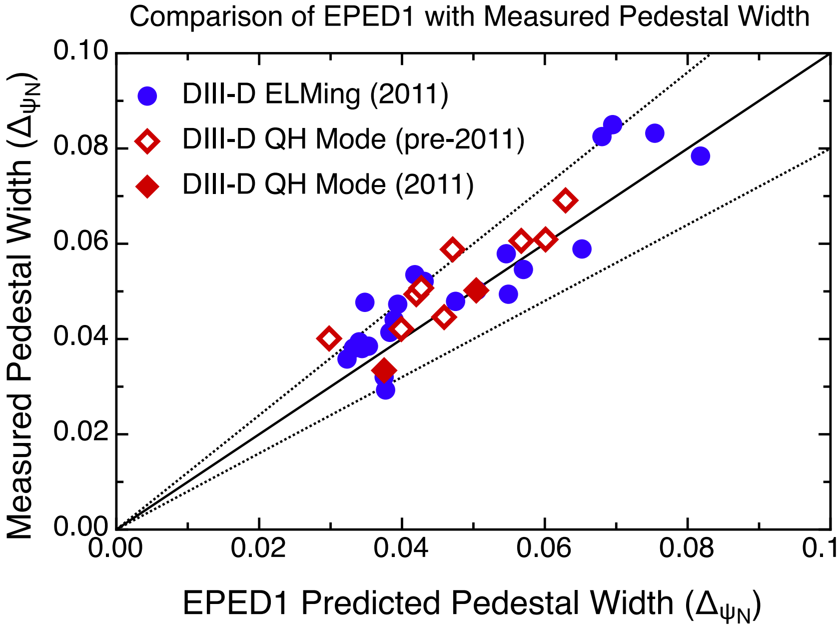
– Captures trends in data

Testing the EPED Model on Quiescent H-Modes (QH)

In QH Mode, there are no ELMs and steady edge conditions are maintained with an Edge Harmonic Oscillation (EHO)

EPED can be Applied to Quiescent H-Mode Discharges

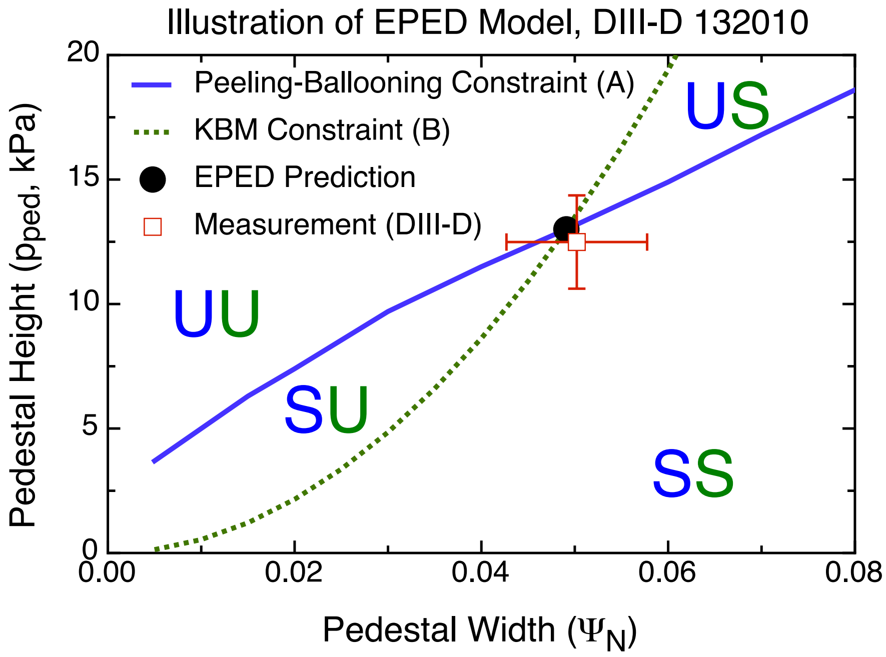




- **P-B studies find that EHO is associated with current driven kink/peeling mode, allows prediction of critical density for QH at a given width**
- **EPED model predicts QH mode pedestal height and width with similar accuracy as ELMing cases (~20%, corr *r*=0.9)**
  - Very high pedestals can be maintained in QH mode operation with no ELMs
- **Gives confidence in prediction that ITER will operate in QH density range. Still quantifying rotation requirements, see *Burrell YI2.00001, Friday***

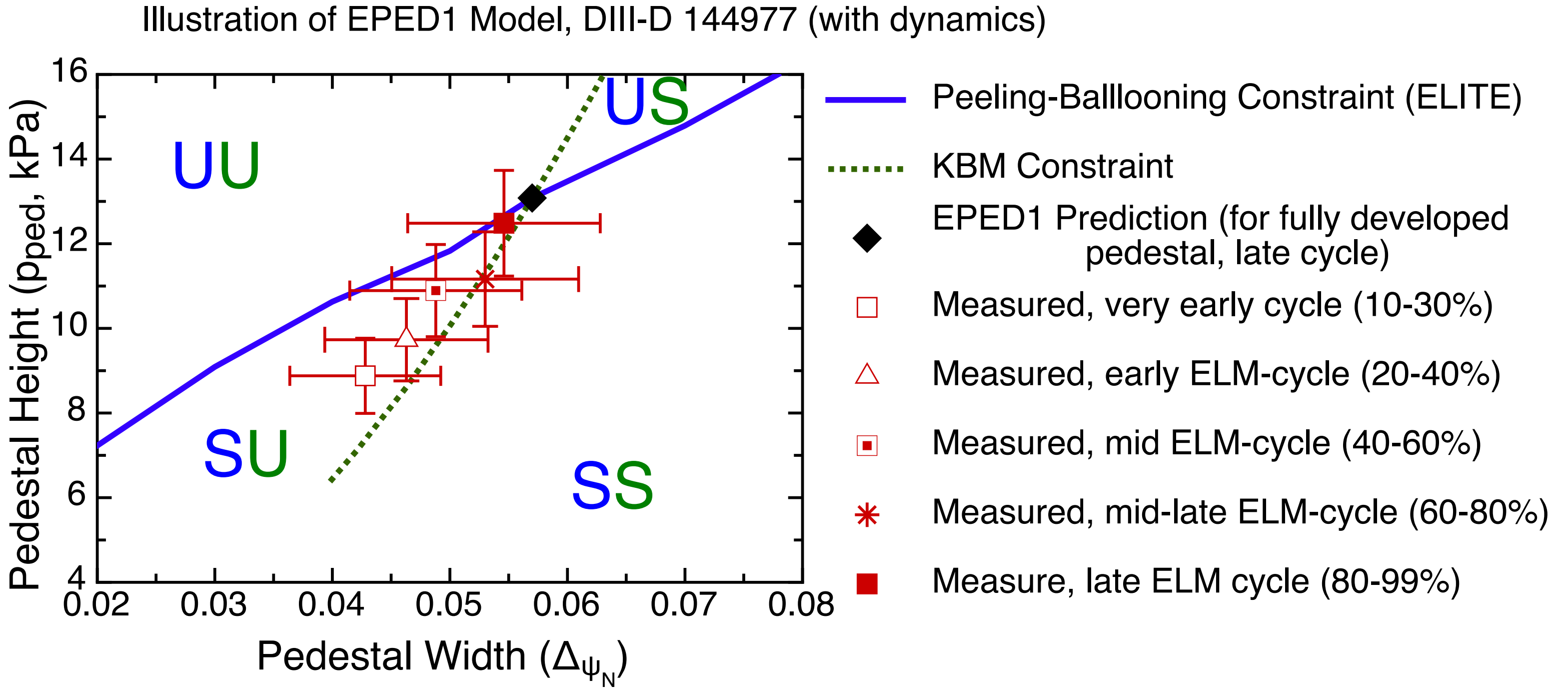
Using EPED to Understand RMP ELM Suppression (low collisionality)

Applying the EPED Model to Develop a Working Model for RMP ELM Suppression



- **When ELMs are suppressed by applied 3D fields (Resonant Magnetic Perturbations or RMPs), the discharges are found to hover in the stable region of the peeling-ballooning stability diagram. WHY? HOW?**
  - Conditions only slightly different between "resonant" ELM suppression, and off-resonant discharges with ELMs (density and gradients similar)
- **Can we understand this in terms of the EPED model?**

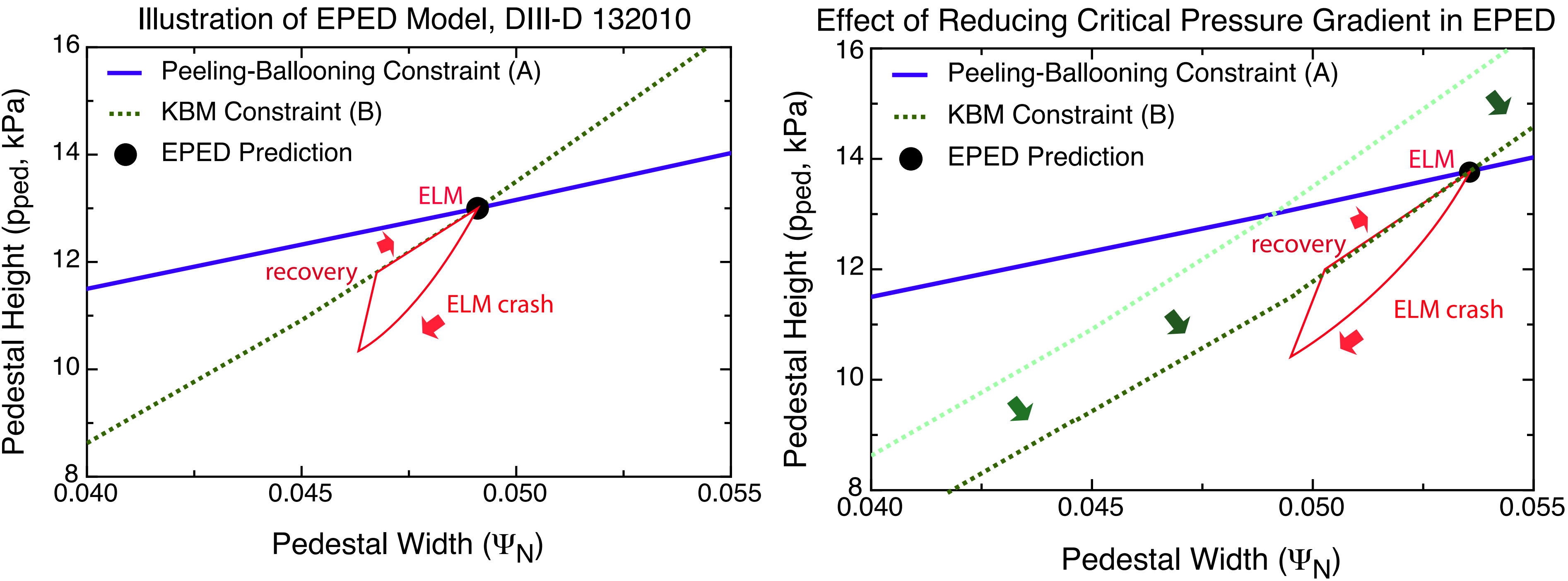
The EPED Model and the ELM Cycle: Comparing to Observation



EPED is a static model for the pedestal structure, but can be used to interpret dynamics

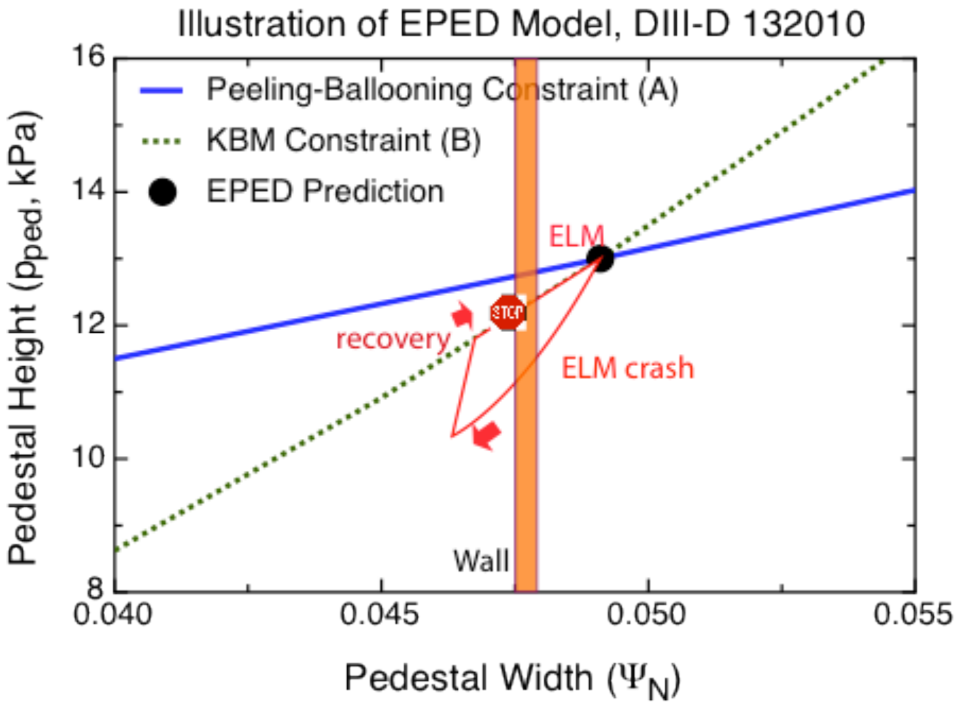
- **In T1 ELMing discharges, the ELM is triggered by a "global" peeling-ballooning mode (solid blue line), typically followed by a crash, fast recovery (pre-KBM) and slow recovery (with KBM)** *[other types of cycle also possible]*
- **This cycle can be directly measured for low frequency, large ELMs, as in DIII-D 144977 above (single ELM cycle)**

The EPED Model and the ELM Cycle: How can (or can't) ELMs be suppressed?



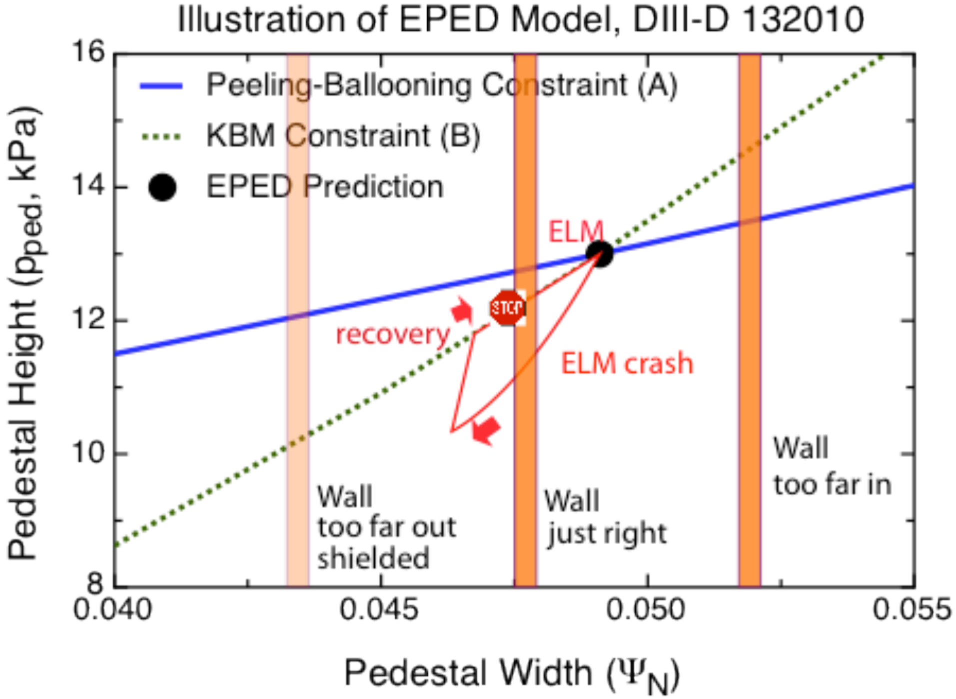
Reducing the pressure gradient below the initial KBM limit does NOT, by itself, prevent the ELM (this was hypothesized as how RMP might work, wrong in 2 ways)

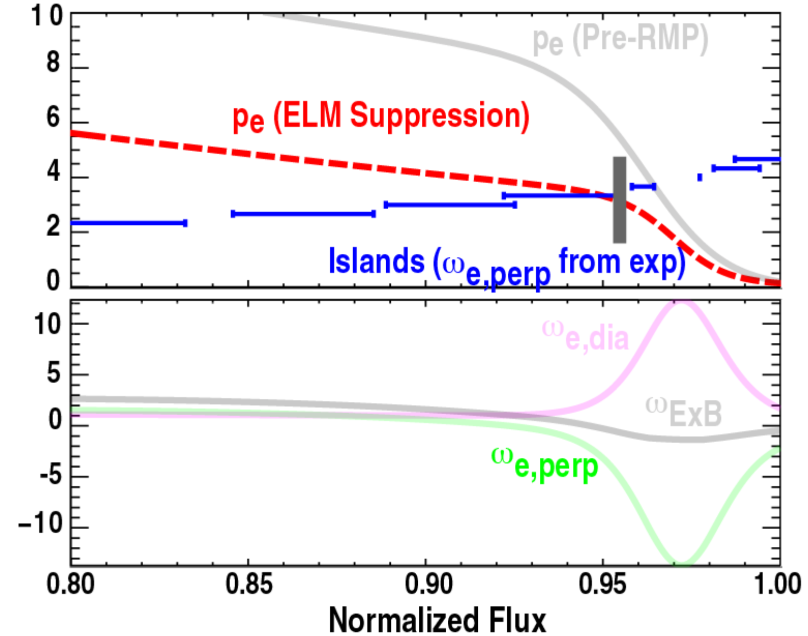
A "Wall" Can Stop the ELM



- **Inserting a "wall" that blocks the expansion of the pedestal can stop the recovery and prevent the next ELM**
- **In RMP ELM suppression, this "wall" can be a resonant island or stochastic region that drives strong transport and prevents inward pedestal propagation**

A “Wall” Can Stop the ELM ➔RMP q windows





- Inserting a “wall” that blocks the expansion of the pedestal can stop the recovery and prevent the next ELM
- In RMP ELM suppression, this “wall” can be a resonant island or stochastic region that drives strong transport and prevents inward pedestal propagation
- **Wall location must be precise: too far in will not stop the ELM, too far out will be shielded by very large $v_{\perp e}$ in the pedestal (2-fluid response physics)**
- **Location of wall determined by q profile ➔ q windows for ELM suppression**

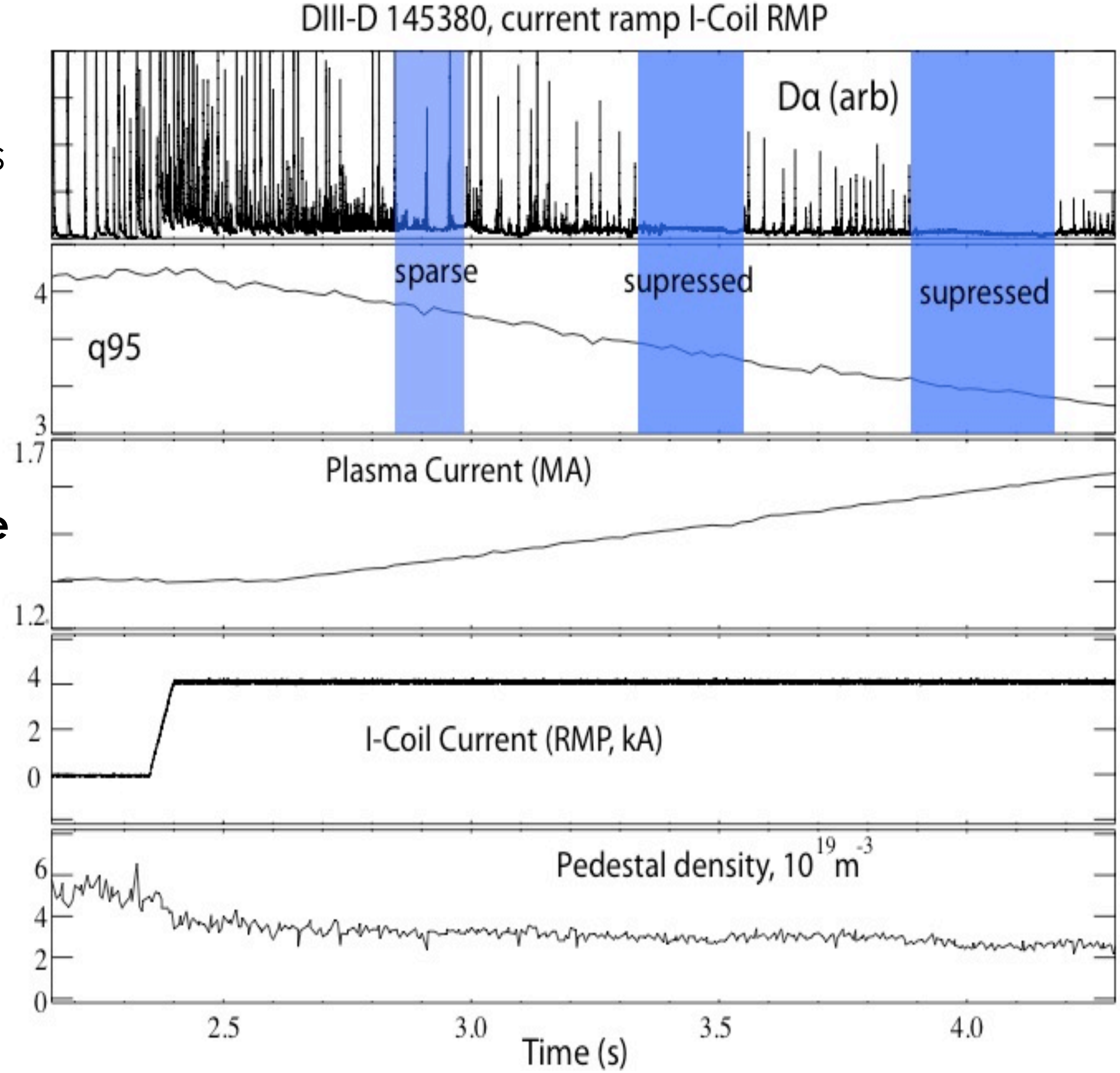
ELM Suppression Occurs in "Windows" of q_{95}

ELM suppression or mitigation occurs in multiple q windows

- DIII-D 145830, I_p ramp, 2 windows of suppression, 1 sparse (blue)

EPED predicts width of 0.03

- **With gradient constrained by KBM, ELM (P-B mode) will be triggered when width exceeds 0.03**
- **To suppress ELMs, must place the outer edge of the "wall" outside of 0.97**
  - Islands cannot penetrate the sharp gradient region due to large diamagnetic term: can't place "wall" any further out than ~0.98



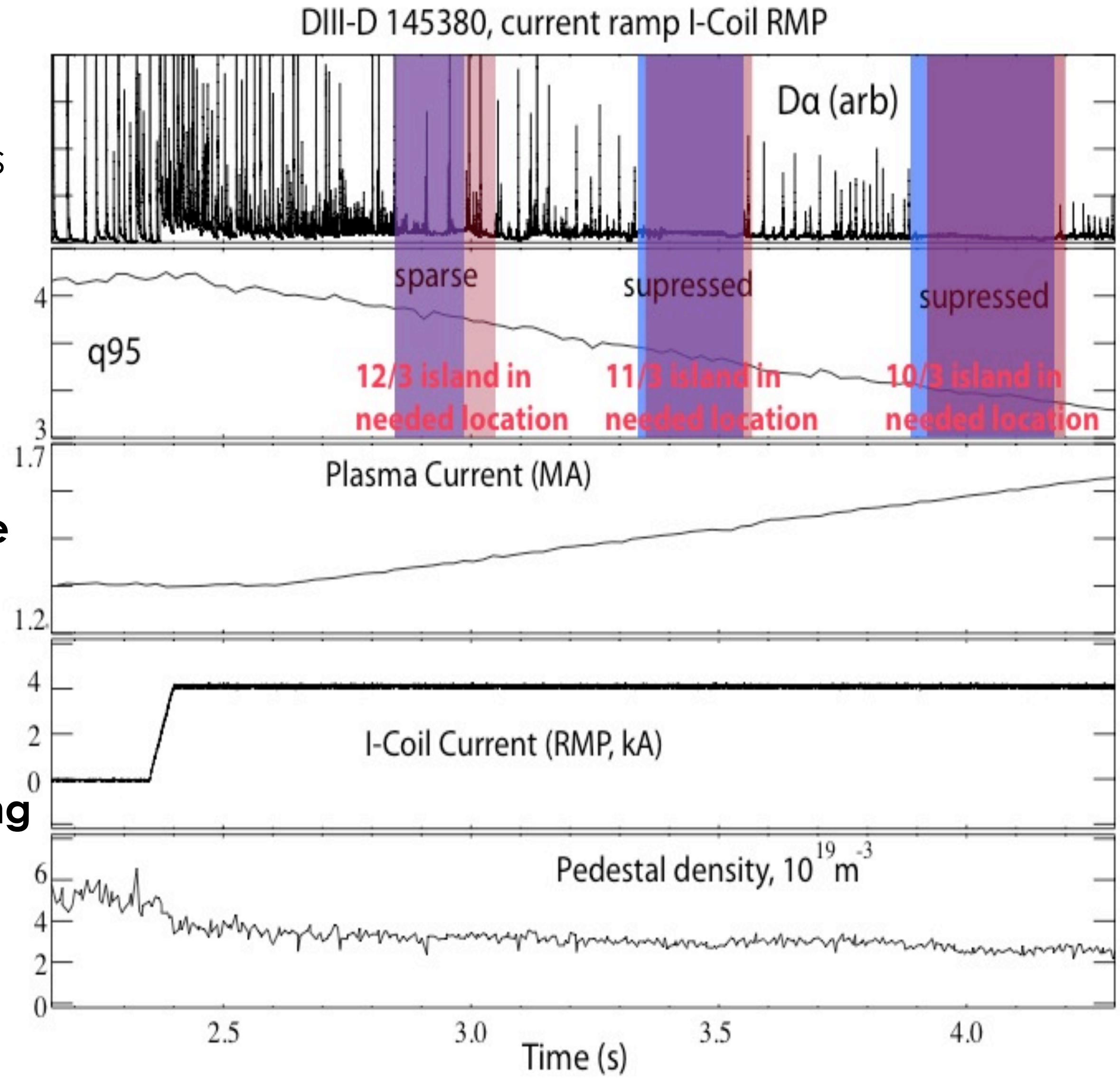
EPED-based Working Model for ELM Suppression Agrees with Observed q_{95} Windows

ELM suppression or mitigation occurs in multiple q windows

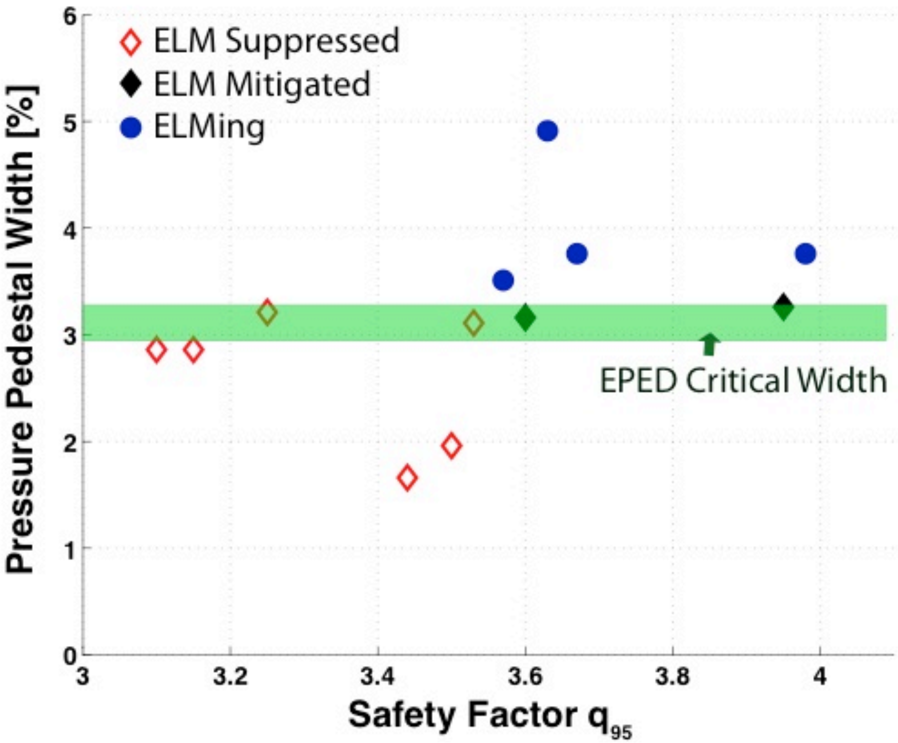
- DIII-D 145830, I_p ramp, 2 windows of suppression, 1 sparse (blue)

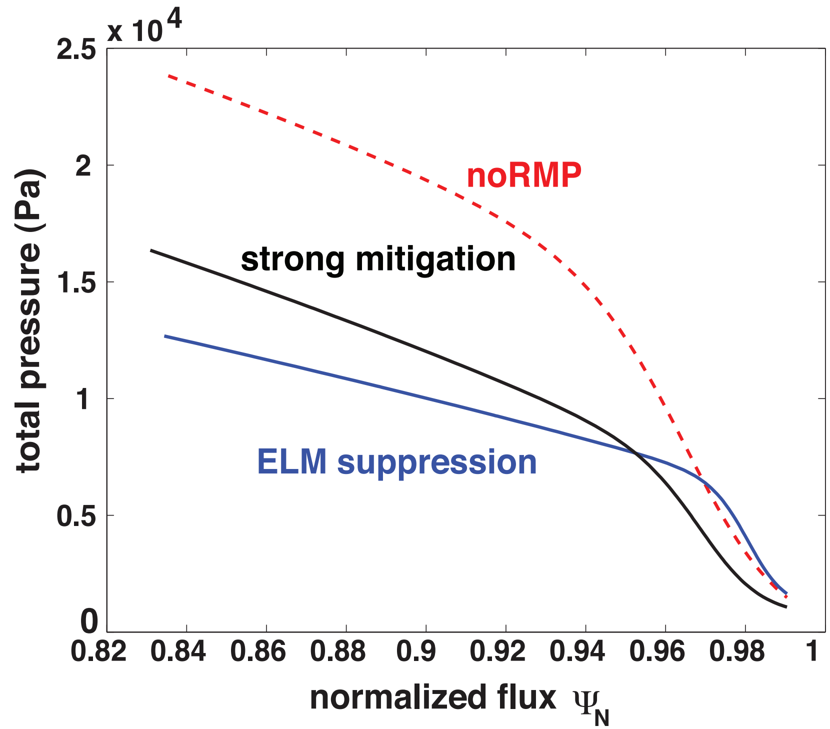
EPED predicts width of 0.03

- **With gradient constrained by KBM, ELM (P-B mode) will be triggered when width exceeds 0.03**
- **To suppress ELMs, must place the outer edge of the "wall" outside of 0.97**
  - Islands can't penetrate the sharp gradient region: can't place "wall" any further out than ~0.98
- **Predicts 3 windows corresponding to when 12/3, 11/3 and 10/3 islands pass through the proper location (red)**
  - **Good agreement with observations**



EPED-based Working Model for RMP ELM Suppression Agrees with Observed Profile Changes





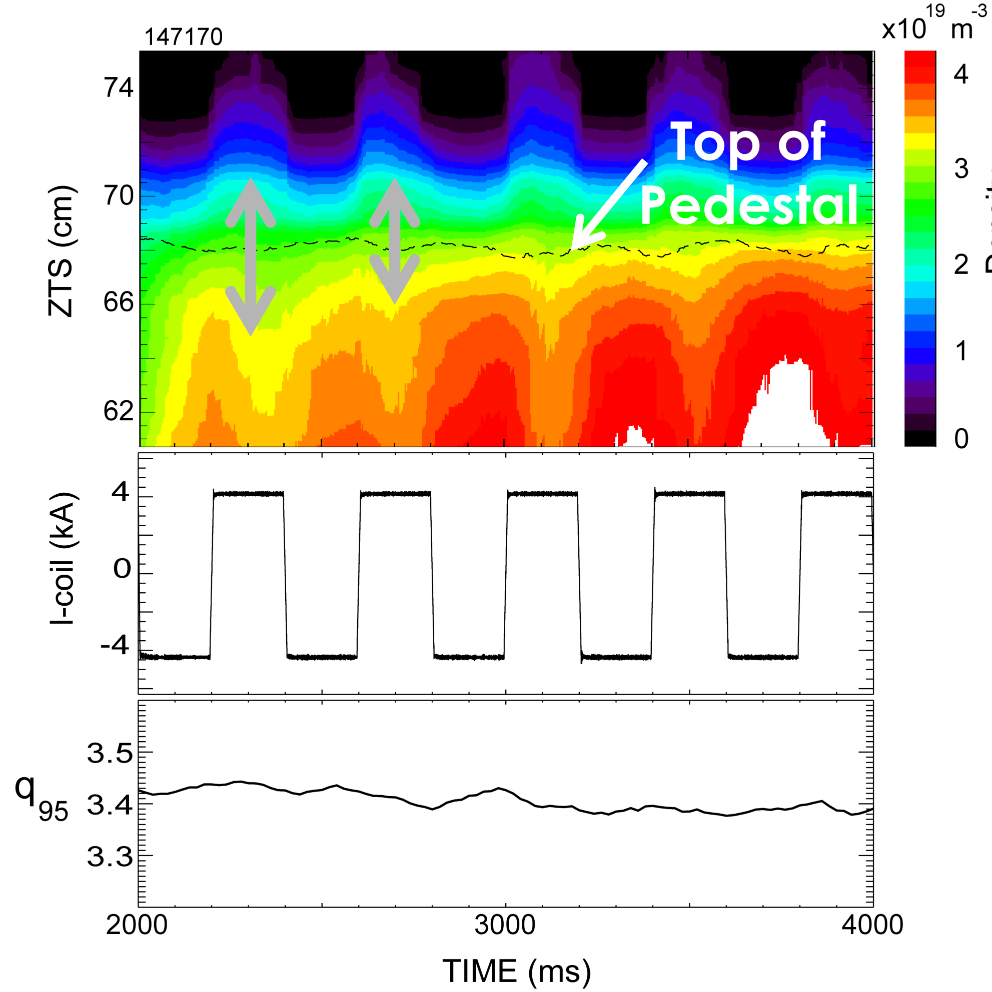
- **If "wall" blocking inward propagation of edge barrier, should be observable in measured profiles (New high-res Thomson system can resolve small changes)**
- **In ELM suppressed cases, pedestal width is indeed constrained**
  - Critical width for suppression is <~3%, in agreement with EPED
  - Pressure gradient inside barrier changes little, as expected from EPED

GENERAL ATOMICS

EPED-based Working Model for RMP ELM Suppression Agrees with Several Observations

Key aspects of working model

1. **Density pumpout (and strikepoint splitting) is ubiquitous due to field penetration at foot and near top of pedestal**
2. **ELM Suppression occurs when island is at proper location to block inward penetration of edge barrier before it reaches EPED critical width (typically~3-4%)**
   - Penetrates where $v_{perp,e}$ is small, near top of pedestal
   - Resonant surface (eg 10/3, 11/3) must be in proper location
   - Explains q resonant windows
   - Agrees with measured profile changes (reduced width, gradient changes little during suppression)
   - *There are strong indications that such islands are directly observed*



M. Wade ***NO4.00002***

Summary: EPED Pedestal Model Developed, Broadly Tested, Used to Study RMP ELM Suppression

- **Predictive model combines non-local Peeling-Ballooning and near-local KBM physics** P.B. Snyder et al., *Phys. Plasmas* **16**, 056118 (2009); *Nucl. Fusion* **49**, 085035 (2009); *Nucl. Fusion* **51,** 103016 (2011)
  - Both constraints directly calculated, and each can be independently tested
  - No free or fit parameters, reasonably efficient (~1-20 CPU hrs/case)
- **Model successfully tested against existing machines over a wide range of parameters, including dedicated experiments, QH Mode**
  - Detailed tests using new Thomson system on DIII-D, C-Mod/DIII-D comparison
  - Good quantitative agreement found in studies on 5 tokamaks, more than 250 total cases studied with ~20% agreement in height and strong correlation (*r*~0.9)
  - Similar level of agreement in Quiescent H-Mode (QH) discharges
- **Working model for RMP ELM suppression developing, combining EPED with 2-fluid/kinetic plasma response calculations, consistent with observed q windows and profile changes, much work to be done**
- **EPED model used to predict and optimize the pedestal in ITER**
  - $\beta_{N,ped}$~0.6-0.7, Δ_{ψ}~0.04. Optimized at higher density and Shafranov shift
  - Understanding/optimization of pedestal and ELM control provides a powerful lever for ITER to achieve and exceed its performance goals *($P_{fus} \sim p_{ped}^2$)*