# Physics of the H-Mode Pedestal and the EPED Model


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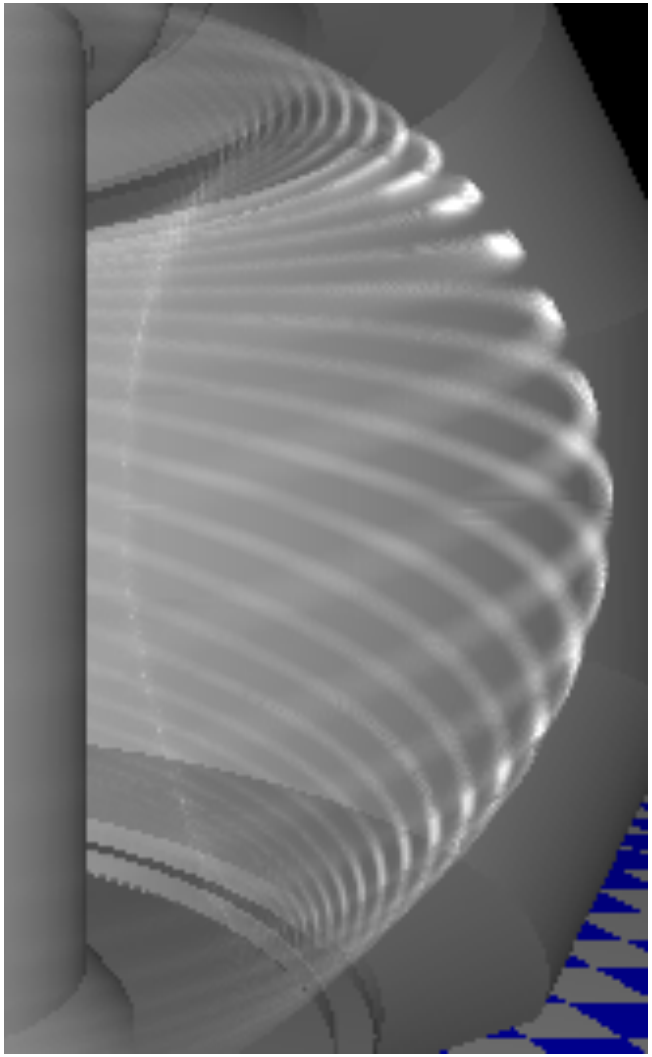

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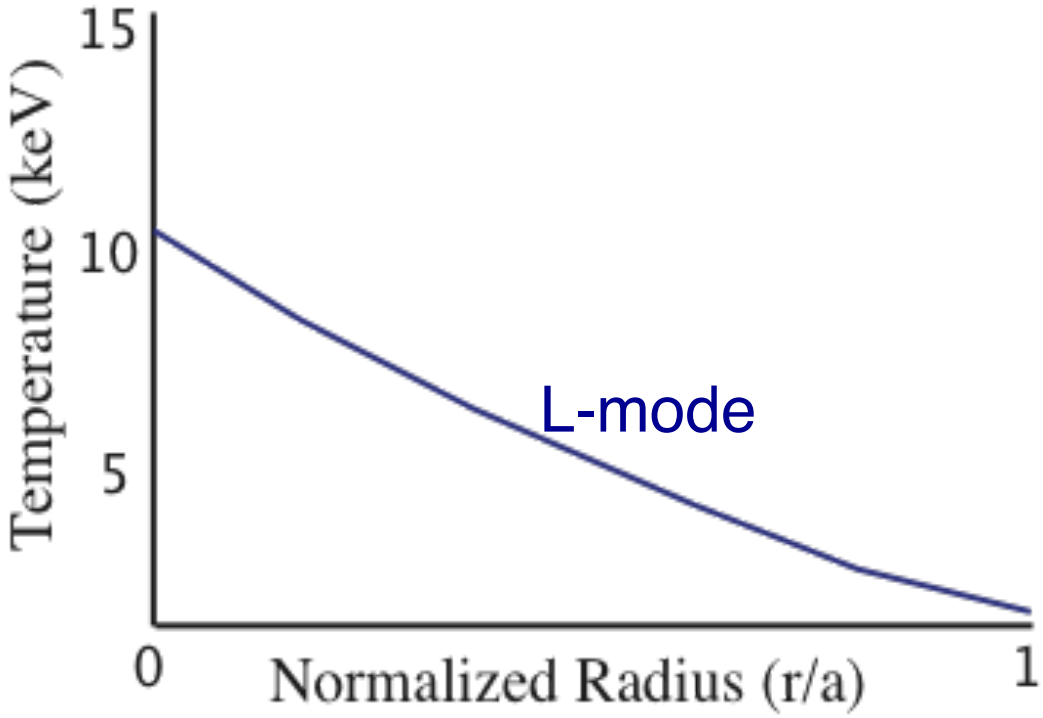
# Outline: Pedestal Physics Key to Predicting and Optimizing ITER

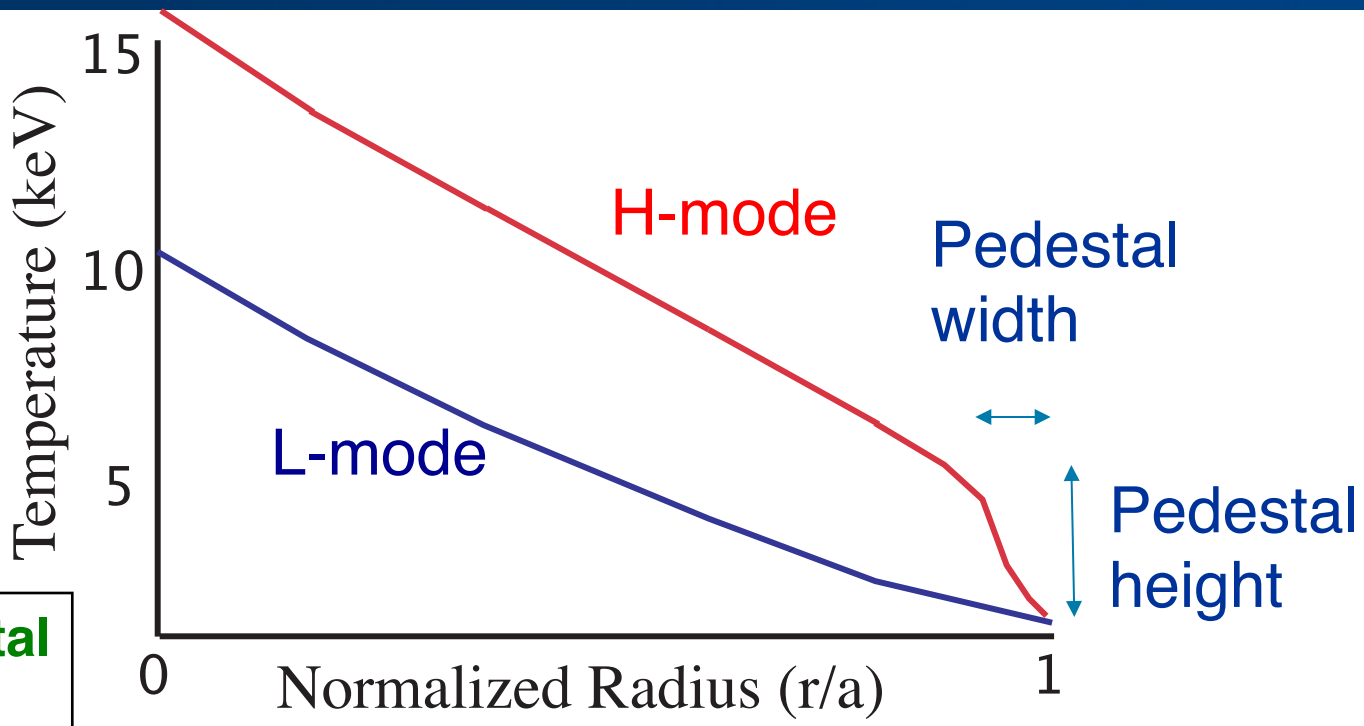
- **The Pedestal: What it is and why it matters**
  - Simultaneous improvement of confinement and stability
  - Predictive capability enables fusion power optimization
- **Physics challenges**
  - Overlap of scales, challenge to methods ($L \sim \lambda \sim \rho$)
- **Peeling-ballooning modes**
  - Global constraint on the pedestal, drive ELMs
- **The EPED model**
  - Kinetic ballooning modes and model derivation
  - Experimental tests on several tokamaks, statistics
  - Super H-Mode
  - Dynamics and ELM suppression
- **Coupled core-pedestal prediction**
- **Directions for future pedestal research**

# High Performance achieved via the Edge Transport Barrier




- **Stiff transport implies approximately fixed gradient scale length in core**
  - Better performance requires bigger machine (cost)

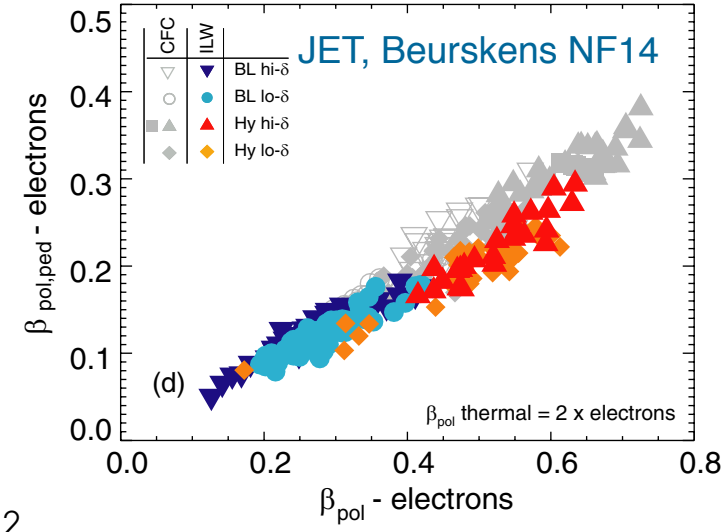
# High Performance achieved via the Edge Transport Barrier


- **H-mode pedestal lifts whole profile**
  - "Height" (pressure) of the pedestal key to performance, multiplicative
- **Analogous to lifting a statue (core) onto a pedestal, but better, because statue gets higher proportional to pedestal**

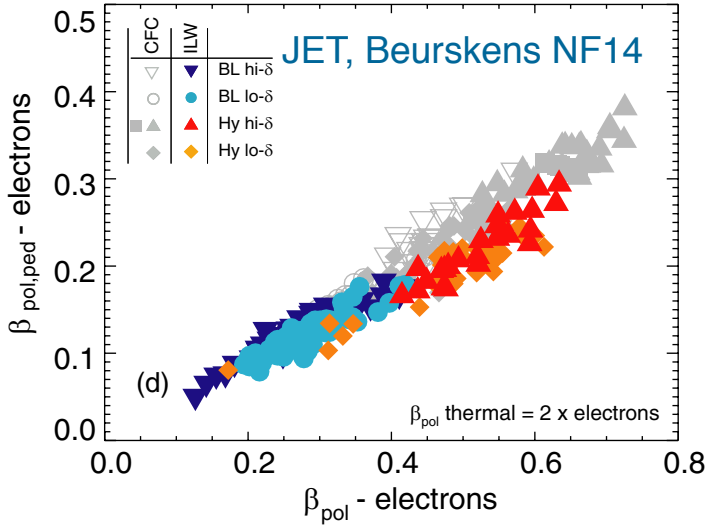
# Pedestal Key to Fusion Performance because it Strongly Improves both Confinement and Stability

- **Raising pedestal pressure dramatically improves global confinement**
  - Core transport due primarily to gradient scale length driven microturbulence (ITG, TEM, ETG…)
  - Roughly fixes the pressure gradient scale length ($L_p$) in the core plasma, resulting in $p_{global} \sim 3\ (\pm 1)\ p_{ped}$ ["stiff transport"]
  - Higher $p_{ped}$ -> high $p_{global}$ -> higher $P_{fus} \sim p_{global}^2$
  - This behavior is both predicted by gyrokinetic simulations and broadly observed in expt



# Pedestal Key to Fusion Performance because it Strongly Improves both Confinement and Stability

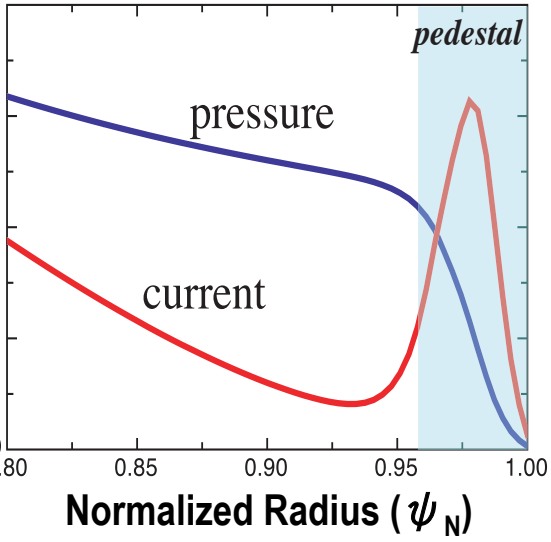
- Raising pedestal pressure dramatically improves global confinement
- **However, benefits of high confinement can't be realized without high stability boundaries (and vise versa)**
- **Global MHD instabilities are driven by gradients (p', j'). Moving gradients as far out as possible (pedestal) maximizes resulting stable pressure (sometimes referred to as profile broadness effect)**
  - **Also increases wall stabilization effect**



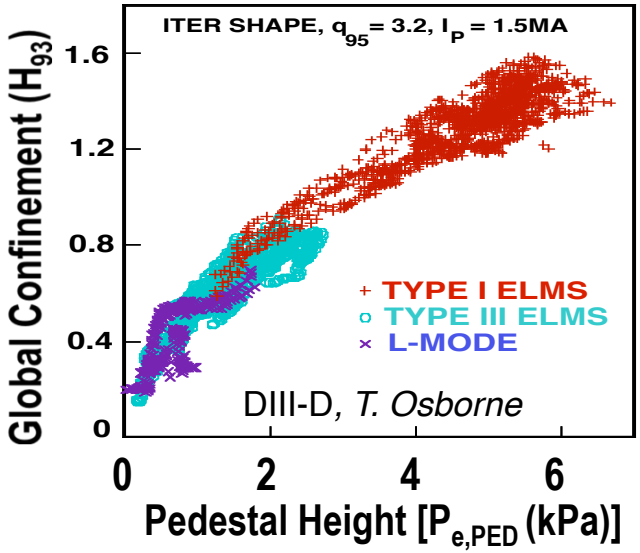

***Because the pedestal increases both confinement and stability it increases both potential and realizable fusion performance***

# Motivation: Pedestal Height Critical for ITER Performance Prediction and Optimization

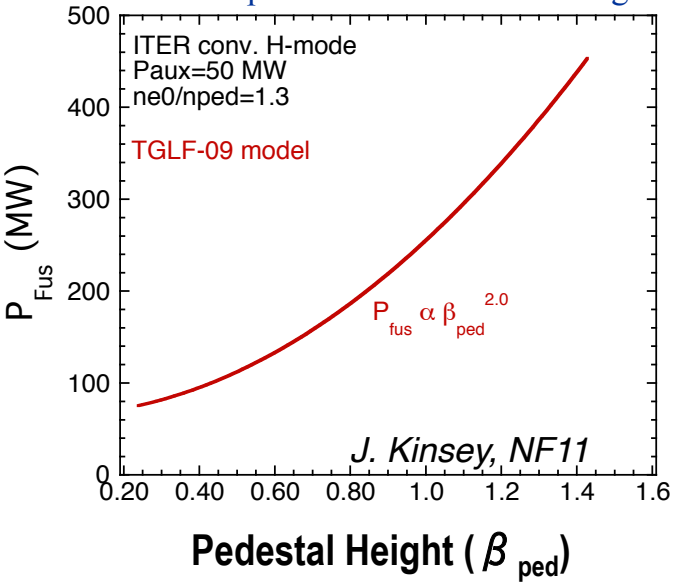
- **High performance ("H-mode") operation in tokamaks due to spontaneous formation of an edge barrier or "pedestal"**
- **Pedestal height has an enormous impact on fusion performance**
  - Dramatically improves both global confinement and stability (observed and predicted)
  - ***Fusion power on ITER predicted to scale with square of the pedestal pressure*** *[Kinsey, NF11]*
- **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

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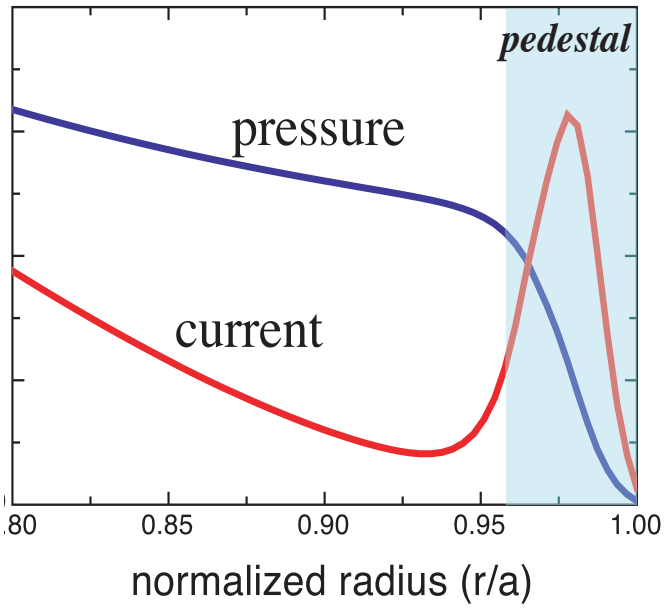
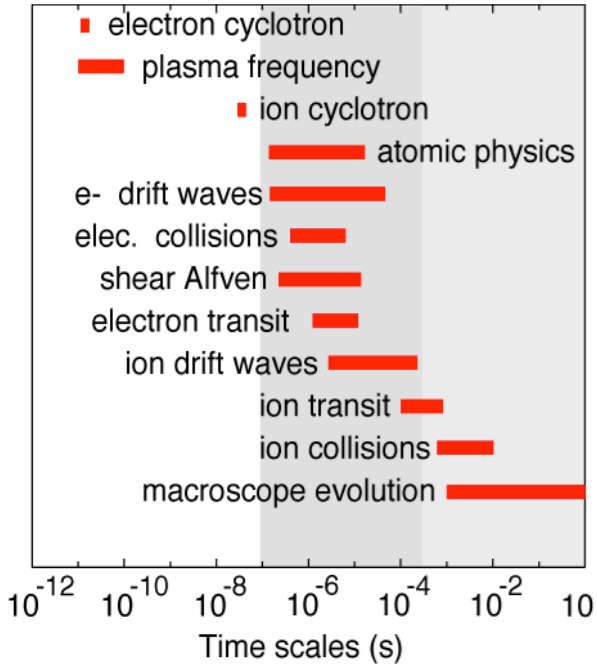
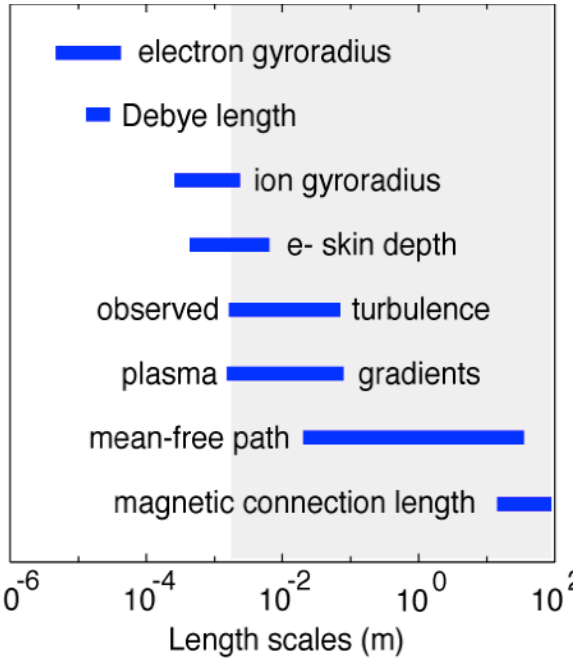
# Very Wide Range of Overlapping Scales in the Edge Barrier Region

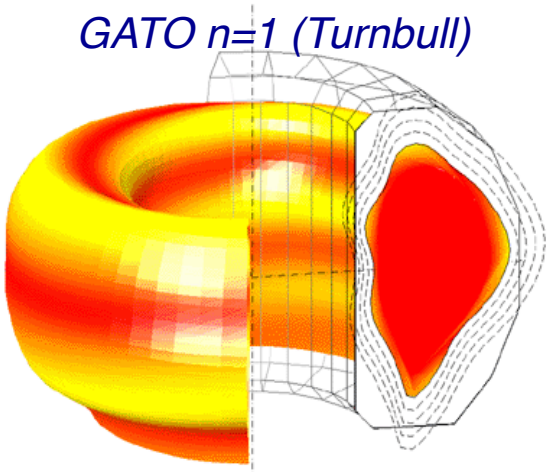


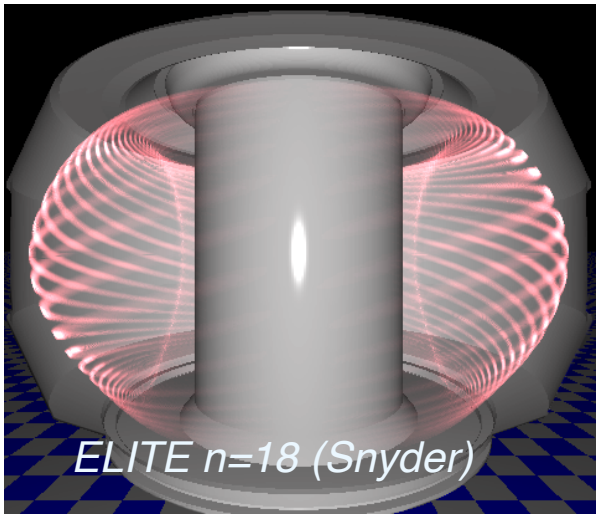



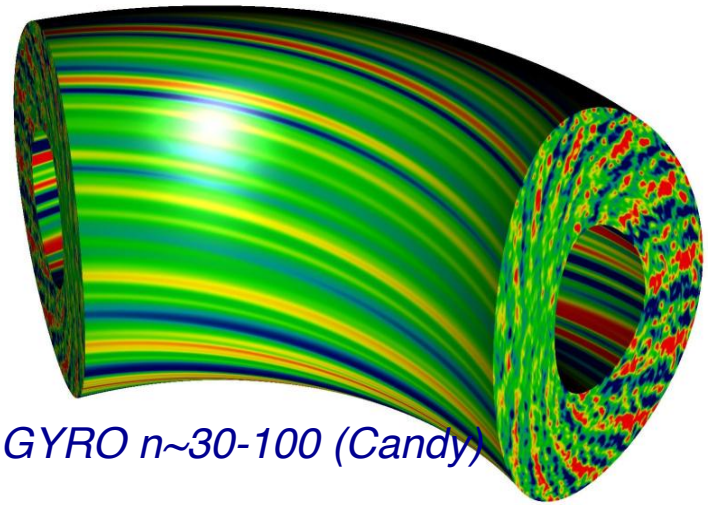




- Both time and spatial scales overlap, from microscopic all the way to global
  - This wide range (6-7 orders of magnitude) is covered by a ***single*** equilibrium, key parameters vary by orders of magnitude across the pedestal
- Pedestal crosses from collisional to collisionless regime
- Equilibrium currents and flows likely important
- Sources/atomic physics important, tightly coupled

# Pedestal Physics Challenges Existing Paradigms

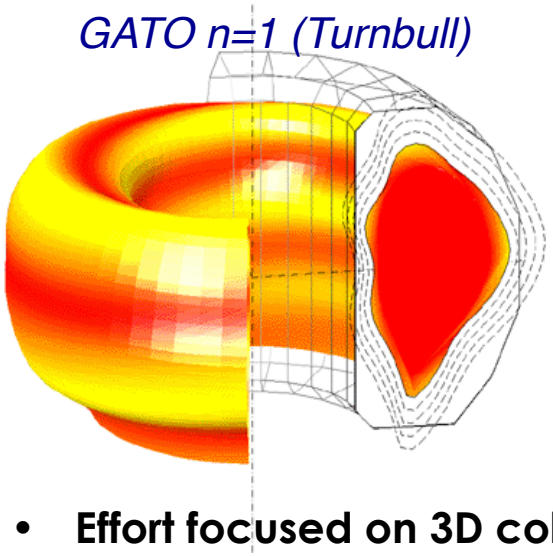


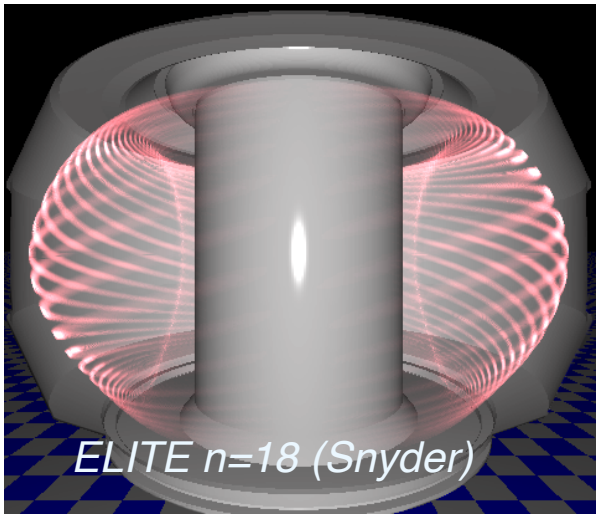



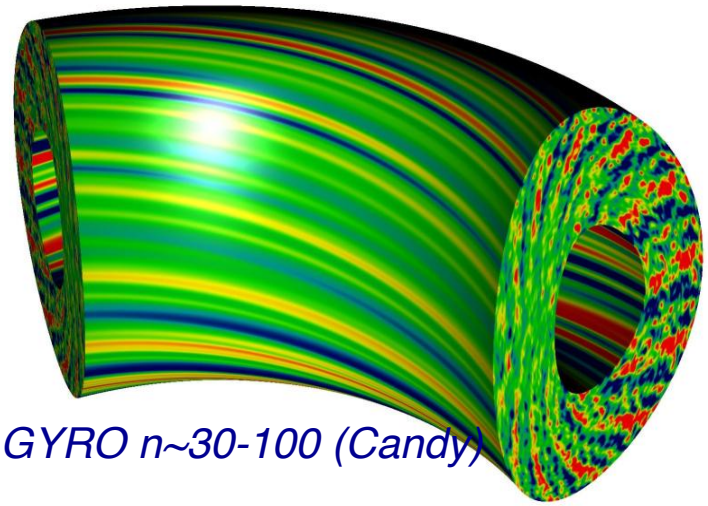




- **Our field traditionally divided into stability (L~ $\lambda$ << $\rho$ ), transport (L<< $\lambda$ ~ $\rho$ ) and source physics**
- **This separation can break down in the edge barrier**
  - Equilibrium scales (T, n, q..) overlap gyro- and drift- scales
  - Equilibrium evolves on a fast timescale (eg during ELMs, L-H transition)
    - Neither (RF, beam, neutral) source nor transport physics occurs in a fixed 2D background
  - There is, in general, no transport steady state
    - Pedestal height physics closely linked to ELM triggering physics
    - Confinement is ***too good***, general goal is to make it worse, not better (ELM control)

# Pedestal Physics Challenges Traditional Approaches to Computation




- **Effort focused on 3D collisional or 5D collisionless equations**
  - Edge barrier is in general both highly collisional and highly collisionless
  - MHD events can't be thought of only in terms of their onset or final state: they are an important part of transport, heat loads
- **Perturbations can be large, potential problem for $\delta f$**
- **Electromagnetic perturbations (and 3D fields) and full geometry essential**
  - Large B perturbations problematic for field aligned coordinates
  - Source/atomic physics tightly coupled
  - Neoclassical important, but traditional (ion scale) neo can break down

# Electromagnetic Fluctuations are Important even though (especially where) $\beta$ is small

$$\psi = \beta_i \frac{\omega(\omega - \omega_{*pi})k_\perp^2 - 2\omega_d(\omega - \omega_{*pi})}{2k_\perp^2 k_\parallel^2 - \beta_i 2\omega_d(\omega - \omega_{*pe})}\phi. \qquad (2.16)$$

In general, each term in the numerator must be small compared to the denominator to satisfy the electrostatic limit. For the first term in the numerator, this requires $\beta_i\omega^2/2k_\parallel^2 \ll 1$, or $\omega^2 \ll 2k_\parallel^2/\beta_i$. In unnormalized units this is $\omega^2 \ll k_\parallel^2 v_A^2$, where $v_A$ is the usual Alfvén speed. Turning to the last term in the numerator, $2\omega_d\omega_{*pi}$, the requirement for the electrostatic limit is $\beta_i\omega_d\omega_*(1+\eta_i)/k_\perp^2 k_\parallel^2 \ll 1$. In the local limit, $\omega_* = k_\theta$, $\omega_d = \epsilon_n\omega_*$, $k_\perp \sim k_\theta$, and $k_\parallel \simeq \epsilon_n/q$, where $\epsilon_n = L_{ne}/R$, this requirement becomes $\beta_i q^2(1+\eta_i)/\epsilon_n \ll 1$. Or, noting that $\epsilon_n/q^2(1+\eta_i)$ is roughly the local ideal ballooning limit $(\beta_{ic})$, the requirement becomes $\beta_i \ll \beta_{ic}$.

- **Derive relationship between magnetic ($\psi$) and electrostatic ($\phi$) potential from GK or GF eqns in simple limit**
- **Electrostatic limit requires (at least) that: (a) $\beta$ is small, (b) frequency small compared to shear Alfven frequency, (c) p' far from ideal ballooning limit ($\alpha$<<1 or $d\beta_p/d\psi_N$ <<1)**
  - (c) is nearly always violated in the pedestal due to sharp gradients, and (b) can be violated as well (small $k_{par}$, drift-Alfven modes)



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# Traditional Transport Theory Requires a Separation of Scales

- **Fluctuation scale= $\lambda$**
- **Equilibrium scale=L (eg pressure gradient scale $L_p$)**
- **Microscopic scale= $\rho$ (toroidal or poloidal gyroradius)**

**Standard transport theory allows ( $\lambda \sim \rho$ ), expands in $\rho$ /L**

**Leading order: gyrokinetic and neoclassical fluxes**

**Next order: evolution of equilibrium (L>> $\lambda \sim \rho$ )**

**Equilibrium scale macrostability (MHD) (L~ $\lambda >> \rho$ )**

**In the pedestal, fluctuation scale overlaps equilibrium and micro scales (L~ $\lambda \sim \rho$ ), transport theory formally breaks down**

- Key research direction: development of new theory and numerical techniques to treat this overlap (6D RBF + implicit time advance, full-F GK without locality, alternate GK expansions such as Hahm09,…)
- Can also proceed using existing tools to develop physics insight, but must always be cautious of limits (in particular the L>> $\lambda$ approximation can lead to arbitrarily large errors for ion scale modes)

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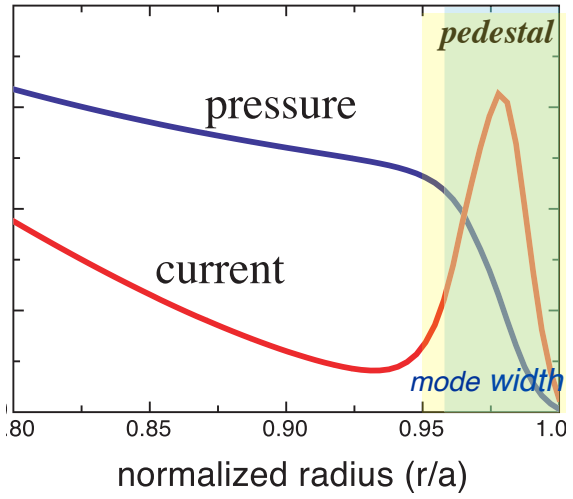
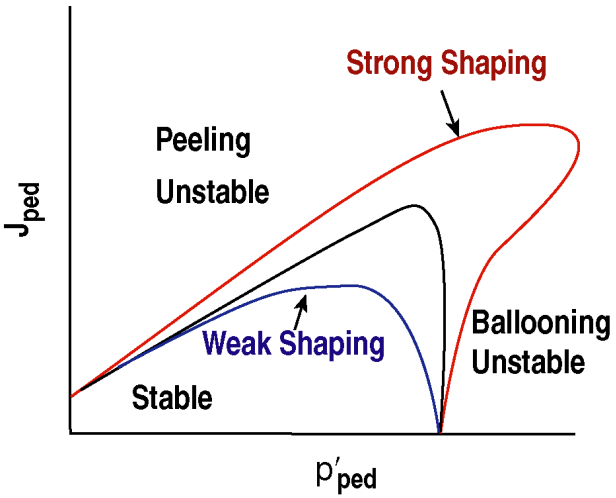
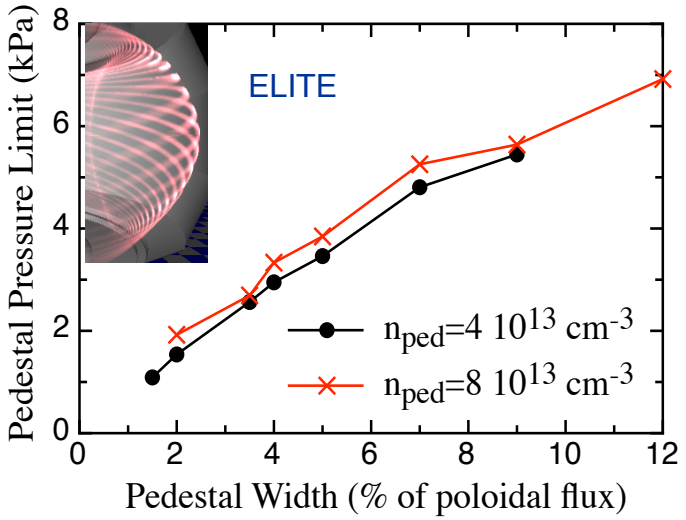
# The Peeling-Ballooning Model Explains ELM Onset and Pedestal Height Constraint




**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 $\nu_*$, 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 ($\Delta_\psi$), 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).*



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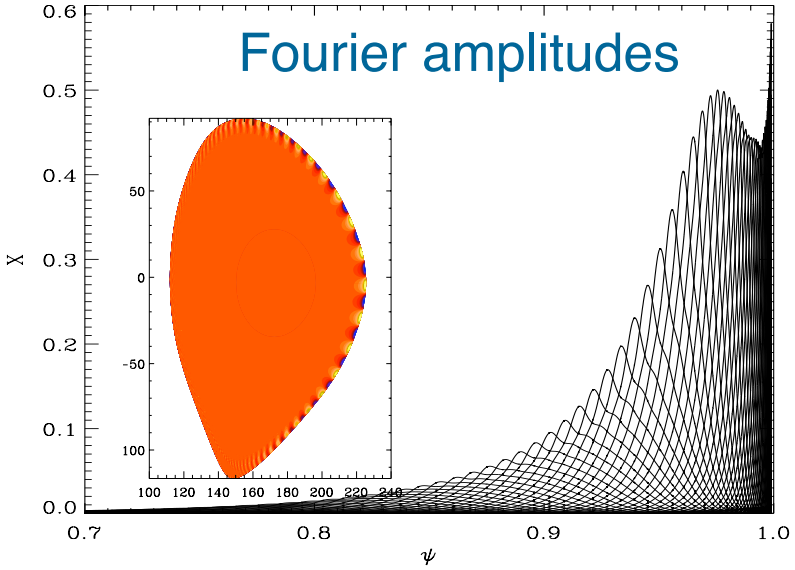
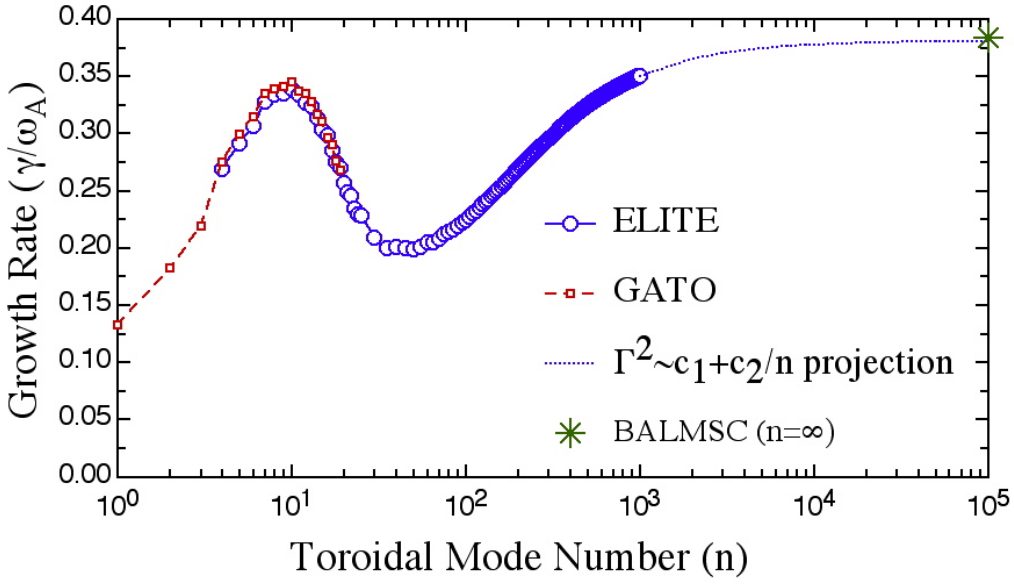
# ELITE Code Efficiently Calculates Peeling-Ballooning Stability

- **ELITE implements high order, non-local peeling-ballooning (MHD) theory**
- Plasma displacement, $X$, expanded in poloidal Fourier harmonics: $X = \sum_{m=m_{min}}^{m=m_{max}} u_m(x)\, e^{-im\omega}$
- Makes use of fact that each $u_m(x)$ is localized about its own mode rational surface where $m=nq \Rightarrow$ *fast and efficient code*
- Study coupled peeling/ballooning modes and quantitative constraints on edge gradients and pedestal height. Growth rates and mode structures generated
- High-n ballooning theory reproduced, but quantitatively valid only at very high n, well above FLR cutoff (due to non-locality)



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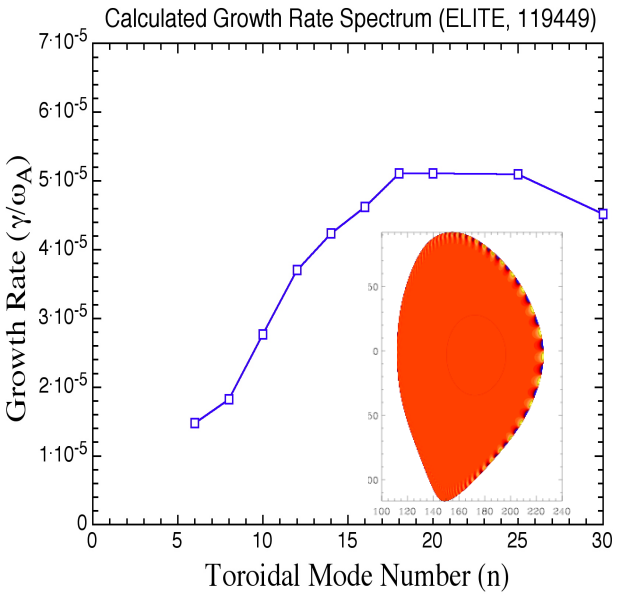
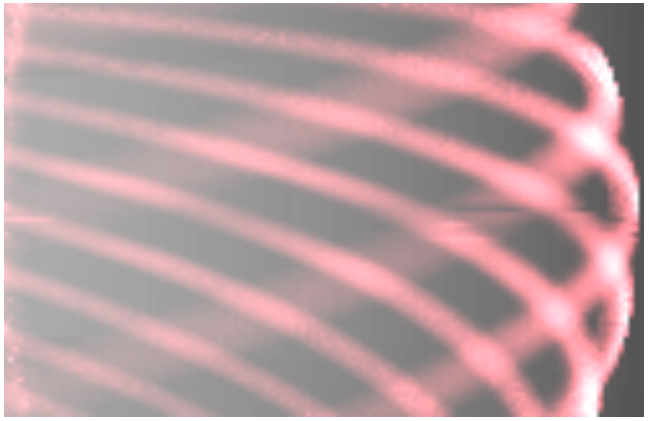
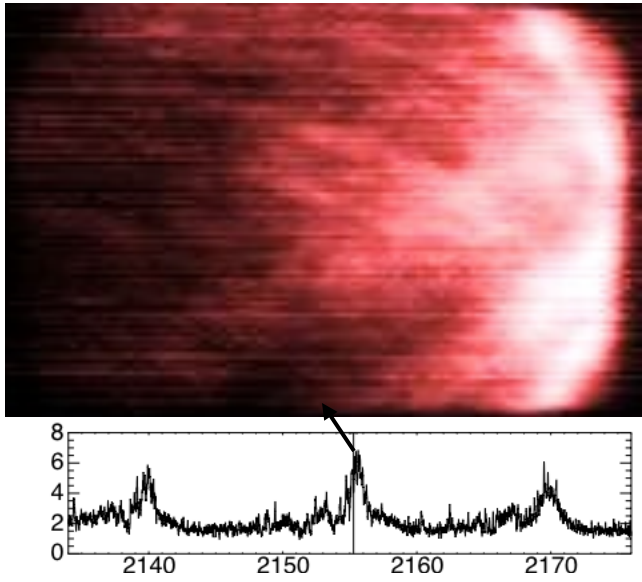
# Observed ELM Similar to Predicted Peeling-Ballooning Structure



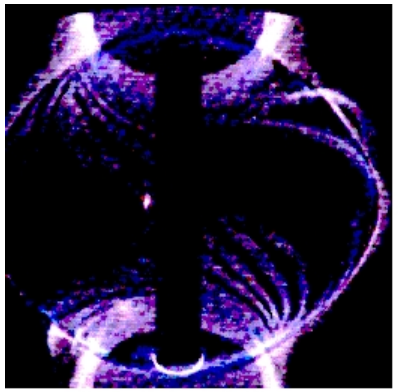

ELITE, n=18



Fast CIII Image, DIII-D 119449
*M. Fenstermacher, DIII-D/LLNL*




- **Use reconstructed equilibrium just before fast camera image of ELM**
  - Most unstable mode n~18
- **Nonlinear simulations** *(eg Snyder'05, Brennan'07, recent BOUT++, NIMROD, JOREK, M3D work)* **find qualitative agreement in filamentary structure, wavelength, radial propagation**
  - Filaments were predicted by simulation and theory before fast camera images



***A. Kirk, MAST, PRL 92 (2004) 245002-1***



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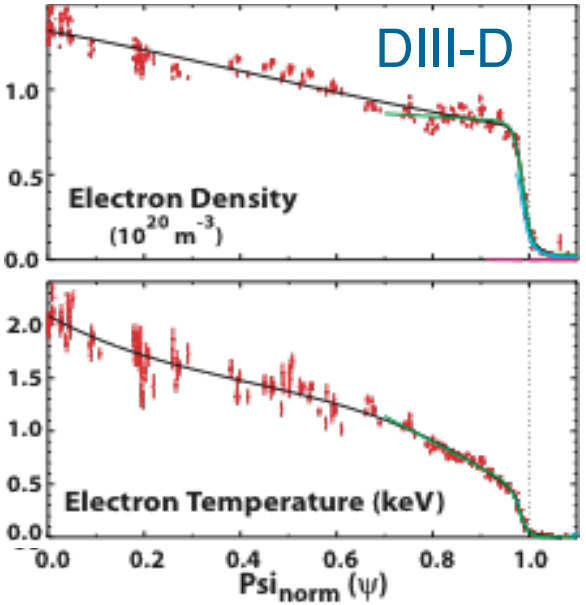
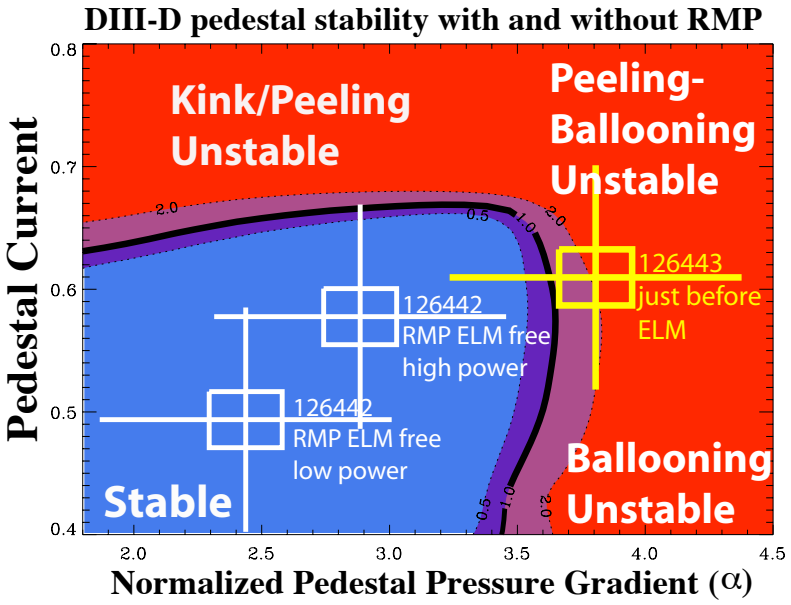
# Peeling-Ballooning Model Extensively Validated Against Observation




- High resolution measurements allow accurate reconstructions and stringent tests of P-B pedestal constraint & 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*

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# EPED Goal: Cut Through Complexity of Pedestal, Generate Predictive Model to Test and Improve

***Paradigm: ETB formation starts near separatrix and propagates inward primarily due to diamagnetic $E_r$***

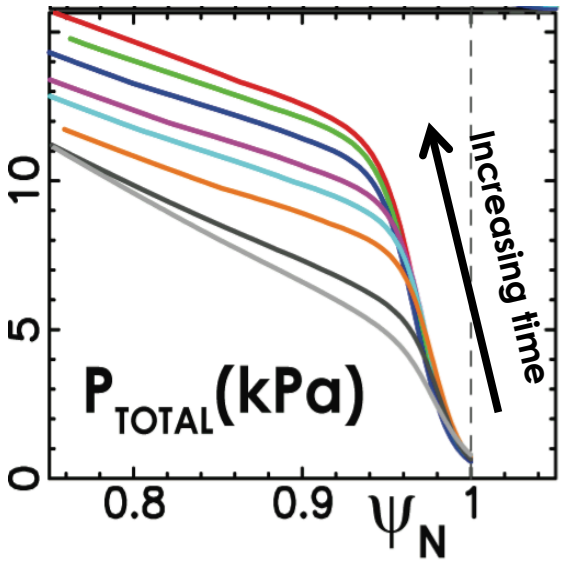
**Schematically divide instabilities that impact transport & stability in the pedestal into 2 categories:**

A. **"Global" modes: extend across edge barrier including significant impact at top**

B. **"Nearly-local" modes within the edge barrier**

**Key distinction is between modes that can stop the inward propagation of the ETB (A), and those which only impact gradients within the ETB (B)**

***Can have similar modes playing both roles***






GENERAL ATOMICS

# EPED1.x Focus on Two Component Prediction of Pedestal Structure: Pressure Height and Width

**Focus on "high performance" (Type I and QH) H-modes. Allow pedestal density as input, predict pedestal pressure (or equivalently average T), and a single metric of pedestal width**

**A. "Global" modes: intermediate-n (n~3-30) peeling-ballooning**

**B. "Nearly-local" modes: KBM, ETG, ITG/TEM, $\mu$T?,…**

**Make further conjecture that KBM provides the final constraint on the pressure gradient. [ETG constrains $\eta_e$ not p', ITG/TEM weakened by $E_r$ shear, ITG stabilized by $\beta$']**

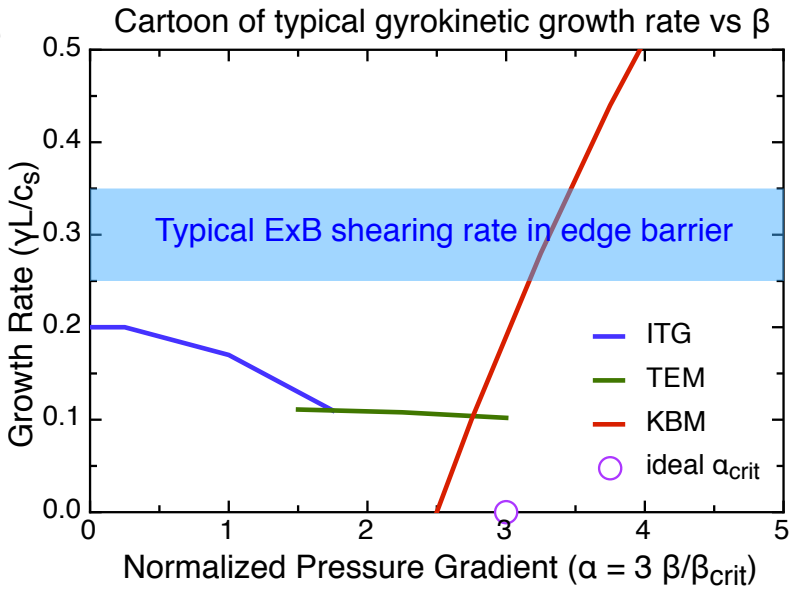
**KBM and P-B together can then provide 2 "equations" for the two unknowns, pedestal height and width**

- Numerous complexities: Bootstrap current key (brings in separate T and n dependence), KBM can't generally be treated as local
- Ongoing development includes multiple impurities, additional transport mechanisms, and fully global KBM calculations (requires strongly nonlocal kinetics)

# KBM Constrains Pedestal p' Near Ideal Ballooning

## $\alpha_{crit} \sim d\beta_p/d\psi_N$

- **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
    - EMGK calcs in edge geometry match expected onset *(Dickinson, Wang)*



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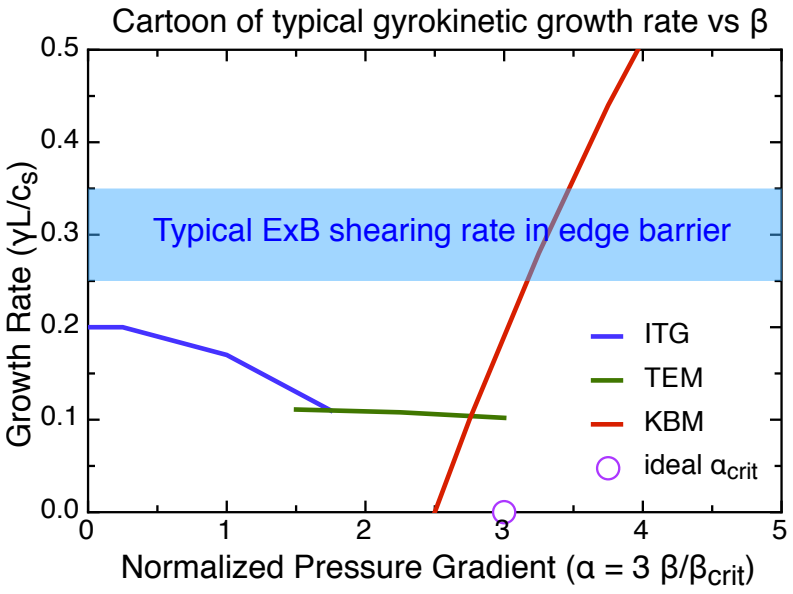
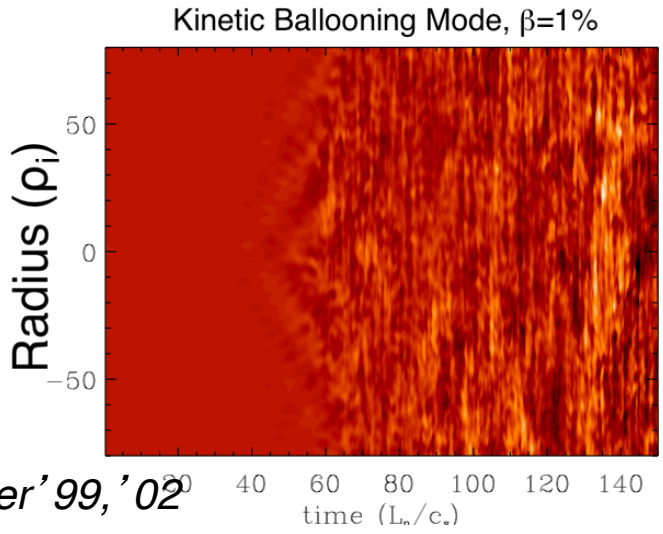
  - Nonlinear: very large fluxes and short correlation times (highly stiff)
    - Flux will match source at gradient near critical
- ➢ **Simple model of the KBM can be quantitatively accurate**
  - Stiff onset near MHD ballooning criticality
  - Use model equilibria to "integrate" local constraint




*Snyder'99,'02*



GENERAL ATOMICS

# KBM Critical Gradient ($\alpha_{crit} \sim d\beta_p/d\psi_N$) Increases Moving Inward

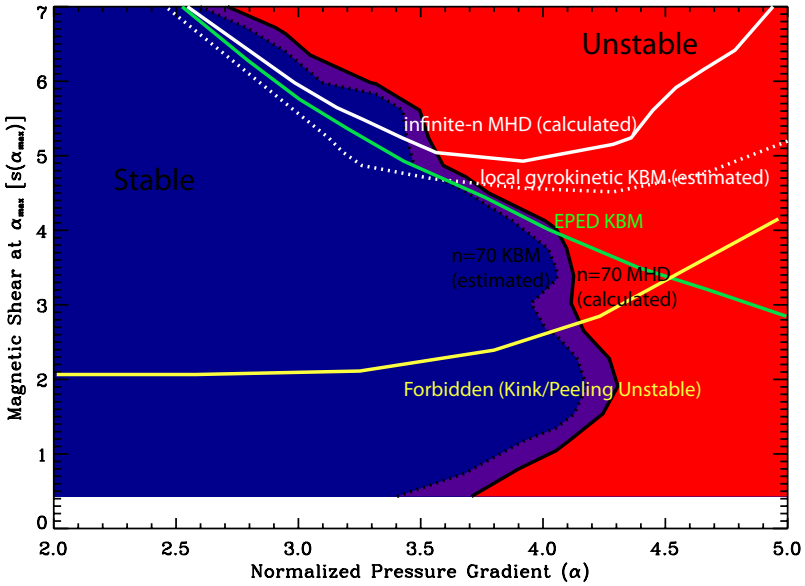
- **If KBM critical gradient were independent of radius, integrating it across the pedestal would yield**

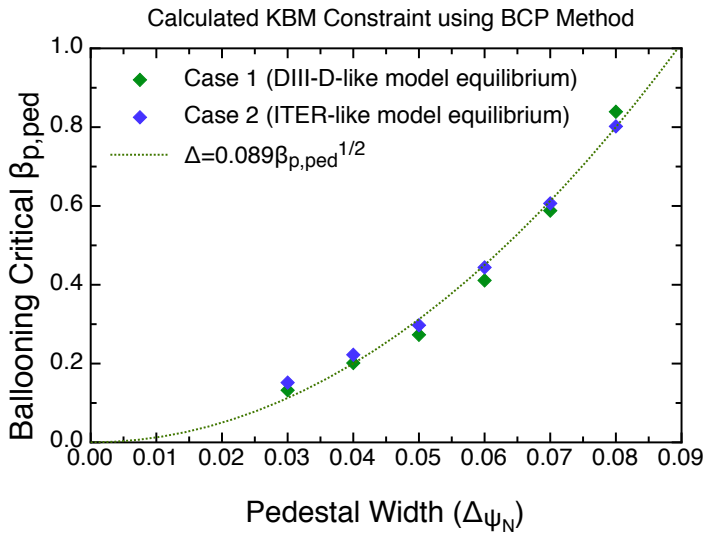
$$\Delta_{\psi_N} \propto \beta_{p,ped}^{1}$$

  - Width in normalized poloidal flux increasing linearly poloidal beta at the pedestal

- **However, $\nu^*$ decreases strongly moving inward from separatrix, decreasing magnetic shear and increasing critical $d\beta_p/d\psi_N$**
  - Calculating with self-consistent collisional bootstrap current yields an average critical gradient that increases with width: $\beta_{p,ped} / \Delta_{\psi_N} \propto \Delta_{\psi_N}$

**or $\Delta_{\psi_N} = \beta_{p,ped}^{1/2} G(\nu_*, \varepsilon \ldots)$ where G~0.07-0.09 is weakly varying (fixed G=0.076 in EPED1)**





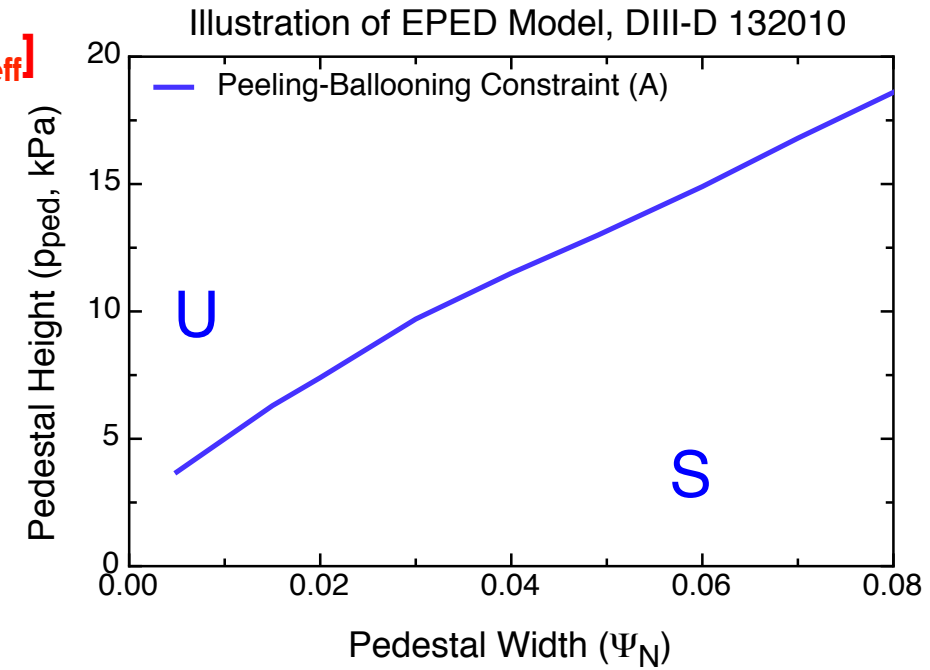

GENERAL ATOMICS

# Mechanics of the EPED Predictive Model

- **Input: $B_t$, $I_p$, R, a, $\kappa$, $\delta$, $n_{ped}$, $m_i$, [$\beta_{global}$, $Z_{eff}$]**
- **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 Plas* ***16*** *056118 (2009), NF* ***51*** *103016 (2011)*

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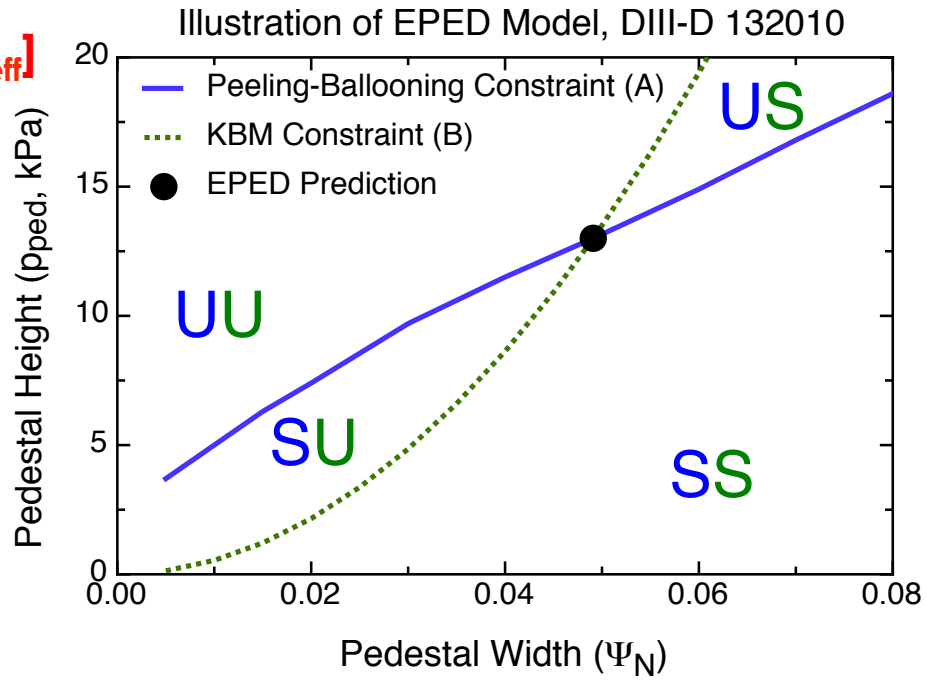
- Directly calculate with ballooning critical pedestal technique

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- **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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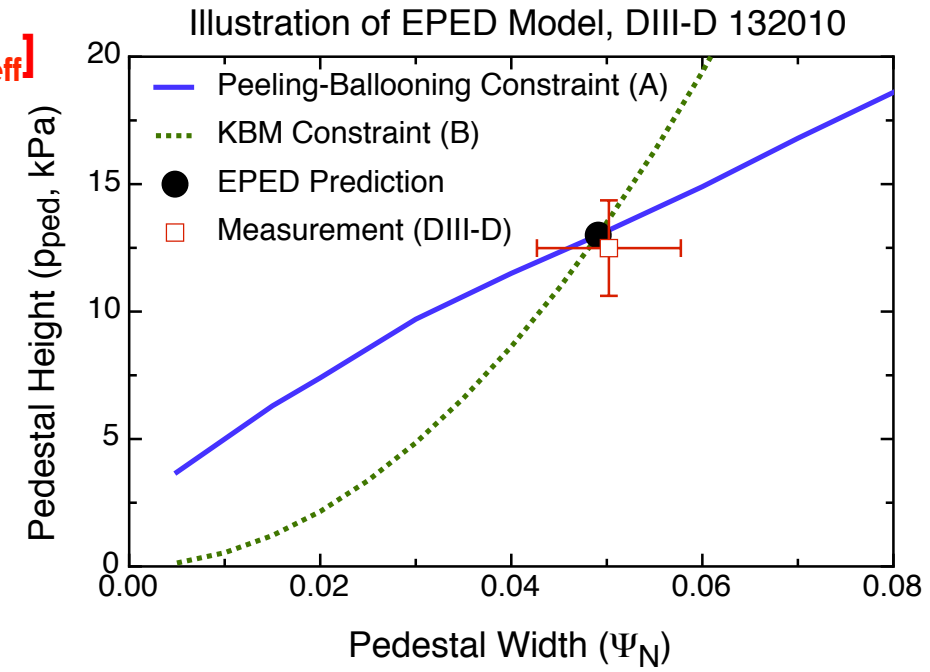


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  - can then be systematically compared to existing data or future experiments

***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***



GENERAL ATOMICS

# Outline: Pedestal Physics Key to Predicting and Optimizing ITER

- **The Pedestal: What it is and why it matters**
  - Simultaneous improvement of confinement and stability
  - Predictive capability enables fusion power optimization
- **Physics challenges**
  - Overlap of scales, challenge to methods ($L \sim \lambda \sim \rho$)
- **Peeling-ballooning modes**
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- **The EPED model**
  - Kinetic ballooning modes and model derivation
  - ***Experimental tests on several tokamaks, statistics***
  - Super H-Mode
  - Dynamics and ELM suppression
- **Coupled core-pedestal prediction**
- **Directions for future pedestal research**

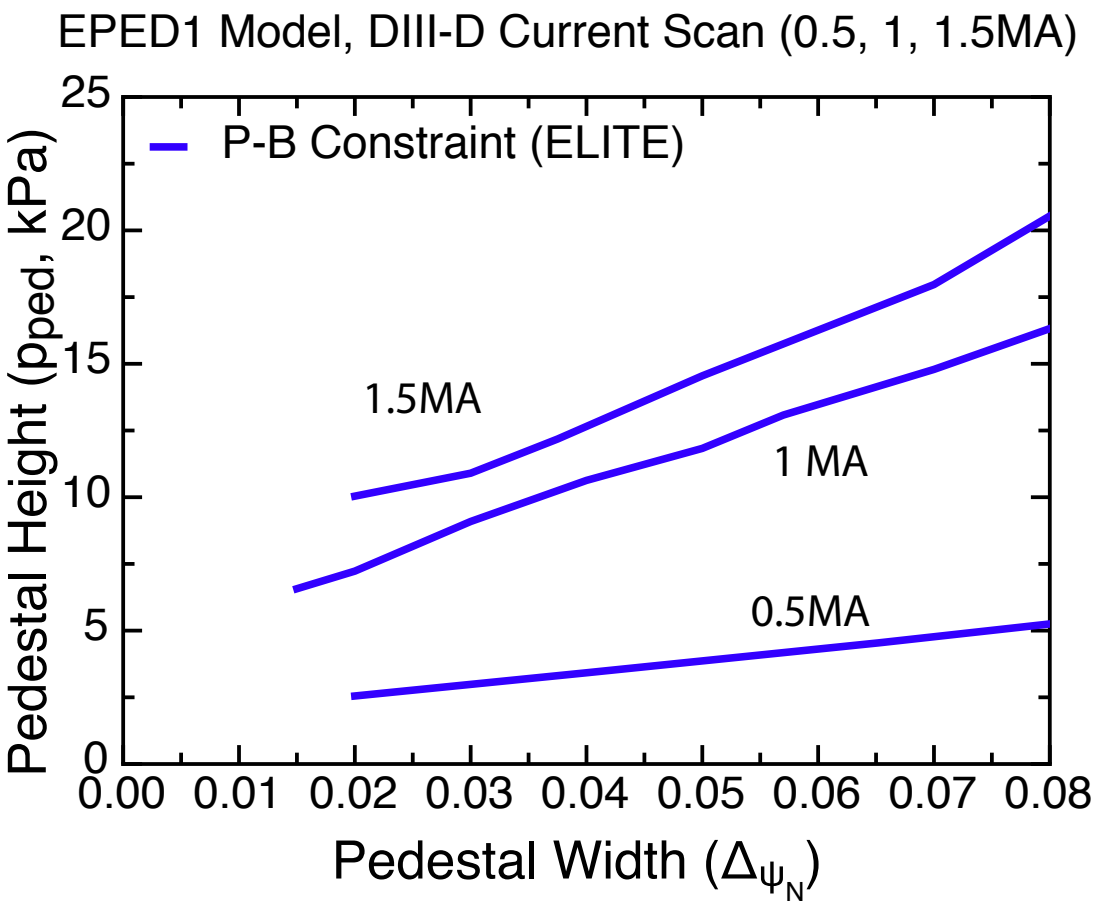
# Highly Detailed Tests of EPED Enabled by new High-Res Thomson on DIII-D

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

- $B_t$=2.1T, $\kappa$=1.74, $\delta$=0.3

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

- $\beta_N$-like, dependence weakens as q gets low



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

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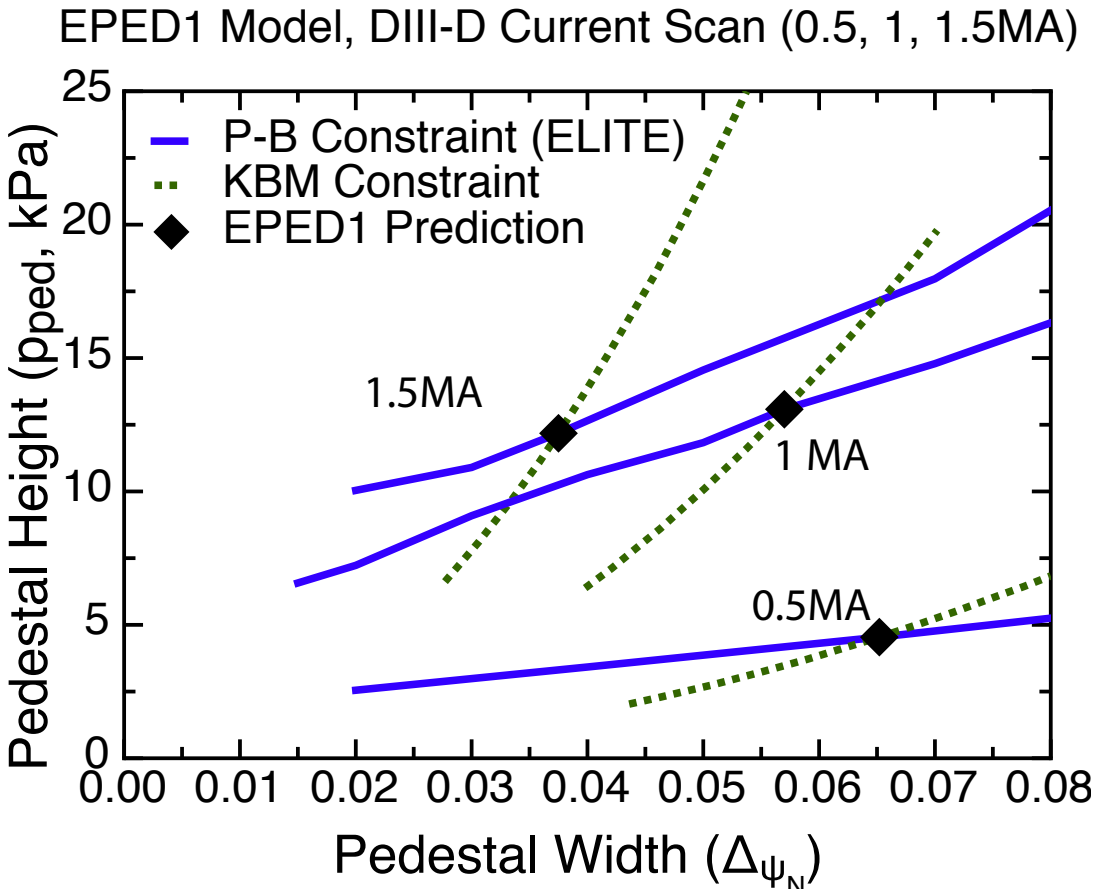
**Interaction of P-B and KBM leads to height that first rises strongly then stagnates, while width decreases with $I_p$**



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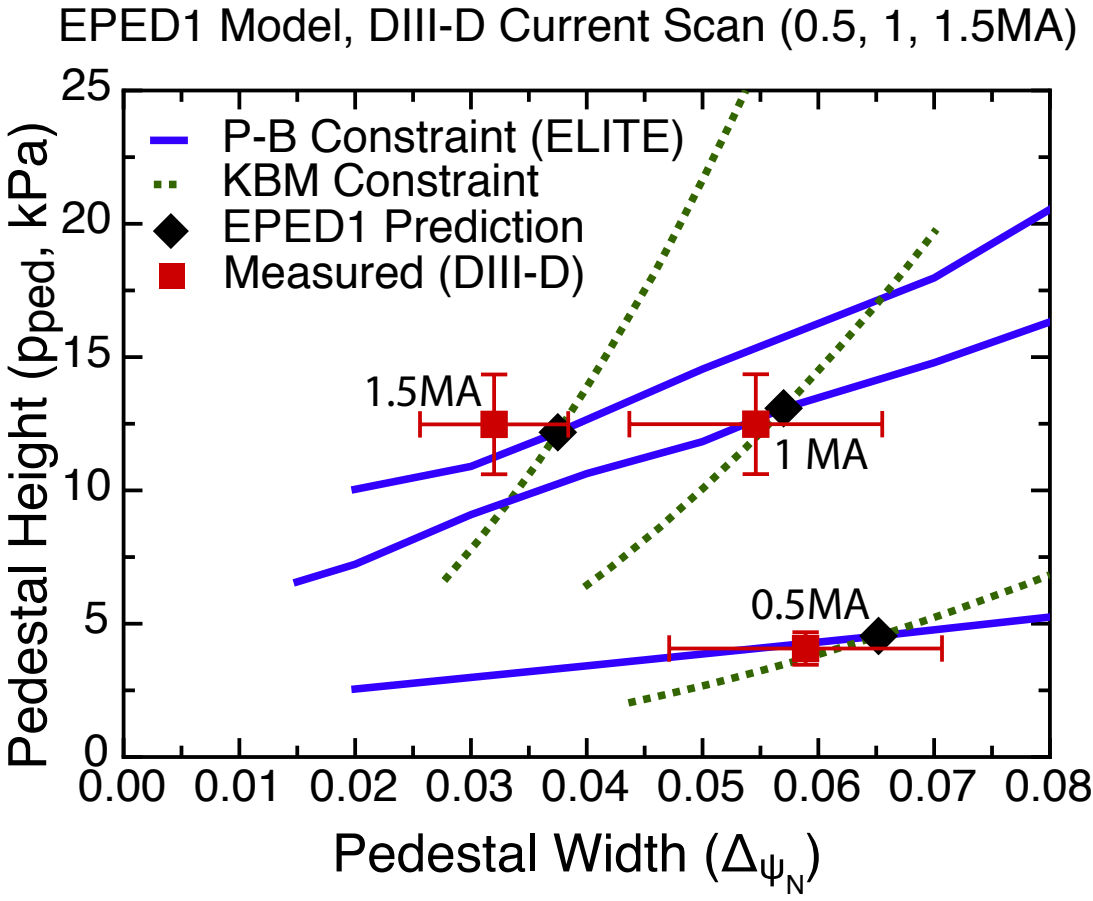
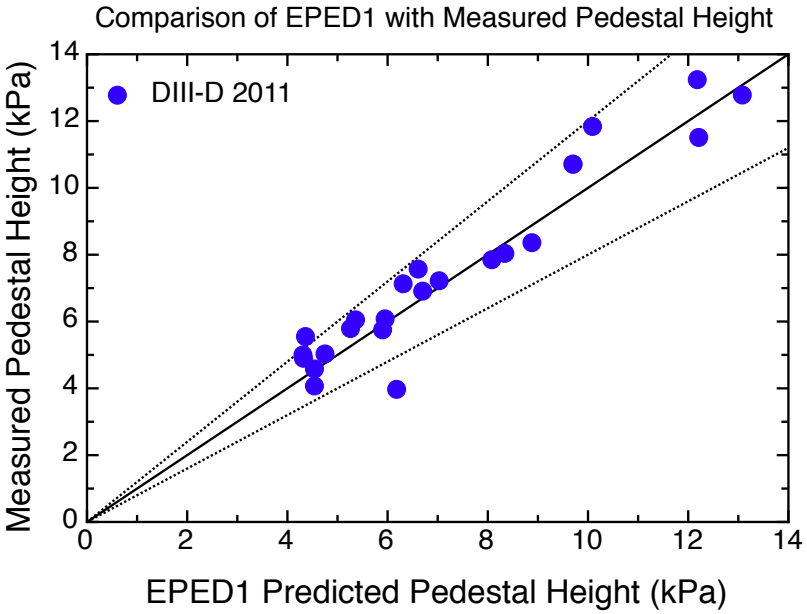
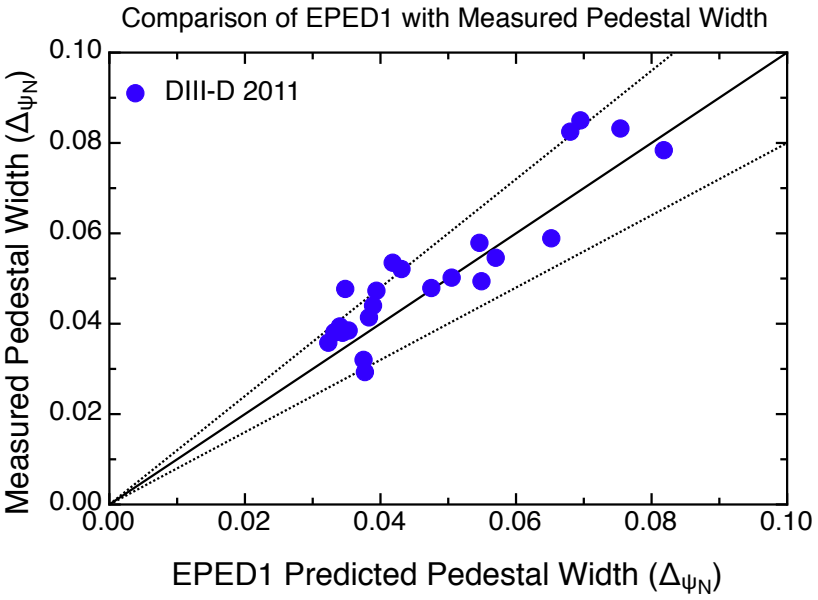
- Good agreement with observations at all $I_p$ values



# DIII-D Upgrade to Thomson System Allows More Precise Height & Width Comparison to Model




**Major Thomson upgrade ~doubles resolution**

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.

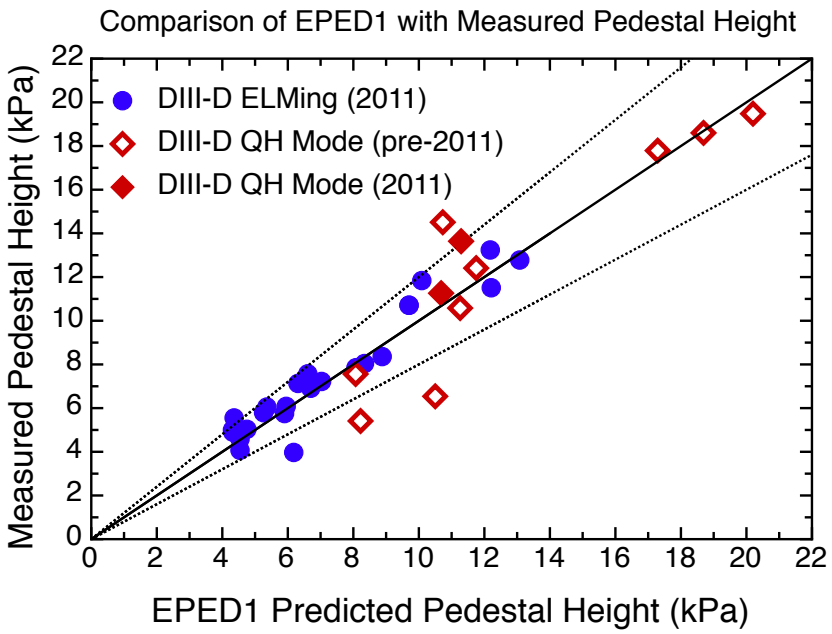
Good agreement with EPED1 model (24 cases, 14 shots):

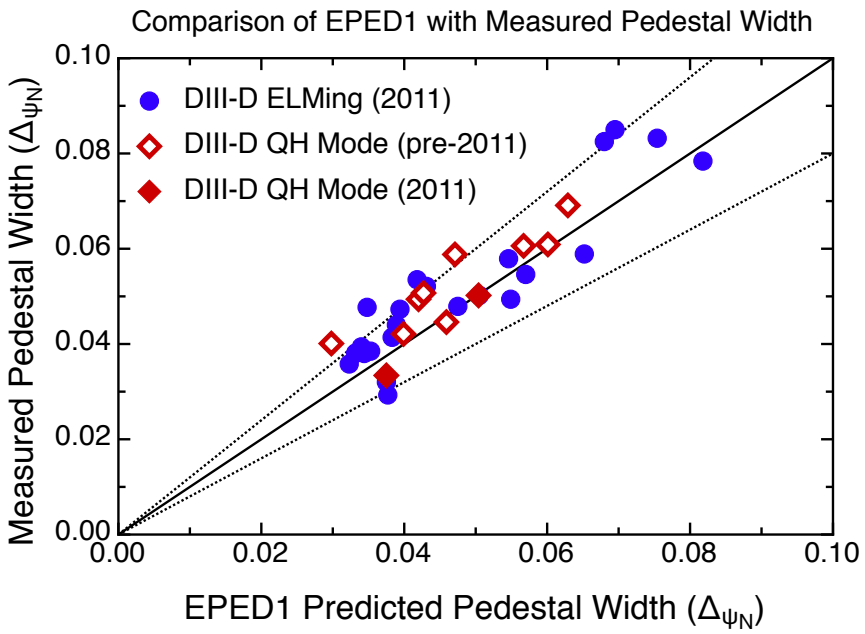
- -Ratio of predicted to observed pedestal height: 0.98 ± 0.15, corr *r*=0.96
- -Ratio of predicted to observed pedestal width: 0.94 ± 0.13, corr *r*=0.91
- -Ratio of predicted to observed pedestal average pprime: 1.05 ± 0.16, corr *r*=0.95



GENERAL ATOMICS

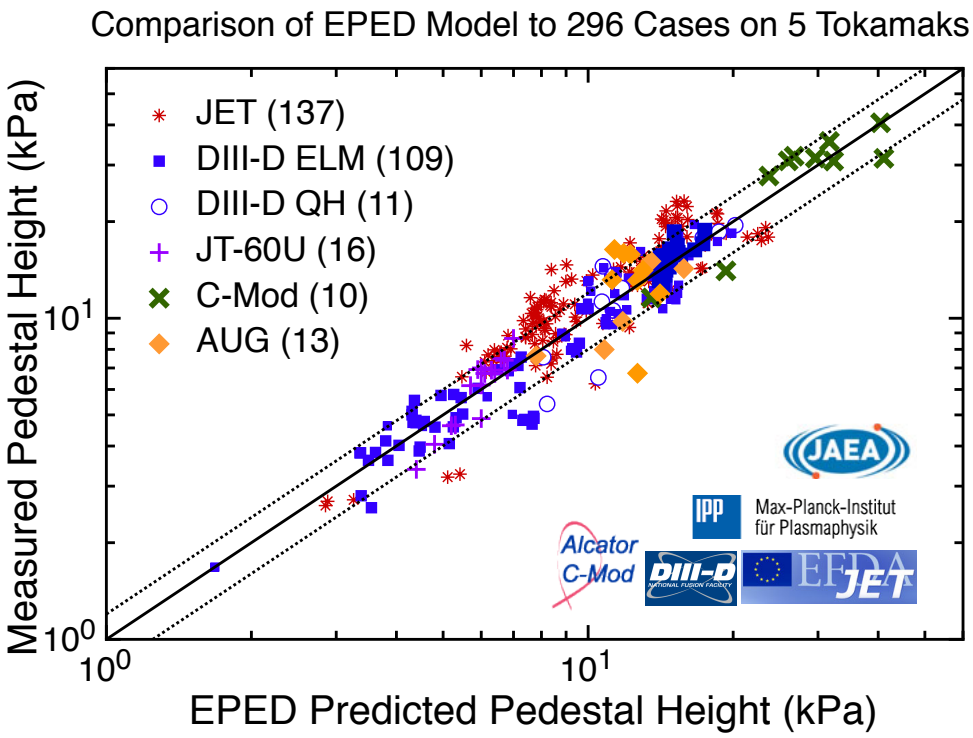
# EPED can be Applied to Quiescent H-Mode Discharges




- **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**

# Numerous Experimental Tests of EPED Conducted: Moving to Systematic Uncertainty Quantification




## Validation efforts coordinated with ITPA pedestal group, US JRT

- >700 Cases on 5 tokamaks
- Broad range of density (~1-24 $10^{19}m^{-3}$), collisionality (~0.01-4), $f_{GW,ped}$ (~0.1-1.0), shape ( $\delta$ ~0.05-0.65), q~2.8-15, pressure (1.7 - 35 kPa), $\beta_N$~0.6-4, $B_t$=0.7-8T
- Includes experiments where predictions were made before expt

**Goal is to move past scatter plots and into systematic uncertainty quantification**

**Experimental uncertainty (measurement error)** $\bar{y} = y + \varepsilon_y$

**Parameter uncertainty (uncertainty in inputs)** $\bar{x} = x + \varepsilon_x$

**Algorithmic uncertainty (approximations made in EPED algorithm)** $\bar{f}(x) = f(x) + \varepsilon_f$

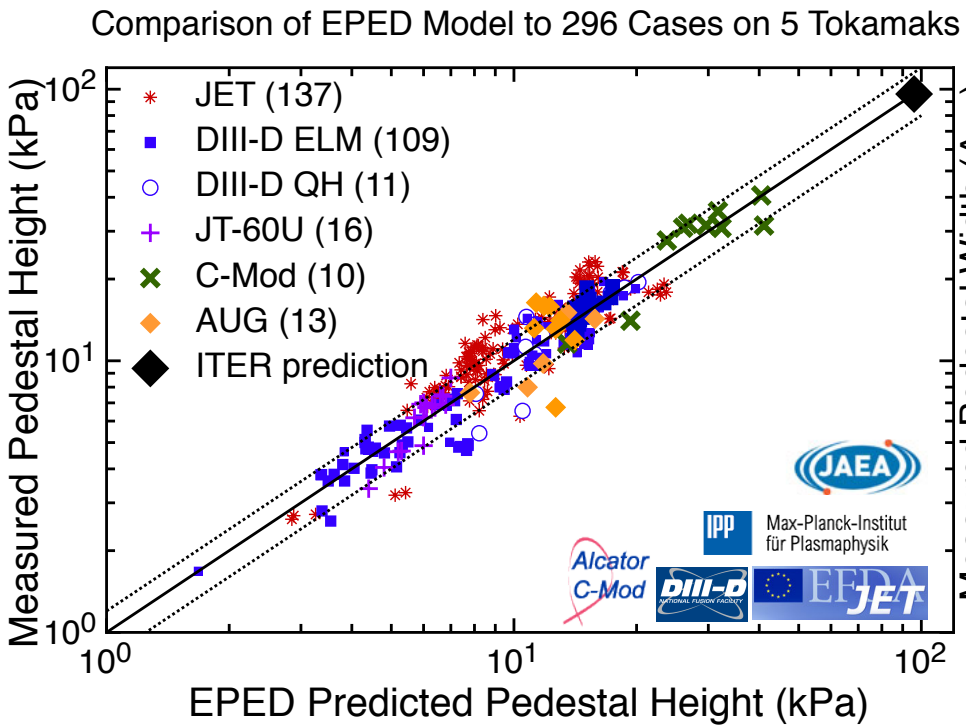
**Structural uncertainty (how accurate is the physics in EPED in describing reality)**

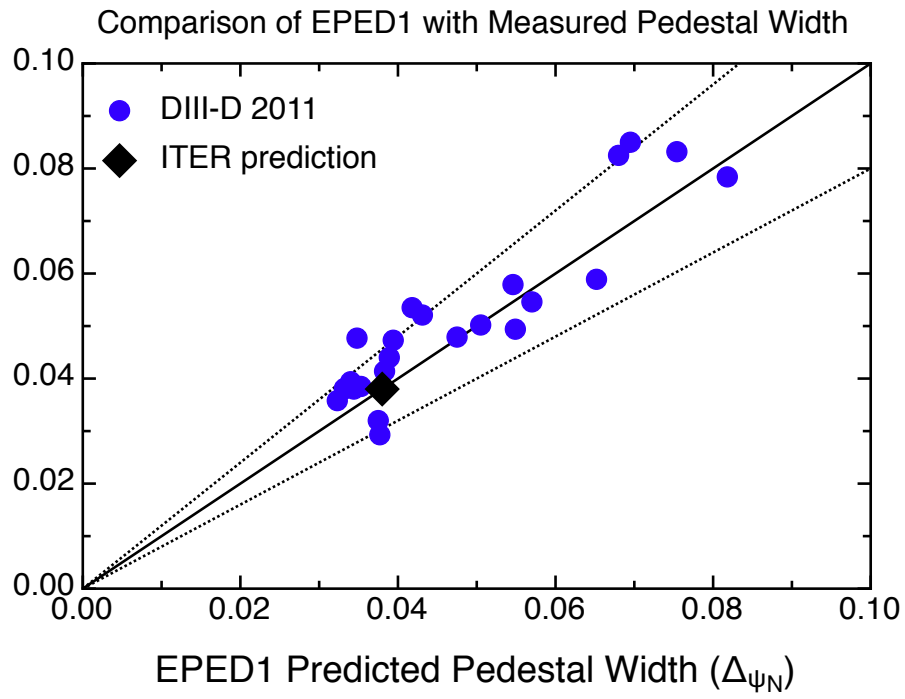
$$\bar{f}(\bar{x}) - \bar{y} = f(x+\varepsilon_x) + \varepsilon_f - y - \varepsilon_y \approx f(x) - y + (\vec{s}\varepsilon_x + \varepsilon_f - \varepsilon_y)$$



GENERAL ATOMICS

# ITER Predictions Within Range of Database in terms of Normalized Parameters



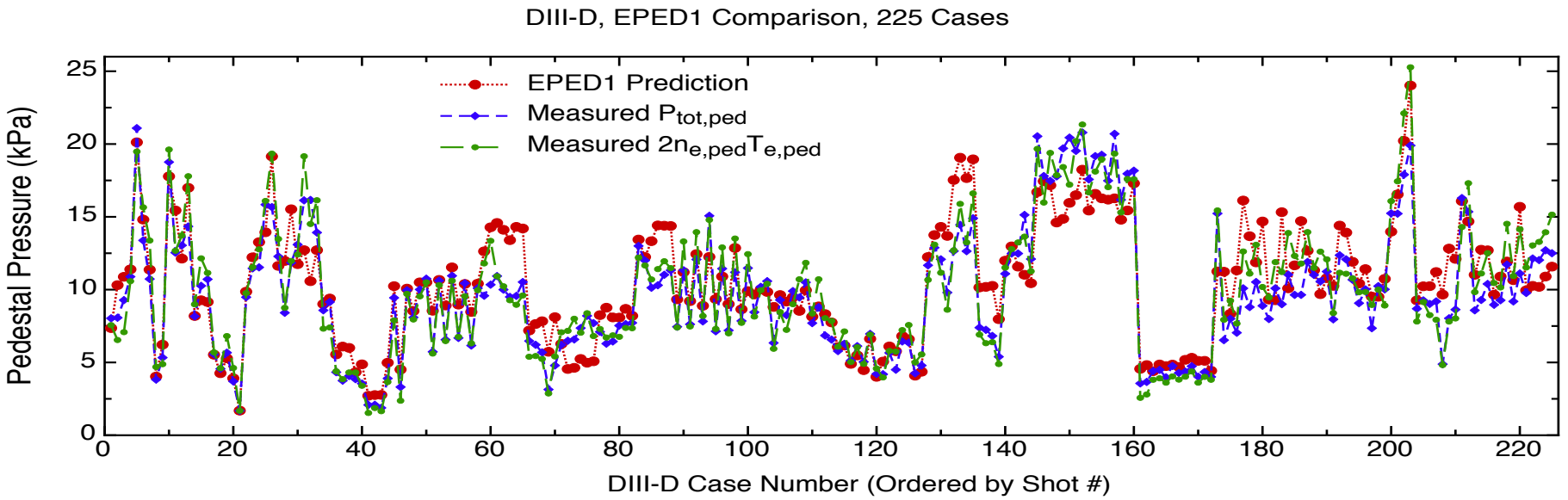




- **Existing studies cover broad range of density (~1-24 $10^{19}m^{-3}$), collisionality (~0.01-4), $f_{GW,ped}$ (~0.1-1.0), shape ($\delta$ ~0.05-0.65), q~2.8-15, $\beta_N$~0.6-4, $B_t$=0.7-8T etc**
- Predicted ITER pressure is ~3x beyond existing machines, however predicted $\beta_{N,ped}$, $\beta_{ped}$, normalized width, collisionality, q, a/R, $f_{GW}$, $\delta$, $\kappa$ within studied range (as are density, $B_t$, but not $\rho^*$)



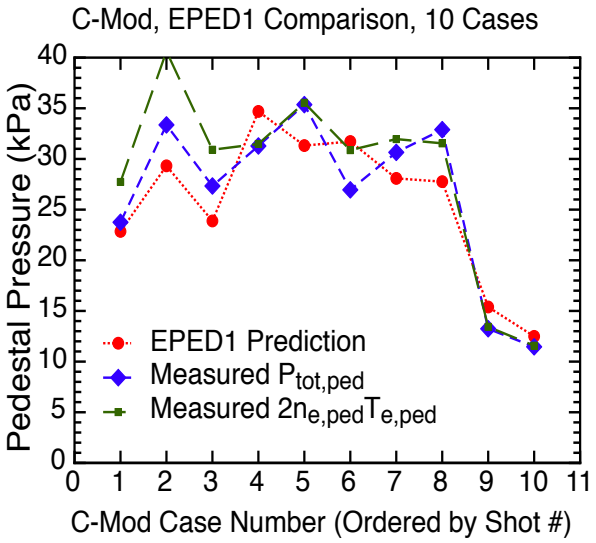
GENERAL ATOMICS

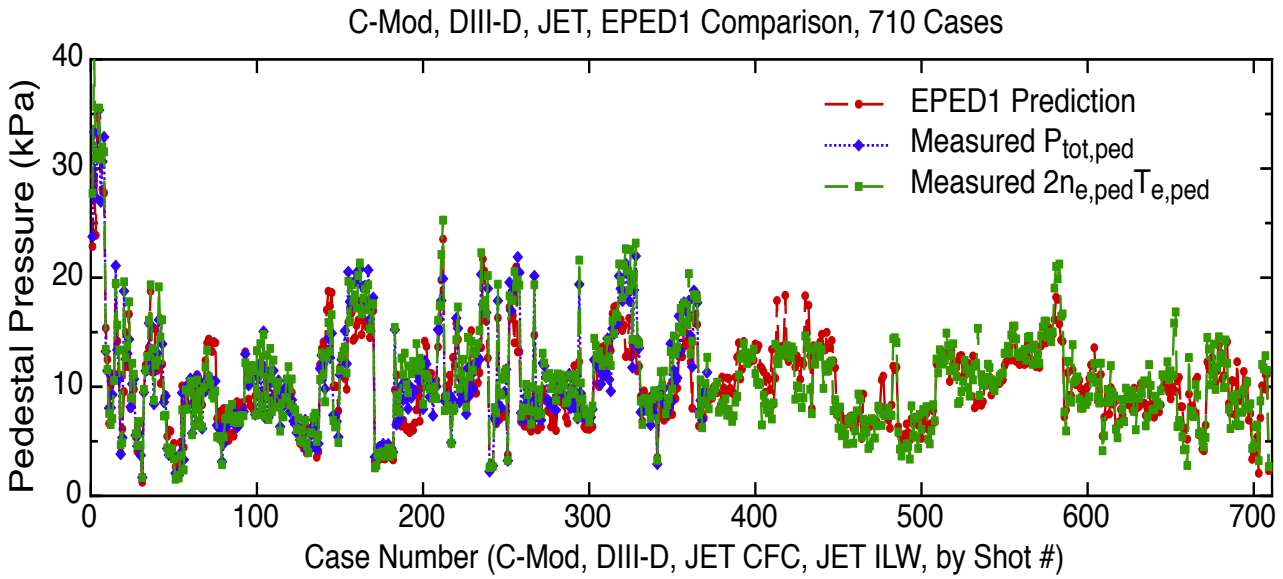
# Large Scale Studies Quantifying EPED uncertainties and accuracy: DIII-D




- **225 case DIII-D study finds agreement with observation to $\sigma$~22%, avg error=1.7 kPa, $<|p_E-p_{exp}|>/<p_{exp}>$=17%, correlation coefficient=0.87**
- **Monte Carlo analysis (using a single Gaussian error to simulate combined expt and parameter uncertainty) finds:**
  - With perfect measurements, model $\sigma$=22% (algorithmic+structural)
  - With $\sigma$=15% for measurements, model $\sigma$=16%, (algorithmic+structural)
  - With $\sigma$=22% for measurements, model is perfect (limit on measurement uncertainty)
- **Level of agreement not strongly dependent on $\nu^*$, shape, etc**

# Large Scale Studies Quantifying EPED uncertainties and accuracy: DIII-D, JET, C-Mod




- **710 case study finds agreement with observation to $\sigma$~21%, avg error=1.68 kPa, $<|p_E-p_{exp}|>/<p_{exp}>$=16%, correlation coefficient=0.87**
- **Monte Carlo analysis (using 1 Gaussian error to simulate combined expt and parameter uncertainty) finds:**
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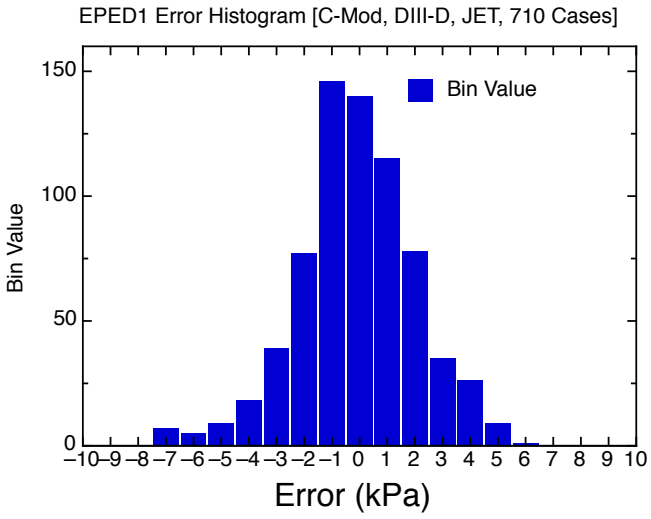
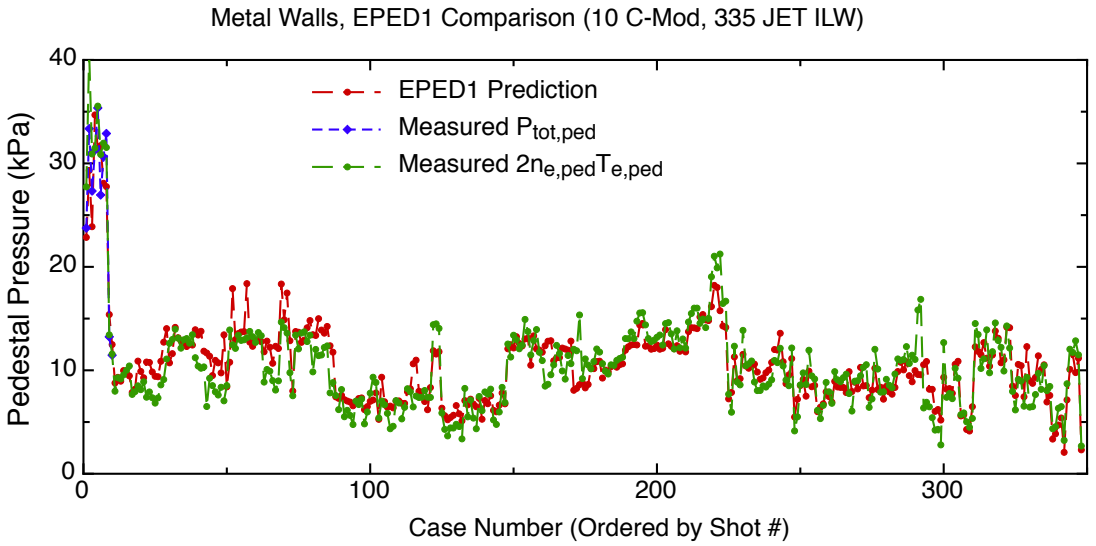


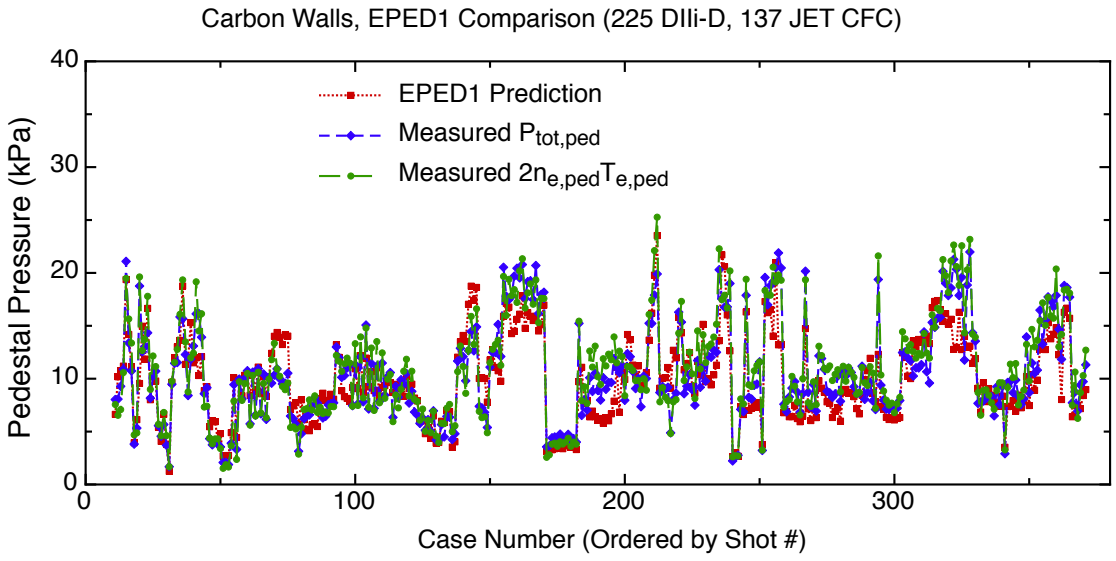



GENERAL ATOMICS

# Similar Level of EPED Accuracy with Metal or Carbon Wall

- **Metal: average error=1.46 (14%), correl=0.90, $\sigma$=0.19**
- **Carbon: average error=1.88 (18%), correl=0.85, $\sigma$=0.22**
- **No indication of strong effect of wall material on *EPED accuracy***
  - JET ILW has lower impurity levels, different operational limits than JET C
  - Studying impact of impurities and gas puffing
- **Working to identify any clear dependencies in EPED accuracy**
  - help identify where additional physics needed






GENERAL ATOMICS

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  - Predictive capability enables fusion power optimization
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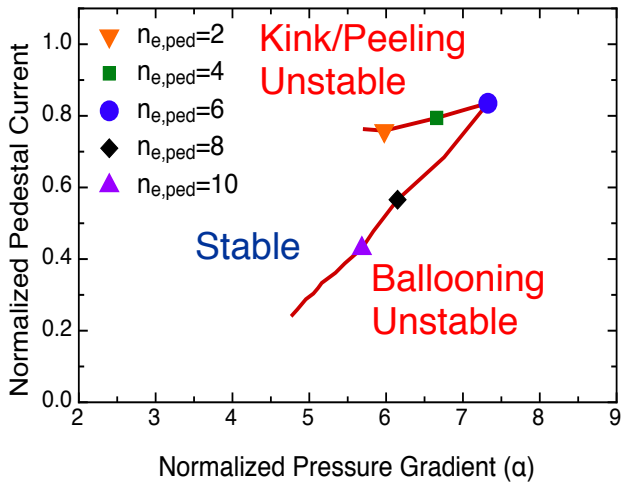
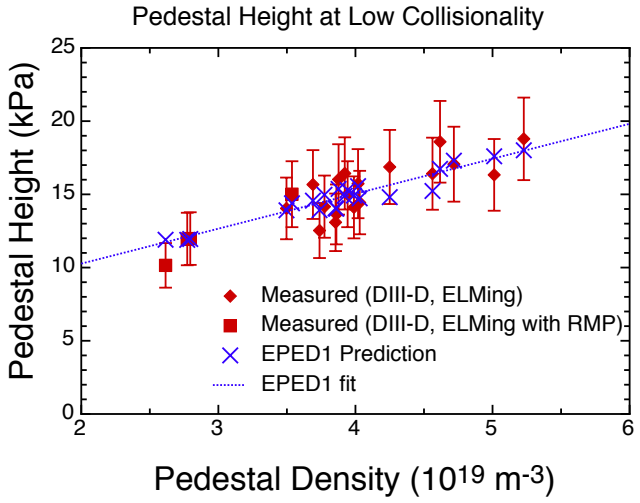
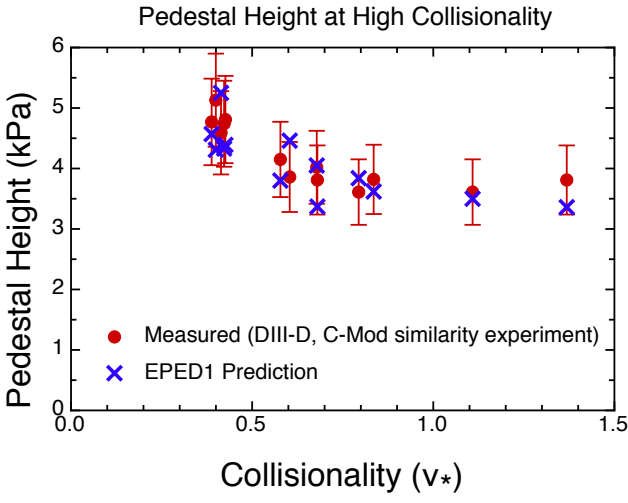
  - Overlap of scales, challenge to methods ($L \sim \lambda \sim \rho$)
- **Peeling-ballooning modes**
  - Global constraint on the pedestal, drive ELMs
- **The EPED model**
  - Kinetic ballooning modes and model derivation
  - Experimental tests on several tokamaks, statistics
  - ***Super H-Mode*** (when 2 eqns have >1 solution)
  - Dynamics and ELM suppression
- **Coupled core-pedestal prediction**
- **Directions for future pedestal research**

# Density (Collisionality) is a Powerful Lever for Pedestal Optimization of Shaped Plasmas

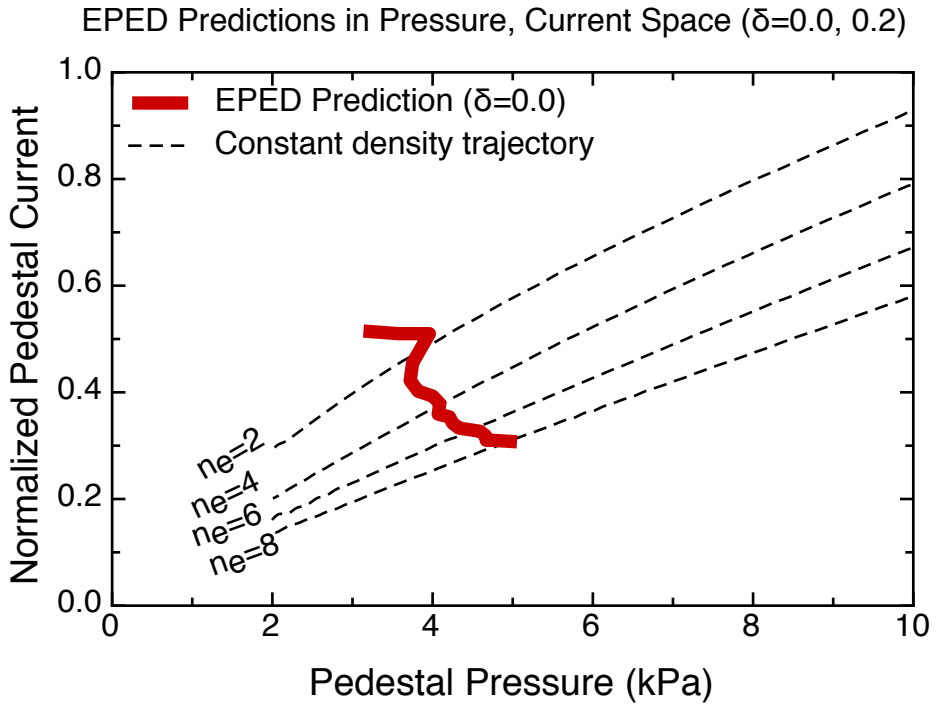


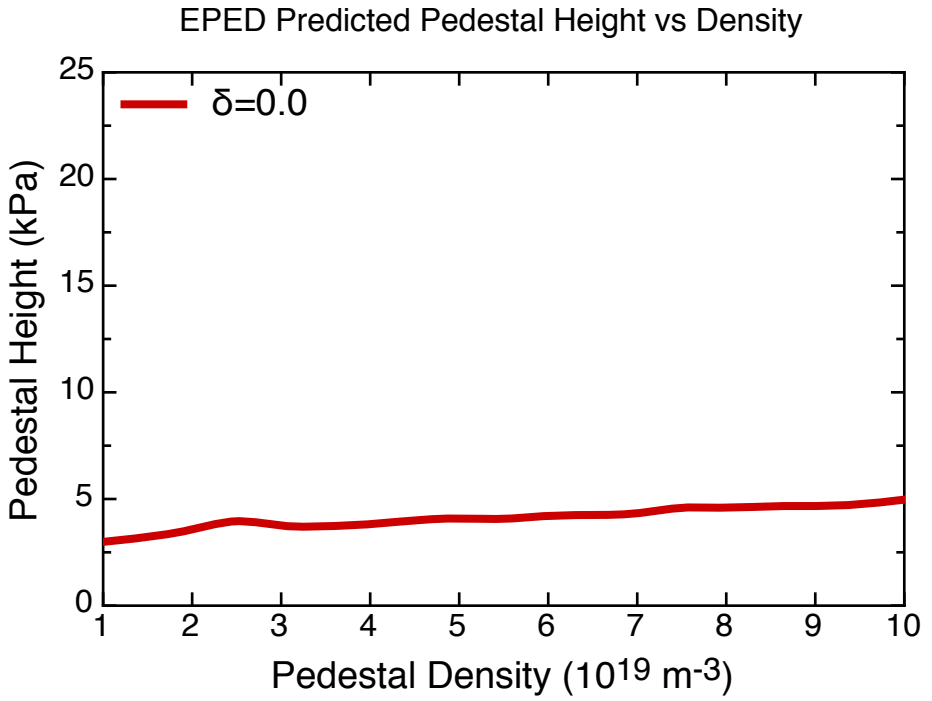




- **Density enters primarily through collisionality dependence of bootstrap current**
  - Increasing density moves from J-driven toward p-driven stability boundary
  - Low density (low $\nu_*$): $P_{ped}$ increases with $n_e$; high $\nu_*$: $P_{ped}$ decreases with $n_e$
  - Density dependence weak for weak shapes, stronger at high triangularity
- **Strongly shaped plasmas have a pronounced optimum in density corresponding to the nose of the stability diagram**
  - High performance regimes typically operate near this optimum

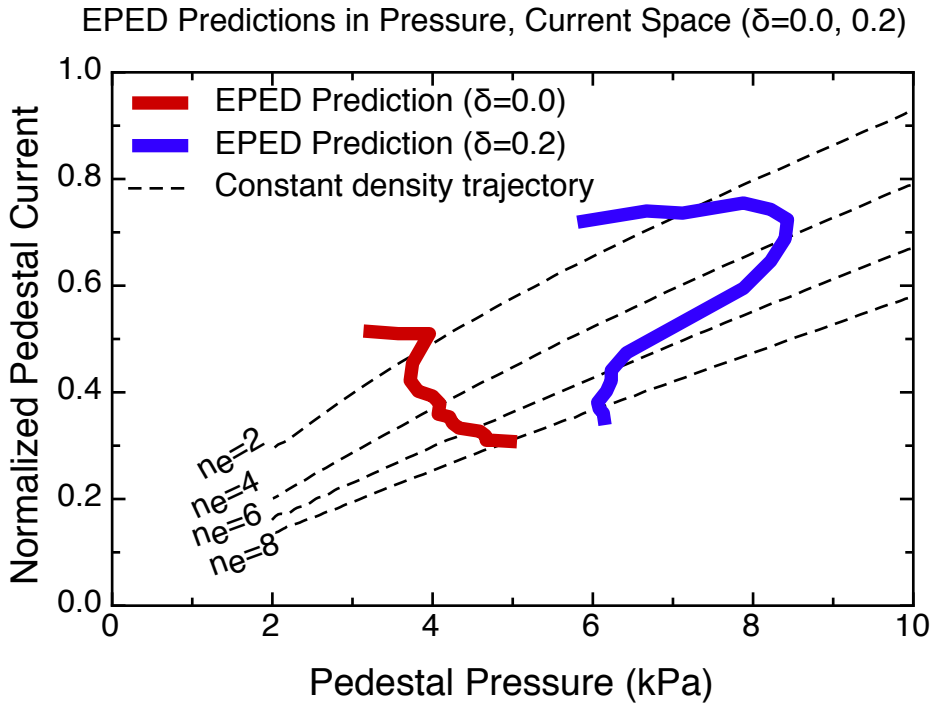
# Complex Interaction Between Shape and Density Dependence

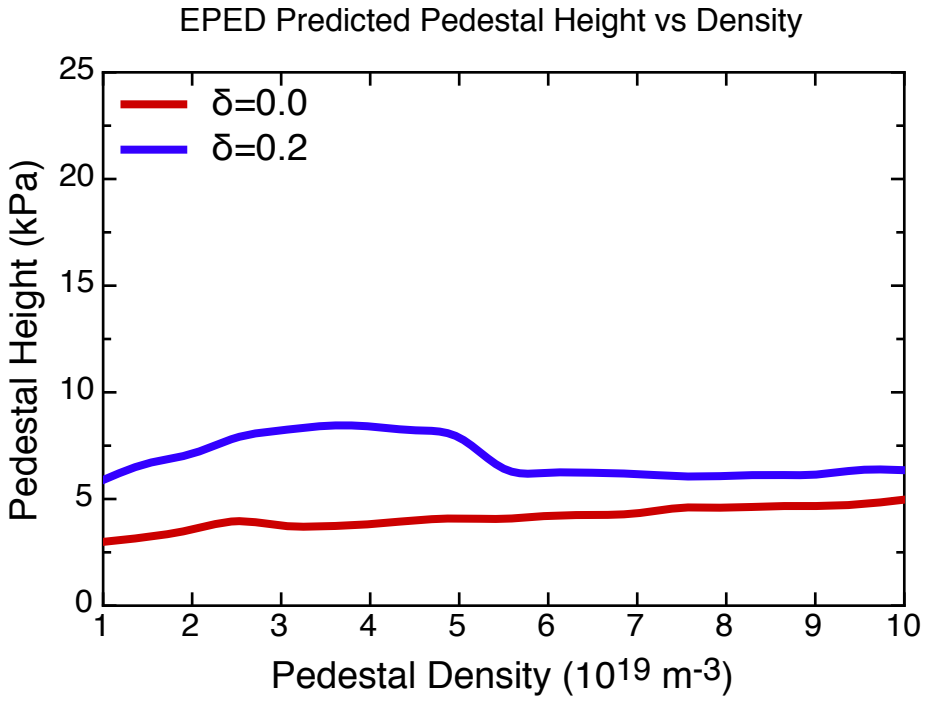



- **At very low triangularity (weak shaping, $\delta$ =0), density dependence is weak**
  - Peeling-ballooning coupling strong, no "nose" in J-P diagram (left)

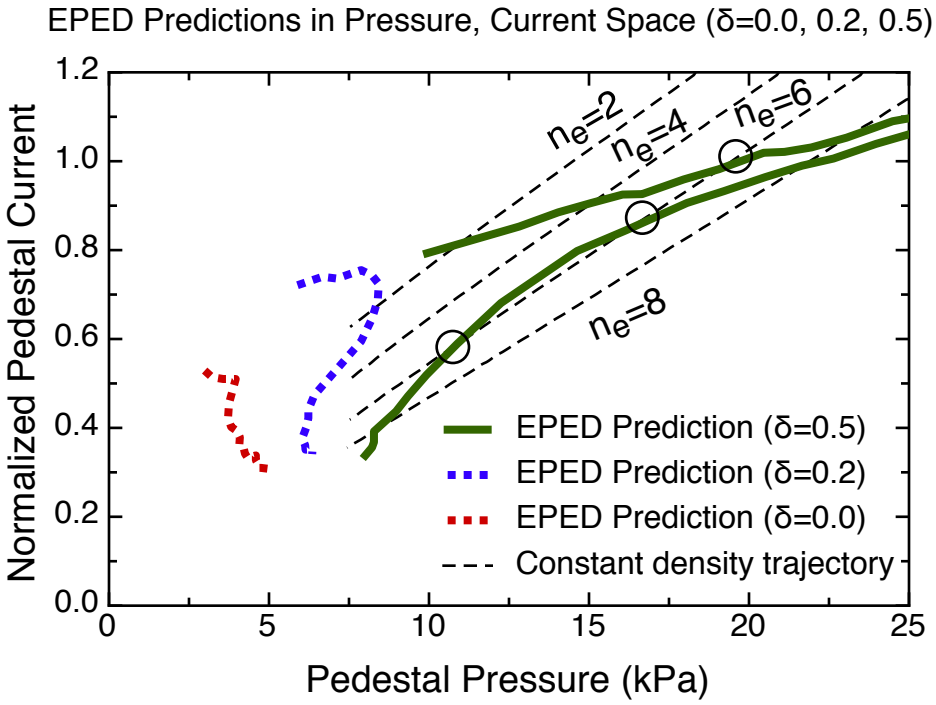
# Complex Interaction Between Shape and Density Dependence

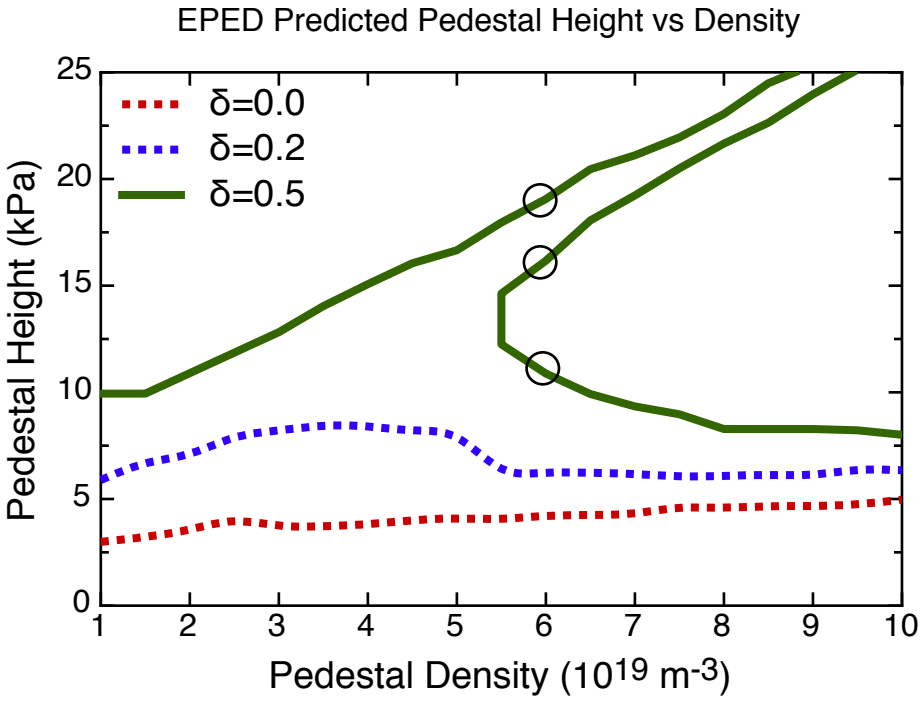



- **At modest triangularity ( $\delta$ =0.2), pedestal height increases, then decreases with density**
  - Peeling-ballooning coupling weakens, "nose" in J-P diagram (blue)

# Complex Interaction Between Shape and Density Dependence



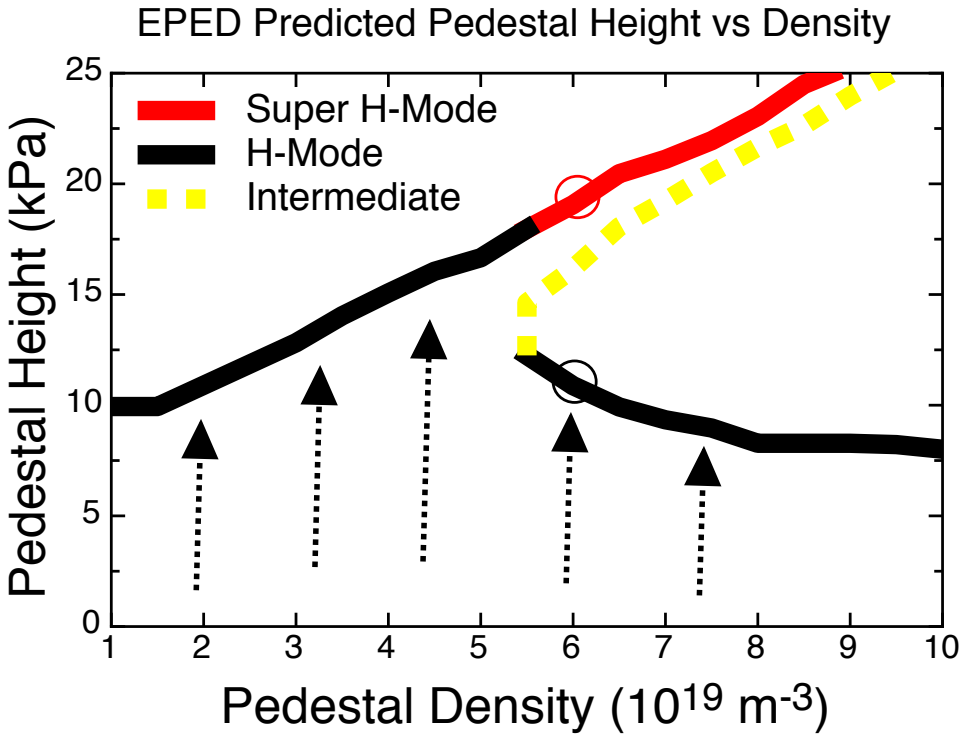




- **At high triangularity ( $\delta$ =0.5), pedestal height solution becomes multi-valued at high density**
  - Peeling-ballooning coupling very weak, "nose" in J-P diagram extends to very high pressure. Effect amplified by KBM, resulting in multiple solutions



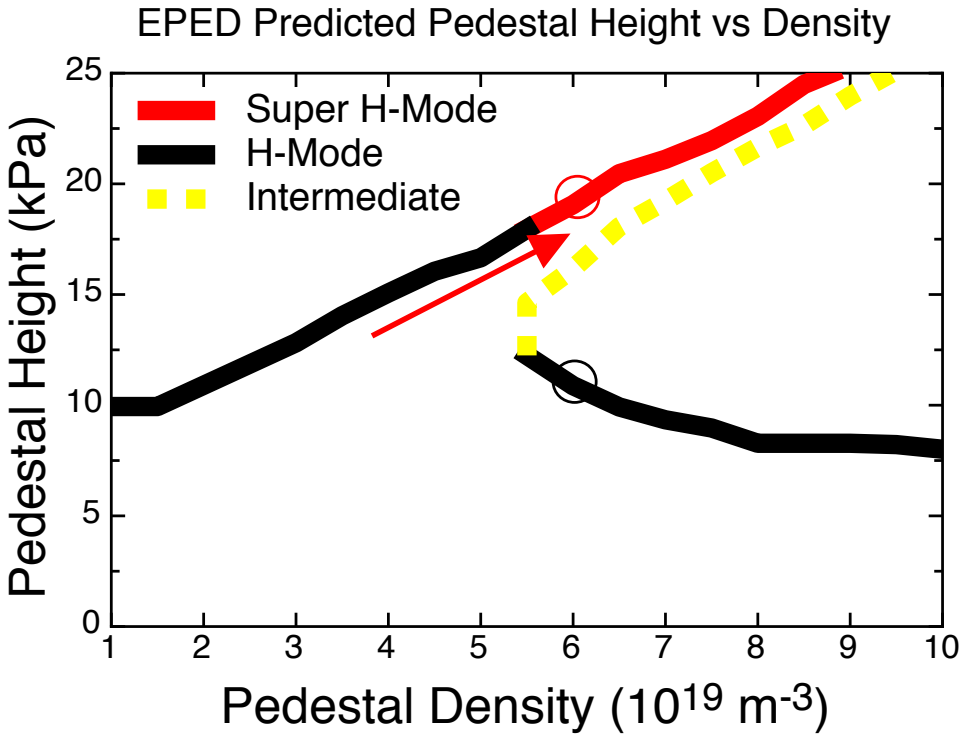
GENERAL ATOMICS

# At High Density and Strong Shaping, Solution Splits into H-Mode and Super H



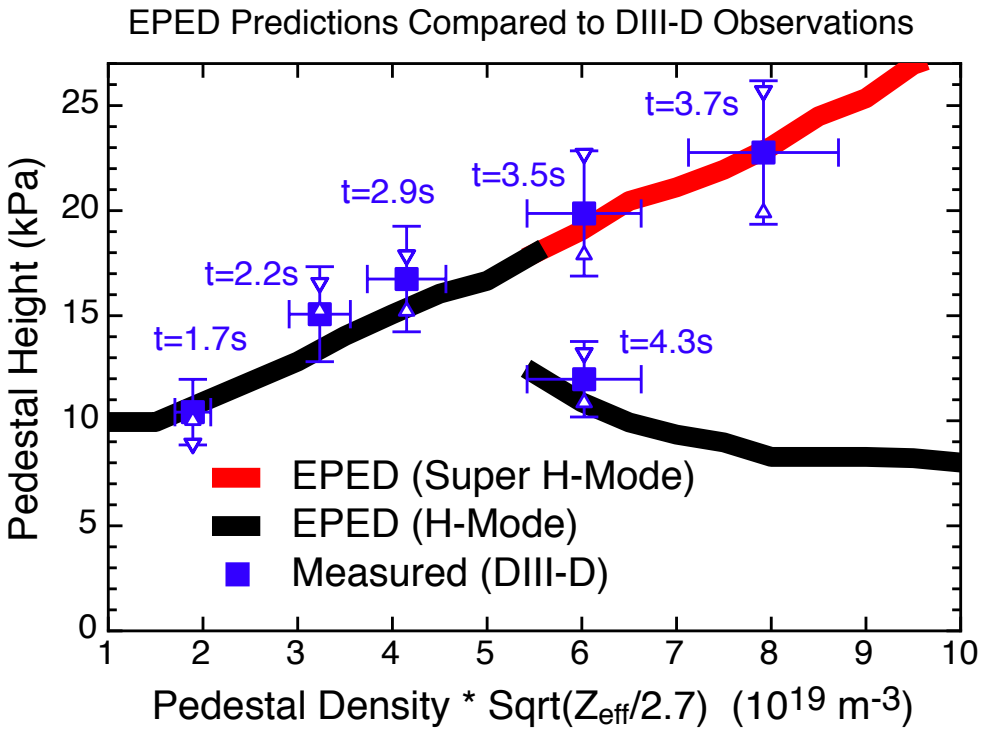

- **Constant density trajectories lead to usual H-Mode solution**
- **Solution above H-mode (red) called Super H-Mode**
  - Much higher pedestal than equivalent H-Mode solution
  - Intermediate solution (yellow) is dynamically unstable

# At High Density and Strong Shaping, Solution Splits into H-Mode and Super H




- **Super H-Mode Regime can be reached by dynamic optimization of the density trajectory**
  - Start at low density, and increase density over time (red arrow). Avoiding large transients (ELMs) enables smooth traversal of parameter space
  - Very high Super H-Mode pedestal should enable both high confinement and higher beta limit (broader profiles), leading to high fusion performance

# Super-H Mode Regime Accessed on DIII-D




*See also:*
*P.B. Snyder NF **55** 083026 (2015),*
*W. Solomon PPC/P2-37, PRL **113** 135001 (2014)*

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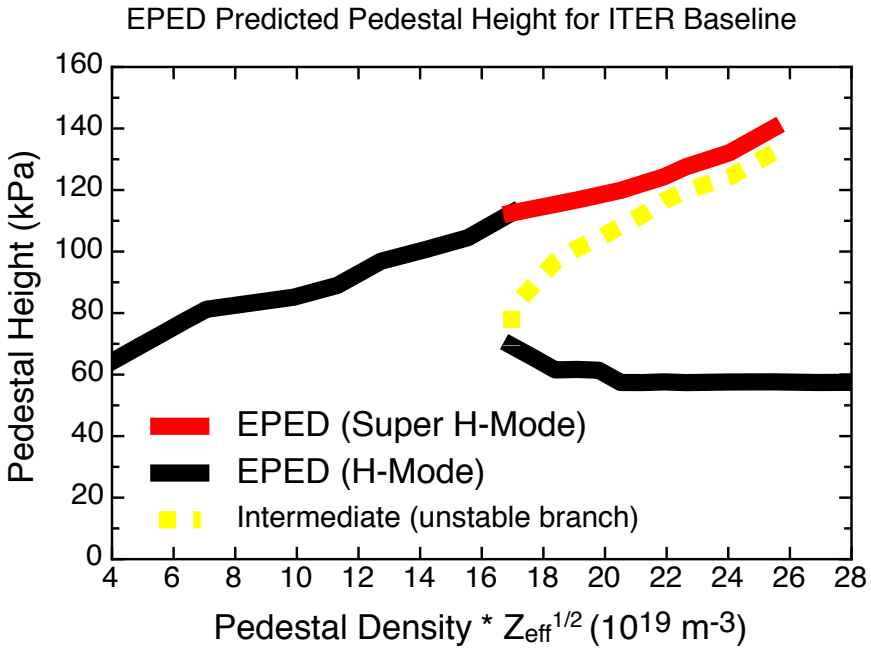
- **Very high $p_{ped}$ reached in density ramp with strong shaping ( $\delta$ ~0.53)**
- **Good agreement with EPED, which predicts this is the Super-H regime for $n_{eped}$>~5.5**
- **Clear indication of bifurcation in $p_{ped}(n_{eped})$**
- **Super H regime accessed sustainably with quiescent edge**



GENERAL ATOMICS

# Predicted Super H-Mode Regime Should Enable further ITER Optimization



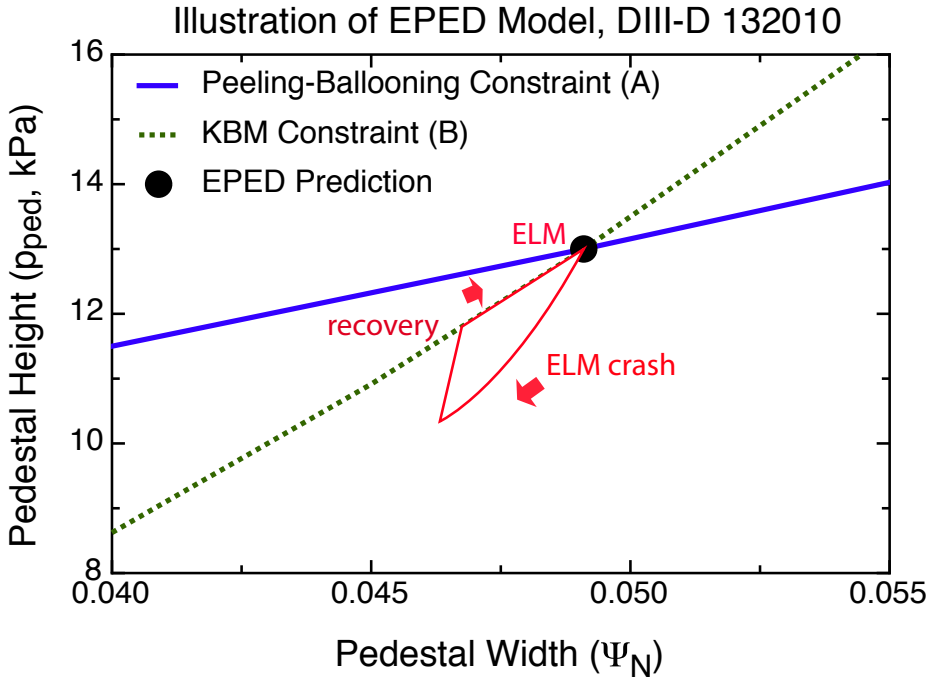

*See also:*
*P.B. Snyder NF* ***55*** *083026 (2015),*
*W. Solomon PPC/P2-37, PRL* ***113*** *135001 (2014)*

- **ITER access to Super H-Mode predicted at high density**
  - Greenwald density limit physics key: exceeding limit would be beneficial
    - Greenwald density reached at low collisionality in Super H-Mode, even on existing devices
  - Collisionality dependence of $j_{BS,}$ scales with density*$Z_{eff}^{1/2}$
    - Path to optimize pedestal (and divertor) via injection of low Z impurities
  - Multiple approaches to access this space (QH-mode edge, RMP ELM suppression, pellet triggered small ELMs)

# Outline: Pedestal Physics Key to Predicting and Optimizing ITER

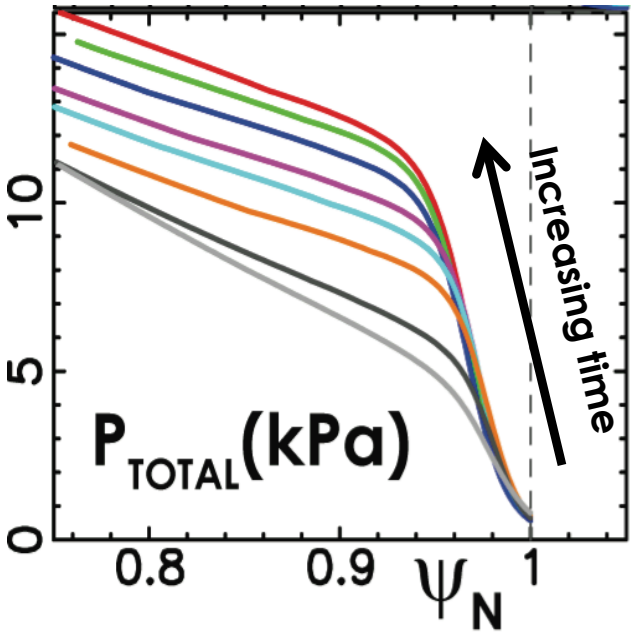
- **The Pedestal: What it is and why it matters**
  - Simultaneous improvement of confinement and stability
  - Predictive capability enables fusion power optimization
- **Physics challenges**
  - Overlap of scales, challenge to methods (L~ $\lambda$ ~ $\rho$ )
- **Peeling-ballooning modes**
  - Global constraint on the pedestal, drive ELMs
- **The EPED model**
  - Kinetic ballooning modes and model derivation
  - Experimental tests on several tokamaks, statistics
  - Super H-Mode (when 2 eqns have >1 solution)
  - ***Dynamics and ELM suppression***
- **Coupled core-pedestal prediction**
- **Directions for future pedestal research**

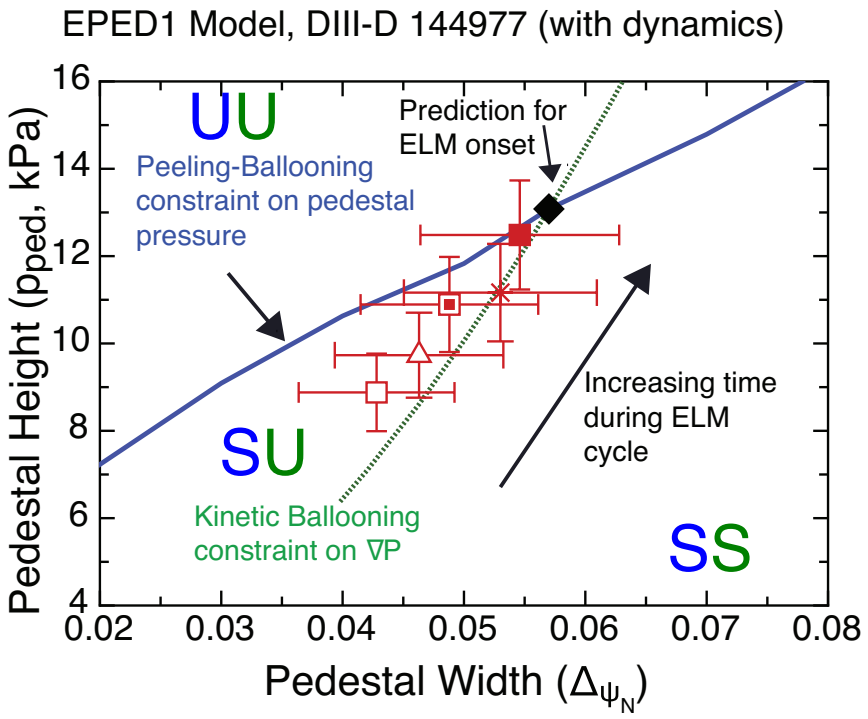
# Applying the EPED Model to Develop a Working Model for RMP ELM Suppression




- **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: Understanding Dynamics

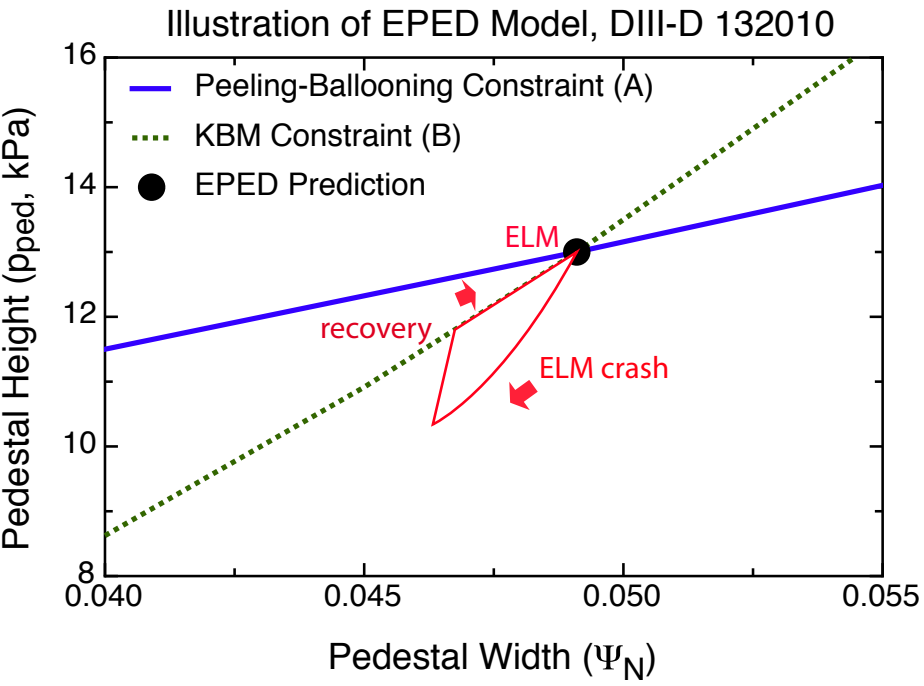


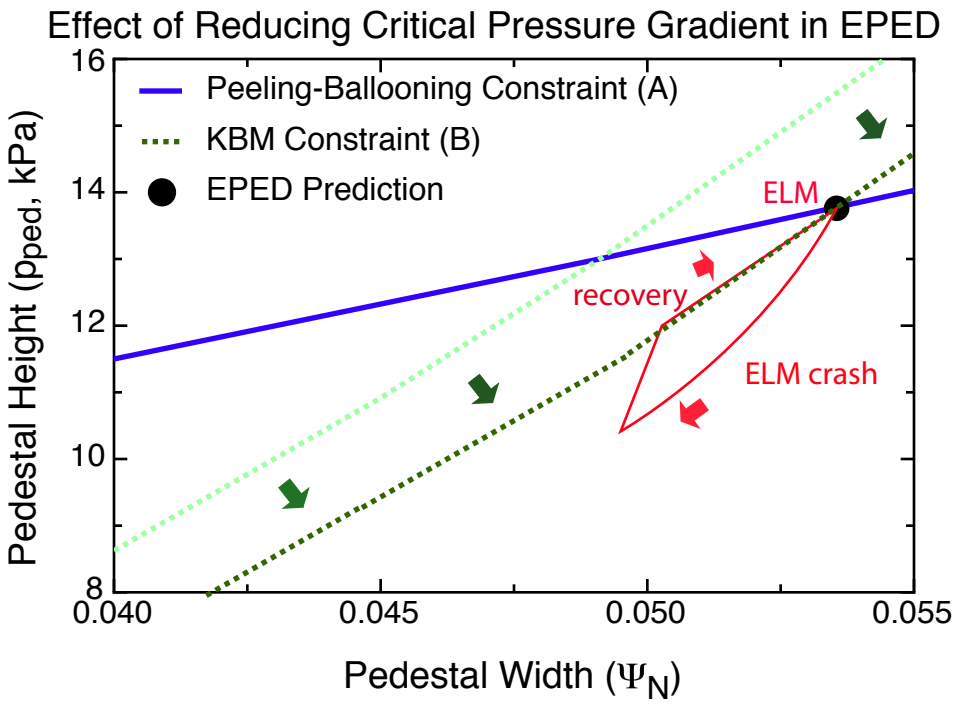




**EPED is a static model for the pedestal structure, but can be used to interpret dynamics**

- Pedestal broadens with time at roughly fixed p' near KBM criticality
- The ELM is triggered by a "global" peeling-ballooning mode (solid blue line), typically followed by a crash, and 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?

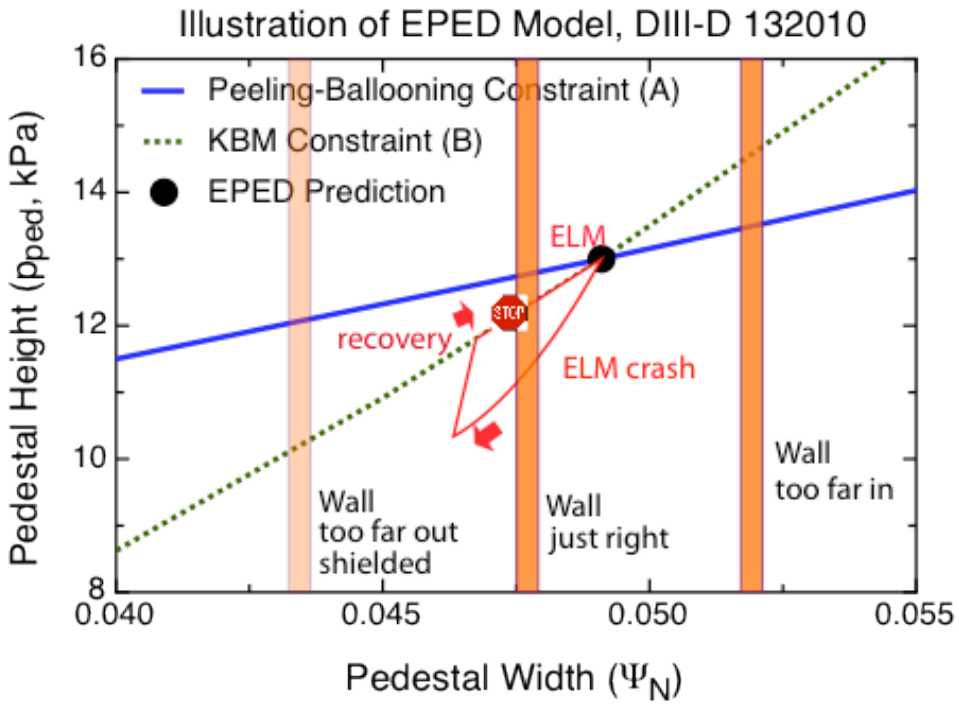


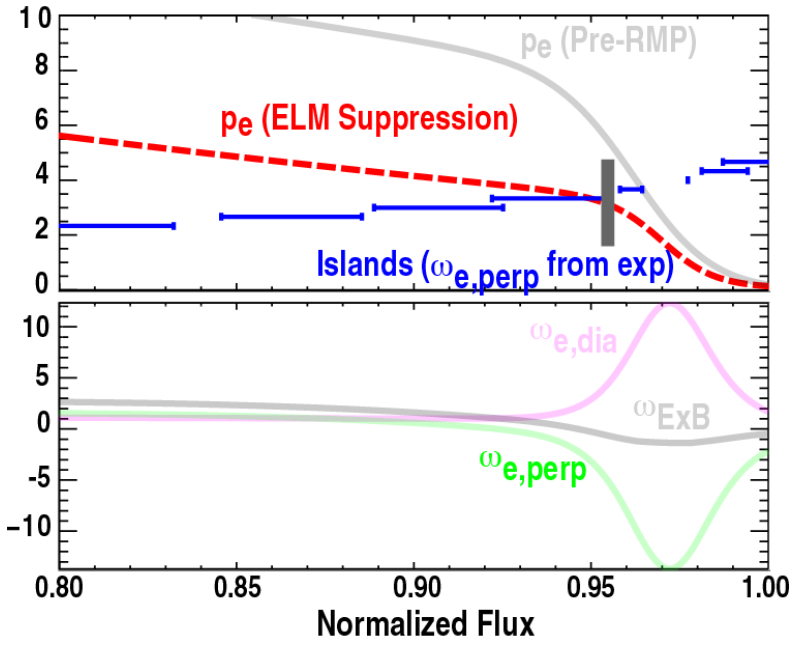




**Reducing the pressure gradient below the initial KBM limit does NOT, by itself, prevent the ELM**

**-Recovery part of cycle continues to P-B instability, unless it is stopped**

# 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 broadening**
- **Wall location must be precise: too far in will not stop the ELM, too far out will be shielded by very large $\omega_{\perp e}$ in the pedestal (2-fluid response)** *[15-17]*
- **Location of "wall" determined by q profile ➔ q windows for ELM suppression**

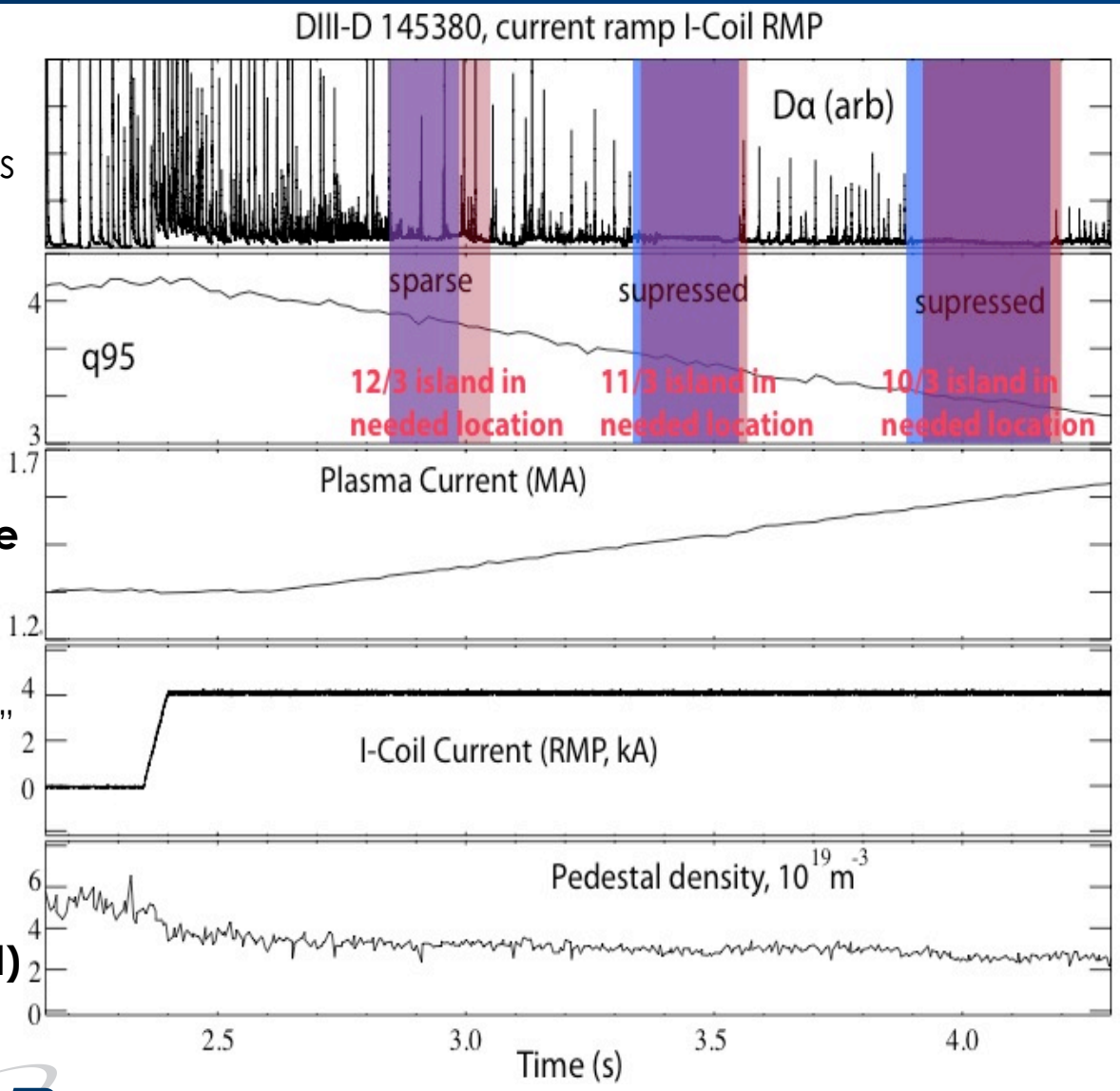
# EPED-based Working Model for ELM Suppression Agrees with Observed $q_{95}$ Windows

**ELM suppression or mitigation occurs in multiple q windows**

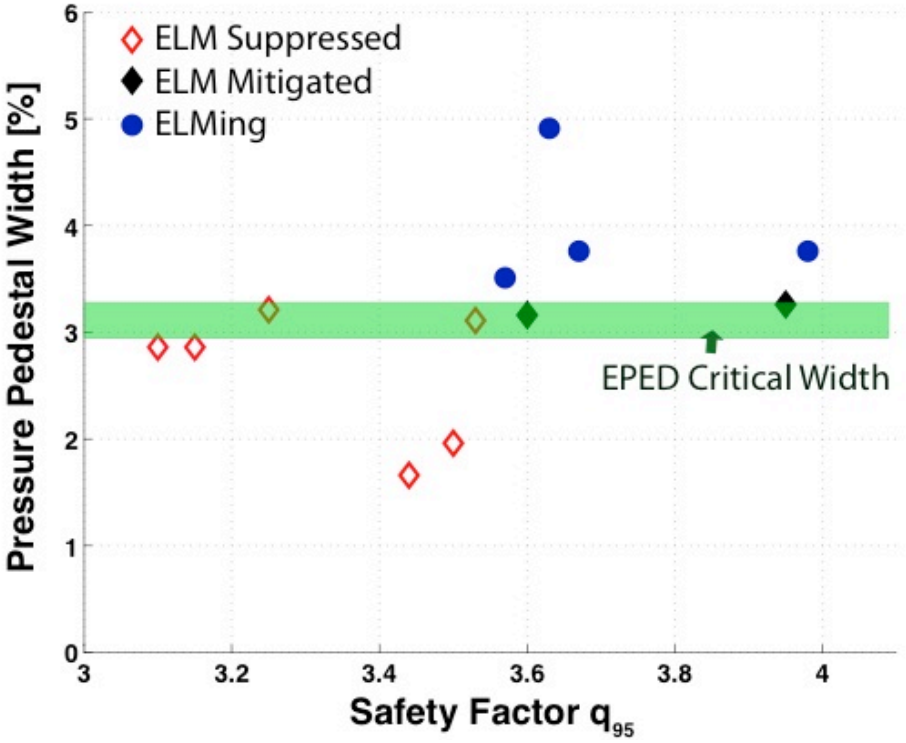
- DIII-D 145830, $I_p$ ramp, 2 windows of suppression, 1 sparse (blue)

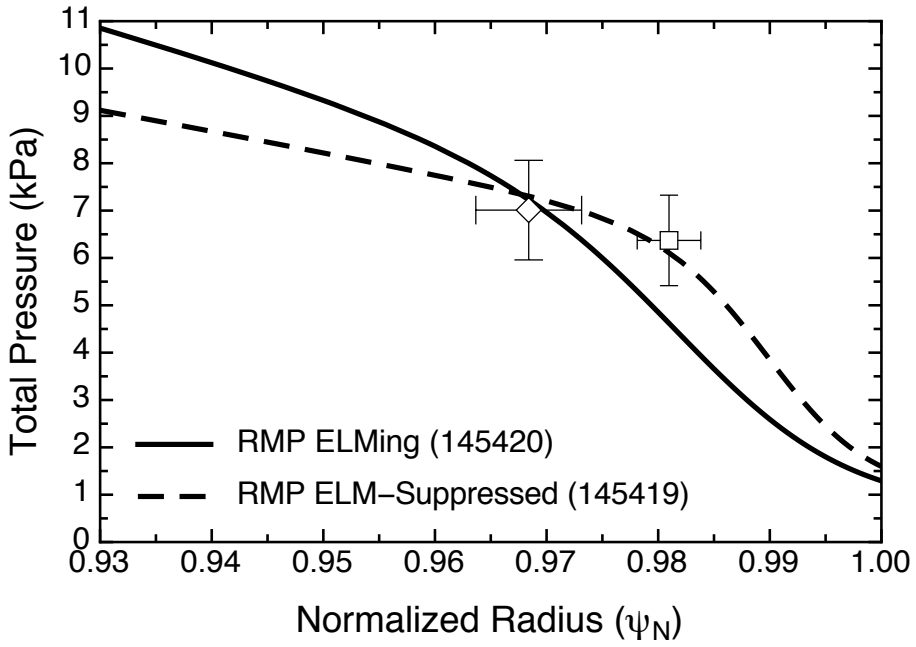
**EPED predicts width of 0.03**

- **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
  - Similar phenomena in pellet-pacing cases

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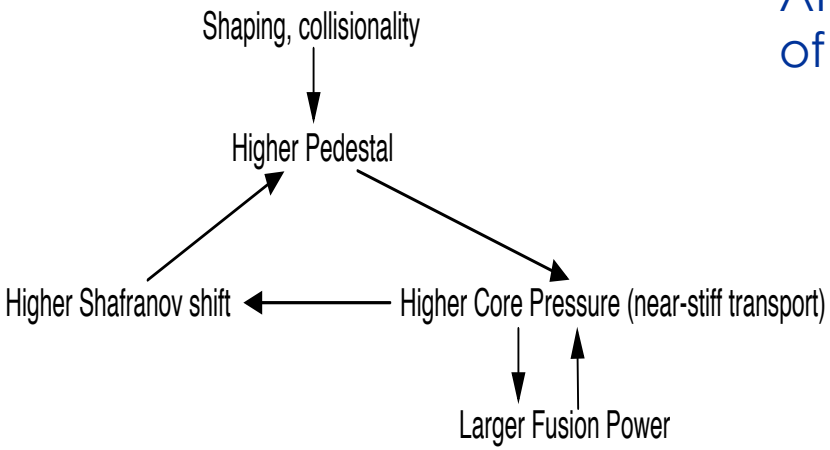
# Integrated Modeling Enables Prediction and Optimization of Coupled Core-Pedestal System

- **Peeling-ballooning stability is enhanced by the global Shafranov shift, which is proportional to global pressure** ***[Snyder07]***
- **Core turbulent transport is ~stiff, and hence core profiles depend strongly on the BC provided by the pedestal**
- ✓ **Potential for a virtuous cycle to strongly enhance performance, but must do self-consistent, coupled pedestal-core modeling**




AToM project has enabled dramatic speedup of EPED pedestal model

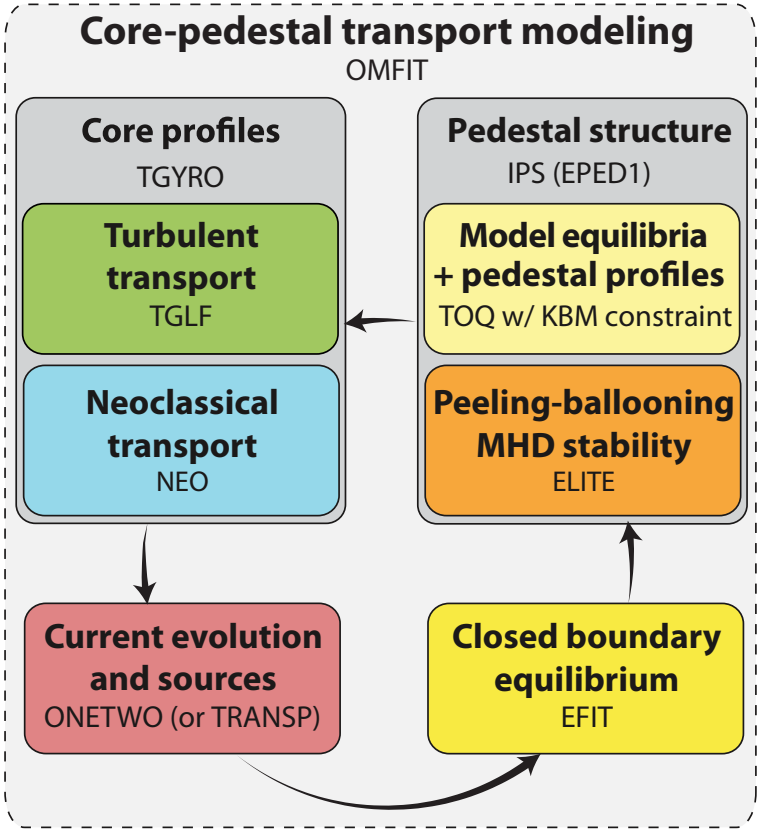
- Previous: 1 case took several hours on single CPU core (~700 ELITE runs). Large dataset took over a week to run on ~40 CPU cores
- IPS: 1 case can be run in ~1.5 minutes using ~700 cores. Large dataset run in ~1 hour on 3600 cores (could use ~150,000 cores to get the job done in ~1.5 minutes)

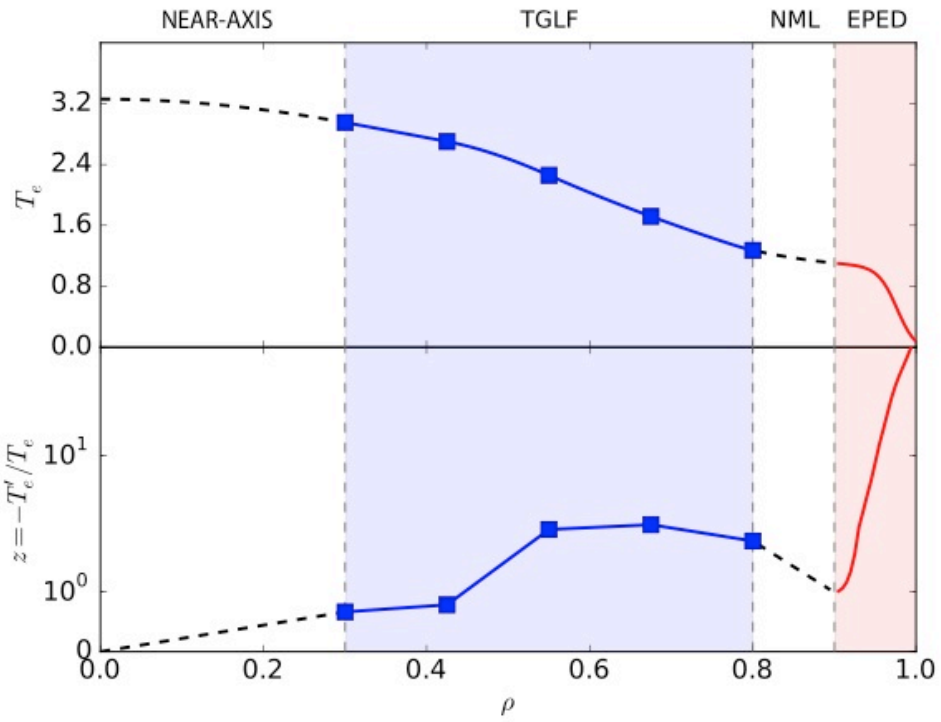


GENERAL ATOMICS

# Initial example is EPED/TGLF/NEO and Core-Pedestal Integrated Modeling: DIII-D ITER-similar discharge 153523

- Divide plasma into 4 regions
- Coupled workflow with OMFIT/IPS






GENERAL ATOMICS

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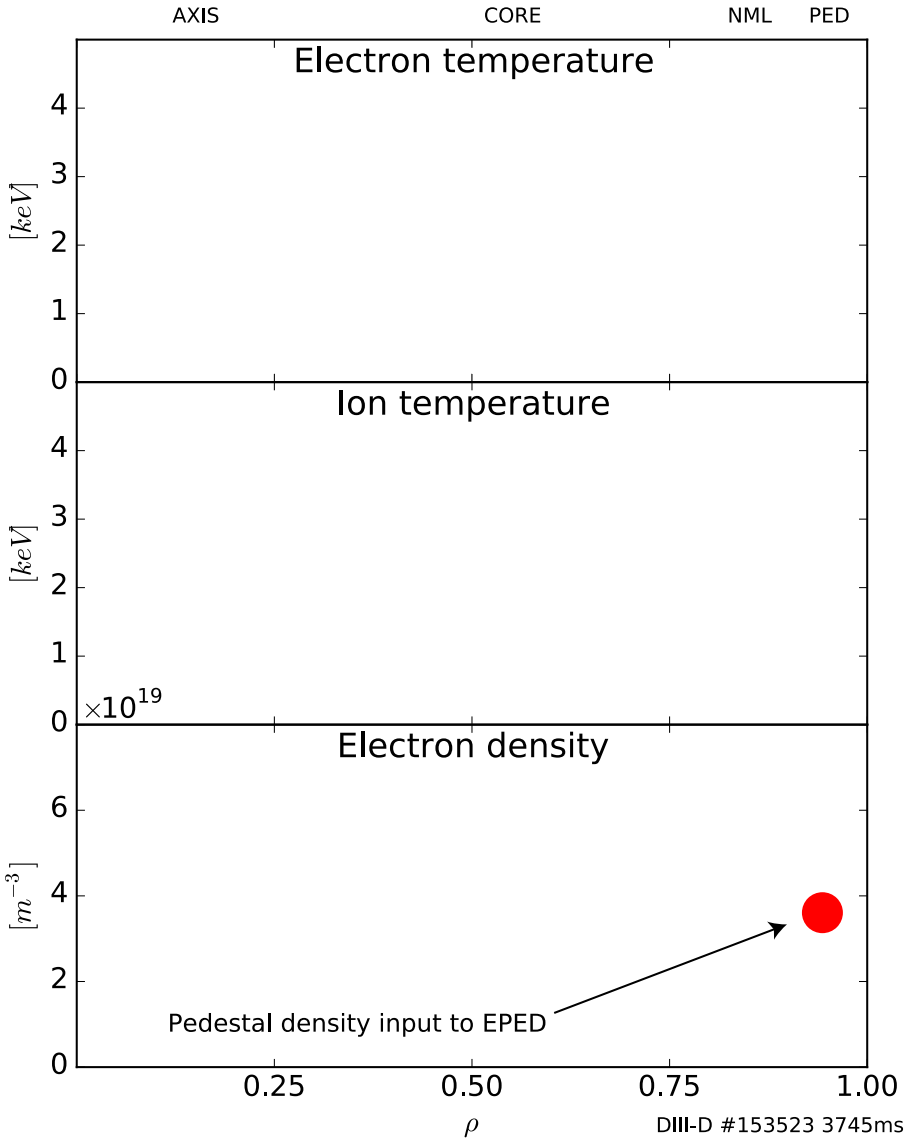
- **No measurements of $T_e$, $T_i$ or pressure input**
- **Density only input at pedestal**
  - Inputs: shape, sources, rot., $B_t$, $I_p$, $n_{e,ped}$
  - Predicting $T_e$, $T_i$, $n_{e,core}$, $\beta_N$, ($P_{fus}$)



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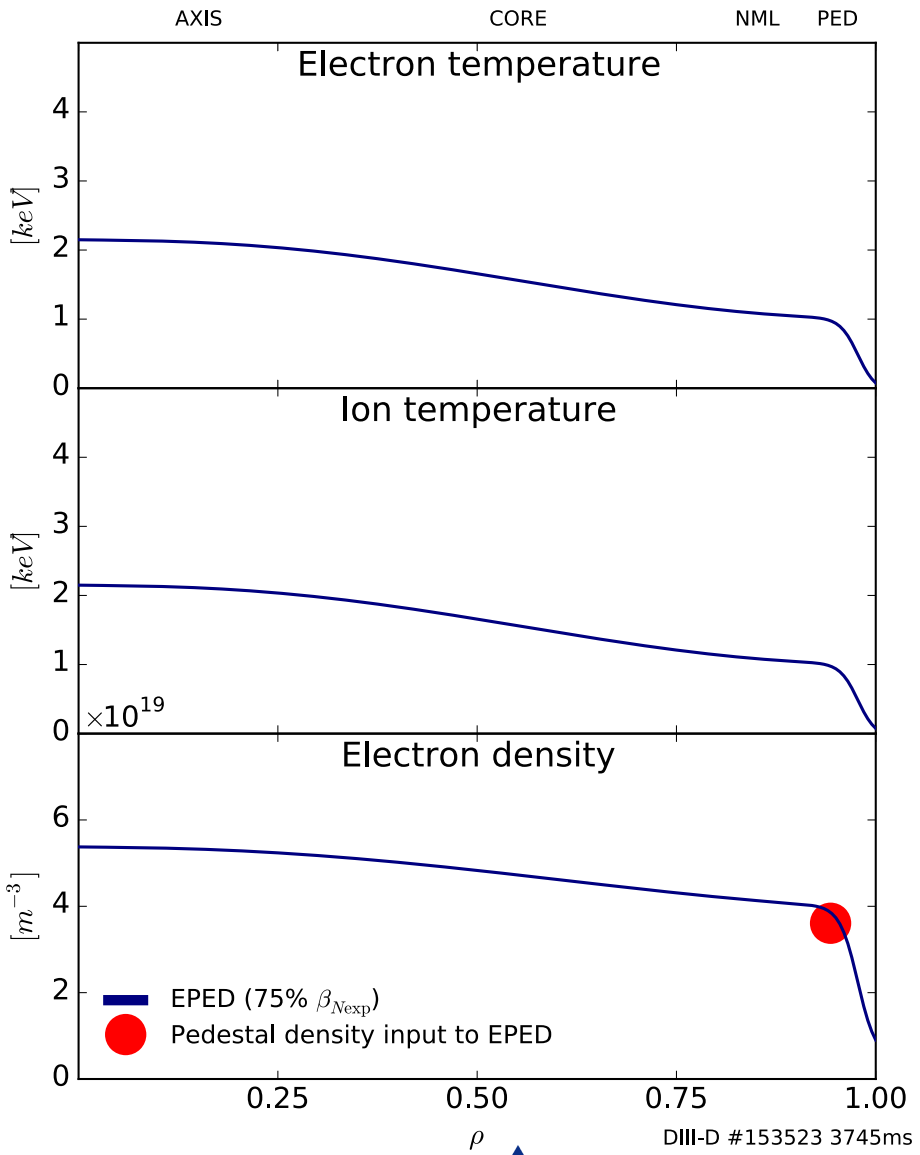
  - Don't yet know $\beta_N$ so use (poor) initial guess






GENERAL ATOMICS

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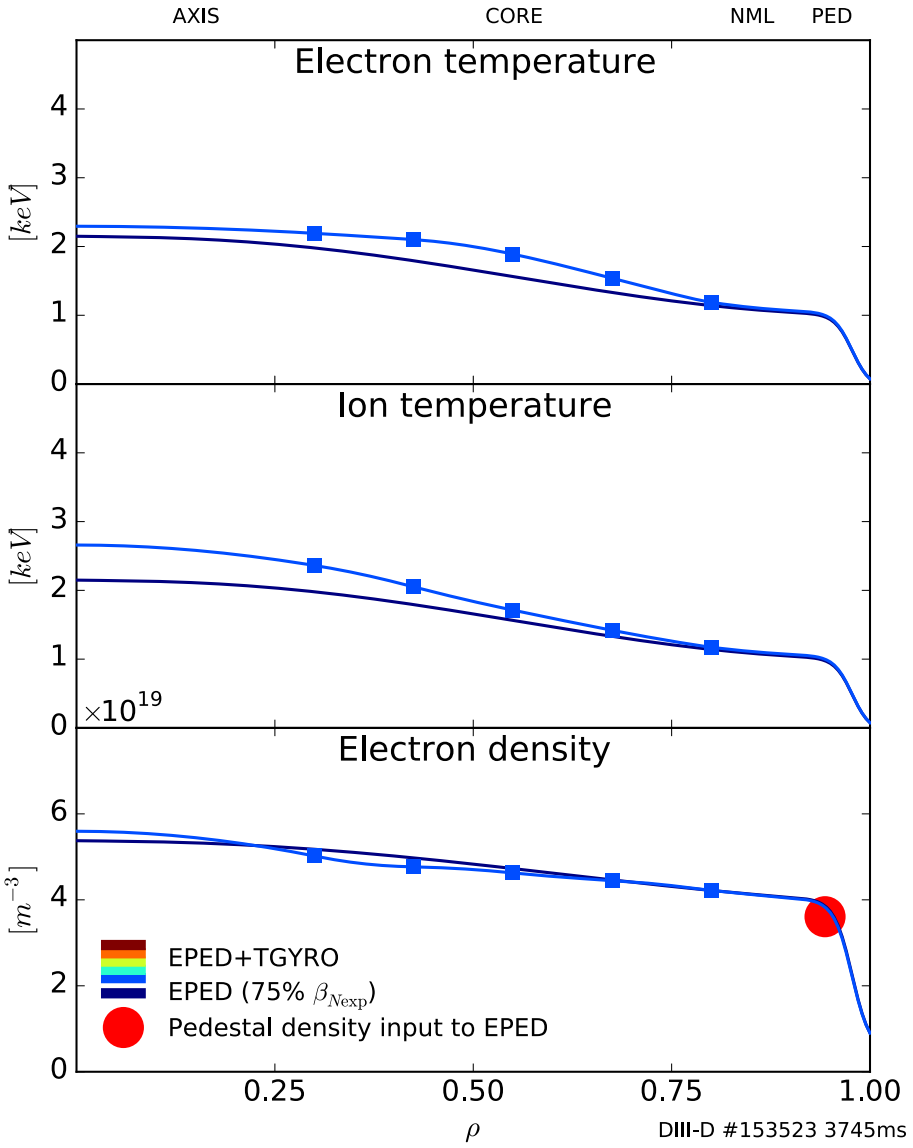




GENERAL ATOMICS

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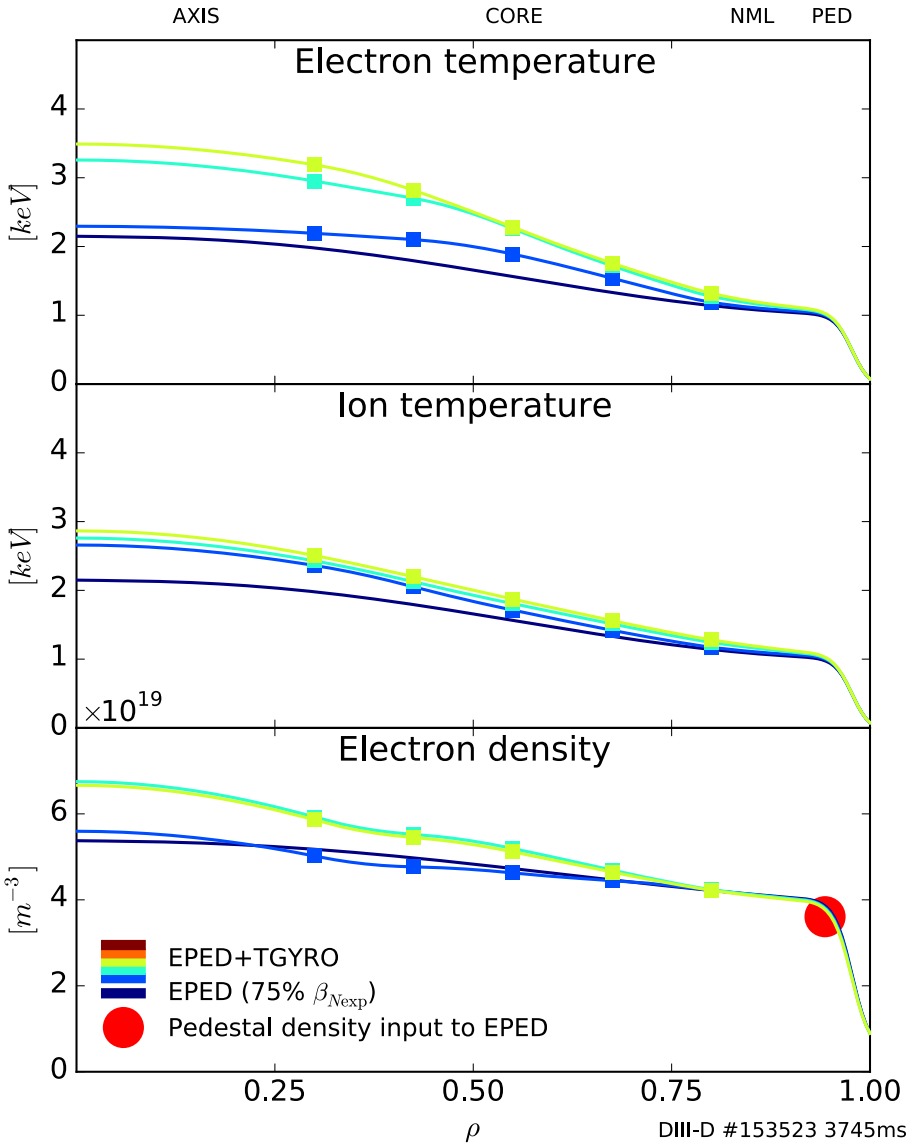
- **Step 3: Run EPED using updated value for $\beta_N$**
- **Step 4: Run TGYRO using updated BC from EPED**






GENERAL ATOMICS

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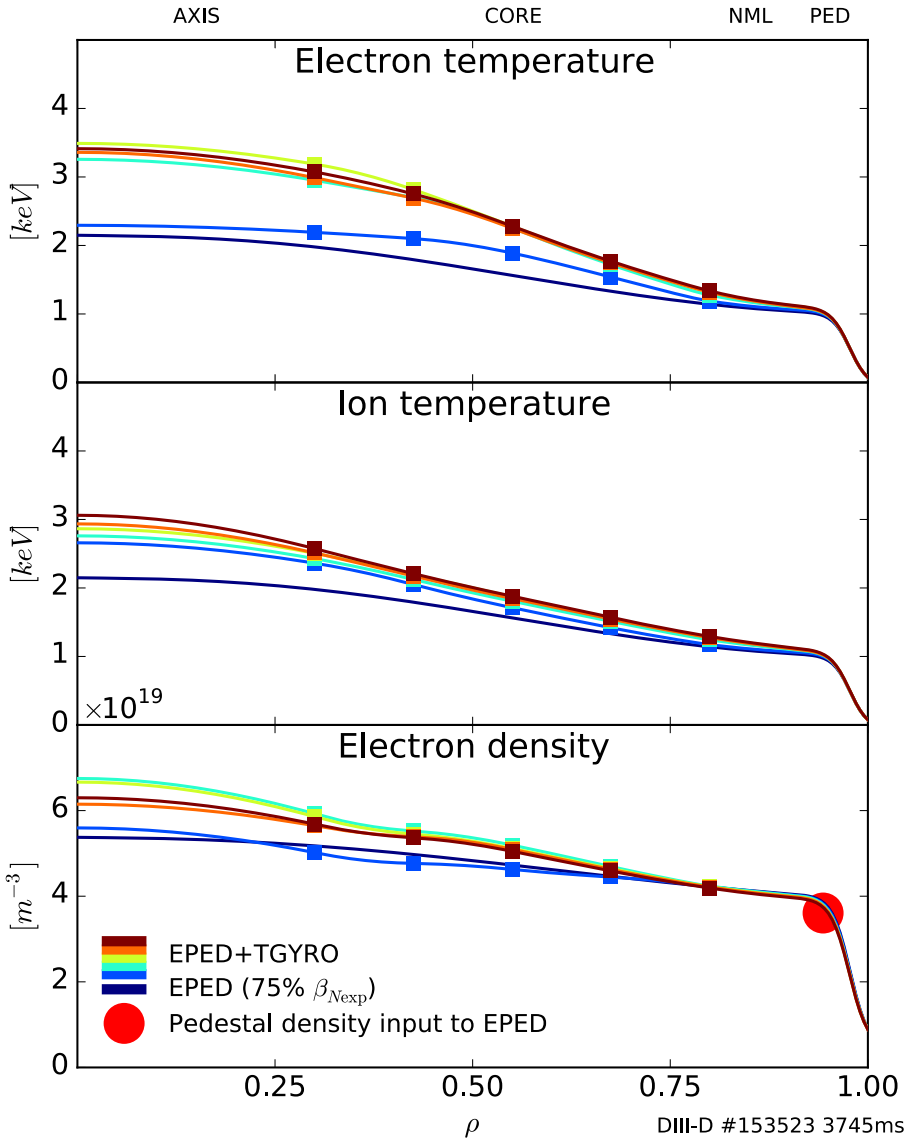
- **Step 3: Run EPED using updated value for $\beta_N$**
- **Step 4: Run TGYRO using updated BC from EPED**
- **Iterate to convergence**
  - Have predicted profiles for $T_e$, $T_i$, $n_e$ and pressure/ $\beta_N$
  - Result independent of initial guess






GENERAL ATOMICS

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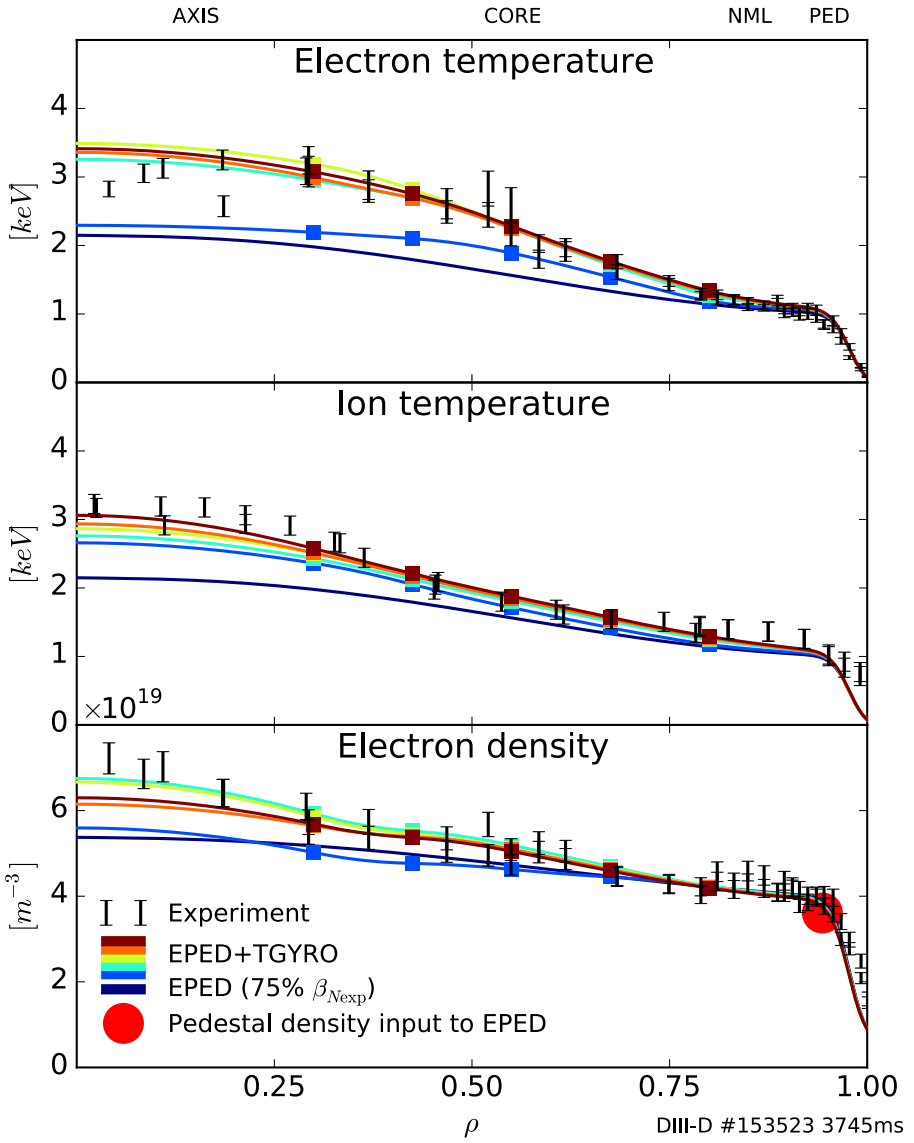
- Density only input at pedestal
  - Inputs: shape, sources, rot., $B_t$, $I_p$, $n_{e,ped}$
  - Predicting $T_e$, $T_i$, $n_{e,core}$, $\beta_N$
- **Accurately predicts full $T_i$ and $T_e$ profile, core density profile and global beta in this case**
  - Core-pedestal coupling essential to achieve this
- **Similar workflow can be applied to ITER or FNSF, optimizing performance as a function of pedestal density and other machine parameters**
- **Direct HPC simulations, such as with GYRO/CGYRO can be used to refine results**
- **Planning to couple to Div/SOL**



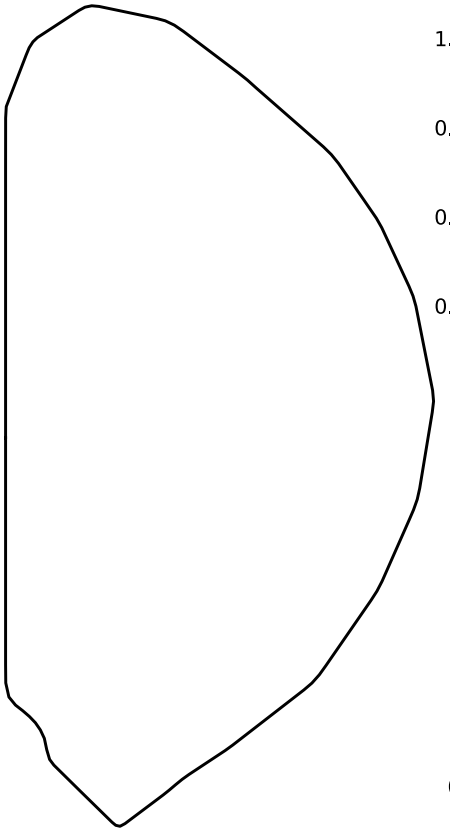


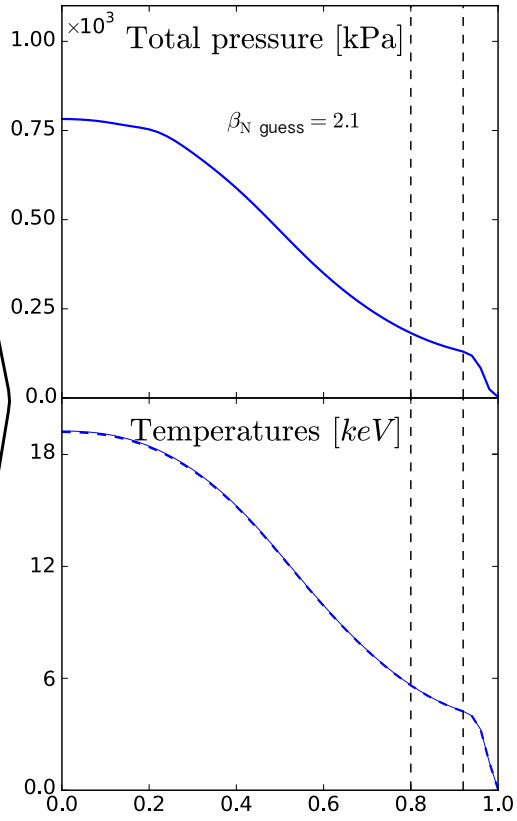

GENERAL ATOMICS

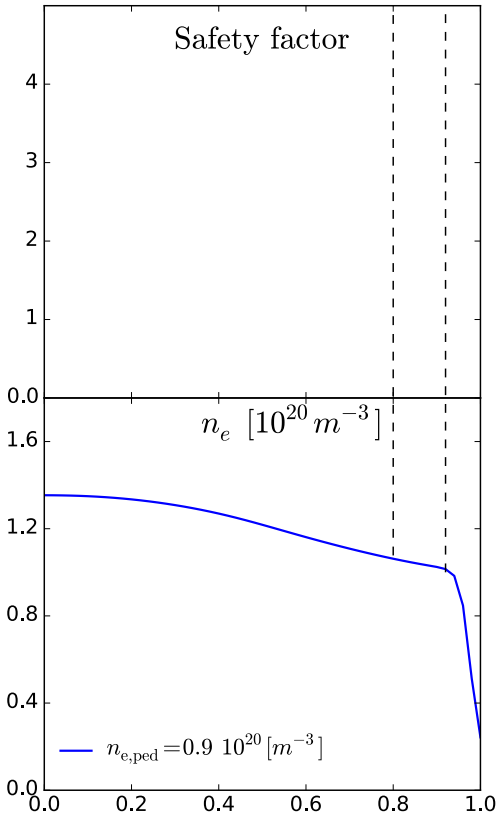
# Couple Core-Pedestal Workflow can be used to Predict and Optimize ITER Performance

- New TGLF improves treatment of coupling of electron and ion scale turbulence, and nonlinear near-critical physics for ITER [Staebler]
- Iterated coupling of EPED w/ TGLF/NEO enables ITER optimization with respect to pedestal density and current etc. **Preliminary** density scan

Step 0: "low" density case





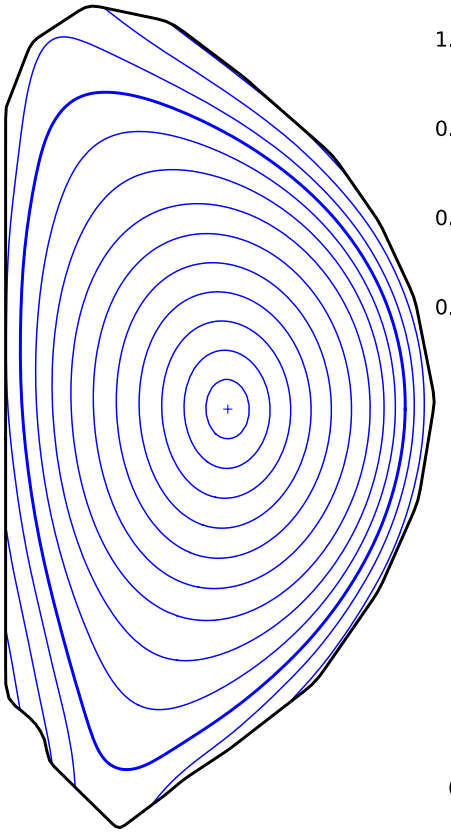


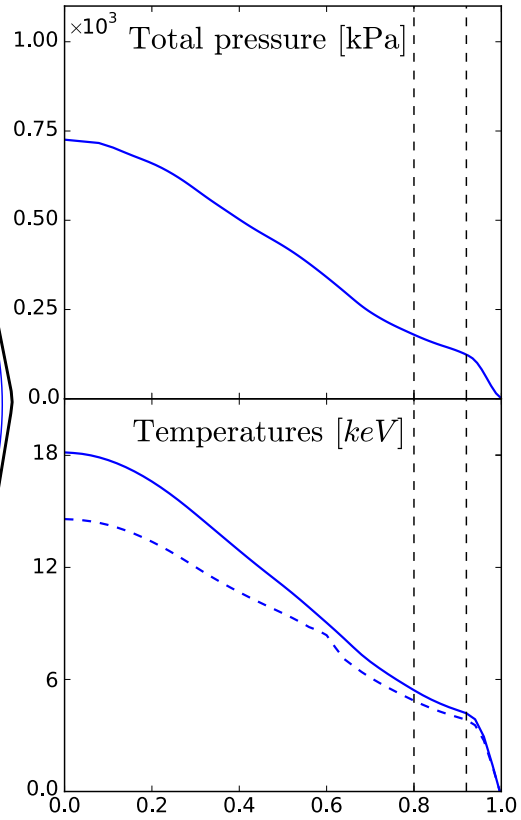

GENERAL ATOMICS

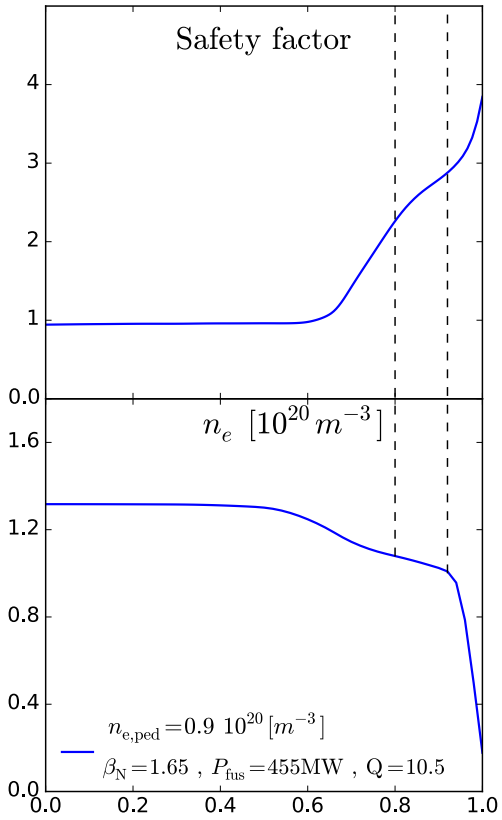
# Couple Core-Pedestal Workflow can be used to Predict and Optimize ITER Performance

- **New TGLF improves treatment of coupling of electron and ion scale turbulence, and nonlinear near-critical physics for ITER [Staebler APS15]**
- **Iterated coupling of EPED w/ TGLF/NEO enables ITER optimization with respect to pedestal density and current etc. Preliminary density scan**

Final step: "low" density case







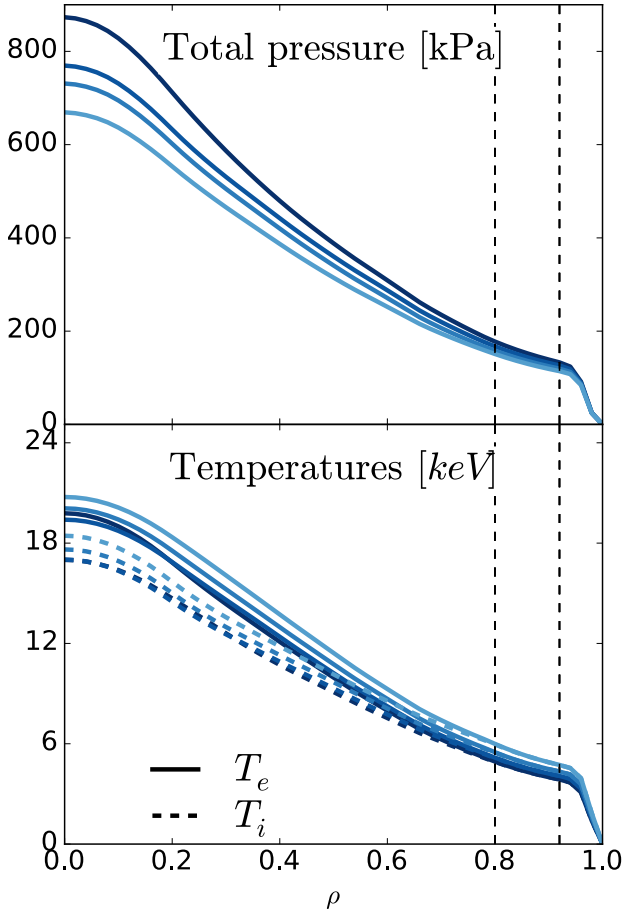

GENERAL ATOMICS

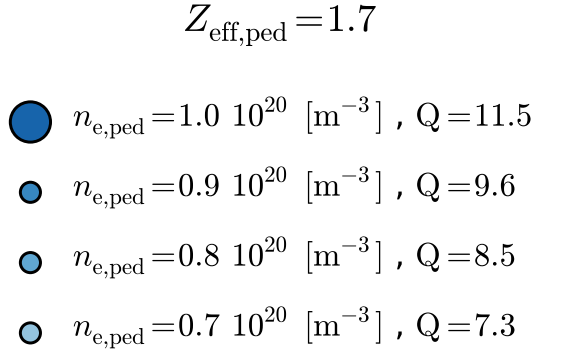
# Couple Core-Pedestal Workflow can be used to Predict and Optimize ITER Performance

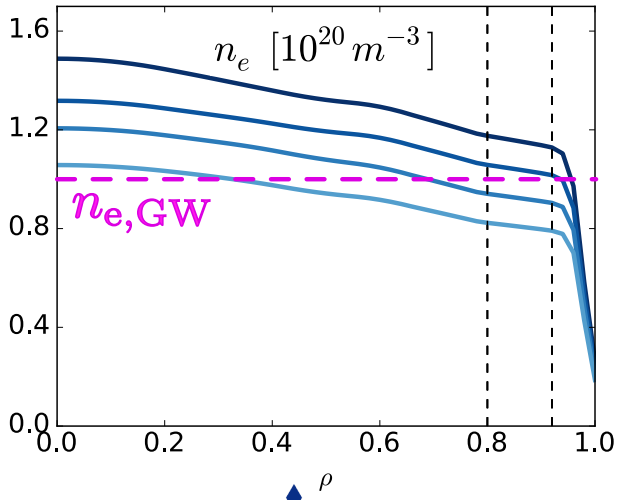
- **New TGLF improves treatment of coupling of electron and ion scale turbulence, and nonlinear near-critical physics for ITER [Staebler, APS15]**
- **Iterated coupling of EPED w/ TGLF/NEO enables ITER optimization with respect to pedestal density and current etc. Preliminary density scan (old TGLF)**

Final step: density scan (preliminary) Fusion power highest at highest density

- Kink/peeling limited pedestal
- At entrance to Super H-Mode






GENERAL ATOMICS

# Outline: Pedestal Physics Key to Predicting and Optimizing ITER

- **The Pedestal: What it is and why it matters**
  - Simultaneous improvement of confinement and stability
  - Predictive capability enables fusion power optimization
- **Physics challenges**
  - Overlap of scales, challenge to methods (L~ $\lambda$ ~ $\rho$ )
- **Peeling-ballooning modes**
  - Global constraint on the pedestal, drive ELMs
- **The EPED model**
  - Kinetic ballooning modes and model derivation
  - Experimental tests on several tokamaks, statistics
  - Super H-Mode
  - Dynamics and ELM suppression
- **Coupled core-pedestal prediction**
- **Directions for future pedestal research**

# Many Important Questions for Future Investigation

- **Formalism for overlapping scales (L~ $\lambda$ ~ $\rho$ )**
  - Present approaches focus on applying MHD and GK/Neo in their areas of applicability and working towards meeting in the middle
    - Kinetic and gyrofluid extensions to MHD, non-local GK with full-F etc
  - Alternate approaches are possible
    - Solving 6D equations, eg with radial basis function + implicit time advance
    - Alternate 5D formulations (eg Hahm09) enabling strong non-locality

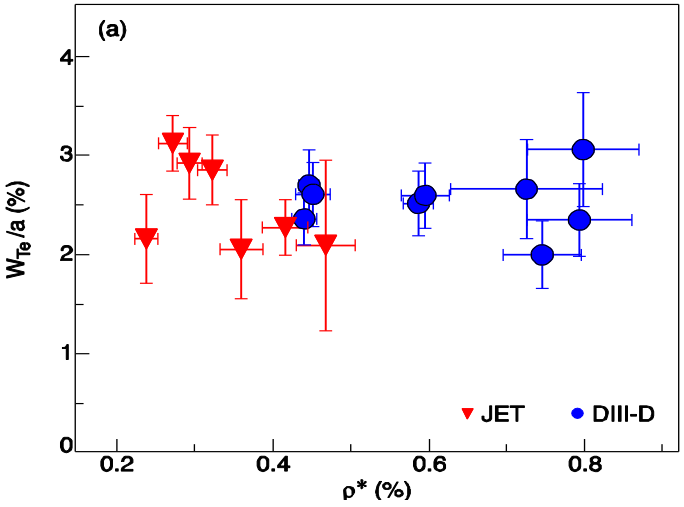
- **Role of impurities (more from R. Maingi tomorrow)**
  - Impurities increase collisionality, affecting $j_{bs}$, and dilute main ion concentration. Also radiate power, and generate neo pinch.
  - Many of these effects can be predicted, but not yet clear whether this explains all the observations
  - Ultimately must couple to SOL and material to predict impurity sources and transport into the pedestal and core

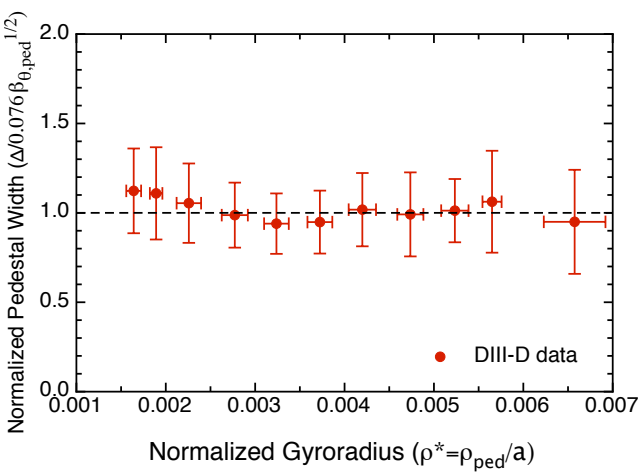
# Many Important Questions for Future Investigation

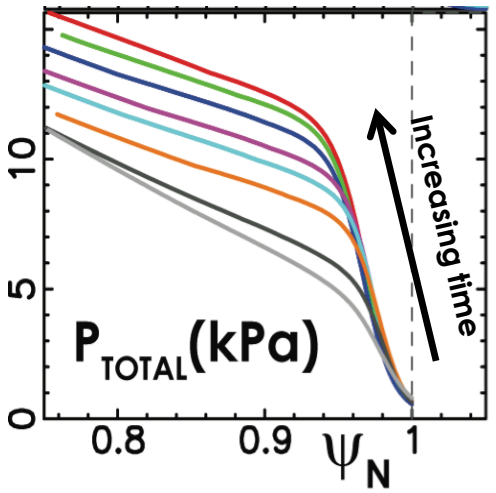
- **Role of particle fuelling and neutrals**
  - Additional physics and coupling to separatrix/SOL needed to predict density profile
    - Are there important effects of neutrals themselves?
  - Key question: does density profile depend on neutral source *inside* the pedestal or only boundary condition at the separatrix
    - ITER and reactors expected to have very small neutral penetration

- **Rotation and momentum transport**
  - Can estimate ExB profile within pedestal assuming diamagnetic term is dominant, but need to predict boundary condition on toroidal rotation for core simulations
    - Strong source of intrinsic torque in edge, need to predict its amplitude and coupling to the core
  - Rotation impacts transport as well as tearing/locked mode physics in the core

# Is there additional physics that enters at the very small values of $\rho^*$ expected in ITER or a reactor?




- **Absence of strong $\rho^*$ scaling predicted by EPED and observed in today's expts**
  - Both dimensionless expts [Beurskens09] or large database normalized to KBM scaling, show ~no dependence on $\rho^*$
- **Diamagnetic ExB shear stabilization (~p'') may weaken relative to microinstability growth rates (~$\rho^*$)**
  - Becomes independent of $\rho^*$ if transition scale also scales with $\rho^*$
  - Also must maintain high gradients within ETB (low s, high $\beta$' sufficient?)



GENERAL ATOMICS

# Summary: Pedestal Key to Tokamak Performance, EPED Model is a Predictive Platform to Build on

- **Predicting the pedestal is essential for tokamak performance optimization. Presents challenges to traditional theory**
- **EPED model combines non-local Peeling-Ballooning and near-local KBM physics** *P.B. Snyder et al PoP **16** 056118 (2009), NF **51** 103016 (2011), PoP **19** 056115 (2012)*
  - No free parameters, extensive tests on several tokamaks ($\sigma$~0.21, 710 cases)
- **Platform to predict and optimize pedestal, including core coupling**
  - Strong dependence on $B_p$, $B_t$, shape, complex dependence on density ($\nu^*$)
  - New Super H-mode regime predicted and accessed via dynamic optimization
  - Working model for RMP ELM suppression developing (more tomorrow)
  - **Coupling to TGLF/NEO in core via AToM project enables core-pedestal prediction**
    - **Pedestal benefits from global Shafranov shift, core from high pedestal (iterate to self-consistent solution)**
    - **Initial ITER predictions for coupled system, work ongoing to fully optimize & exploit Super H**
- **Many important open/related questions:**
  - Efficient formalism & numerics for $L \sim \lambda \sim \rho$ (6D, extended GK or GF…)
  - Role of impurities and fuelling (neutrals?), prediction of pedestal density & rotation
  - $\rho^*$: observed lack of strong dependence consistent with EPED. Limits?
  - Connection to SOL and divertor, transient dynamics
  - As understanding improves, continue to use it to enable new discoveries

# Extra Slides

# References (not up to date)


[1] P.B. Snyder, *et al.*, Nucl. Fusion 51, 103016 (2011).

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[9] M.J. Leyland *et al.*, "Pedestal width study in dense high triangularity ELMy H-mode plasmas on JET," in preparation (2012).

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[11] T.E. Evans *et al.*, Phys. Rev. Lett 92, 235003 (2004); Nature Phys. 2, 419 (2006).

[12] E. Wang, *et al.*, "Linear gyrokinetic analysis of a DIII-D H-Mode pedestal near ideal ballooning threshold," submitted to Nucl. Fusion (2012).

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[14] W. Wan, *et al.*, "Global gyrokinetic simulation of tokamak edge pedestal instabilities," submitted to Phys. Rev. Lett. (2012).

[15] N. Ferraro, Phys. Plasmas 19 056105 (2012).

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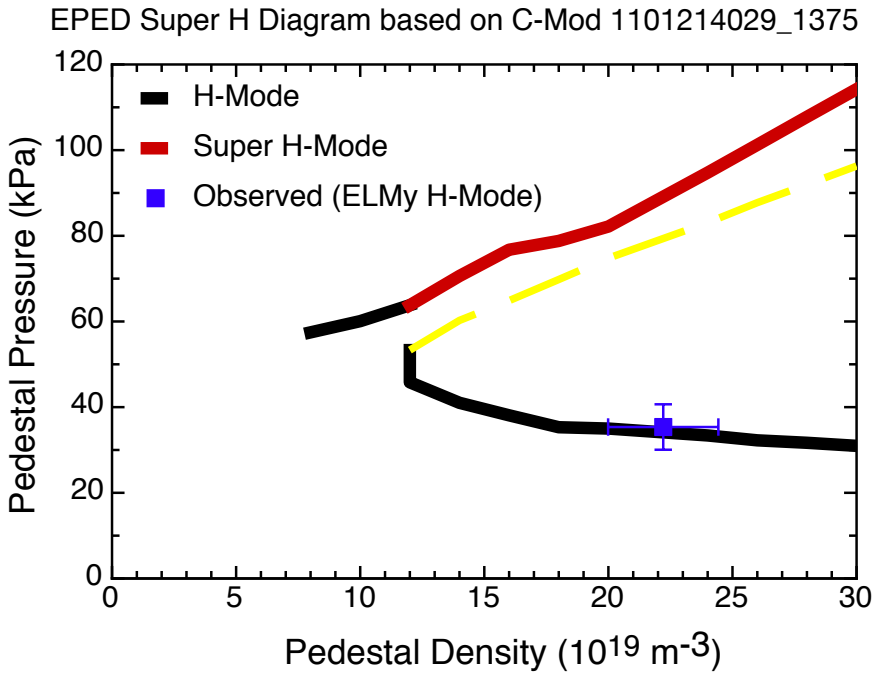
[17] E. Nardon et al., Nucl. Fusion 50 034002 (2010).

# Super H-Mode Access in C-Mod may be possible at lower density




- **Calculated based on ELMing H-mode shot with** $I_p$=0.908MA, Bt=5.39T, $\kappa$=1.54, $\delta$=0.49
- Variations of Ip and shape should improve access. Even approaching SH conditions would represent large in $P_{ped}$
- Consider starting in ELMing H-mode ramp up Ip and triangularity with time

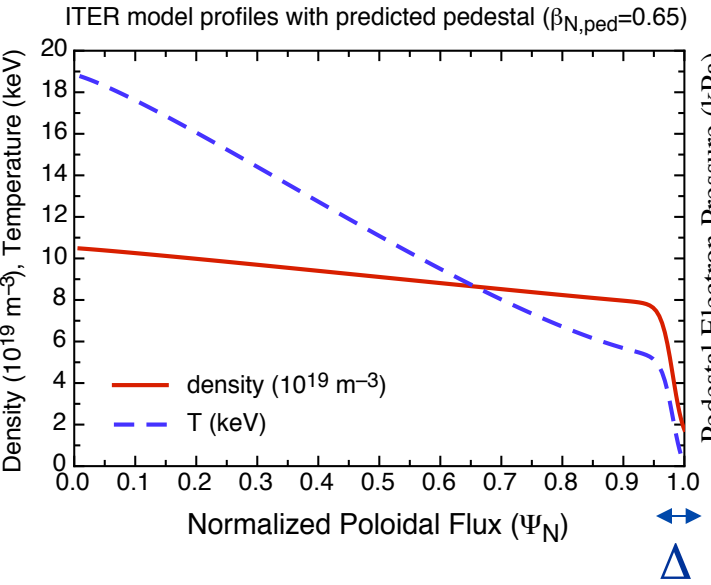
# Peeling-Ballooning Theory Derived as an Extension of Ballooning Theory

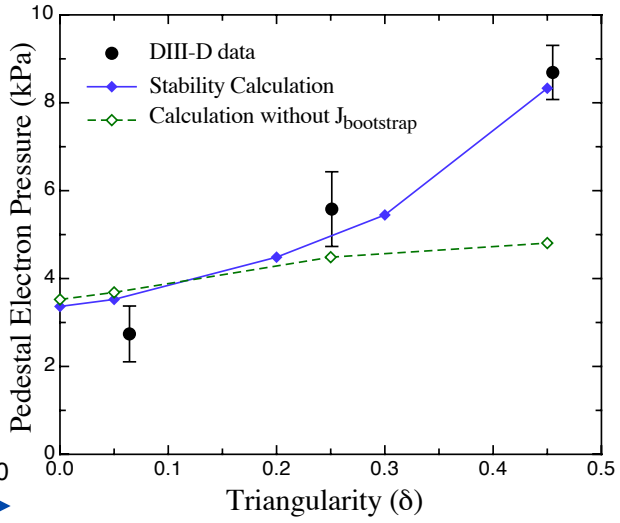
- **Ballooning theory developed in late 1970's (Culham,PPPL)**
  - Expansion in 1/n yields 2nd order ODE, 1D eigenvalue eqn, internal
- **H-Mode and ELMs discovered on ASDEX in early 80's**
- **High and low n MHD considered as mechanism for ELMs** *[eg Manickam'92, Turnbull'86, Ferron'00]*
- **Edge ballooning theory allows external current-driven modes** *[CHTWMH'96,'98]*
  - Local, external, pure peeling modes
  - Importance of peeling-ballooning coupling
- **Extension to next order in 1/n allows quantitative study of edge localized modes** *[WS'02, SW'02]*
  - 2D *nonlocal*, but eliminates 1 component of displacement
  - Coupled p' and j' driven modes (still use 'peeling' terminology)
  - Extended to include flow shear and compression *[SW'07]*

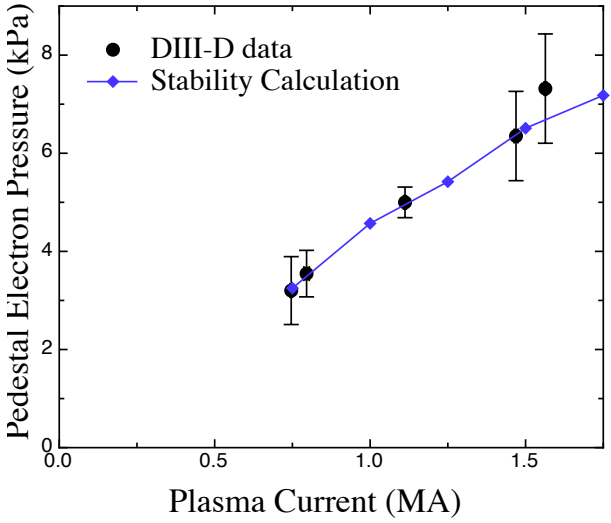


GENERAL ATOMICS

# 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 ($\Delta$ ,$B_t$, $I_p$, R, a, $\kappa$, $\delta$, $n_{e,ped,}$ $\beta_p$)
  - Calculations using pedestal width ($\Delta$) as an input find good agreement with observation (model equilibria capturing important stability physics) *[Snyder04]*

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