Super H-Mode: Theoretical Prediction and Initial Observations of a New High Performance Regime for Tokamak Operation

Philip B. Snyder[1], W. Solomon[2], K. Burrell[1], A. Garofalo[1], B. Grierson[2], R.J. Groebner[1], A. Leonard[1], R. Nazikian[2], T.H. Osborne[1], E.A. Belli[1], J. Candy[1], H.R. Wilson[3]

Acknowledgments: M. Beurskens[4], M. Leyland[3], J.R. Walk[5], J.W. Hughes[5], D. Orlov[6], R. Maingi[2], M. Fenstermacher[7], A. Diallo[2], M. Wade[1], L. Frassinetti[8], X.Q. Xu[7], Alcator C-Mod and DIII-D Teams, and JET-EFDA Contributors

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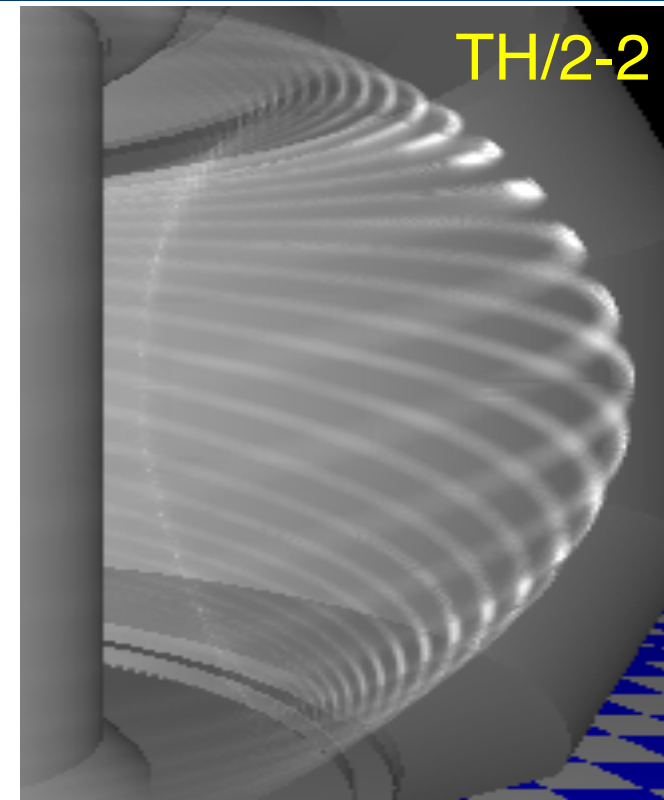[4]EURATOM /CCFE Fusion Association and EFDA/JET
[5]MIT/PSFC, Cambridge MA, USA
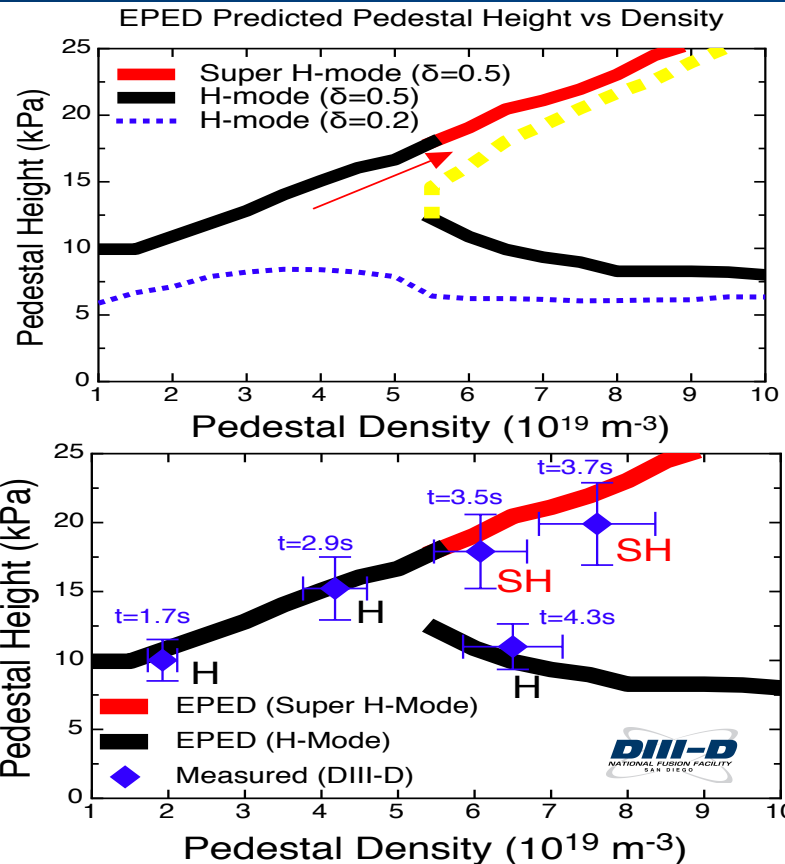[6]UCSD, San Diego CA, USA
[7]LLNL, Livermore CA, USA
[8]EURATOM-VR, Stockholm, Sweden

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DIII-D
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GENERAL ATOMICS

New High Performance "Super H-Mode" Regime Predicted by Theory, Observed on DIII-D

- **Theory (EPED) predicts that the solution for the height of the H-mode pedestal splits at strong shaping and high density**
  - H-mode root at low pedestal pressure
  - Super H-mode root sits above at very high pressure (red line)
    - **Accessible via dynamic density variation (red arrow)**

- **Super H regime accessed on DIII-D**
  - High pedestal (>2x H-mode) & confinement
  - Record β_N with quiescent edge

- **Prospect for improved fusion performance on ITER/DEMO ($P_{fus} \sim p_{ped}^2$)**
  - High confinement due to high pedestal
  - Higher global beta limits with broad profiles
  - Potentially transformative

EPED Predicted Pedestal Height vs Density

Legend:
- Super H-mode ($\delta = 0.5$)
- H-mode ($\delta = 0.5$)
- H-mode ($\delta = 0.2$)

y-axis: Pedestal Height (kPa)
x-axis: Pedestal Density (10^{19} m^{-3})

y-axis: Pedestal Height (kPa)
x-axis: Pedestal Density (10^{19} m^{-3})

Data labels: t=1.7s, t=2.9s, t=3.5s, t=3.7s, t=4.3s

Legend:
- EPED (Super H-Mode)
- EPED (H-Mode)
- Measured (DIII-D)

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Outline: New High Performance "Super H-Mode" Regime Predicted by EPED, Discovered on DIII-D
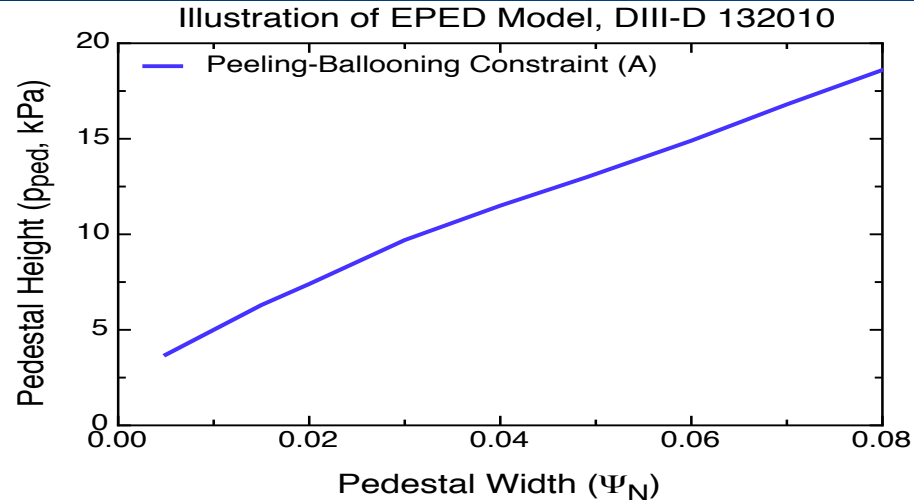
A. The EPED Model

B. Coupled Plasma Shape and Density (Collisionality) Dependence of the Pedestal, and the "Super H-Mode" bifurcation

C. Discovery and Initial Optimization of Super H-Mode on DIII-D

D. Summary and Future Work

GENERAL ATOMICS

Outline: New High Performance "Super H-Mode" Regime Predicted by EPED, Discovered on DIII-D

A. **The EPED Model**

*P.B. Snyder et al NF **51** 103016 (2011), Phys Plas **19** 056115 (2012)*

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GENERAL ATOMICS

Mechanics of the EPED Predictive Model

- **Input: B_t, I_p, R, a, κ, δ, n_{ped}, m_i, [β_{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
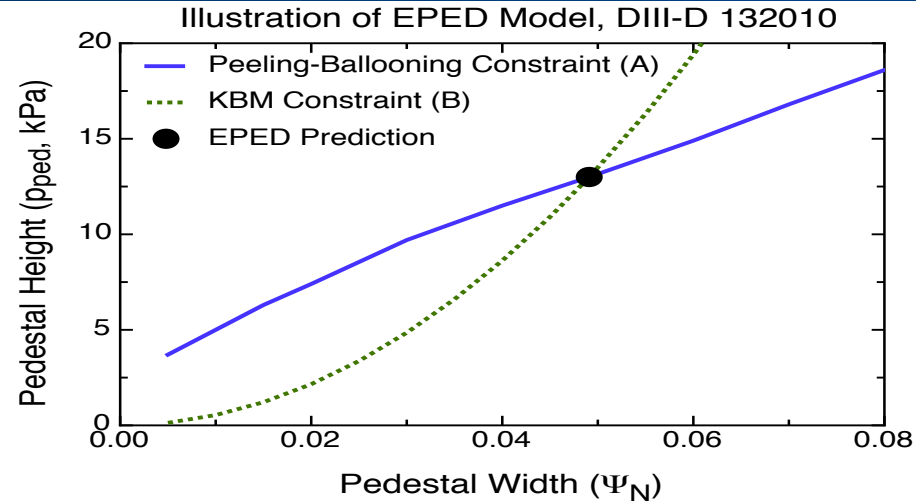
Illustration of EPED Model, DIII-D 132010

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GENERAL ATOMICS

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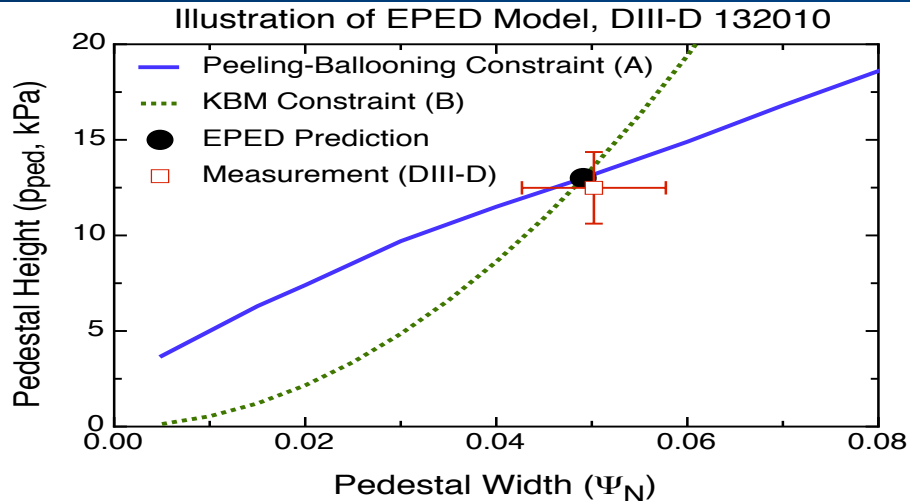- ELITE, n=5-30; non-local diamag model from BOUT++ calculations

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

- Directly calculate with ballooning critical pedestal technique (Integrated constraint)

Illustration of EPED Model, DIII-D 132010

- Peeling-Ballooning Constraint (A)
- KBM Constraint (B)
- ● EPED Prediction

Pedestal Height (p_{ped}, kPa) vs Pedestal Width (Ψ_N)

GENERAL ATOMICS

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Illustration of EPED Model, DIII-D 132010

*P.B. Snyder et al Phys Plas **16** 056118 (2009), NF **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 solution, which is the EPED prediction (black circle)**

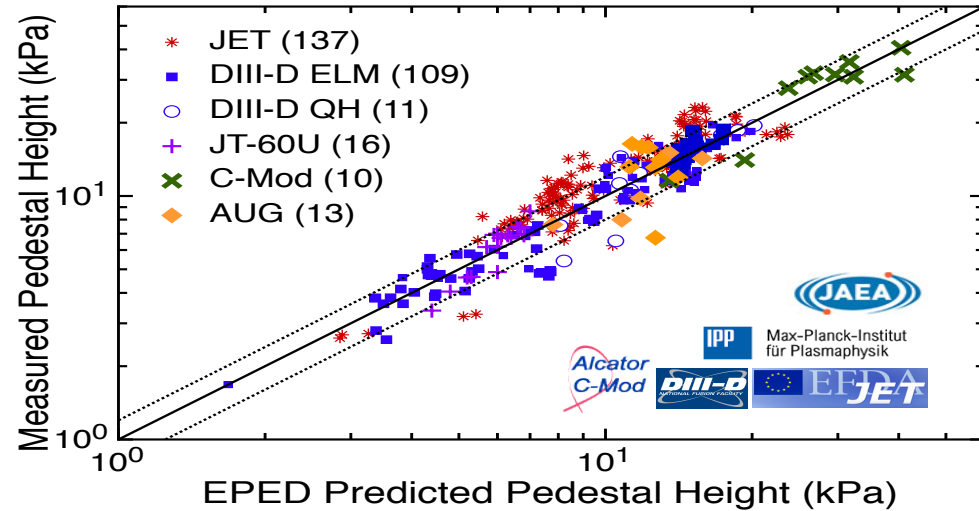   **-**can then be systematically compared to existing data or future experiments

Physics of P-B, KBM, and bootstrap current combine to yield complex set of parametric dependencies of the pedestal (including Super H regime)

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GENERAL ATOMICS

Test of EPED on 296 Cases on 5 Tokamaks Finds Agreement within ~20%

Comparison of EPED Model to 296 Cases on 5 Tokamaks

Legend:
- * JET (137)
- ■ DIII-D ELM (109)
- ○ DIII-D QH (11)
- + JT-60U (16)
- ✕ C-Mod (10)
- ◆ AUG (13)

X-axis: EPED Predicted Pedestal Height (kPa)
Y-axis: Measured Pedestal Height (kPa)

Validation efforts coordinated with ITPA pedestal group, US JRT

- Broad range of density ($\sim$1-24 10^{19}m^{-3}), collisionality ($\sim$0.01-4), $f_{GW,ped}$ ($\sim$0.1-1.0), shape ($\delta \sim$0.05-0.65), q$\sim$2.8-15, pressure (1.7 - 35 kPa), $\beta_N \sim$0.6-4, B$_t$=0.7-8T

Ratio of predicted to observed height = 0.99 ± 0.22 (corr r=0.91)

Consistent with ~10-15% measurement error and EPED accuracy to ~15-20%. No free or fit parameters in model. Similar agreement on each machine, at high/low collisionality, strong/weak shaping, with/without local 2nd stability, metal/carbon wall

Ongoing model development to enable multiple impurity species, direct neoclassical calculations (NEO) with full collision operator etc.

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Model Enables Exploration of Key Parametric Dependencies, and Pedestal Optimization

Pedestal variation with $I_p * B_t$ and triangularity
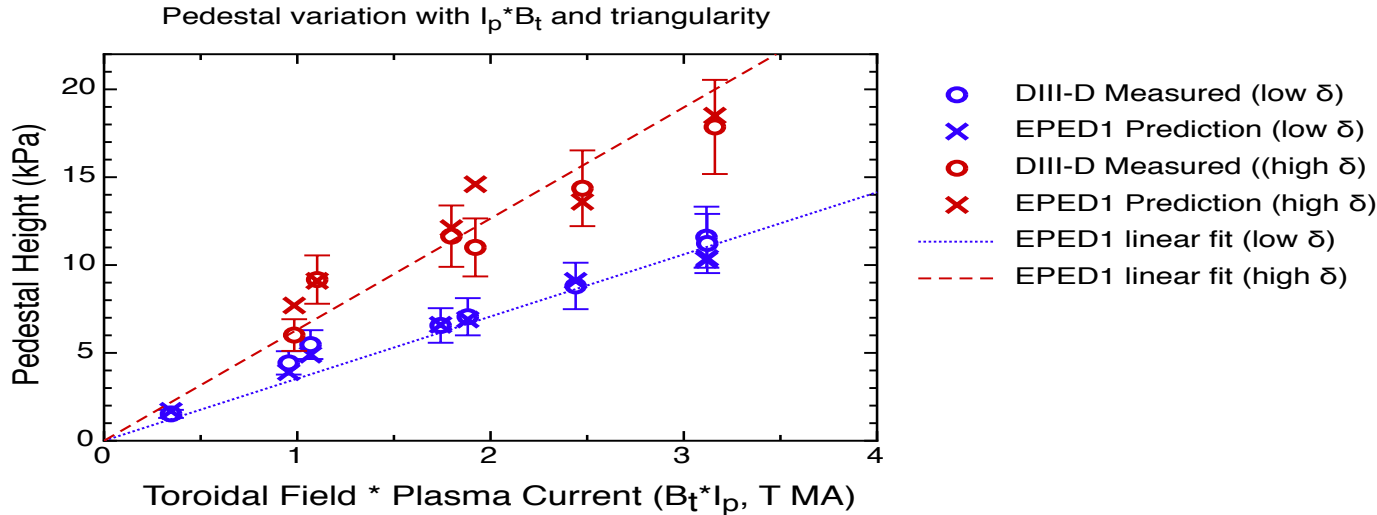
- **Near linear increase in p_{ped} with $B_t * B_p$, weakens at low q ($\beta_{N,ped}$ is figure of merit)**
- **Strong dependence on triangularity**
  - p_{ped} increases ~80% in going from δ~0.22 to δ~0.55
- **Observed dependence on B_t, B_p & shape well reproduced by EPED model: p_{ped} optimized at high B_t & B_p, moderate q, strong shaping**

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GENERAL ATOMICS

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GENERAL ATOMICS

# Density (Collisionality) is a Powerful Lever for Pedestal Optimization of Shaped Plasmas
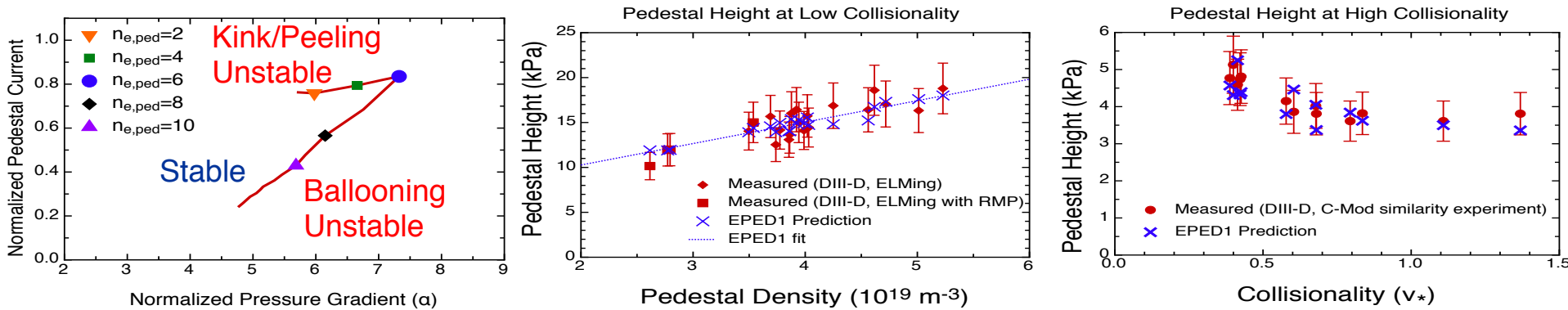
- **Density enters primarily through collisionality dependence of bootstrap current**
  - Increasing density moves from J-driven toward p-driven stability boundary
  - Low density (low ν_*): P_{ped} increases with n_e; high ν_*: P_{ped} decreases with n_e
  - Density dependence weak for weak shapes, 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

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GENERAL ATOMICS

Complex Interaction Between Shape and Density Dependence

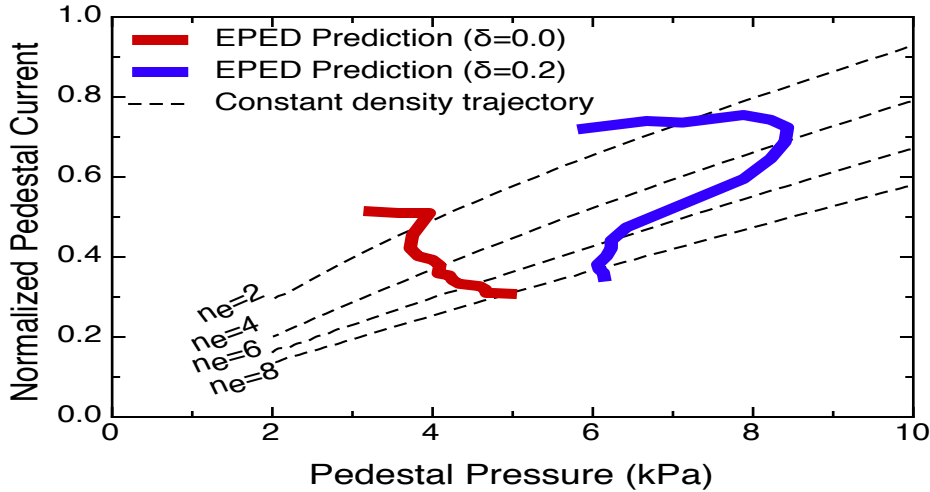EPED Predictions in Pressure, Current Space (δ=0.0, 0.2)
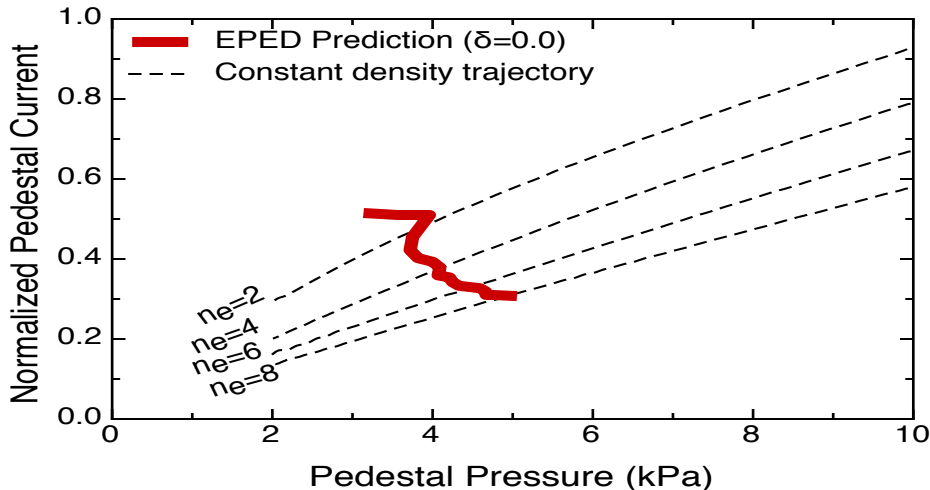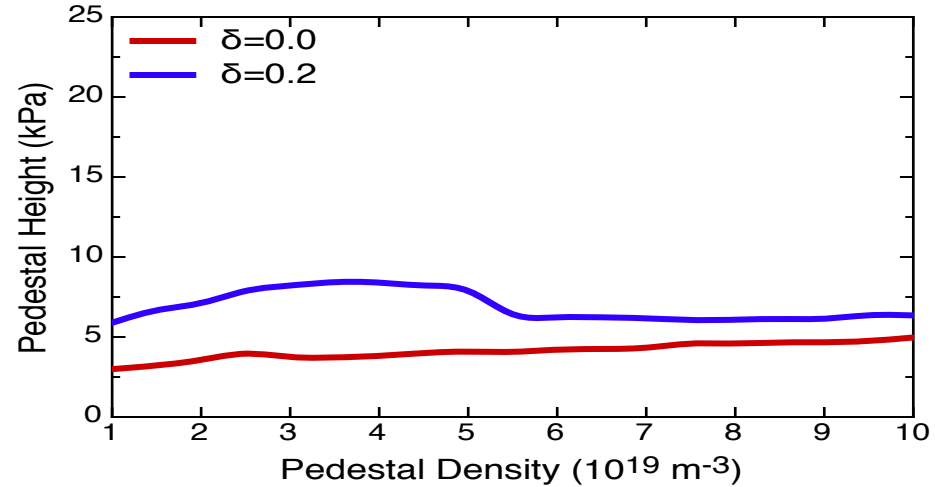
EPED Predicted Pedestal Height vs Density
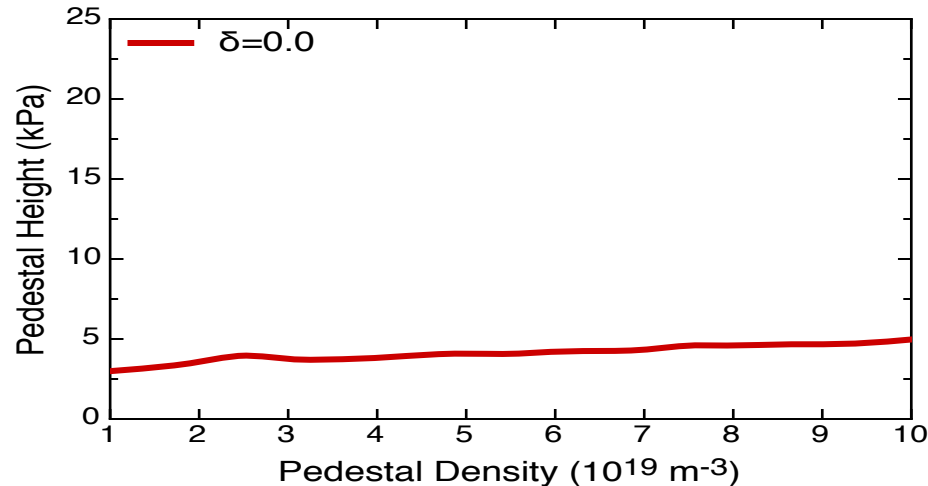
- ## At very low triangularity (weak shaping, δ=0), density dependence is weak

  - Peeling-ballooning coupling strong, no "nose" in J-P diagram (left)

GENERAL ATOMICS

Complex Interaction Between Shape and Density Dependence

EPED Predictions in Pressure, Current Space (δ=0.0, 0.2)

- EPED Prediction (δ=0.0)
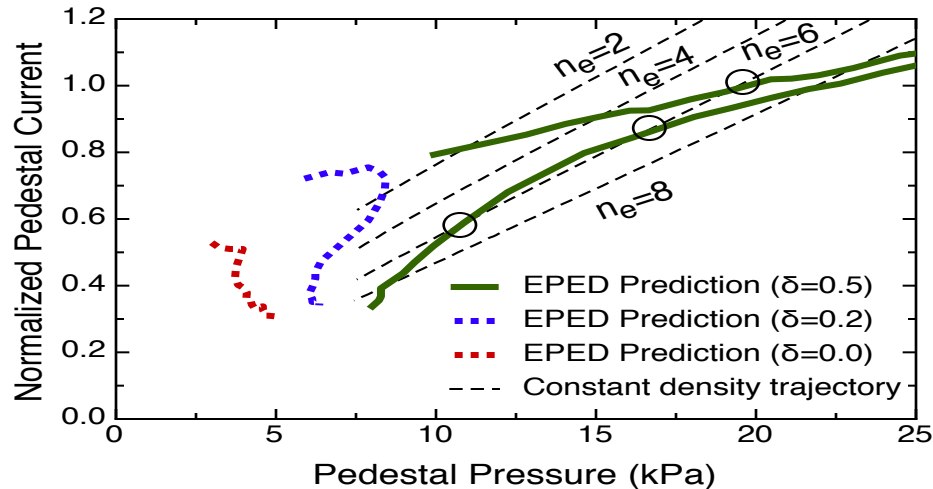- EPED Prediction (δ=0.2)
- Constant density trajectory

EPED Predicted Pedestal Height vs Density

- δ=0.0
- δ=0.2

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

GENERAL ATOMICS

Complex Interaction Between Shape and Density Dependence

EPED Predictions in Pressure, Current Space (δ=0.0, 0.2, 0.5)

EPED Predicted Pedestal Height vs Density
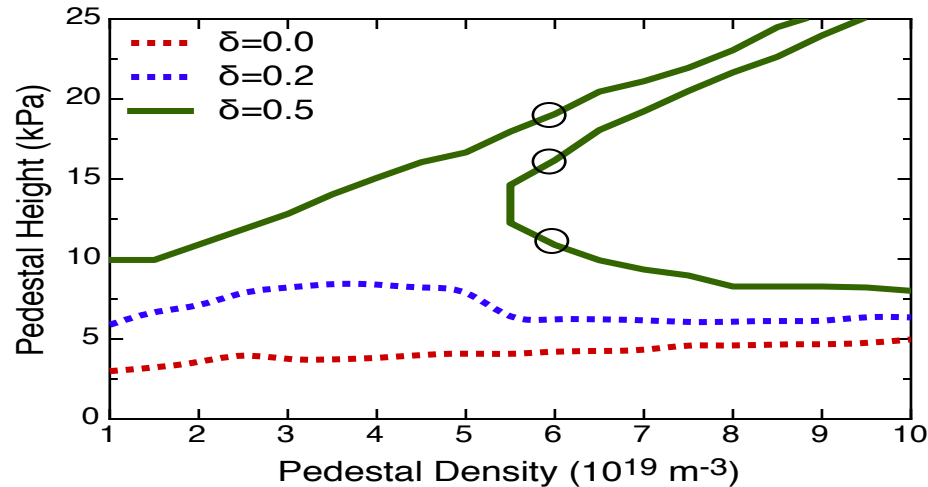
- ## At high triangularity (δ=0.5), pedestal height solution becomes multi-valued at high density

  - Peeling-ballooning coupling very weak, "nose" in J-P diagram extends to very high pressure (effect is amplified by KBM constraint in EPED model)

GENERAL ATOMICS

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

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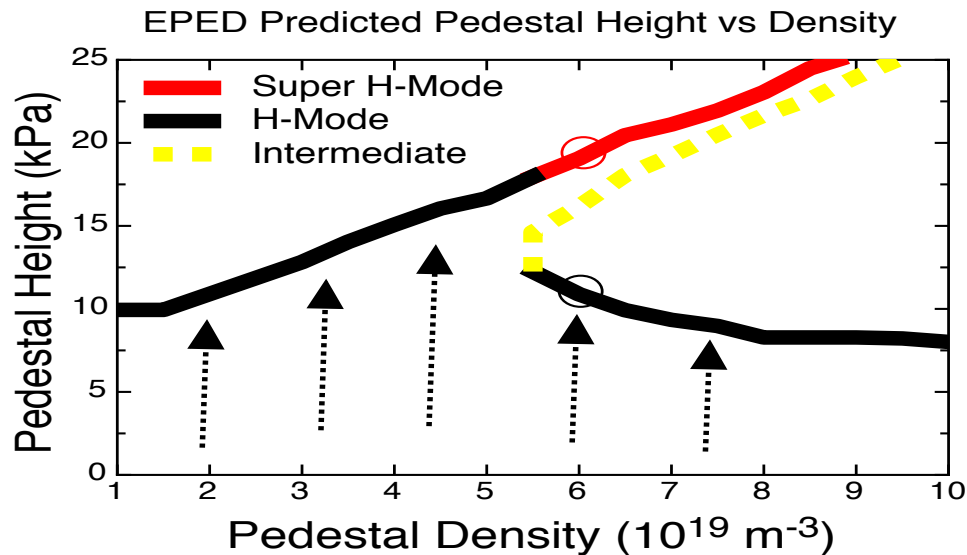
- **Constant density trajectories lead to usual H-Mode solution**
- **Solution above H-mode (red) called Super H-Mode**
  - Much higher pedestal than equivalent H-Mode solution
  - Intermediate solution (yellow) is dynamically unstable

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GENERAL ATOMICS

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

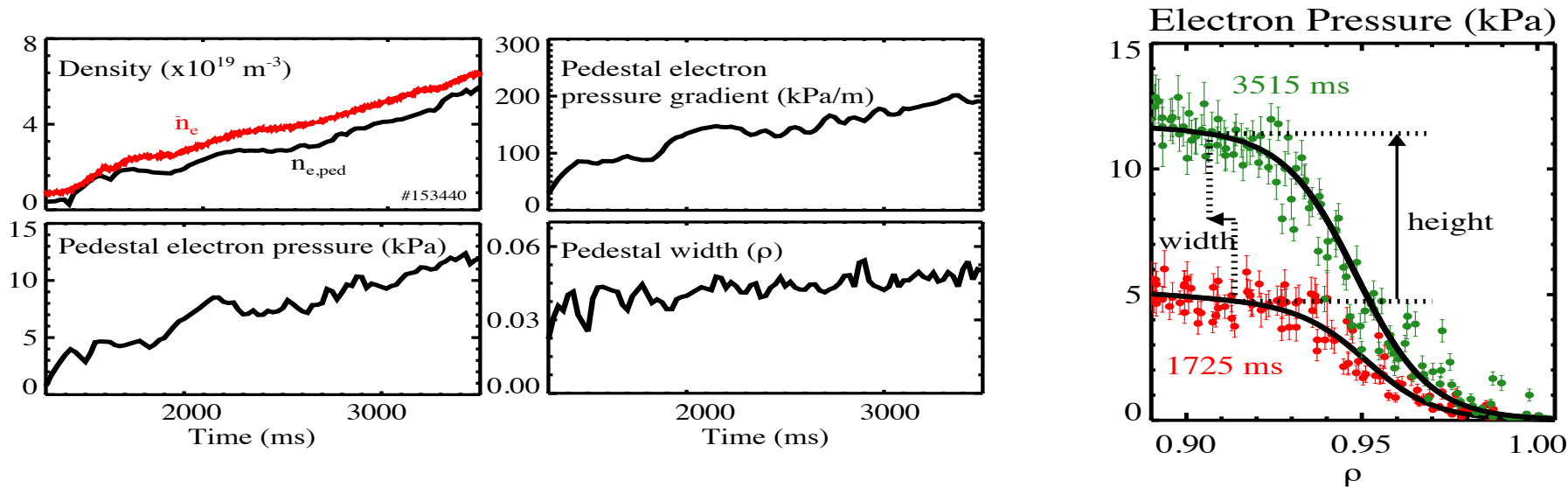EPED Predicted Pedestal Height vs Density
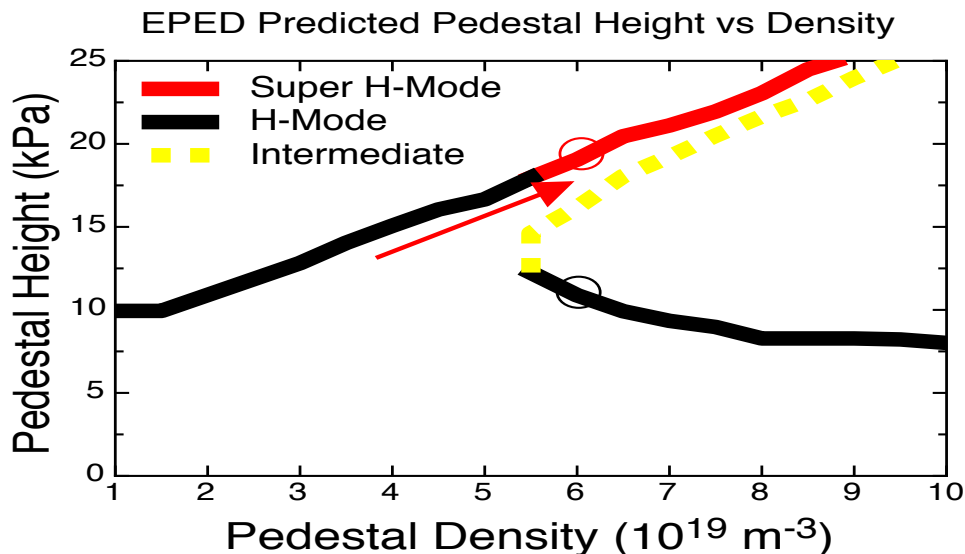
- **Super H-Mode Regime can be reached by dynamic optimization of the density trajectory**
  - Start at low density, and increase density over time (red arrow). Avoiding large transients (ELMs) enables smooth traversal of parameter space
  - Very high Super H-Mode pedestal should enable both high confinement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

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GENERAL ATOMICS

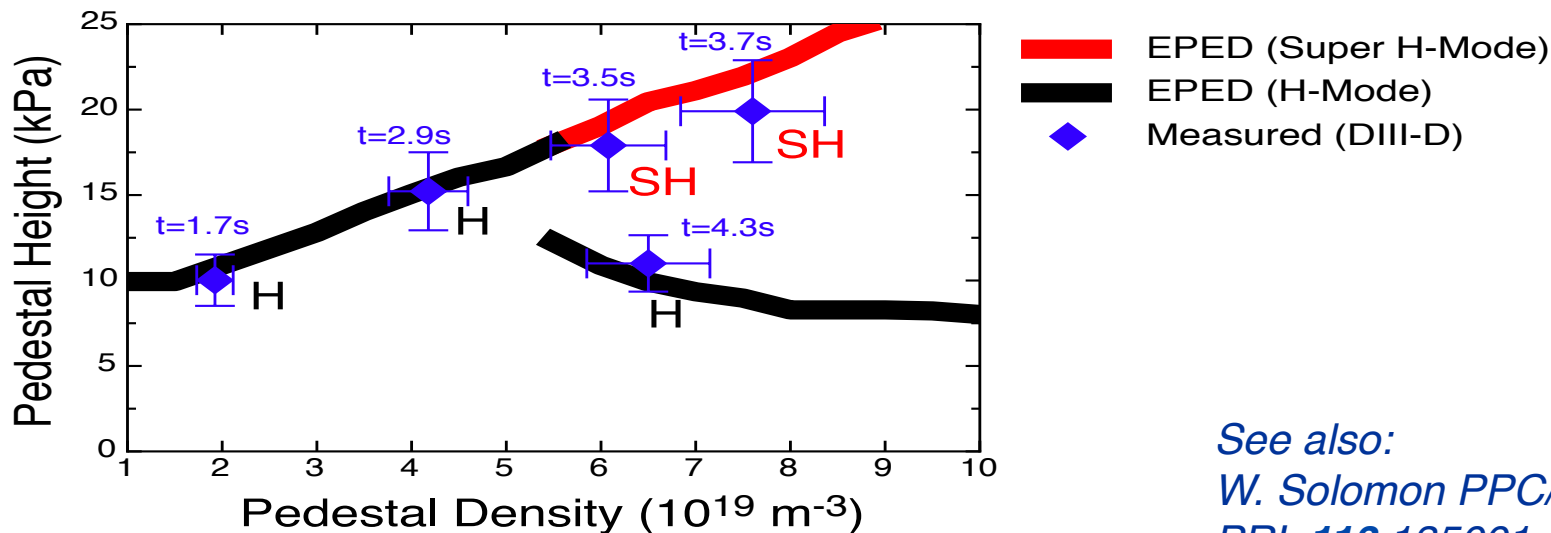# Outline: New High Performance "Super H-Mode" Regime Predicted by EPED, Discovered on DIII-D

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GENERAL ATOMICS

- **Very high p$_{ped}$ reached in density ramp with strong shaping ($\delta \sim 0.53$)**

GENERAL ATOMICS

Super-H Mode Regime Accessed on DIII-D

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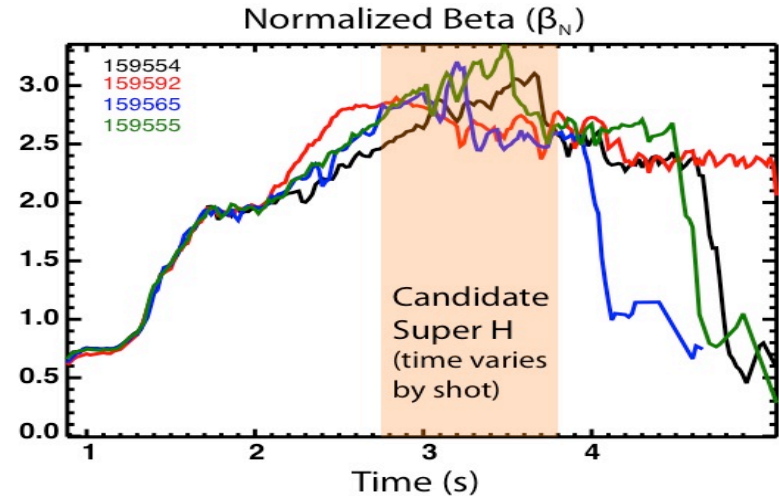- **Good agreement with EPED, which predicts Super-H regime for $n_{eped} > \sim 5.5$**
- **Clear indication of bifurcation in $p_{ped}(n_{eped})$**
- **Super H regime accessed sustainably with quiescent edge**

See also:
W. Solomon PPC/P2-37,
PRL 113 135001 (2014)

GENERAL ATOMICS

Super H Pedestal Provides a Platform for Global High Performance

Observations Compared to EPED Model for DIII-D 159554

Normalized Beta (β_N)

- **Recent DIII-D experiments have begun to investigate coupled core-pedestal optimization**

- **Record values of $\beta_N \sim 3$ achieved for operation with a quiescent edge**
  - High beta limit expected due to profile broadening with Super H pedestal

- **High confinement ($H_{98} \sim 1.4$) enables high normalized fusion gain ($\beta_N H_{89}/q_{95}^2 \sim 0.4$)**

- **Additional experiments planned to optimize and extend Super H Mode performance**

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ITER Predicted to have Access to Super H-Mode Regime

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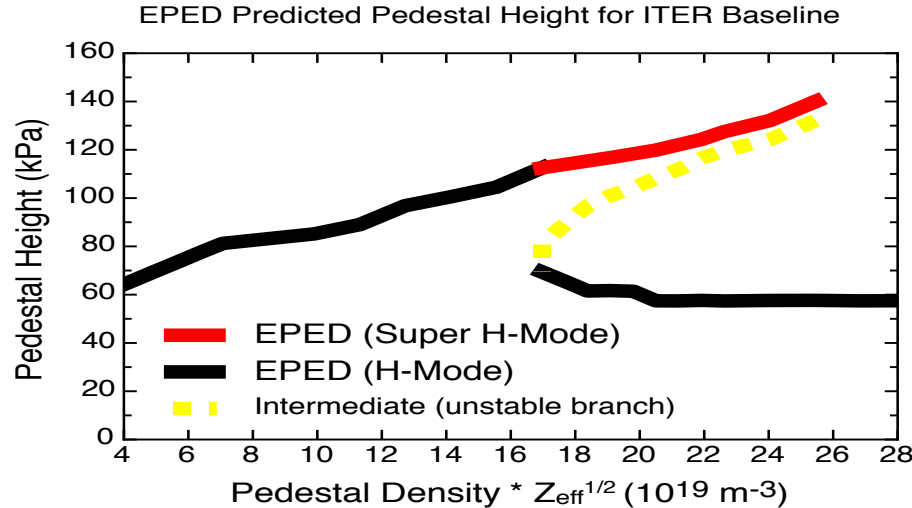
- **Greenwald density limit physics key: exceeding limit would be beneficial**
  - Greenwald density reached at low collisionality in Super H-Mode, even on existing devices
- **Collisionality dependence of j_{BS}, scales with density$*Z_{eff}^{1/2}$**
  - Path to optimize pedestal (and divertor) via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

GENERAL ATOMICS

Summary: High Performance Super H-Mode Regime Predicted by EPED and Discovered on DIII-D

- **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, reasonably efficient (~1-20 CPU hrs), extensively tested

- **Provides platform to predict and optimize pedestal**

  – Strong dependence on B_p, B_t, shape. Coupled dependence on density ($\nu*$) and shape leads to multiple solutions (H and Super H) at high δ

- **New Super H-mode regime accessible via dynamic optimization**

  – Super H-Mode with very high p_{ped} achieved on DIII-D using theory-driven optimization of shape, density (prediction and observation are path dependent)

  – High performance enabled by high pedestal, including record β_N~3 with quiescent edge

  – Super H access predicted for ITER at high density, impurities can increase p_{ped}

  The Super H-Mode regime is a product of theoretical understanding and potentially enables substantial improvements in tokamak fusion performance. Further experiments are planned to optimize and lengthen duration of Super H operation.

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Extra Slides

PB Snyder/IAEA/Oct 2014

GENERAL ATOMICS

EPED FAQ: Answers to Frequently Asked Questions

Can EPED Separately Predict Density and Temperature Profiles? (No)

If Global Beta is an Input, Is EPED Really Predicting the Pedestal? (Yes)

Do the EPED Constraints Apply Locally at a Particular Radius? (No)

Does Local 2nd Stability Mean no KBM Limit Exists? (No)

Does EPED Suppose KBM is only Mechanism for ETB Transport? (No)

Does EPED Predict or Require a Particular Type of ELM Cycle? (No)
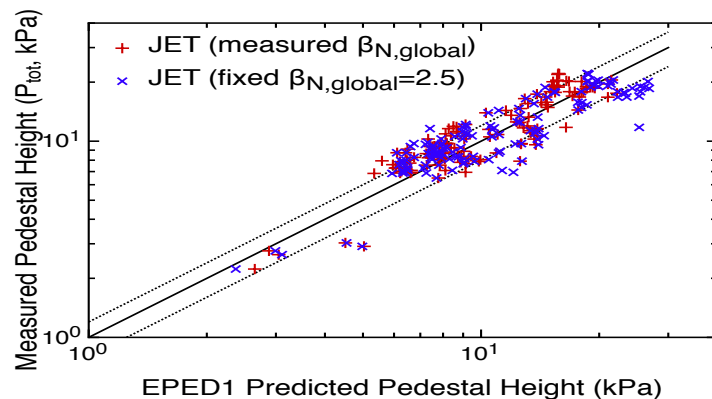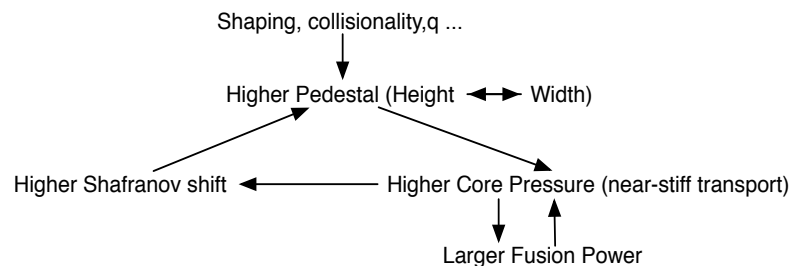
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Can EPED Separately Predict Density and Temperature Profiles? (No)

- **No. EPED is essentially solving 2 equations (P-B and KBM) for 2 unknowns**
  - Solves for pedestal height (pressure or temperature) and width (as a function of density, field, shape etc)

- **Solving separately for density and temperature heights and widths would require at least 4 equations**
  - Furthermore, while the 2 EPED constraints are highly stiff and can be solved (to good approximation) independent of sources and dynamics, many other constraints cannot be

- **The simplicity of EPED is a feature, not a bug**
  - Predictive and easily testable. Learn something when it works and when it doesn't (suggests what other type of physics likely to be important). Further physics is of course of interest and under study, but likely requires sources & dynamics

- **Work ongoing to develop dynamic model by combining TGLF/GYRO with ELITE/EPED & source physics**

GENERAL ATOMICS

If Global Beta is an Input, Is EPED Really Predicting the Pedestal? (Yes)

- **Global Shafranov shift changes geometry and generally improves P-B stability**
  - Having a good estimate of global β_p allows EPED to predict more accurately
  - Can lead to a "virtuous cycle" with the core that can be important for high performance hybrid/AT

- **However, this is not a dominant effect overall (B_t, B_p, shape and collisionality are more important)**
  - Using fixed β_N rather than measured in the 137 case JET CFC dataset hurts EPED accuracy by only ~5% (ratio 1.03 ± 0.25 vs 0.96 ± 0.20)
  - Can couple EPED to core transport model to self-consistently predict both

Strong correlation between core and pedestal beta due mostly to core stiffness

Shaping, collisionality,q ...

Higher Pedestal (Height ←→ Width)

Higher Shafranov shift ← Higher Core Pressure (near-stiff transport)

Larger Fusion Power

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GENERAL ATOMICS

- **The two EPED constraints are both global across the edge barrier and do not apply at a particular radius**

  - Peeling-ballooning physics is inherently non-local: the mode width is typically ≥ the pedestal width (roughly $\beta_{Nped} \sim \Delta_\psi^{3/4}$)

  - The KBM constraint in EPED is an integrated constraint across the ETB, and applies on average, not at a particular radial location

    - The relation $\boxed{\Delta_{\psi_N} = \beta_{p,ped}^{1/2} G(\nu_*, \varepsilon ...)}$ or $\boxed{\beta_{p,ped} / \Delta_{\psi_N} = \Delta_{\psi_N} G^{-2}(\nu_*, \varepsilon ...)}$

      Follows from the improvement in ballooning stability on average as the pedestal broadens and a larger fraction of it extends into the low collisionality, low shear regime. However, this does not imply a particular gradient at a particular location – notably gradient must roll over for continuity near pedestal top (and note that an exponent >1/2 can results for wide widths).

GENERAL ATOMICS

- **Due to short equilibrium scale lengths in the edge barrier, even the hign-n ballooning mode exhibits coupling to equilibrium scales**
  - Infinite-n MHD or flux-tube gyrokinetic calculations can approximate the finite-n stability bound only outside the "2nd stable" regime (ie at high shear)
  - In "2nd stable" (low shear) regime, must either do non-local calculations or apply an extrapolative method such as BCP technique in EPED model
- **Local 2nd stability is very commonly found in shaped tokamaks**
  - EPED works ~equally well with or without it
  - Non-local GK studies underway
   - Existing formulations sufficient?
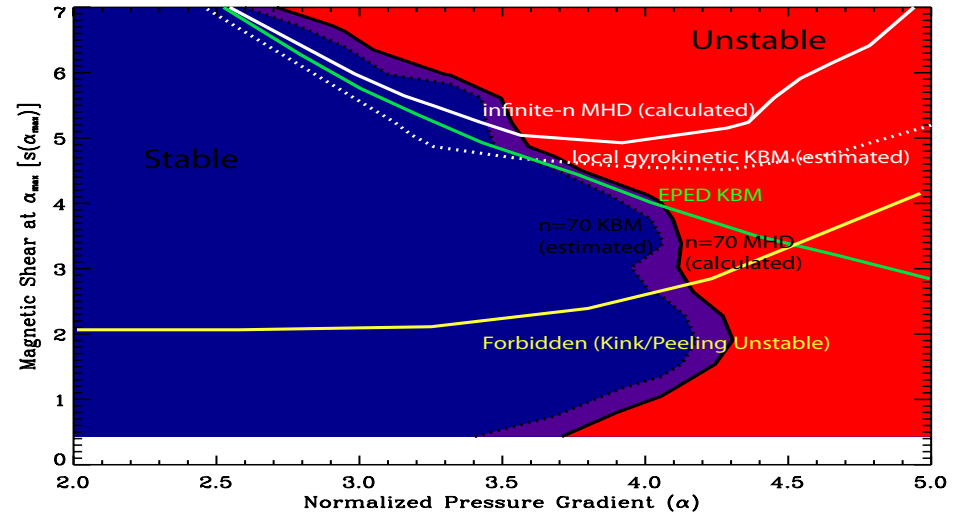
n=70 stability bound (black) well approximated by n=∞ limit (white) at high shear, but not low. EPED's BCP method (green) gives a reasonable approximation throughout allowed (kink stable) region

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GENERAL ATOMICS

- **Many mechanisms besides the KBM can drive transport across the edge barrier**
  - Neoclassical ion heat
  - ETG and other electron-scale instabilities
  - Non-KBM Ion scale micro-instabilities…
- **Some of these transport mechanisms may nearly or fully saturate certain profiles (eg T_i, η_e…)**
- **What EPED hypothesizes: In the presence of the strong heat source, particle source and ExB shear typical of the ETB, these mechanisms do not saturate all profiles simultaneously in a way that prevents the pressure gradient rising**
  - K(R)BM is the mechanism for the final saturation of p'
    - Can be coherent or turbulent, varying amplitude, depending on drive

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Does EPED Predict or Require a Particular Type of ELM Cycle? (No)

- **EPED is a static model. It predicts conditions shortly before an ELM or with a coherent mode (EHO)**
  - Generally yields a reasonable prediction of average conditions unless ELMs are very large and recovery is slow
- **Can be interesting to study how the pedestal evolves across the ELM cycle relative to the EPED constraints, but EPED does not predict this evolution**
  - Often observed (DIII-D, MAST, some JET) that the pedestal recovers to the KBM limit shortly after an ELM and then broadens until the P-B limit is reached
    - Context for possible RMP ELM suppression model
  - Sometimes broadening by the ELM and a slow recovery is observed on JET [Beurskens, Saarelma, Leyland]
- **EPED works ~equally well for both cycles**
  - Interesting study by M. Leyland on strongly fuelled JET discharges with wide pedestals
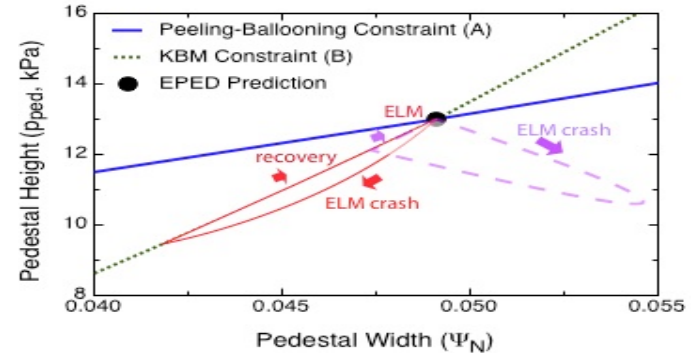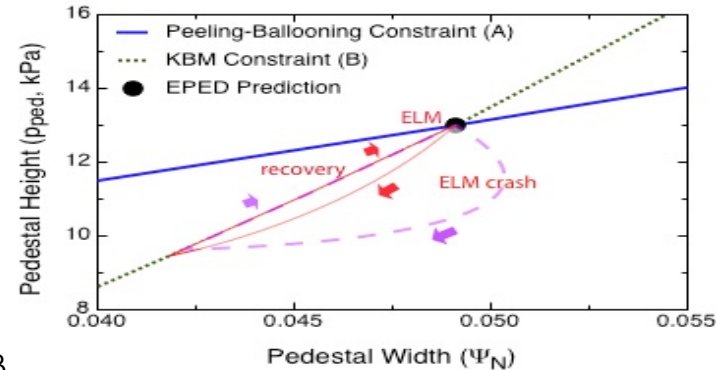
ELMs can broaden profiles but narrow barrier [Wade05]. Dynamics complex

GENERAL ATOMICS

Ongoing and Future Work: NEO and GYRO

- **Ongoing tests of EPED in ELMing, QH and RMP plasmas, further predictions for ITER, FNSF and other devices (eg JT-60SA)**

- **EPED model equilibria constructed using Sauter bootstrap current model**
  - Direct calculations with NEO [Belli 2009] can efficiently incorporate full kinetic neoclassical bootstrap current with multiple species, full geometry, full collision operator
    - Important for studying detailed impact of impurities and collisionality
  - NEO incorporated into TGYRO and OMFIT, direct coupling to EPED in progress through Edge Simulation Laboratory (ESL) project

- **Gyrokinetic extensions of the EPED model**
  - EPED1.6 uses efficient "BCP" technique involving series of model equilibria and large numbers of infinite-n MHD calculations
    - Attempts to account for non-locality (finite bound in 2nd stability region)
  - Exploring non-local GK effects with GYRO, also explore extended GK formulations (ESL project)
  - Direct GK (or TGLF) calculations for KBM
    - Need efficient methods for accurate treatment of collisional and non-local effects

- **Long term: Extend to incorporate other modes beyond KBM and P-B, include sources & dynamics, predict additional profiles**

ESL

GENERAL ATOMICS