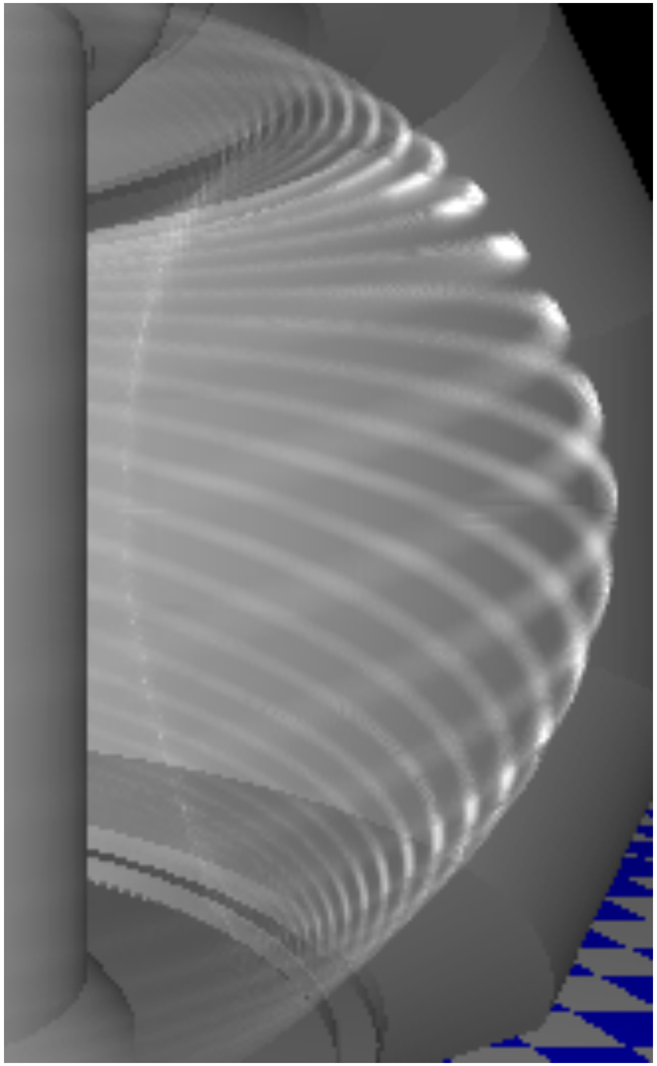
The EPED Pedestal Model: Tests on JET and Predictions for ISM ITER Scenarios

P.B. Snyder[1], M. Beurskens[2], R.J. Groebner[1], J.R. Hughes[3], T.H. Osborne[1], L. Frassinetti[4], J.R. Walk[3], H.R. Wilson[5], X.Q. Xu[6]

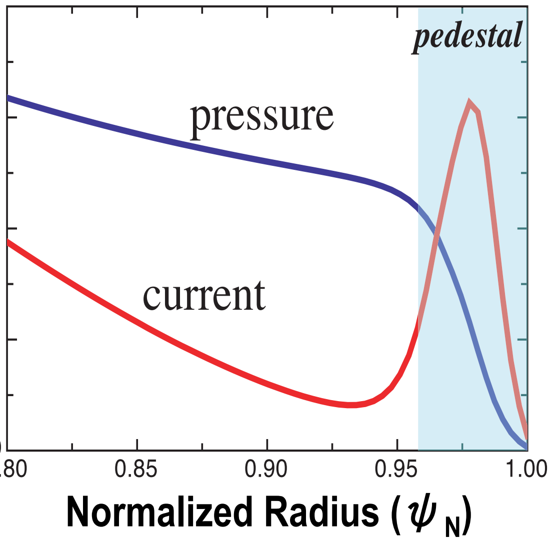
[1]*General Atomics, San Diego CA, USA*
[2]*EFDA/JET, Oxfordshire UK*
[3]*MIT/PSFC, Cambridge MA, USA*
[4]*EURATOM-VR, Stockholm, Sweden*
[5]*University of York, York UK*
[6]*LLNL, Livermore CA, USA*



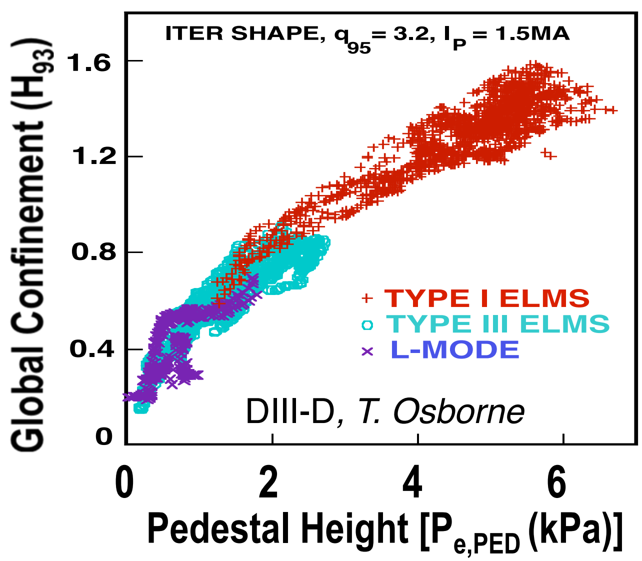
3rd 2011 ISM Working Session
Abingdon, UK (remote)
9 November 2011

Motivation: Pedestal Height Critical for ITER Performance Prediction and Optimization

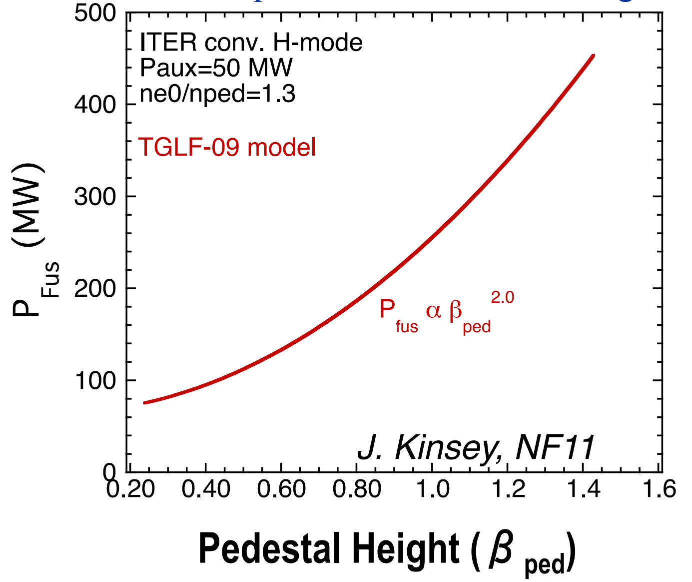
- **High performance ("H-mode") operation in tokamaks due to spontaneous formation of an edge barrier or "pedestal"**
- **Pedestal height has an enormous impact on fusion performance**
  - Dramatically improves both global confinement and stability (observed and predicted)
  - ***Fusion power on ITER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



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

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

*P.B. Snyder et al Phys Plas **16** 056118 (2009), NF **49** 085035 (2009), NF **51** 103016 (2011)*

A. The Peeling-Ballooning Model

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

B. Kinetic Ballooning Mode Onset

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

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

- 2 "equations" for 2 unknowns: pedestal height and width
- EPED1.6: Both P-B and KBM constraints calculated directly (EPED1 simplified KBM)
  - ***No free or fitting parameters in any part of model, straightforward & predictive***

D. Validate Model Against JET and Other Devices

- Large study of 137 hybrid and baselines discharges on JET

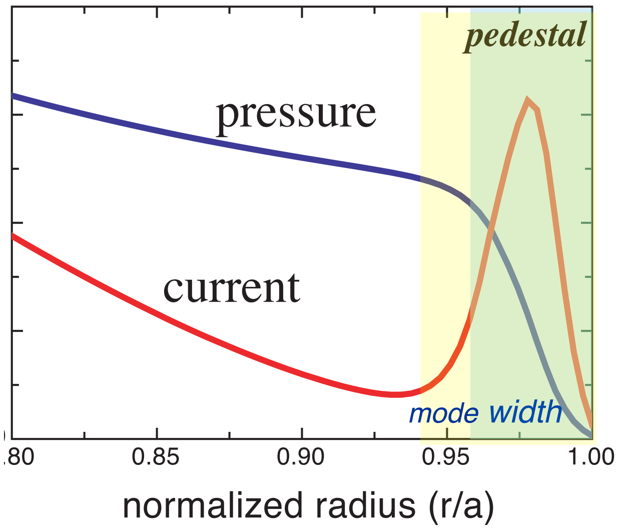
E. Pedestal Prediction and Optimization for ITER

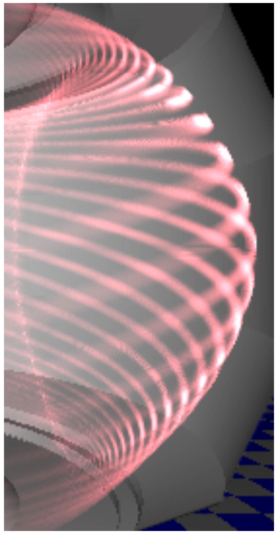
- Previous baseline ITER study, ITER_citrin, ITER_hybrid, ITER_reference

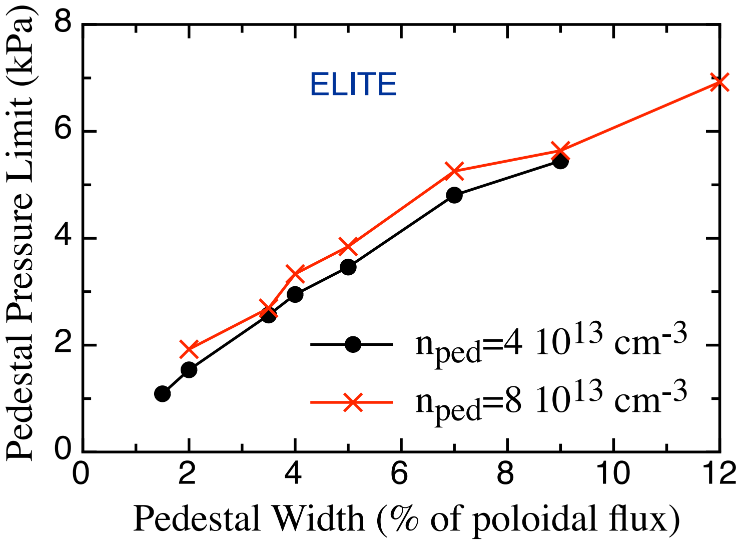
Peeling-Ballooning Modes

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

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







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

- Driven by sharp pressure gradient and bootstrap current in the edge barrier (pedestal)
- Complex dependencies on ν_*, shape etc., extensively tested against experiment

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

- Model equilibrium technique used to apply P-B constraint predictively $\beta_{Nped}=f(\Delta_\psi)$
- P-B limit increases with pedestal width (Δ_ψ), but not linearly (roughly $\beta_{Nped}\sim\Delta_\psi^{3/4}$)

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

H.R. Wilson, 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).*

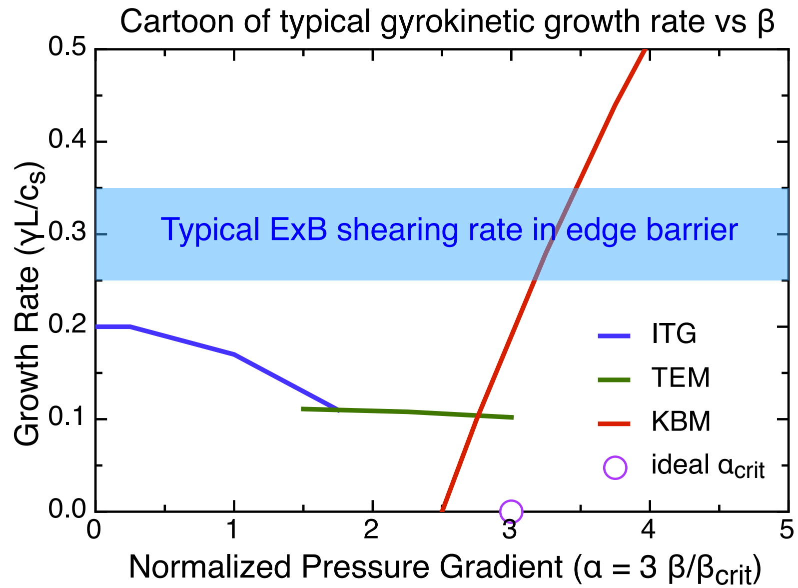
Kinetic Ballooning Mode Onset Provides 2nd Constraint

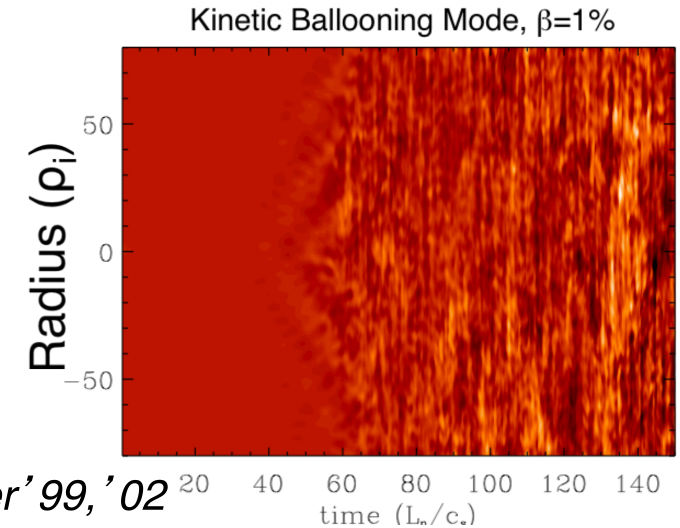
Many mechanisms drive transport across the edge barrier. We hypothesize that the KBM is the mechanism by which the pressure gradient is finally constrained in the presence of strong ExB shear (in the regime of interest to ITER – moderate to low collisionality and standard aspect ratio)

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

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

➢ **Simple model of the KBM can be quantitatively accurate**
  - Stiff onset near MHD ballooning criticality
  - Integrate using model equilibrium technique





Snyder'99,'02

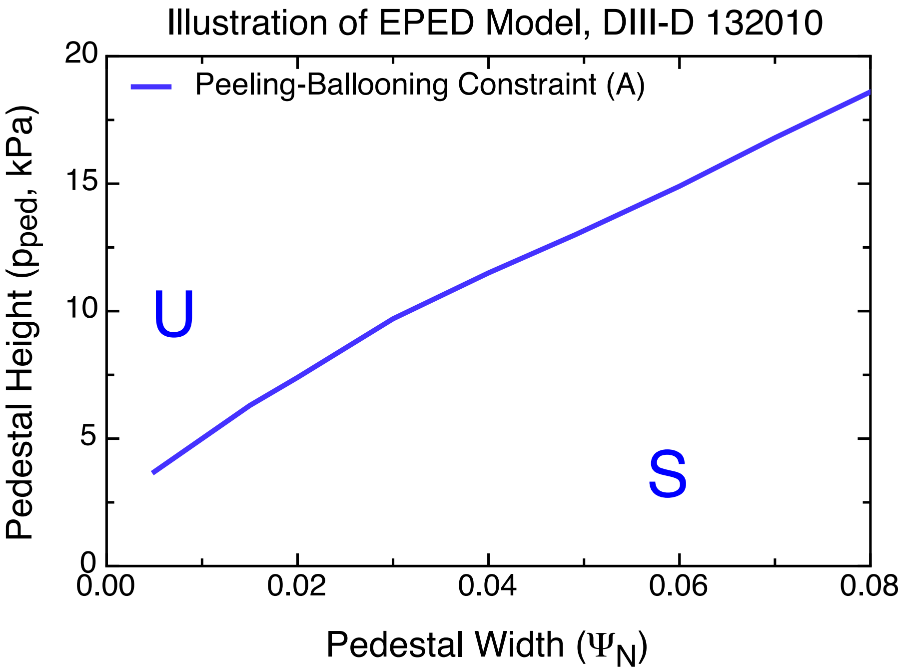
Implementing and Testing the EPED Model

Mechanics of the EPED Predictive Model

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

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

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



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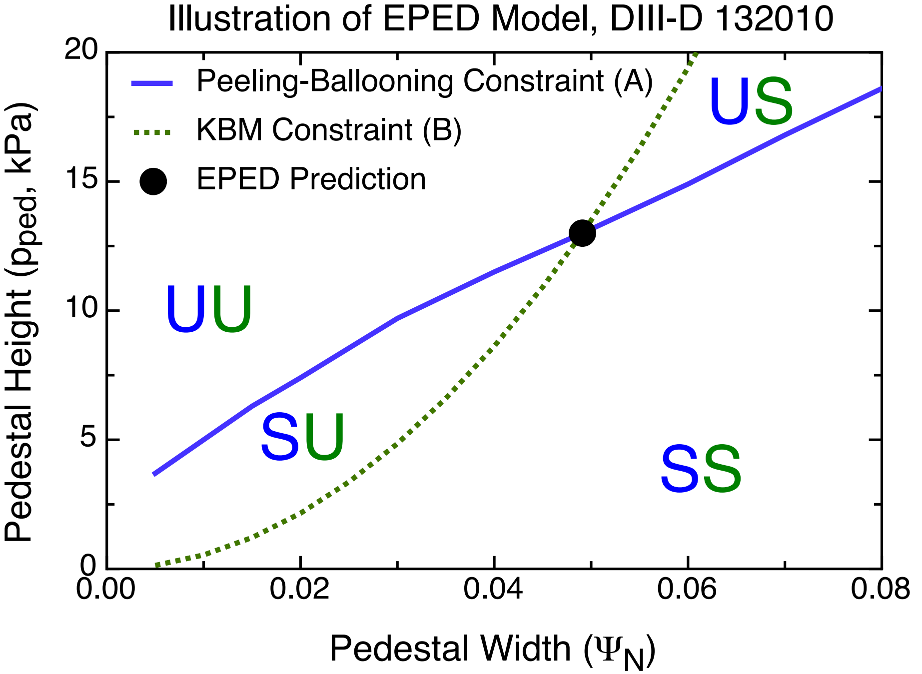
– Directly calculate with ballooning critical pedestal technique



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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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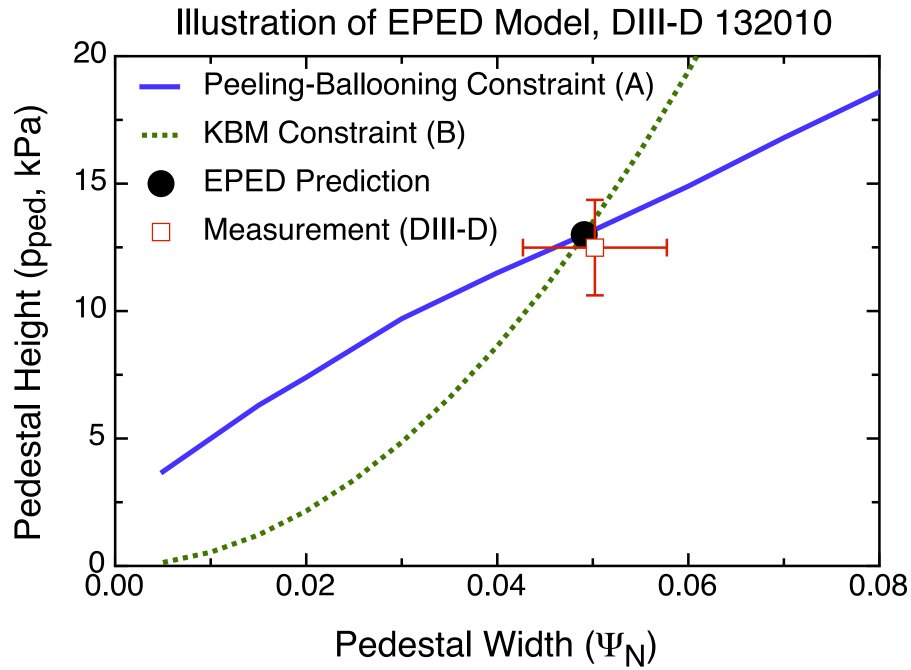

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  -can then be systematically compared to existing data or future experiments

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

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

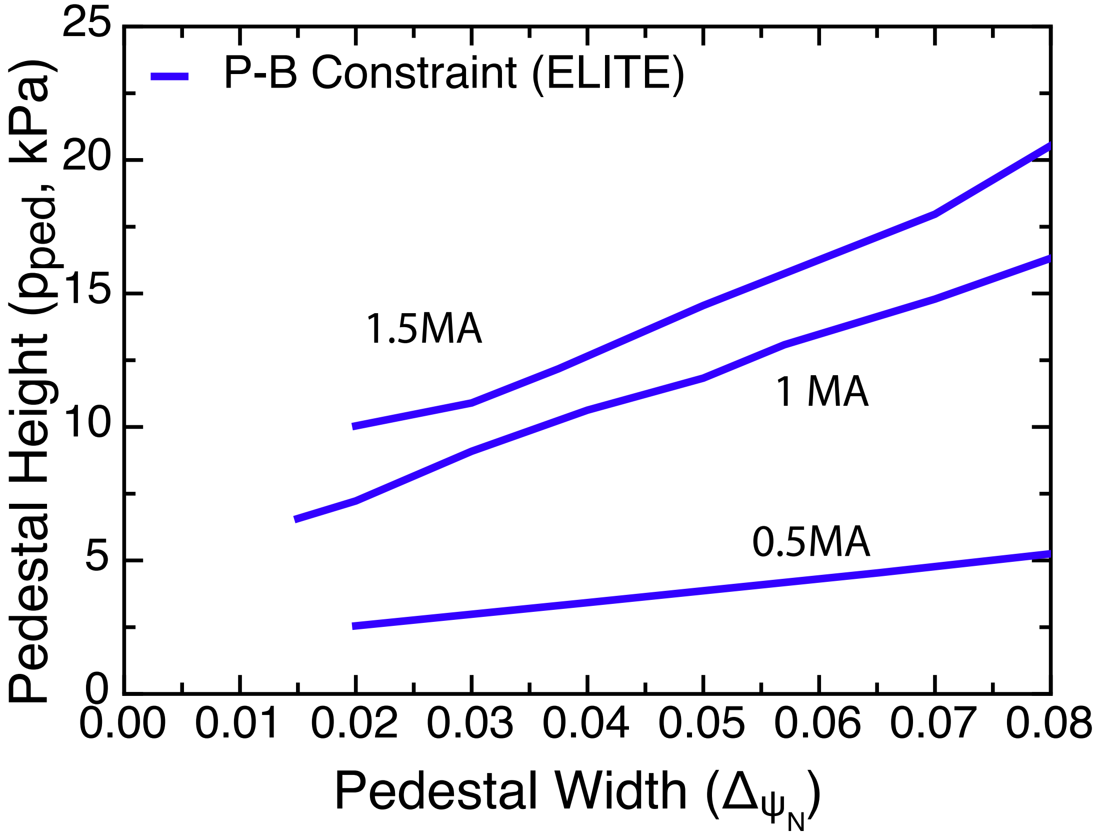
DIII-D: I_p varied by a factor of 3 (0.5, 1, 1.5MA)

- B_t=2.1T, κ=1.74, δ=0.3

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

- β_N-like, dependence weakens as q gets low

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



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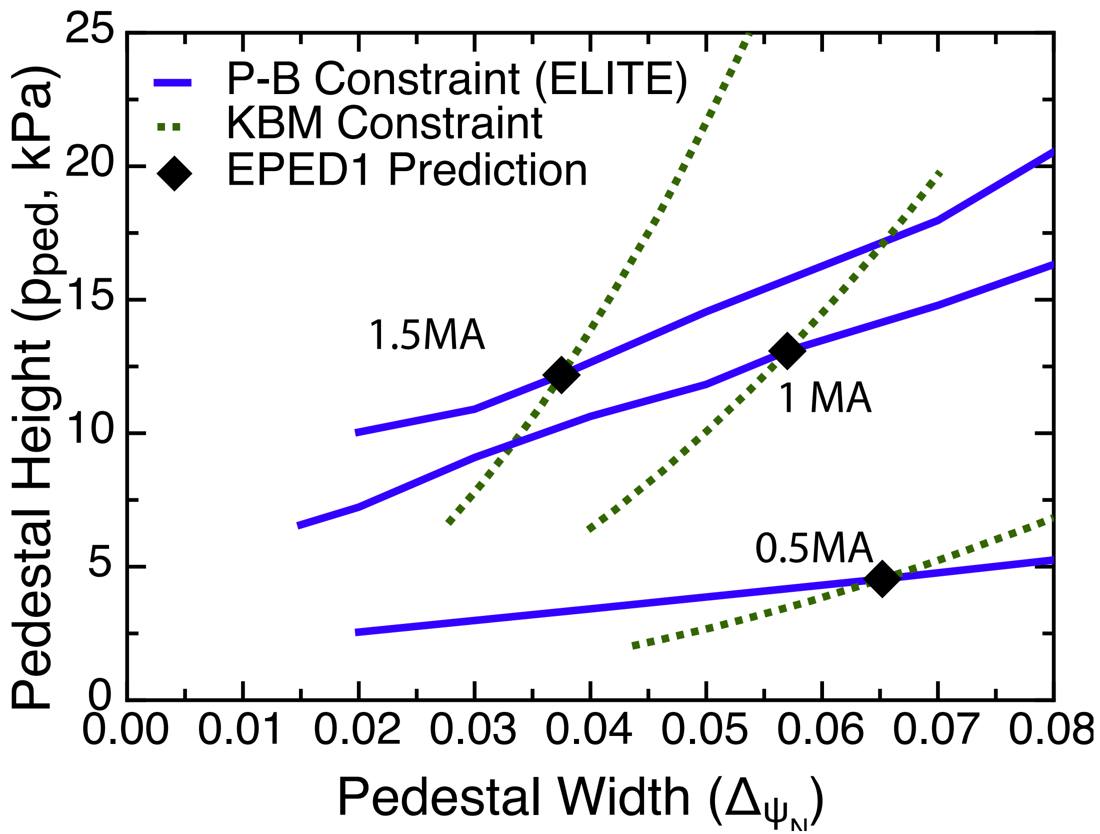

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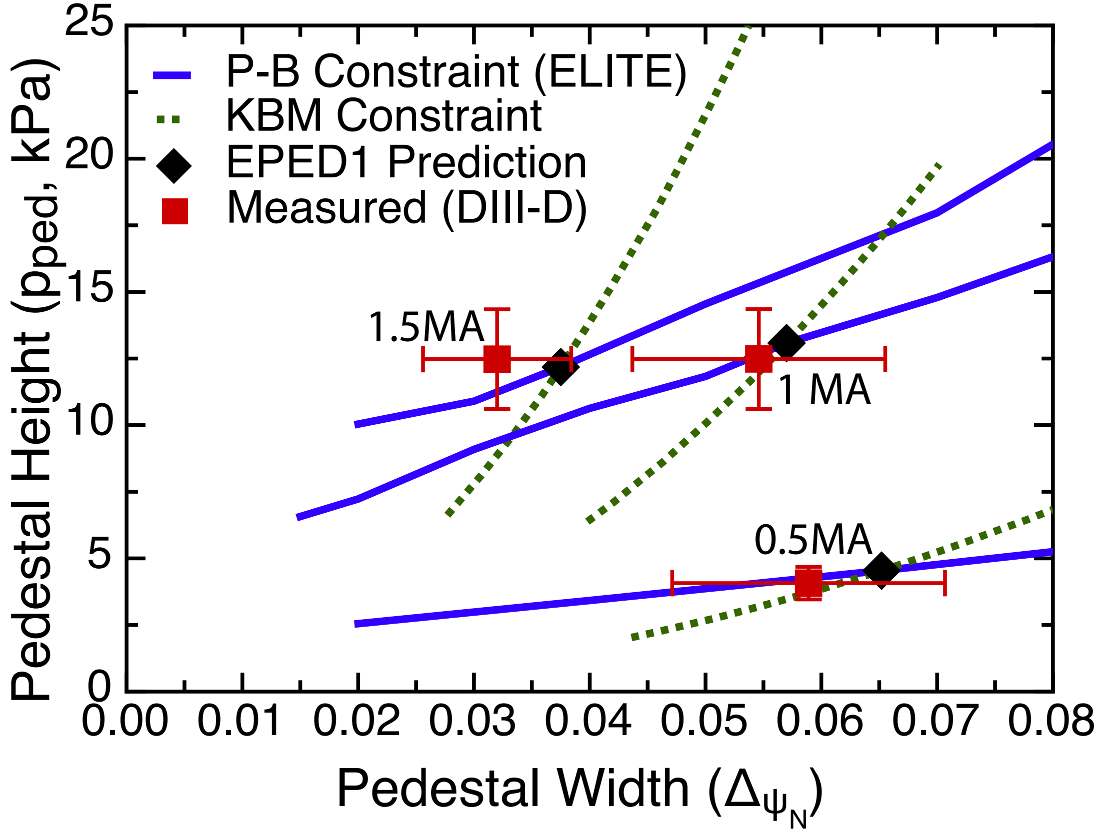
- Good agreement with observations at all I_p values

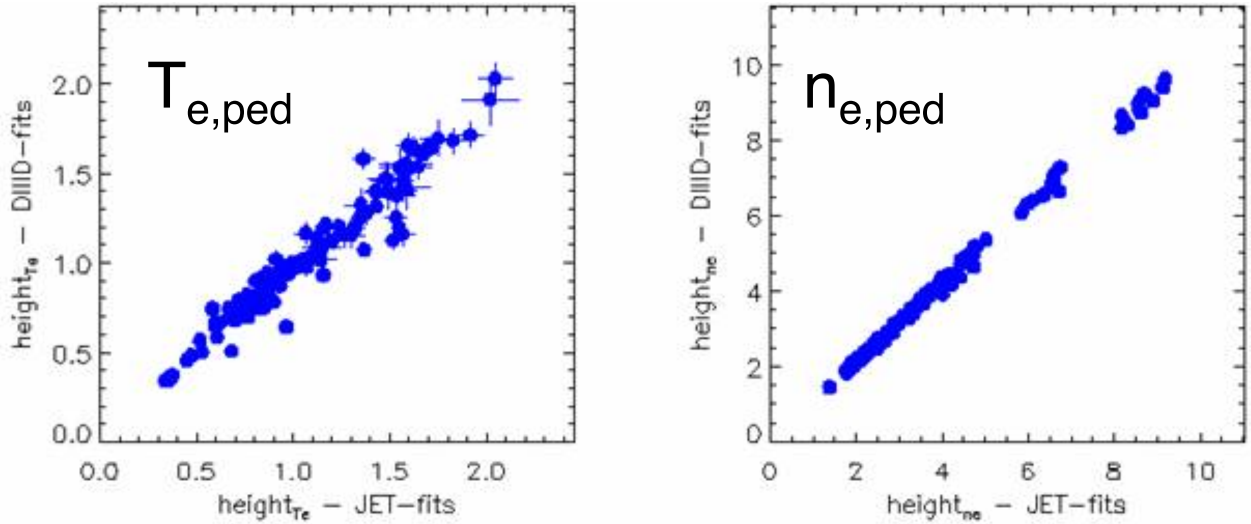
EPED1 Model, DIII-D Current Scan (0.5, 1, 1.5MA)



Tests of EPED on Large Dataset of JET Hybrid and Baseline Shots

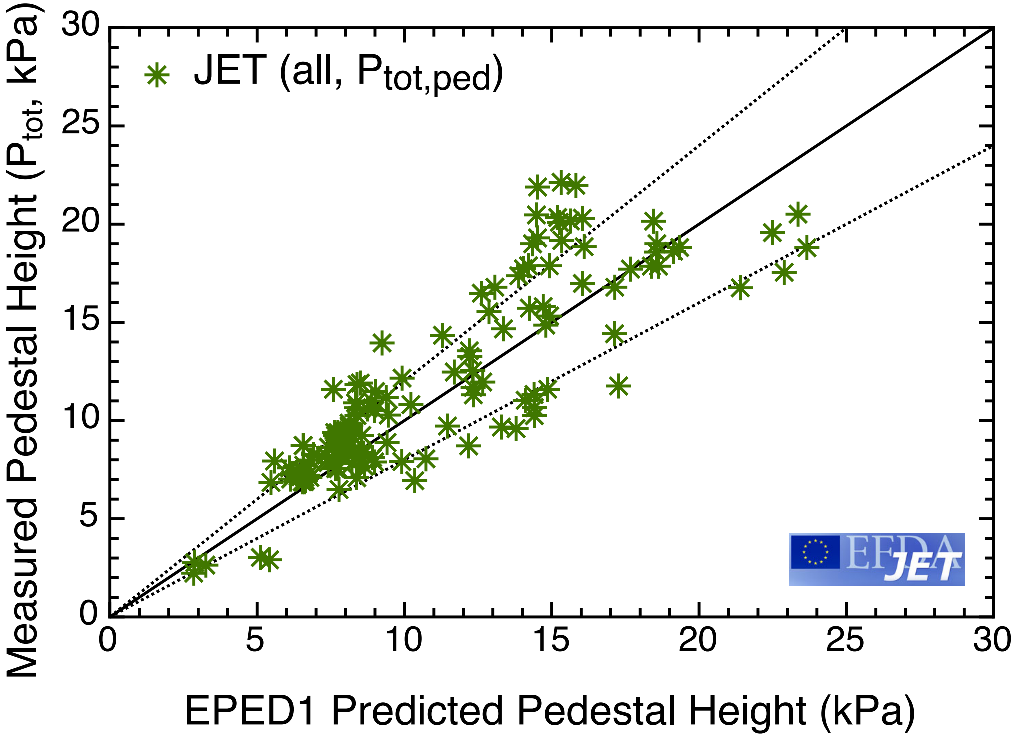
Extensive JET Dataset Allows Detailed Tests of Models

Comparison of measured JET pedestal T_e and n_e using slightly different analysis techniques ("JET fits" vs "DIII-D fits")



- **137 Discharges in four categories: low and high δ hybrids, low and high δ baseline (including low and high δ rhostar expt)**
  - $0.98 < I_p < 2.49$MA, $1.08 < B_t < 2.79$T, $0.20 < \delta < 0.45$, $1.4 < n_{eped} < 9.6$, $0.3 < f_{GWped} < 1.0$, $1.5 < \beta_N < 3.4$,
  - Full dataset used, no down selection
- **Pedestal measurement and analysis is always a challenge, lots of hard work here by Beurskens, Osborne, Groebner et al**
  - Variation due to analysis technique ~10% for T_e, <~5% for n_e (use "DIII-D" fits)
  - Add to measurement uncertainty -> pedestal pressure uncertainty ~10-20%

Test of EPED1 on Full JET Dataset (137 cases)



Comparison to full JET dataset with HRTS measurements *(see M. Beurskens, HMWS)*

Ratio of predicted to observed height = 0.97 ± 0.21 (corr *r*=0.86)

Interpreting the Correlation between Model and Experiment

$$r = \frac{\text{covariance of X and Y}}{(\text{standard deviation of X})(\text{standard deviation of Y})}$$

Expected correlation for this 137 point data set

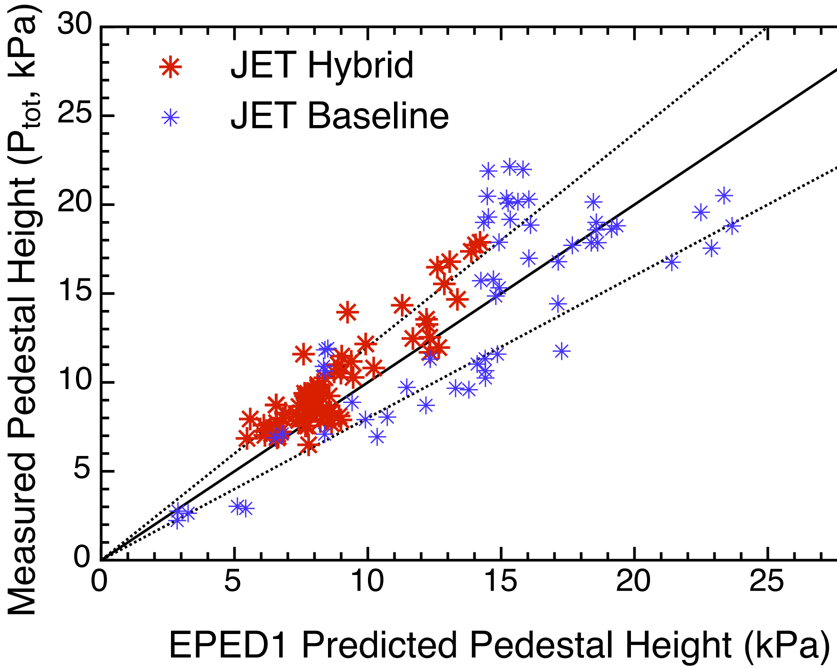
(simple model with Gaussian random errors, reality more complex)

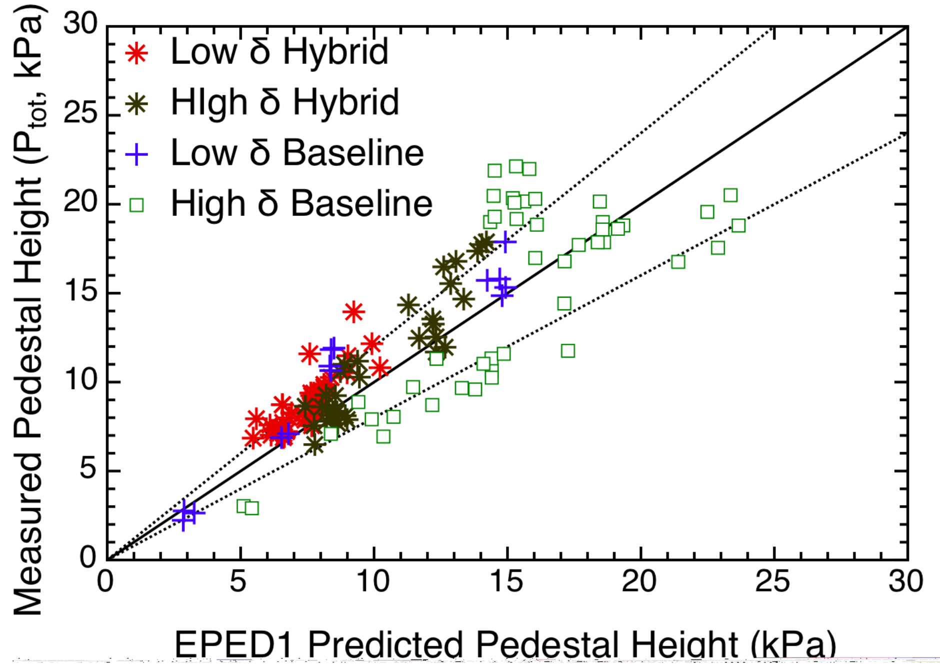
Model Uncertainty (ie model accuracy)

Measurement Uncertainty	0%	5%	10%	15%	20%	25%
0%	1	.99±.00	.97±.01	.93±.01	.88±.02	.84±.03
5%	.99±.00	.98±.00	.96±.01	.92±.01	.88±.02	.83±.03
10%	.97±.01	.96±.01	.94±.01	.90±.02	.86±.02	.81±.03
15%	.93±.01	.92±.01	.90±.02	.87±.02	.83±.03	.79±.03
20%	.88±.02	.88±.02	.86±.02	.83±.03	.80±.03	.76±.03
25%	.84±.03	.83±.03	.81±.03	.79±.03	.76±.03	.73±.04

- **The (Pearson) correlation coefficient, *r*=(-1,1), is a measure of linear dependence**
  - High values indicate strong correlation, but what value represents "good agreement" depends on uncertainties vs range of data (data set dependent)
- **For the 137 point comparison, the correlation between the EPED1 model and measurements (0.86) is consistent with:**
  - ~15% uncertainty in measurement and model, ~20% uncertainty in measurement and ~10% uncertainty in model, ~10% measurement uncertainty and ~20% in model
- **This measure is consistent with model accuracy of ~20% or better**

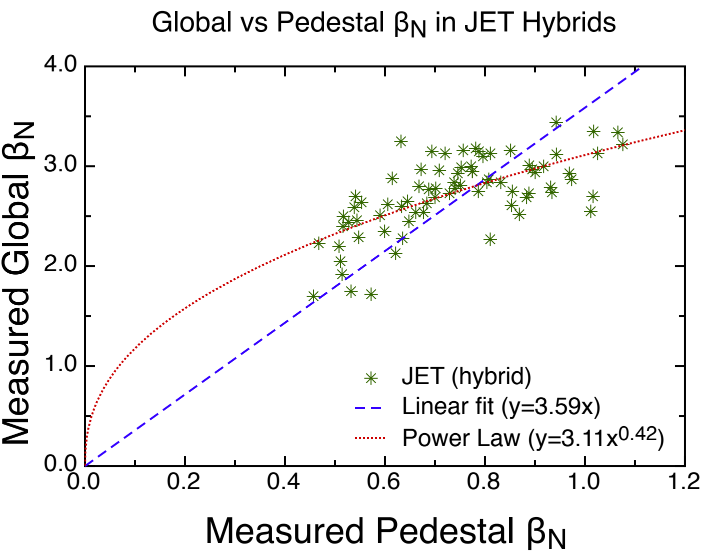
Comparison of Hybrid vs Baseline Discharges

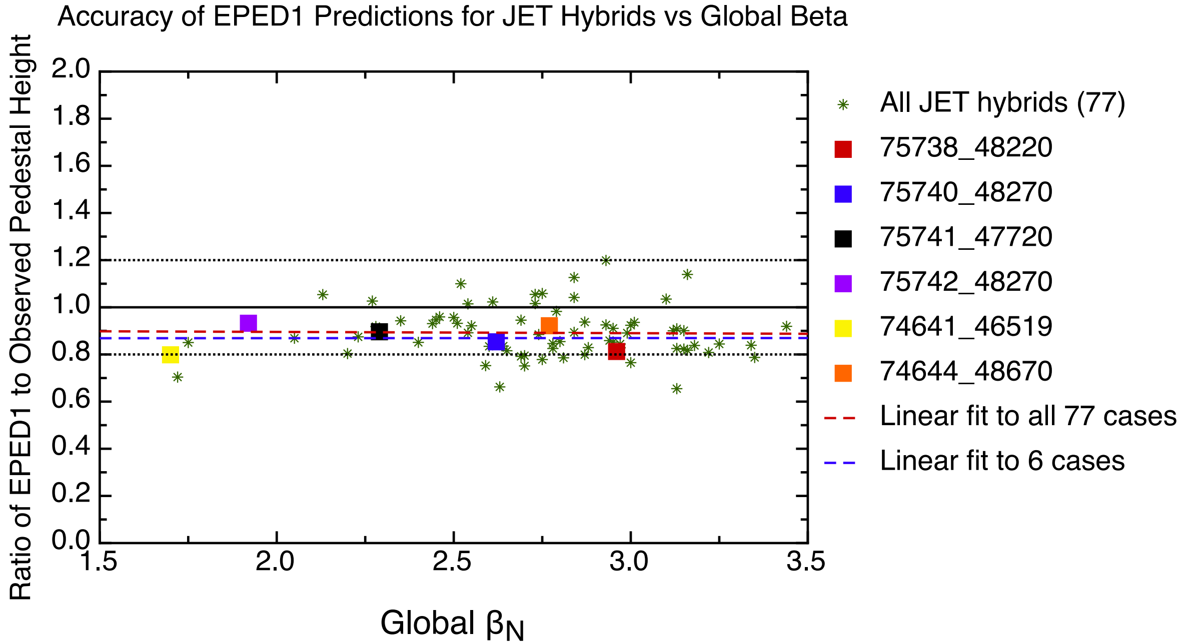




- **Hybrids have stronger decoupling of Ti and Te**
- **77 Hybrid: ratio of predicted to observed p_{ped}=0.89 ± 0.10 (corr *r*=0.91)**
- **60 Baseline: 1.06 ± 0.26 (corr *r*=0.82)**
- **Similar overall agreement, less variation in hybrid dataset**

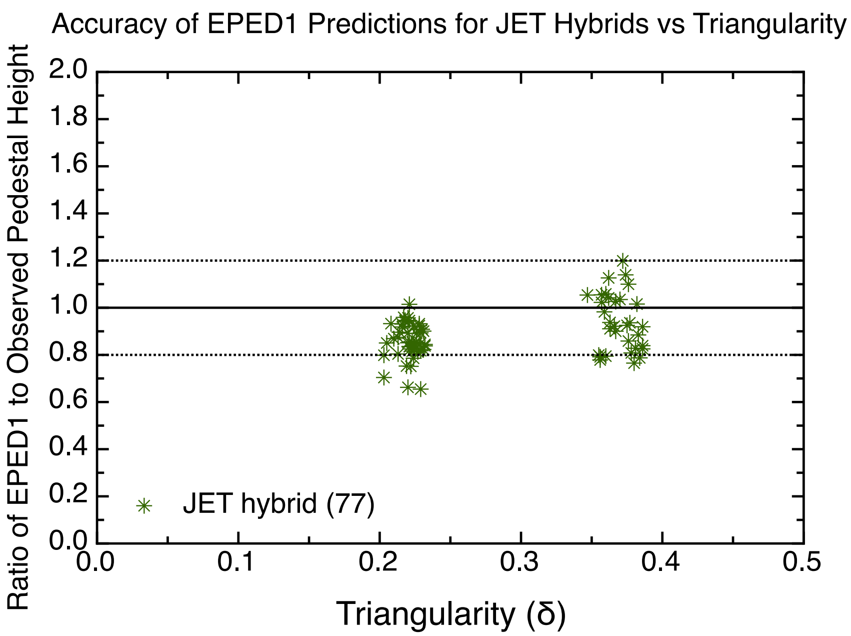
EPED Model Captures Variation with Global Beta (Shafranov shift) in JET Hybrids

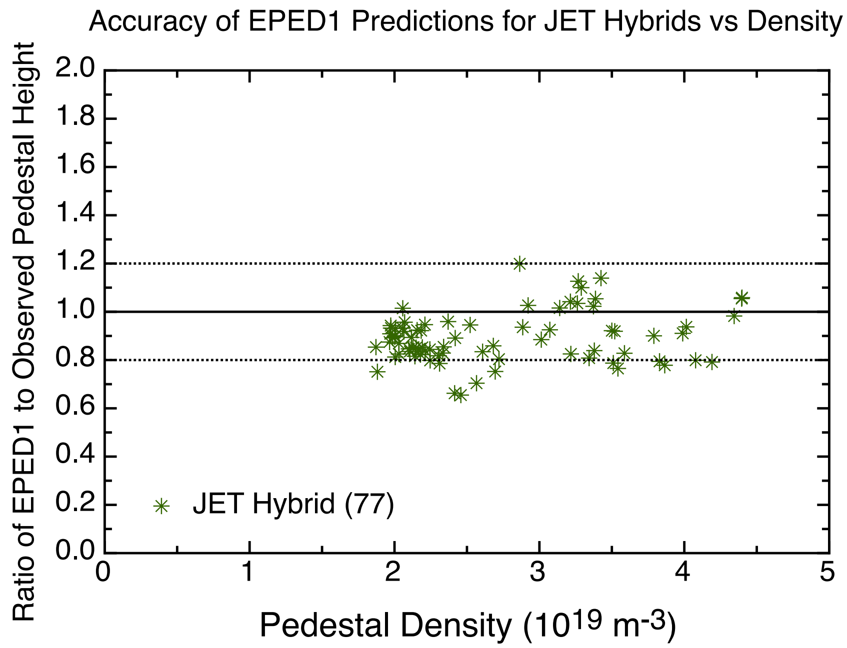




- **Significant correlation between observed global and pedestal beta (*r*~0.66, left figure)**
- **This dependence captured reasonably well by EPED model**
  - Ratio varies little in full hybrid dataset or 6 specified shots
  - Note there is no power dependence in EPED, but P-B stability is sensitive to global Shafranov shift

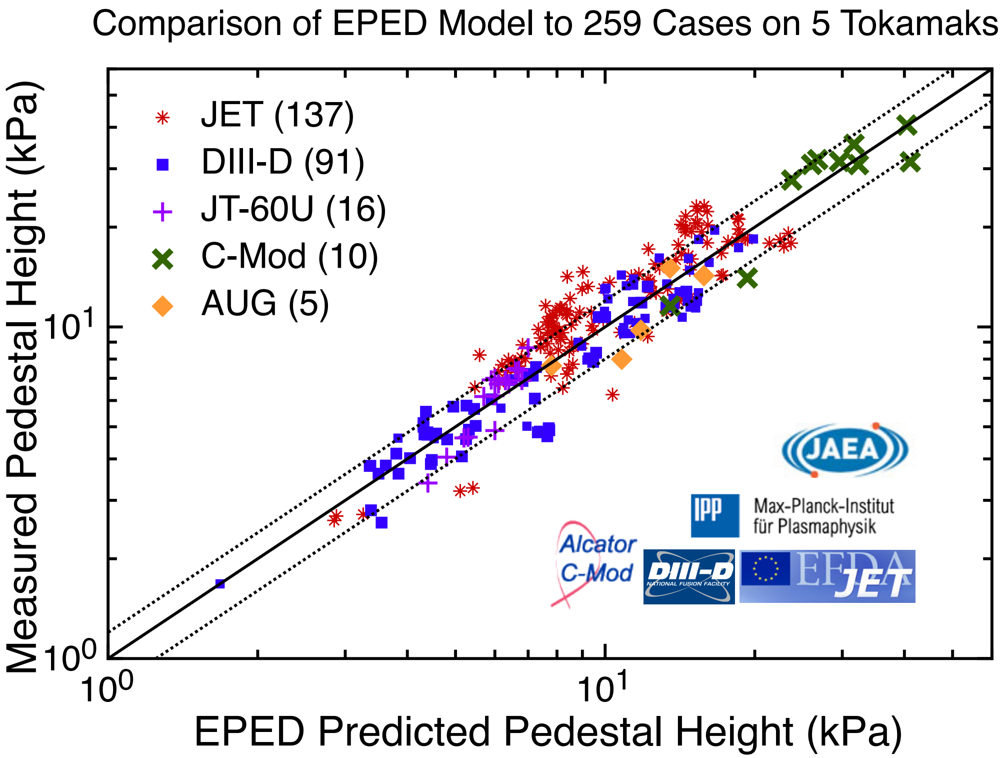
EPED Model Captures Variation with Triangularity and Density in JET Hybrids





- **Strong increase in pedestal height (~50% in $\beta_{N,ped}$) with triangularity largely captured by EPED1 Model**
- **Variation in pedestal height with pedestal density also captured (much of this is really triangularity and I_p dependence)**

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



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

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

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

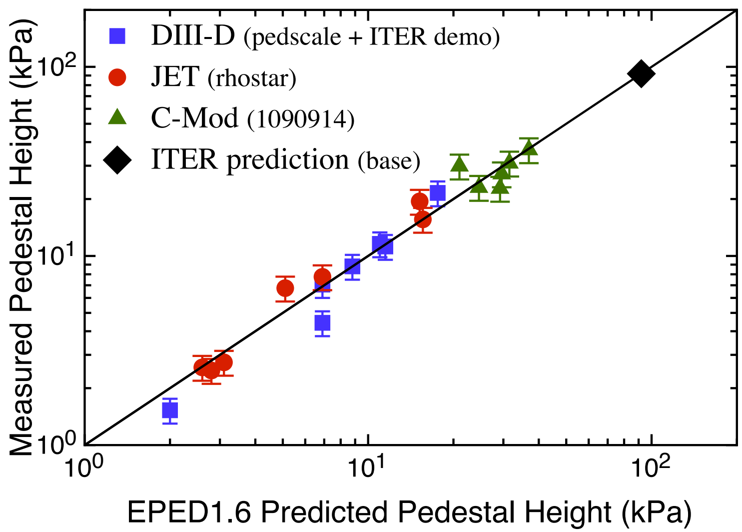
Consistent with ~10-15% measurement error and EPED accuracy to ~15-20%

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

-Captures trends in data

EPED Predictions and Optimization for ITER

Pedestal Prediction for ITER *(NF 51 103016 2011)*



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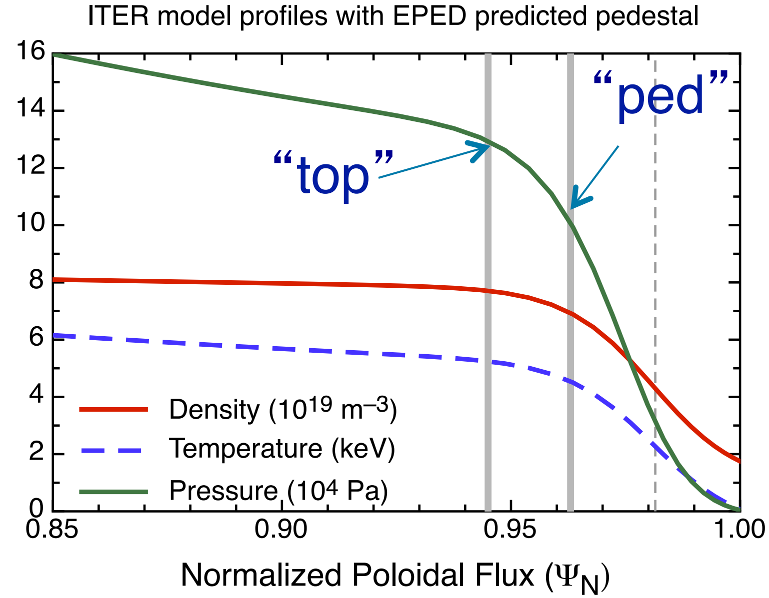
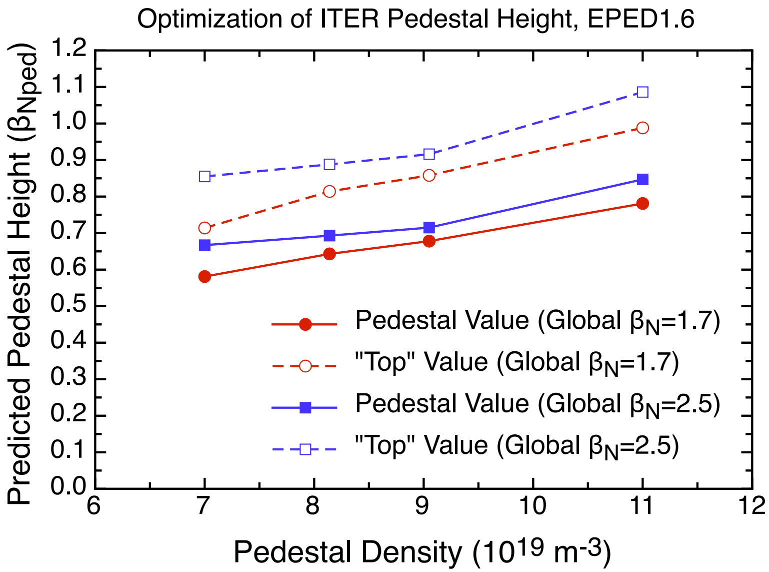


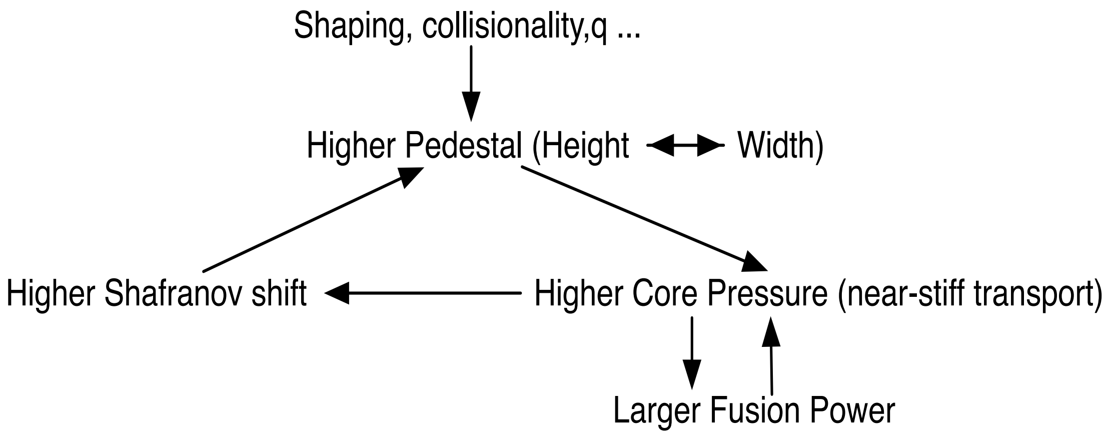
- **For ITER baseline, EPED1.6 (full model) predicts a pedestal height of $\beta_{N,ped}$~0.6 and a width $\Delta_{\psi ped}$~0.04 (~4.4cm), for n_{ped}~7x10^{19} m^{-3}**
  - In normalized units, values similar to predictions and observations on existing devices
- **Predictions given for pedestal as defined by the tanh function half width ("ped")**
  - To connect to core simulations, we define a pedestal "top" that is another half-width in, inside the sharp gradient region
  - Reference EPED prediction is $\beta_{N,top}$~0.75 at the "top", $\Delta_{\psi top}$~0.06, $\Psi_{N top}$~0.94

Recommend using "top" values as the Boundary Condition for core transport studies

GENERAL ATOMICS

Understanding the Pedestal Allows ITER Performance Optimization





- **EPED predicted pedestal height increases with density and Shafranov shift (global β)**
  - Low density kink/peeling regime: *RMP ELM control and Quiescent H-Mode operate in this regime* (not sufficient condition – more research needed)
  - Virtuous cycle: Increasing core pressure improves pedestal height, which in turn increases core pressure **(P_{fus}~p_{ped}^2)**
  - Pedestal top values of $\beta_{N,top}$~0.9 can be achieved with optimization, which allows high predicted global performance in ITER *[Kinsey, NF11]*

EPED1 Predictions for ISM ITER Cases: ITER_Citrin

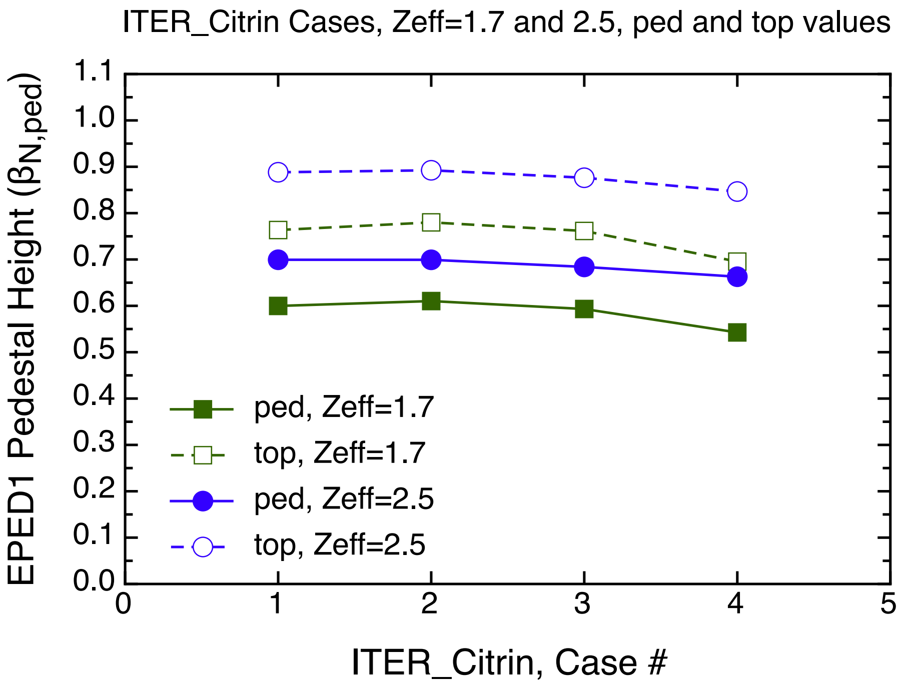
ITER_Citrin Hybrid Cases, Z_{eff}=1.7

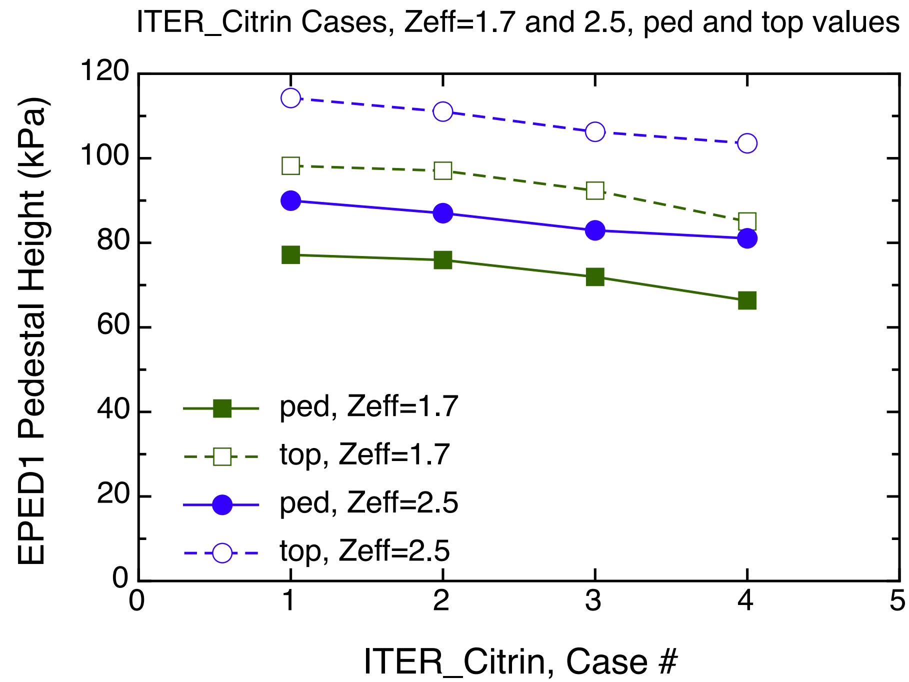
- **Based on** *J Citrin et al Nucl. Fus 50 115007 2010*
- **All Cases: R=6.2m, a=2m, κ=1.9, δ=0.485, B_t=5.3T, Z_{eff}=1.7**
- **Case 1: I_p=12.2MA, n_{eped}=9.35, β_N=1.822 (Assumed T_{ped}=3keV, p_{ped}<~90kPa)**
  - EPED1 (ped): p_{ped}=77.2 kPa, β_{Nped}=0.60, $\Delta_{ped}(\psi_N)$=0.041
  - EPED1 (top): p_{top}=98.2 kPa, β_{Ntop}=0.76, $\Delta_{top}(\psi_N)$=0.062
- **Case 2: I_p=11.8MA, n_{eped}=9.02, β_N=2.015 (Assumed T_{ped}=4keV, p_{ped}<~116kPa)**
  - EPED1 (ped): p_{ped}=75.9 kPa, β_{Nped}=0.61, $\Delta_{ped}(\psi_N)$=0.042
  - EPED1 (top): p_{top}=97.1 kPa, β_{Ntop}=0.78, $\Delta_{top}(\psi_N)$=0.063
- **Case 3: I_p=11.5MA, n_{eped}=8.43, β_N=2.156 (Assumed T_{ped}=5keV, p_{ped}<~135kPa)**
  - EPED1 (ped): p_{ped}=71.9 kPa, β_{Nped}=0.59, $\Delta_{ped}(\psi_N)$=0.042
  - EPED1 (top): p_{top}=92.3 kPa, β_{Ntop}=0.76, $\Delta_{top}(\psi_N)$=0.063
- **Case 4: I_p=11.6MA, n_{eped}=7.25, β_N=2.156 (Assumed T_{ped}=5keV, p_{ped}<~116kPa)**
  - EPED1 (ped): p_{ped}=66.4 kPa, β_{Nped}=0.54, $\Delta_{ped}(\psi_N)$=0.040
  - EPED1 (top): p_{top}=85.1 kPa, β_{Ntop}=0.70, $\Delta_{top}(\psi_N)$=0.063

ITER_Citrin Hybrid Cases, Z_{eff}=2.5

- **Based on** *J Citrin et al Nucl. Fus 50 115007 2010*
- **All Cases: R=6.2m, a=2m, κ=1.9, δ=0.485, B_t=5.3T, Z_{eff}=2.5**
- **Case 1: I_p=12.2MA, n_{eped}=9.35, β_N=1.822 (Assumed T_{ped}=3keV, p_{ped}<~90kPa)**
  - EPED1 (ped): p_{ped}=90.0 kPa, β_{Nped}=0.70, $\Delta_{ped}(\psi_N)$=0.044
  - EPED1 (top): p_{top}=114.3 kPa, β_{Ntop}=0.89, $\Delta_{top}(\psi_N)$=0.066
- **Case 2: I_p=11.8MA, n_{eped}=9.02, β_N=2.015 (Assumed T_{ped}=4keV, p_{ped}<~116kPa)**
  - EPED1 (ped): p_{ped}=87.0 kPa, β_{Nped}=0.70, $\Delta_{ped}(\psi_N)$=0.045
  - EPED1 (top): p_{top}=111.0 kPa, β_{Ntop}=0.89, $\Delta_{top}(\psi_N)$=0.068
- **Case 3: I_p=11.5MA, n_{eped}=8.43, β_N=2.156 (Assumed T_{ped}=5keV, p_{ped}<~135kPa)**
  - EPED1 (ped): p_{ped}=82.9 kPa, β_{Nped}=0.68, $\Delta_{ped}(\psi_N)$=0.045
  - EPED1 (top): p_{top}=106.3 kPa, β_{Ntop}=0.87, $\Delta_{top}(\psi_N)$=0.068
- **Case 4: I_p=11.6MA, n_{eped}=7.25, β_N=2.156 (Assumed T_{ped}=5keV, p_{ped}<~116kPa)**
  - EPED1 (ped): p_{ped}=81.1 kPa, β_{Nped}=0.66, $\Delta_{ped}(\psi_N)$=0.044
  - EPED1 (top): p_{top}=103.5 kPa, β_{Ntop}=0.84, $\Delta_{top}(\psi_N)$=0.066

Comparison of EPED1 Predictions for ITER_Citrin Cases





Increasing Z_{eff} from 1.7 to 2.5 significantly increases EPED predicted p_{ped}

- Related to density (ie collisionality) dependence of kink/peeling limit
- Can similarly achieve higher predicted p_{ped} by increasing density

EPED1 Predictions for ISM ITER Cases: ITER_Hybrid (ISM requests 1,2,3)

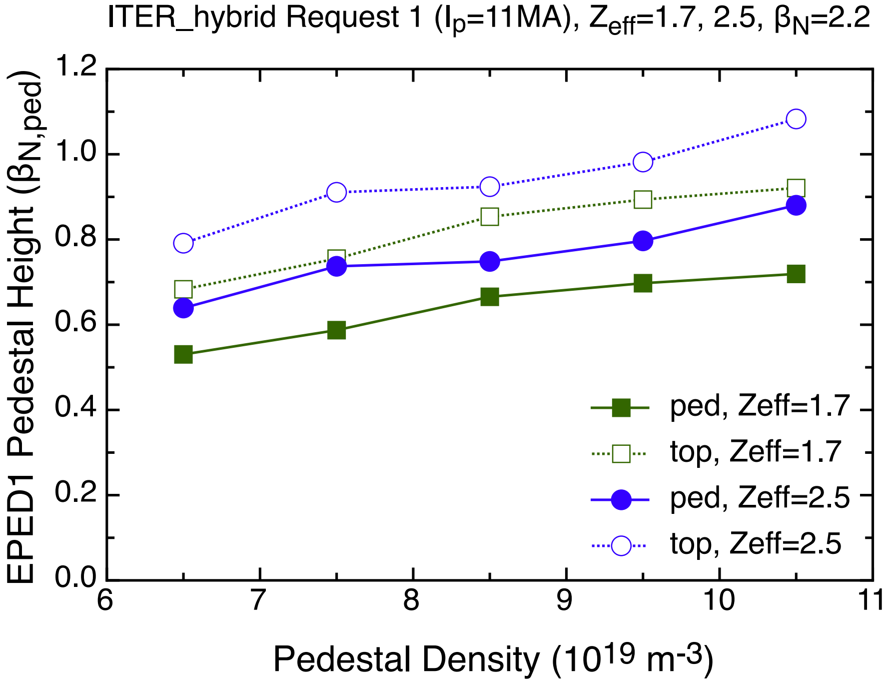
ITER_Hybrid Cases, Request 1 (I_p=11MA) Z_{eff}=1.7, 2.5

- **Request 1: R=6.2m, a=2m, κ=1.85, δ=0.485, B_t=5.3T, I_p=11MA**
- **Requested range: n_{eped}=6.5 – 10.5 10^{-19} m^{-3}, β_N=1.8, 2.2, 2.6, 3.0**
  - β_N dependence is weak for this density range, focus on β_N=2.2 and show β_N dependence later in plots

n_{eped}	Z_{eff}	β_N	EPED1 P_{ped} (kPa)	EPED1 β_{Nped}	EPED1 $\Delta_{ped}(\psi_N)$	EPED1 p_{top} (kPa)	EPED1 β_{Ntop}	EPED1 $\Delta_{top}(\psi_N)$
6.5	1.7	2.2	61.5	0.53	0.040	79.2	0.68	0.060
7.5	1.7	2.2	68.1	0.59	0.042	87.6	0.76	0.063
8.5	1.7	2.2	77.2	0.67	0.045	99.0	0.85	0.067
9.5	1.7	2.2	80.9	0.70	0.046	103.7	0.89	0.069
10.5	1.7	2.2	83.4	0.72	0.046	106.8	0.92	0.070
6.5	2.5	2.2	71.4	0.62	0.043	91.8	0.79	0.064
7.5	2.5	2.2	82.4	0.71	0.046	105.6	0.91	0.069
8.5	2.5	2.2	83.7	0.72	0.046	107.2	0.92	0.070
9.5	2.5	2.2	89.1	0.77	0.048	113.9	0.98	0.072
10.5	2.5	2.2	98.4	0.85	0.050	125.6	1.08	0.076

ITER_Hybrid Cases, Request 1 (I_p=11MA) Z_{eff}=1.7, 2.5

- **Request 1: R=6.2m, a=2m, κ=1.85, δ=0.485, B_t=5.3T, I_p=11MA**
- **Requested range: n_{eped}=6.5 – 10.5 10^{-19} m^{-3}, β_N=1.8, 2.2, 2.6, 3.0**
  - β_N dependence is weak for this density range, focus on β_N=2.2 and show β_N dependence later in plots
- **EPED predicted pedestal height increasing with density**
  - Suggests possibility of QH and RMP ELM control, optimization at high density



ITER_Hybrid Cases, Request 2 (I_p=12MA) Z_{eff}=1.7, 2.5

- **Request 2: R=6.2m, a=2m, κ=1.85, δ=0.485, B_t=5.3T, I_p=12MA**
- **Requested range: n_{eped}=6.5 – 10.5 10^{-19} m^{-3}, β_N=1.8, 2.2, 2.6, 3.0**
  - β_N dependence is weak for this density range, focus on β_N=2.2 and show β_N dependence later in plots

n_{eped}	Z_{eff}	β_N	EPED1 P_{ped} (kPa)	EPED1 β_{Nped}	EPED1 $\Delta_{ped}(\psi_N)$	EPED1 p_{top} (kPa)	EPED1 β_{Ntop}	EPED1 $\Delta_{top}(\psi_N)$
6.5	1.7	2.2	71.4	0.56	0.039	91.7	0.72	0.059
7.5	1.7	2.2	76.7	0.61	0.041	98.3	0.78	0.061
8.5	1.7	2.2	77.2	0.61	0.041	98.9	0.78	0.061
9.5	1.7	2.2	80.9	0.64	0.042	103.6	0.82	0.063
10.5	1.7	2.2	92.4	0.73	0.045	118.0	0.93	0.067
6.5	2.5	2.2	76.4	0.60	0.041	97.9	0.77	0.061
7.5	2.5	2.2	82.4	0.65	0.042	105.5	0.83	0.063
8.5	2.5	2.2	93.4	0.74	0.045	119.3	0.94	0.068
9.5	2.5	2.2	94.4	0.75	0.045	120.6	0.95	0.068
10.5	2.5	2.2	104.4	0.83	0.048	133.0	1.05	0.071

ITER_Hybrid Cases, Request 3 (I_p=13MA) Z_{eff}=1.7, 2.5

- **Request 2: R=6.2m, a=2m, κ=1.85, δ=0.485, B_t=5.3T, I_p=13MA**
- **Requested range: n_{eped}=6.5 – 10.5 10^{-19} m^{-3}, β_N=1.8, 2.2, 2.6, 3.0**
  - β_N dependence is weak for this density range, focus on β_N=2.2 and show β_N dependence later in plots

n_{eped}	Z_{eff}	β_N	EPED1 P_{ped} (kPa)	EPED1 β_{Nped}	EPED1 $\Delta_{ped}(\psi_N)$	EPED1 p_{top} (kPa)	EPED1 β_{Ntop}	EPED1 $\Delta_{top}(\psi_N)$
6.5	1.7	2.2	71.4	0.52	0.036	91.6	0.67	0.055
7.5	1.7	2.2	76.7	0.56	0.038	98.2	0.72	0.056
8.5	1.7	2.2	86.9	0.63	0.040	111.1	0.81	0.060
9.5	1.7	2.2	83.6	0.61	0.039	106.9	0.78	0.059
10.5	1.7	2.2	89.4	0.65	0.041	114.2	0.83	0.061
6.5	2.5	2.2	81.4	0.59	0.039	104.1	0.76	0.058
7.5	2.5	2.2	85.3	0.62	0.040	109.0	0.80	0.060
8.5	2.5	2.2	90.1	0.66	0.041	115.1	0.84	0.061
9.5	2.5	2.2	97.2	0.71	0.042	123.9	0.90	0.064
10.5	2.5	2.2	107.4	0.78	0.045	136.8	1.00	0.067

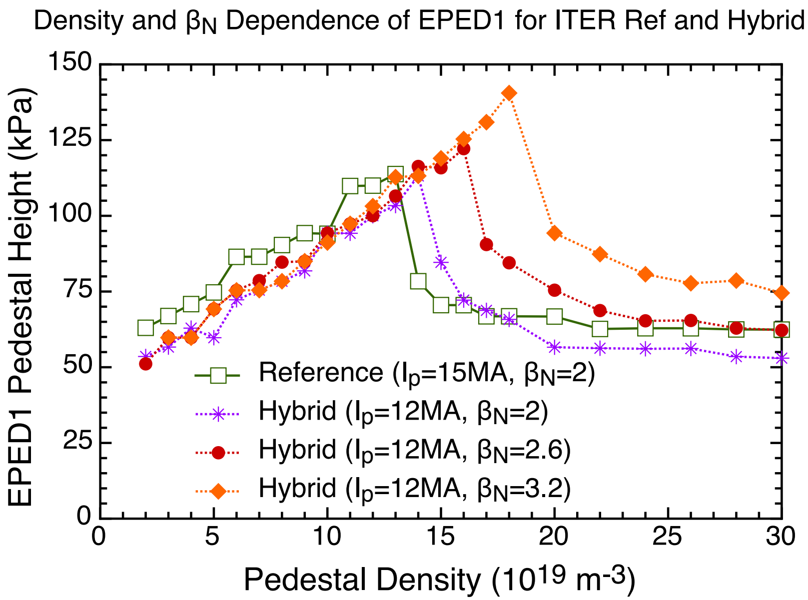
EPED1 Predictions for ISM ITER Cases: ITER_reference

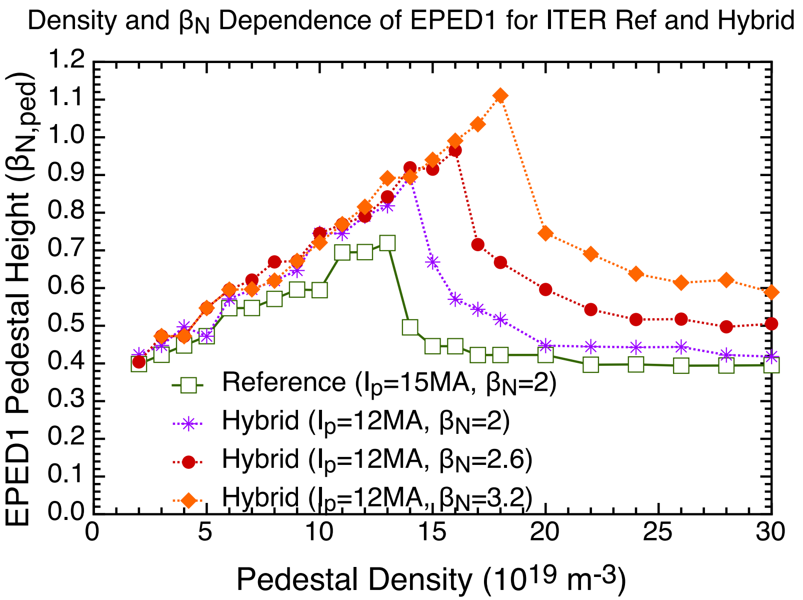
ITER_Reference Scenario, Z_{eff}=1.7, 2.5

- **Reference: R=6.2m, a=2m, κ =1.85, δ =0.485, B_t=5.3T, I_p=15MA**
- **Requested range: n_{eped}=8.5 – 10.5 10^{-19} m^{-3}, β_N=1.8, 2.0, 2.2**
  - β_N dependence is weak for this density range, focus on β_N=2.0 and show β_N dependence later in plots

n_{eped}	Z_{eff}	β_N	EPED1 P_{ped} (kPa)	EPED1 β_{Nped}	EPED1 $\Delta_{ped}(\psi_N)$	EPED1 p_{top} (kPa)	EPED1 β_{Ntop}	EPED1 $\Delta_{top}(\psi_N)$
8.5	1.7	2	89.2	0.56	0.035	113.4	0.72	0.053
9.5	1.7	2	93.1	0.59	0.036	118.3	0.75	0.054
10.5	1.7	2	97.1	0.61	0.037	123.3	0.78	0.055
8.5	2.5	2	104.9	0.66	0.038	133.1	0.84	0.057
9.5	2.5	2	104.9	0.66	0.038	133.1	0.84	0.057
10.5	2.5	2	109.0	0.69	0.039	138.2	0.87	0.058

Dependence on Global β_N and Density are Linked





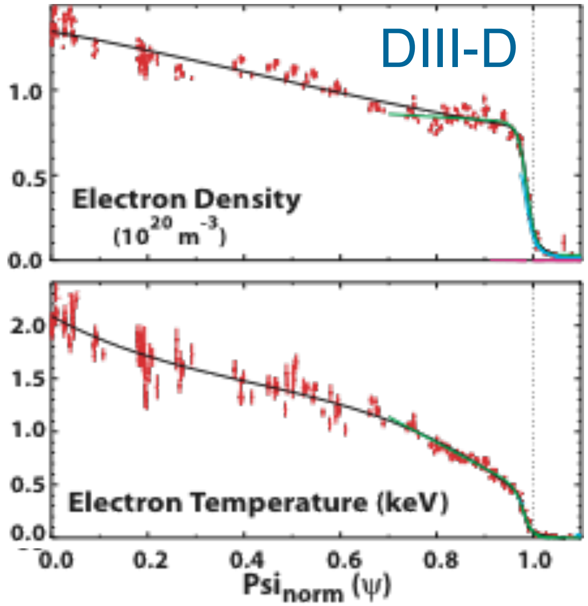
- **At low density, pedestal is limited by kink/peeling modes with very little dependence on global β_N, p_{ped} increases with density** (note: plots above have $Z_{eff}=2$)
  - For ITER, this "low" density regime extends to quite high values (12-18 10^{19} m^{-3})
  - This is regime where QH and RMP are accessible, promising for ELM control
  - However, pedestal height optimizes at densities above the Greenwald limit!
    - Studied range of density is 6.5-10.5. Optimal density for high pedestal is ~12-18 depending on case
- **At higher density, peeling-ballooning mode stability is quite sensitive to global Shafranov shift (ie β_N)**
  - High performance regimes in existing devices generally operate near optimal density
  - **How close ITER can get to this optimal density very important (physics of Greenwald limit?)**

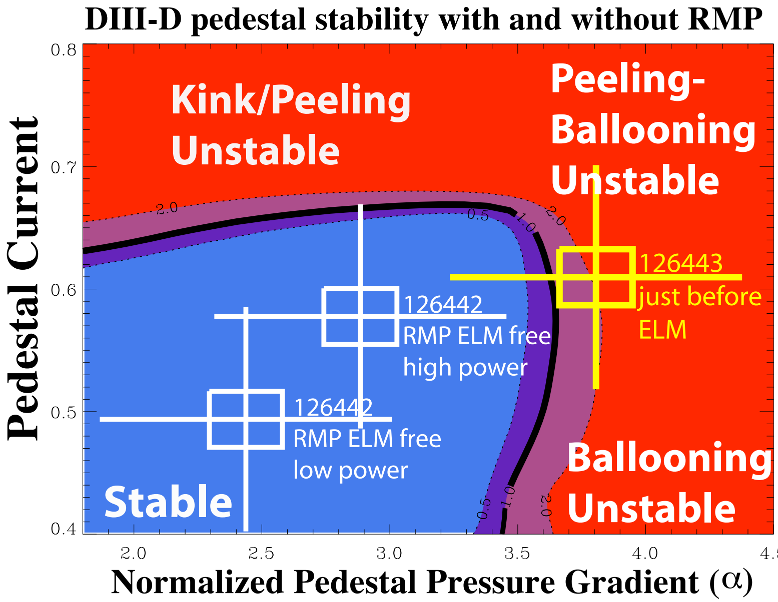
Summary: EPED Pedestal Model Tested on JET and Other Devices, Used to Predict ITER ISM Cases

- **Predictive model combines non-local Peeling-Ballooning and near-local KBM physics** *P.B. Snyder et al Phys Plas **16** 056118 (2009), NF **49** 085035 (2009), NF **51** 103016 (2011)*
  - Both constraints directly calculated, and each can be independently tested
  - No free or fit parameters, reasonably efficient (~1-20 CPU hrs/case)
- **Model successfully tested against existing machines over a wide range of parameters, including dedicated experiments**
  - JET study finds ~20% agreement with EPED model, consistent with observed pedestal variation with global beta, triangularity and density in hybrids
  - Good quantitative agreement found in studies on 5 tokamaks, more than 250 total cases studied with ~20% agreement in height and strong correlation (*r*~0.9)
- **EPED model used to predict and optimize the pedestal in ITER**
  - Hybrid and reference cases studied over range of density and β_N
    - EPED1 used in most cases, spot-checked with EPED1.63, similar results
  - $\beta_{N,ped}$~0.6-0.8, $\Delta_{\psi ped}$~0.04-.045; $\beta_{N,top}$~0.75-1, $\Delta_{\psi top}$~0.055-.07, Ψ_{Ntop}~0.93-0.945
  - Optimizes at higher density and Shafranov shift
    - Physics of the Greenwald density limit becomes an important question
    - *Important to look at pedestal pressure, not temperature, because going to lower density to raise T_{ped} will generally reduce fusion performance*
  - Understanding/optimization of pedestal provides a powerful lever for ITER to achieve and exceed its performance goals *(P_{fus}~p_{ped}^2)*

Extra Slides

Peeling-Ballooning Model Extensively Validated Against Observation

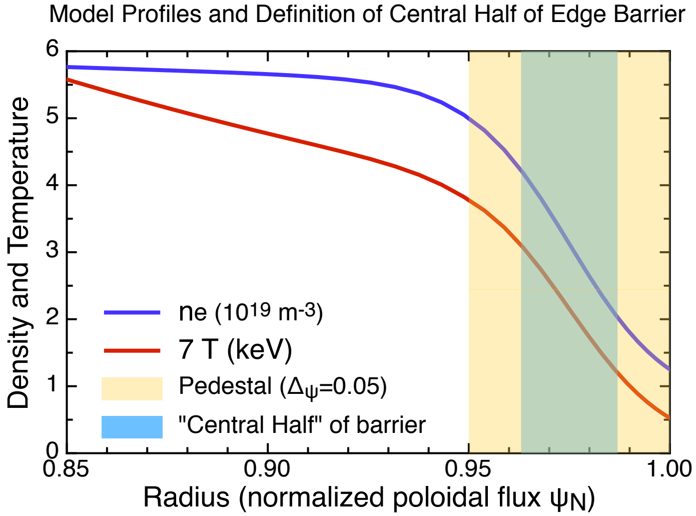


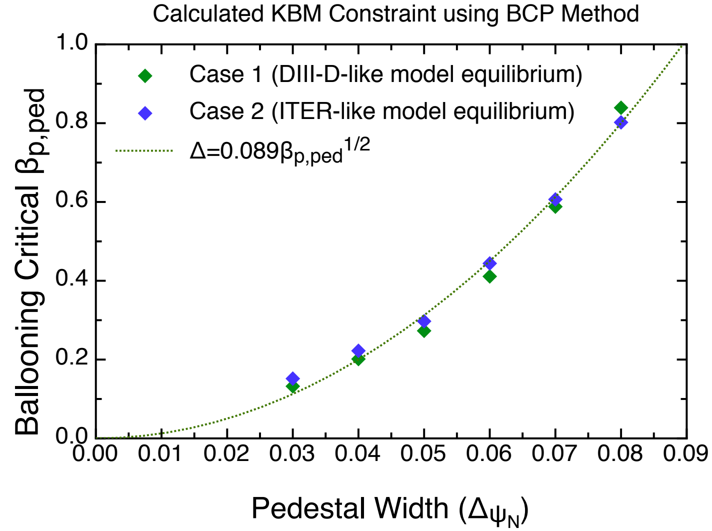


- **High resolution measurements allow accurate reconstructions and stringent tests of P-B pedestal constraint & ELM onset condition**
- **Pedestal constraint and ELM onset found to correlate to P-B stability boundary** ***[Multiple machines, >200 cases studied, ratio of 1.05 ± 0.19 in 39 discharges]***
- **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

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





"Ballooning critical pedestal" calculations to quantify KBM constraint

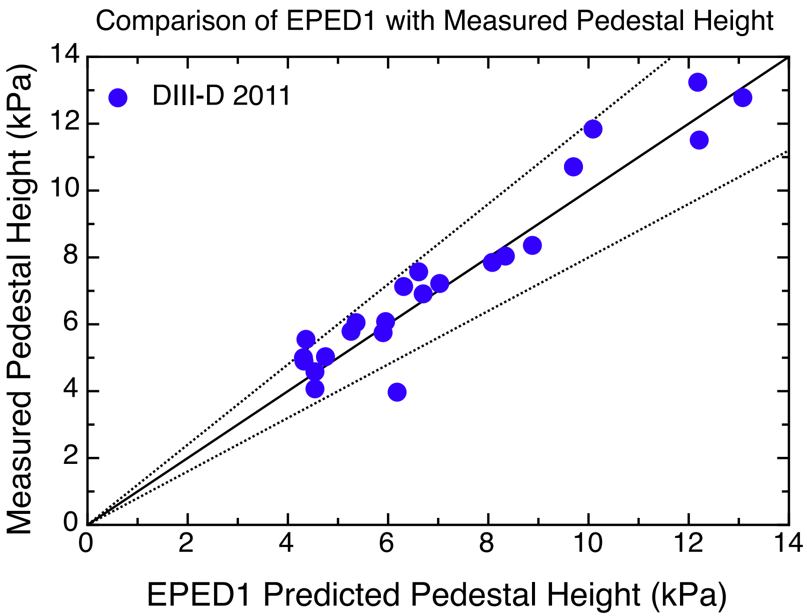
- Model equilibria used to integrate local KBM constraint
- "ballooning critical" when central half of edge at or beyond MHD critical gradient
- Find expected dominant dependence: $\beta_{p,ped} \sim \Delta^2_{\psi_N} \Rightarrow \Delta_{\psi_N} \sim \beta^{1/2}_{p,ped}$
- Lump weak dependencies into G function, calculate <G>~0.07-0.1 for standard aspect ratio tokamaks (0.084 ± 0.10 for ensemble of 16 cases), collisionality dependence

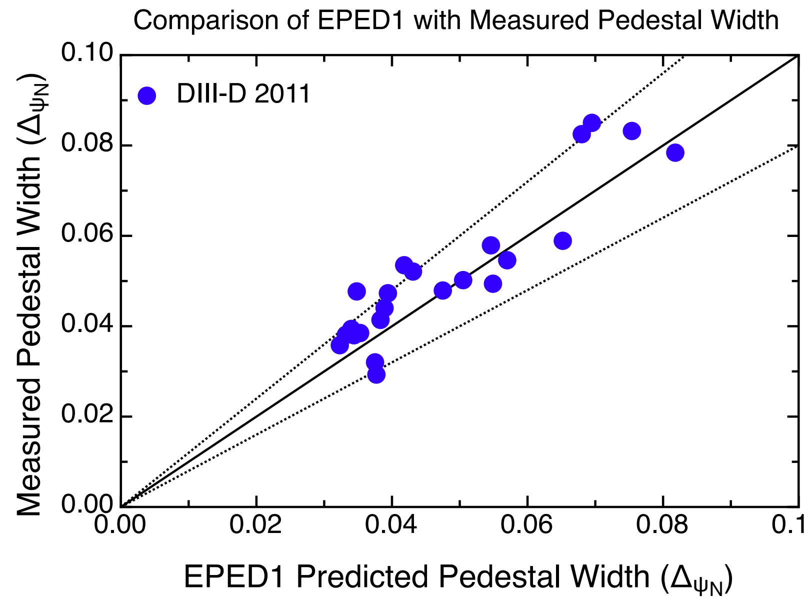
$$\Delta_{\psi_N} = \beta^{1/2}_{p,ped} G(\nu_*, \varepsilon \ldots)$$

EPED1.6: Directly calculate for each case
EPED1: Simplified, <G>=0.076

KBM constraint consistent with many observations, eg Z. Yan PRL11, Groebner10, Snyder09

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





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

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

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

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

-Ratio of predicted to observed pedestal height: 0.98 ± 0.15, corr *r*=0.96

-Ratio of predicted to observed pedestal width: 0.94 ± 0.13, corr *r*=0.91

-Ratio of predicted to observed pedestal average pprime: 1.05 ± 0.16, corr *r*=0.95