Using Pedestal Physics Coupled to the Boundary to Close the Integrated Tokamak Exhaust and Performance (ITEP) Gap

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Acknowledgments: Jerry Hughes[3], Orso Meneghini[2], Wayne Solomon[2], Howard Wilson[4], C-Mod team, DIII-D team

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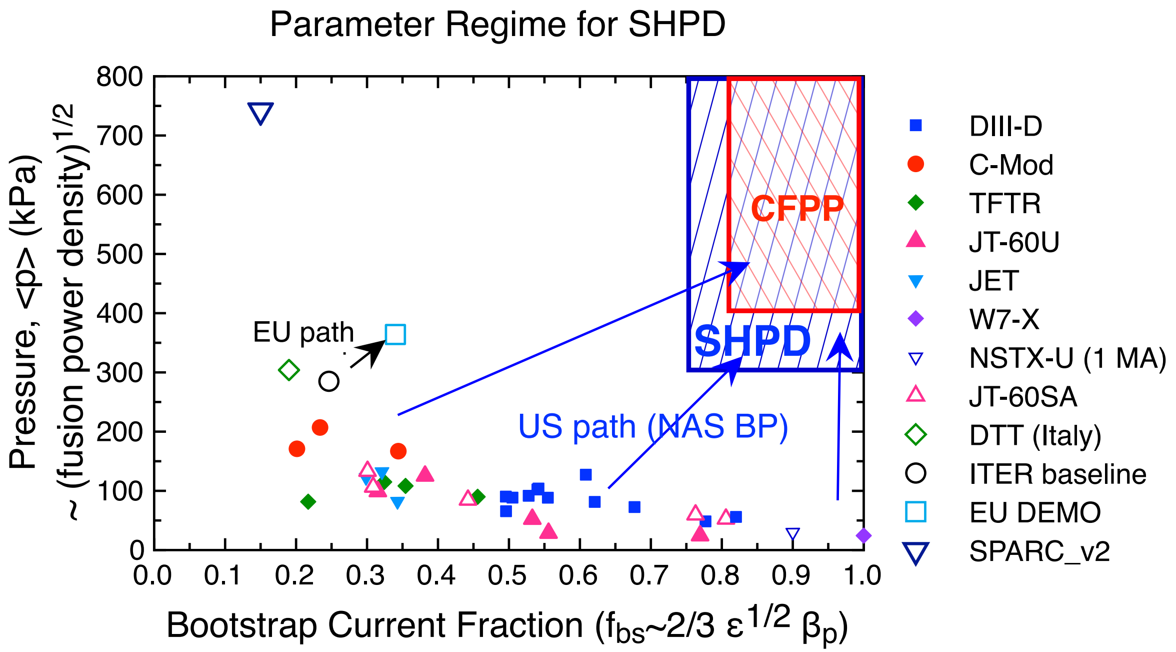
BOUT++ Workshop
11 January 2023

Achieving High Fusion Power Density (~<p>^{2}) and Bootstrap Fraction Essential for Compact Sustained Tokamak Vision



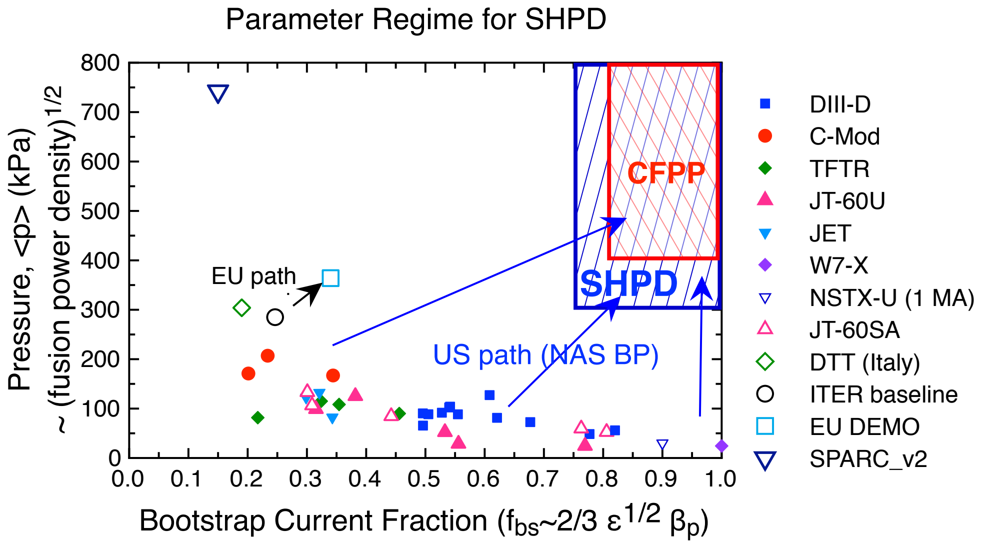
Solid symbols = achieved, Open symbols = projected

- National Academies Burning Plasma Report: Sustained High Power Density (SHPD) device (w/ ITER, materials, tech, theory, discovery…) leading to Compact Fusion Pilot Plant (CFPP) with net electricity (device with SHPD-like mission re-named EXCITE in FESAC Long Range Plan, ITEP gap to CFPP params)

- Fusion power density ~<p>^{2}. A CFPP with power 1-2x ITER (~500-1000 MW) at ½ to 1/4 the volume, requires <p> ~400-800 kPa (ITER baseline ~ 285 kPa). High <p> implies high n_e, low CD efficiency

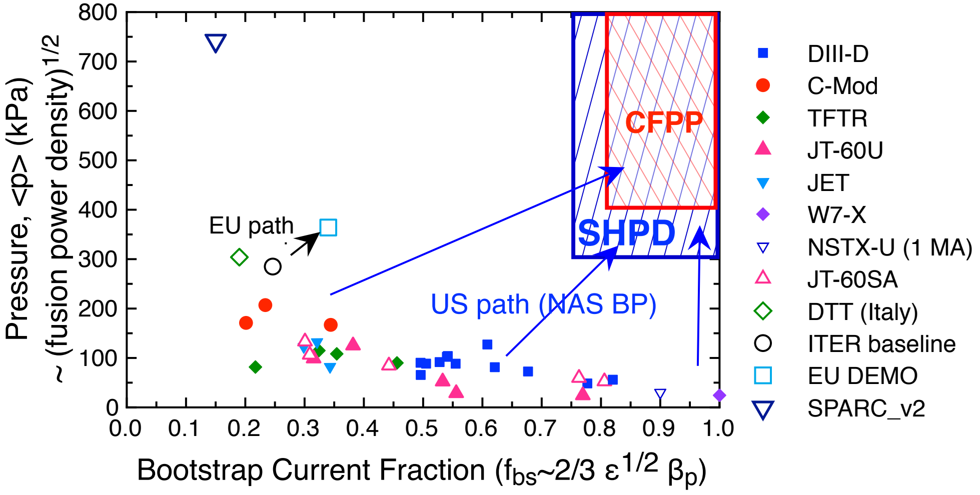
- For a compact, sustained device to produce net electricity, it must minimize recirculating power which reduces net electricity and increases power handling requirements -> high f_{bs}

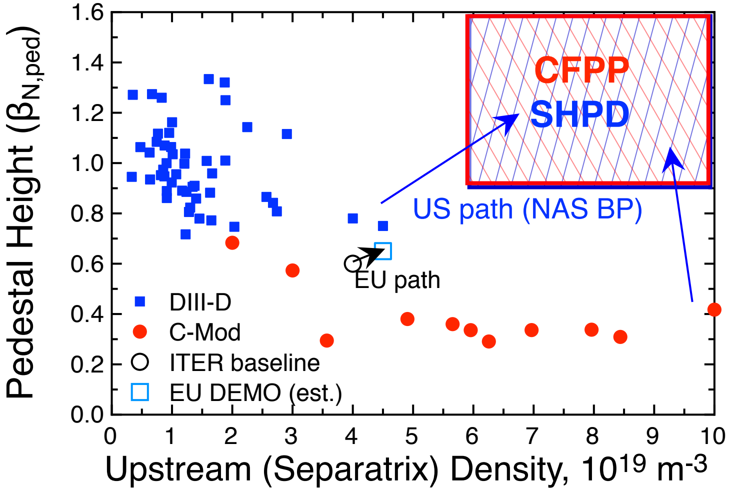
The challenge: Achieving high fusion power density (~<p>^{2}) and bootstrap fraction essential for compact sustained tokamak vision


Parameter Regime for SHPD

- Simultaneous high <p> and f_{bs} requires optimization of both physics and technology (eg HTS): High B_T and β_N~ C $\beta_{N,ped}$ simultaneously (<p>~ $\beta_N B_T B_p$, f_{bs}~ $\beta_N B_T / B_p$)
  - <p>: C-Mod 208 kPa, DIII-D/JET/TFTR/JT-60U/JT-60SA ~70-140 kPa, ITER BL 285 kPa, **CFPP 400-800 kPa**
  - B β_N: Existing 5-11 T, ITER base ~9-11 T, **CFPP 20-35 T**

The challenge: Achieving high fusion power density (~<p>^{2}) and bootstrap fraction essential for compact sustained tokamak vision – **Must be compatible with a viable exhaust solution**

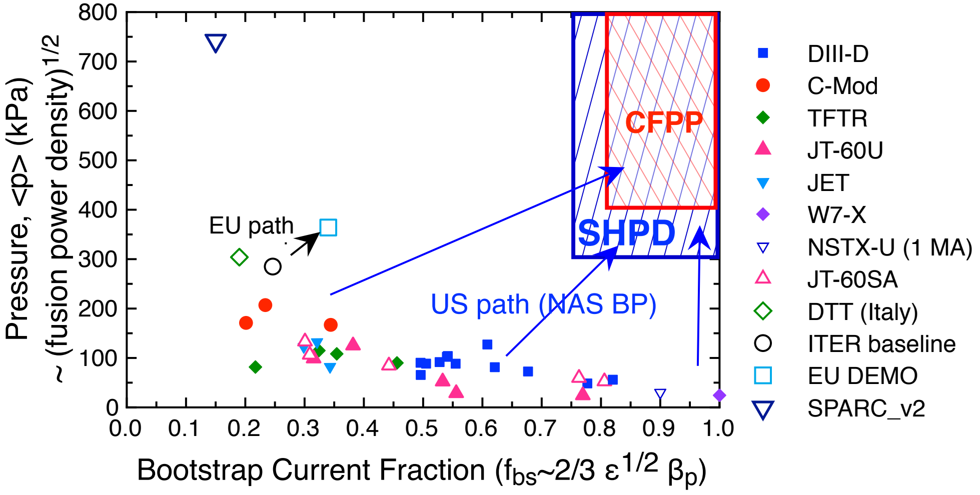

Parameter Regime for SHPD


Compatibility of High Pedestal β_N with High Separatrix Density

- Compact devices have high heat loads on material surfaces. High separatrix (upstream) density and pressure facilitates radiative power dissipation, cool divertor
  - Must be consistent with high core performance, typically implies high pedestal due to stiff core transport
- Optimize pedestal to achieve required <p>~C p_{ped}, β_p~ C $\beta_{p,ped}$ ($\beta_{N,ped}$), n_{sep}
  - Study optimal aspect ratio and shape for SHPD/EXCITE & Compact Fusion Pilot Plant (CFPP)

The challenge: Achieving high fusion power density (~<p>^{2}) and bootstrap fraction essential for compact sustained tokamak vision – **Must be compatible with a viable exhaust solution**

Parameter Regime for SHPD



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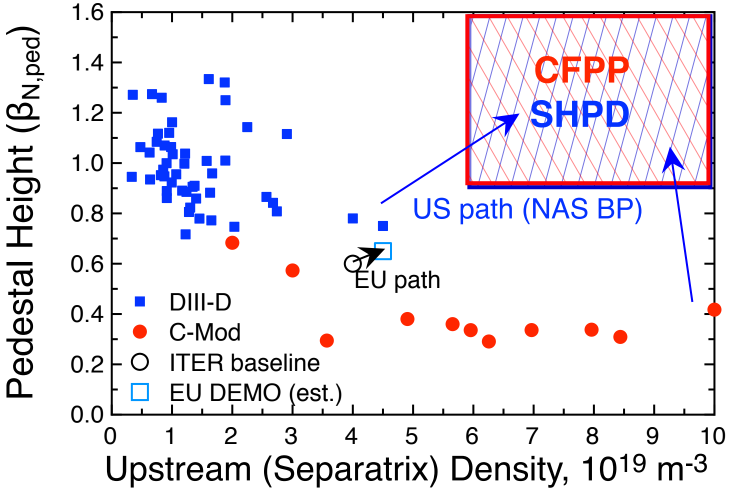
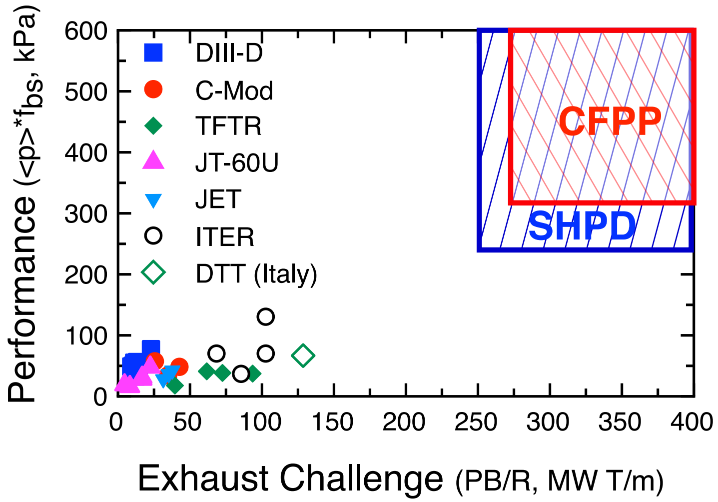


Exhuast & Performance Regime for CFPP/SHPD



- Compact devices have high heat loads on material surfaces. High separatrix (upstream) density and pressure facilitates radiative power dissipation, cool divertor
- Core-edge solution must be consistent with high core performance, at much larger PB/R than existing devices
  - <p>: C-Mod 208 kPa, DIII-D/JET/TFTR/JT-60U/JT-60SA ~70-140 kPa, ITER BL 285 kPa, **CFPP 400-800 kPa**
  - B β_N: Existing 5-11 T, ITER base ~9-11 T, **CFPP 20-35 T**
  - PB/R: Existing ~10-100 MW T/m, ITER 60-110 MW T/m, **CFPP ~ 275-400 MW T/m**
  - Pulsed device relaxes constraint on f_{bs} (not <p> or PB/R) in exchange for repetitive stress, low q

The Approach: Self-consistent modeling of the pedestal, scrape-off-layer and divertor system

- What's been done in the past
  - Standalone pedestal (eg EPED) and coupled pedestal-core modeling (eg EPED/TGLF/NEO) to predict and optimize pedestal-core performance
    - Optimize pedestal (EPED), via shaping, aspect ratio, q etc., to achieve required $<p>\sim C\ p_{ped}$, $\beta_p \sim C\ \beta_{p,ped}$ $(\beta_{N,ped})$
  - Boundary modeling (eg SOLPS) to determine requirements for a cool, radiative divertor
- The plan for the future
  - Self-consistent coupling of (core-)pedestal-divSOL models
  - Development of practical equations valid for coupled pedestal-divSOL system
- This presentation
  - Initial progress and results from coupled pedestal-divSOL (EPED-SOLPS) modeling

Use the EPED Model to Predict and Optimize p_{ped}, $\beta_{p,ped}$, $\beta_{N,ped}$

EPED combines insight and calculations from GK/GF/NEO ($\rho \sim \lambda << L$), local MHD ($\rho << \lambda << L$), global MHD and xMHD ($\rho << \lambda \sim L$) *P.B. Snyder et al Phys Plas **16** 056118 (2009), NF **51** 103016 (2011)*

- 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 diamagnetic 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
  - **BOUT++ has been used to test this and found similar results**

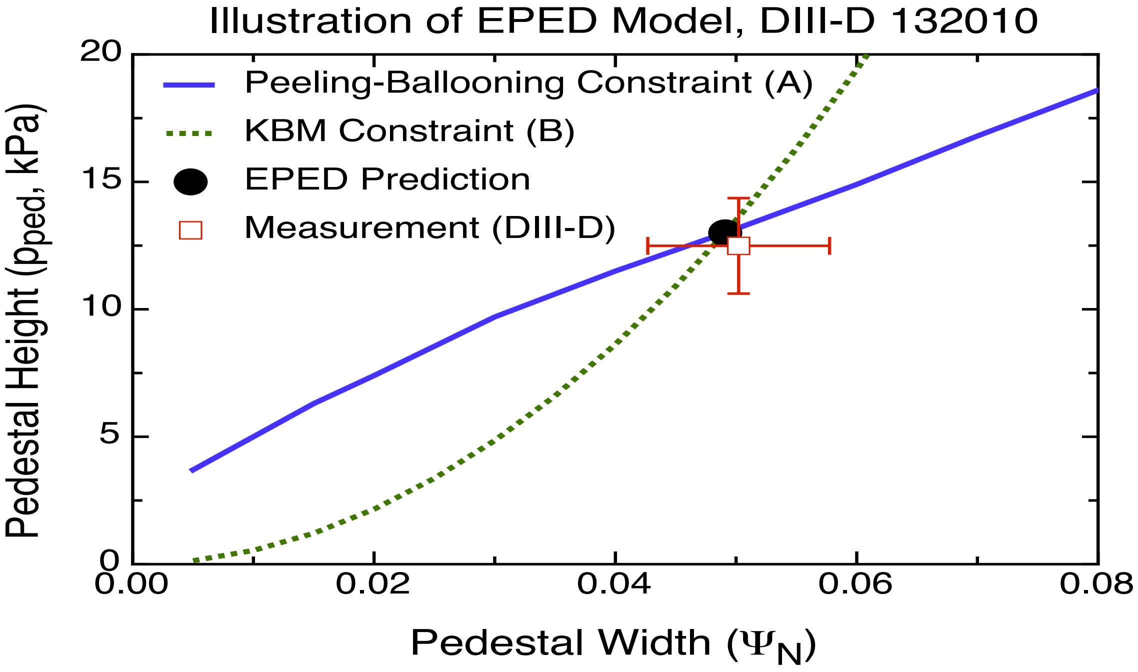
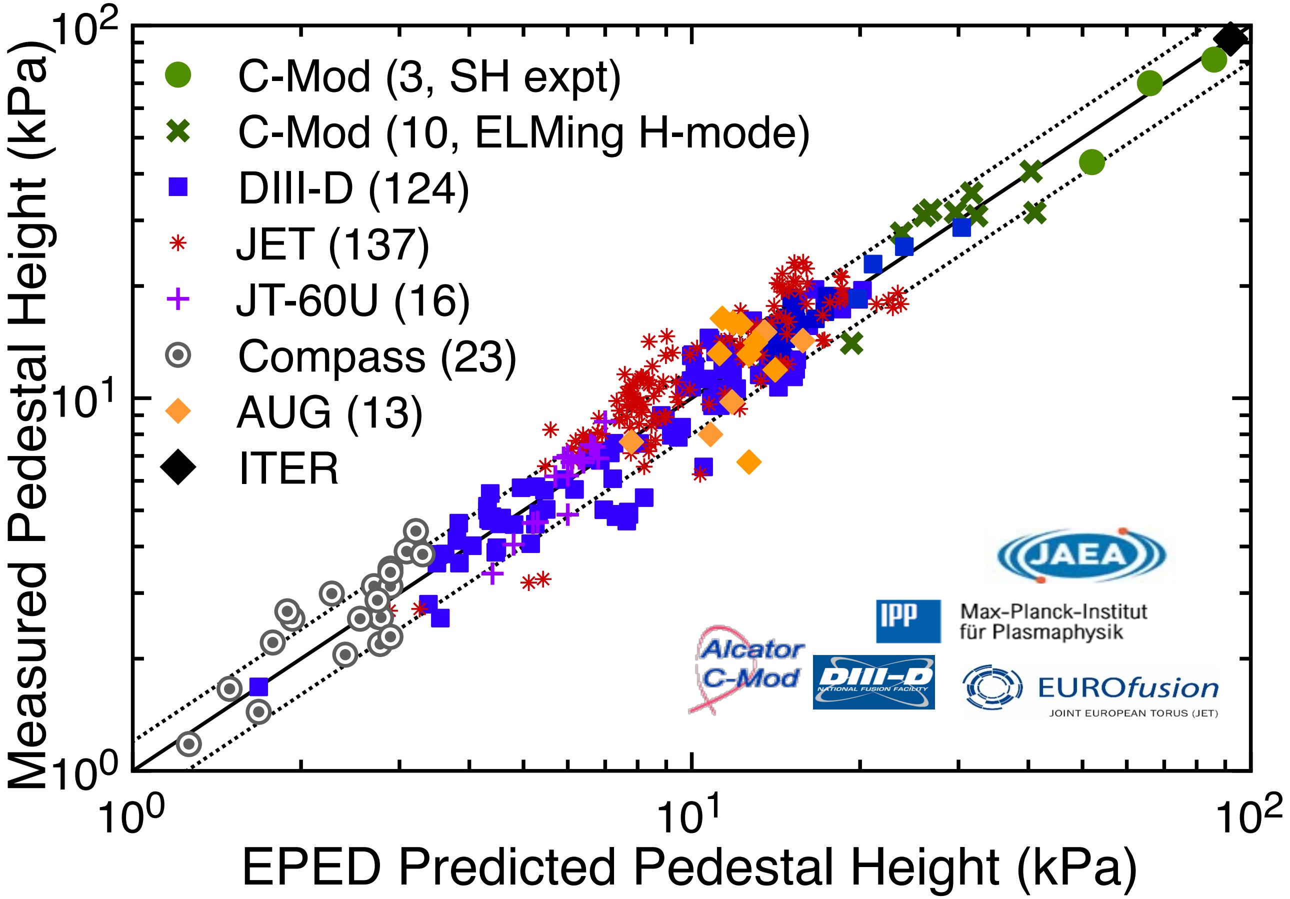


Illustration of EPED Model, DIII-D 132010

- **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

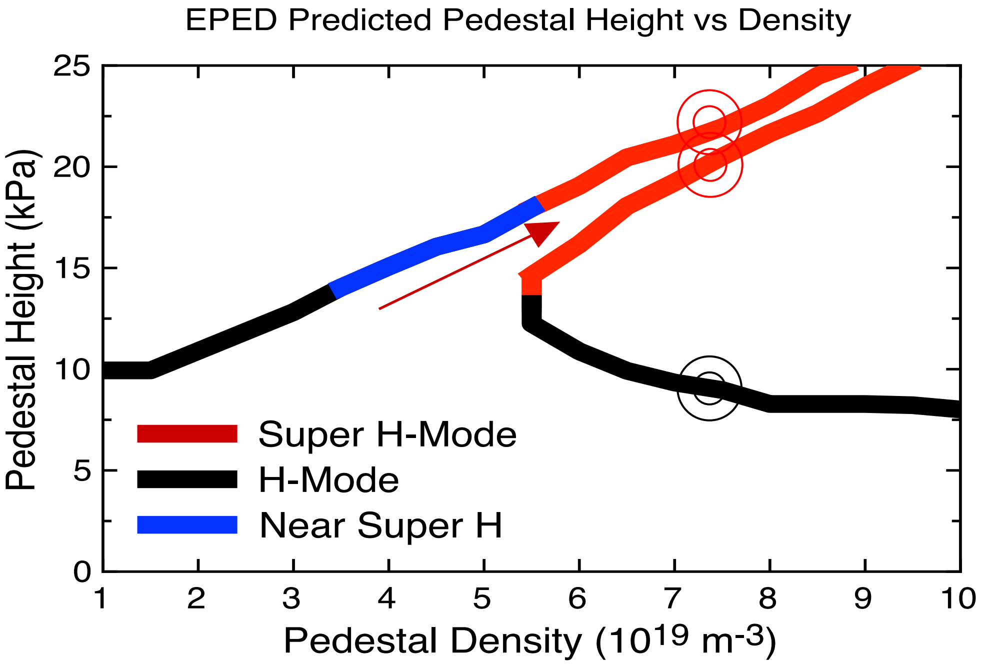
Numerous Experimental Tests of EPED Conducted

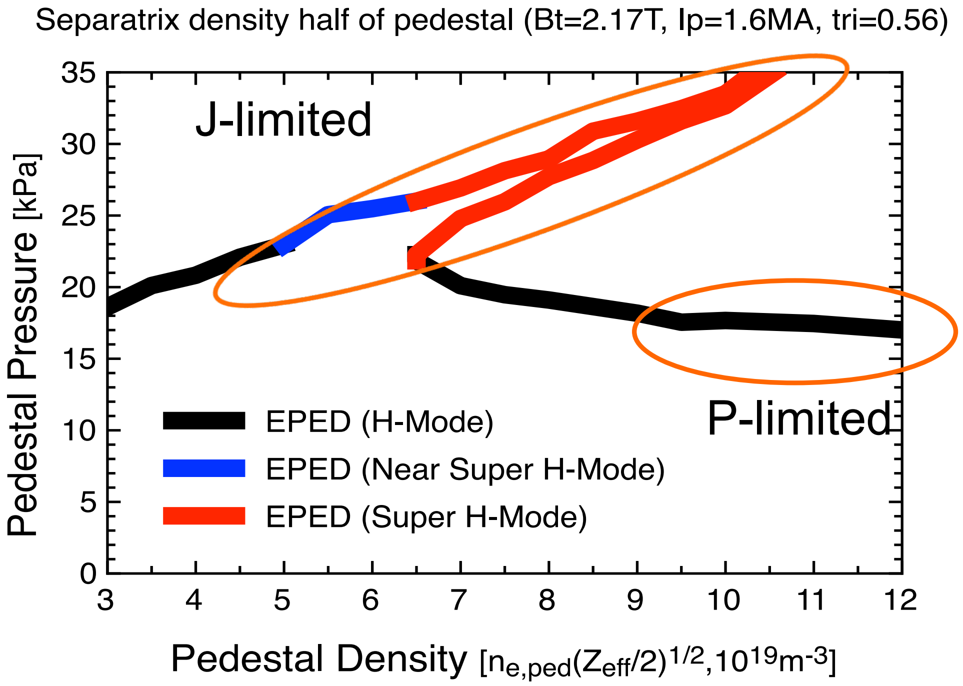


Validation efforts coordinated with ITPA pedestal group, US JRT

- >800 Cases on 6 tokamaks
- Broad range of density (~1-24 $10^{19}m^{-3}$), collisionality (~0.01-4), $f_{GW,ped}$ (~0.1-1.0), shape (δ~0.05-0.65), q~2.8-15, pressure (1.2 - 80 kPa), β_N~0.6-4, B_t=0.7-8T
- Includes experiments where predictions were made before expt
- Typical σ~20-25%
- No significant variation in level of agreement with rhostar (other ITER/CFPP dimensionless parameters matched in dataset)

EPED: Peeling-limited pedestals including "Super H" provide promising solution to core-edge problem

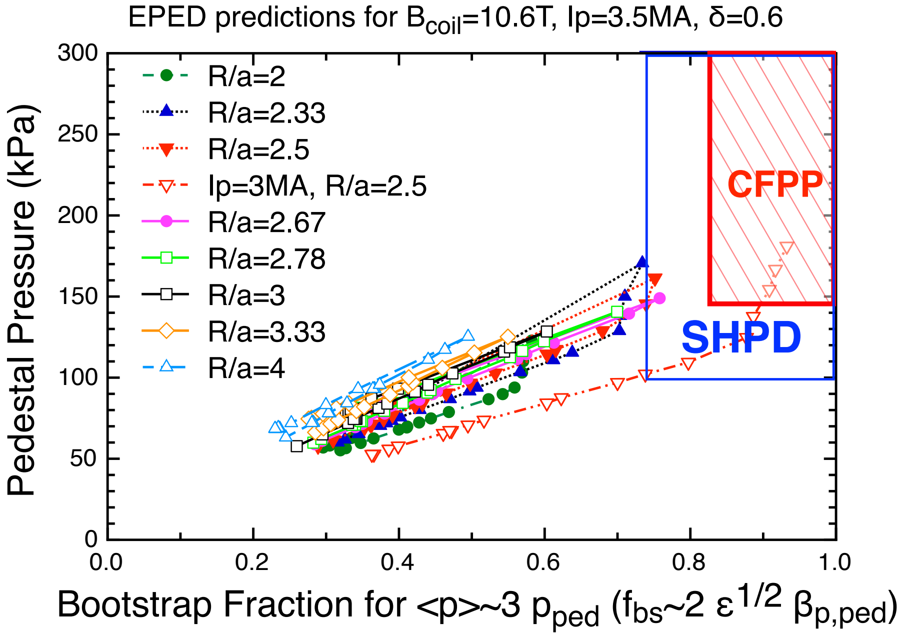

EPED Predicted Pedestal Height vs Density

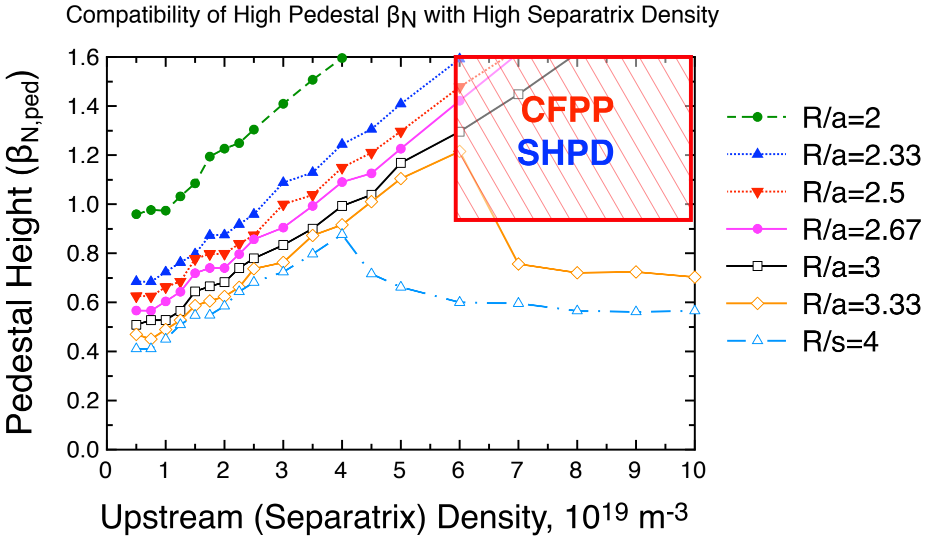

Separatrix density half of pedestal (Bt=2.17T, Ip=1.6MA, tri=0.56)

- Super H-Mode reached by dynamic optimization of the density *[Solomon PRL14, SnyderNF15]*
- Record pedestal pressure (80 kPa on C-Mod) and high fusion performance ($Q_{DT,eq,peak}$~0.54, $Q_{DT,eq,sustained}$~0.15 on DIII-D) in SH experiments *[Hughes NF18, Snyder NF19]*
- Recent DIII-D experiments achieved SH in JET-compatible shapes *[Knolker PoP20]*
- SH and other peeling-limited regimes resilient to gas and impurity puffing to achieve high separatrix density, cooler divertor *[Wilks NF21]* – ***degradation of ballooning limited pedestals at high density expected***

EPED standalone for initial exploration: Strong shaping (δ~0.6), R/a~2.3-2.7, optimal density and q95 predicted to enable SHPD/EXCITE & CFPP goals

- Fix B_t at coil (10.6T), and distance from coil to plasma, optimize R/a
    - Scan density – optimal value is near transition from peeling-limited to ballooning-limited pedestal
- Broad optimum for R/a~2.3-2.7
- Further optimization of Bt/Ip to achieve SHPD/CFPP parameters
- Further increase in Bt at coil (eg HTS) enables higher pressure or higher f_{bs} at given pressure
- Maintains high pedestal at high separatrix density





SOLPS-ITER simulations of divertor and SOL to predict and optimize exhaust solution

- SOLPS-ITER models coupled fluid plasma/neutral transport
  - 2D: radial+poloidal
  - Collisional transport parallel to magnetic field
  - Ad-hoc radial transport coefficients
  - Comprehensive atomic reaction rates (ionization, radiation, etc)
  - Used to predict, e.g., divertor plasma density, temperature, heat flux; how much density/impurity concentration is required for detachment
- Limitation: no physics-based radial transport model
  - $\chi_e = \chi_i$ adjusted to yield $\lambda_q^{SOLPS} \sim \lambda_q^{Eich}$ or ballooning critical SOL alpha~2.5
  - D likewise tuned based on experiments

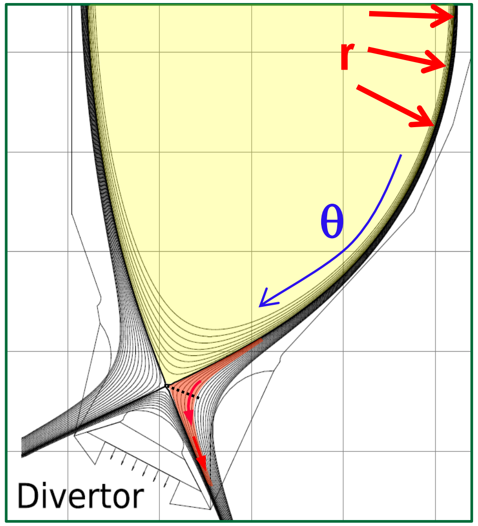
Neutral transport

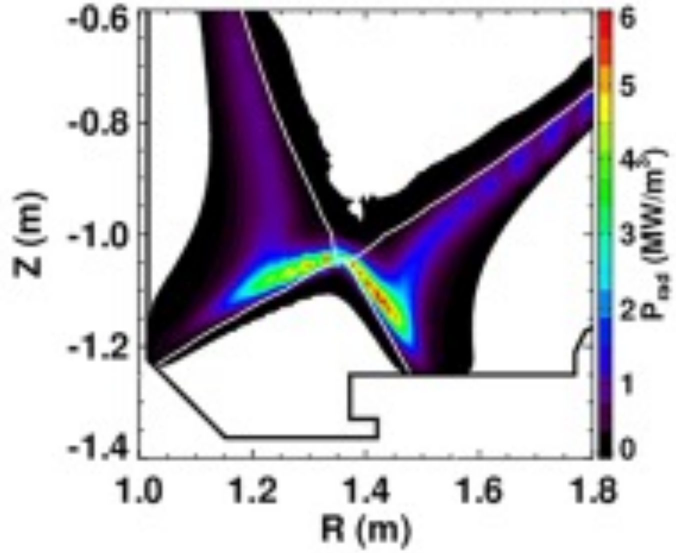
$$\frac{\partial}{\partial t} n_i + \nabla \cdot \boldsymbol{\Gamma}_i = \boxed{S_p}$$

$$\frac{\partial}{\partial t} m_i n_i v_{i||} + \nabla \cdot \left(m_i n_i v_{i||} \boldsymbol{v}_i + (p_i + p_e)\bar{\bar{I}} + \boldsymbol{b} \cdot \bar{\bar{\pi}}_i \right) = \boxed{S_{||,mom}}$$

$$\frac{3}{2}\frac{\partial}{\partial t} p + \nabla \cdot \left(\boldsymbol{h} + \frac{3}{2} p \boldsymbol{v} \right) + p \nabla \cdot \boldsymbol{v} + \bar{\bar{\pi}} : \nabla \boldsymbol{v} - Q = \boxed{S_z} + \boxed{S_E + \frac{1}{2} m v^2 S_p - \boldsymbol{v} \cdot \boldsymbol{S}_{mom}}$$

Impurity transport

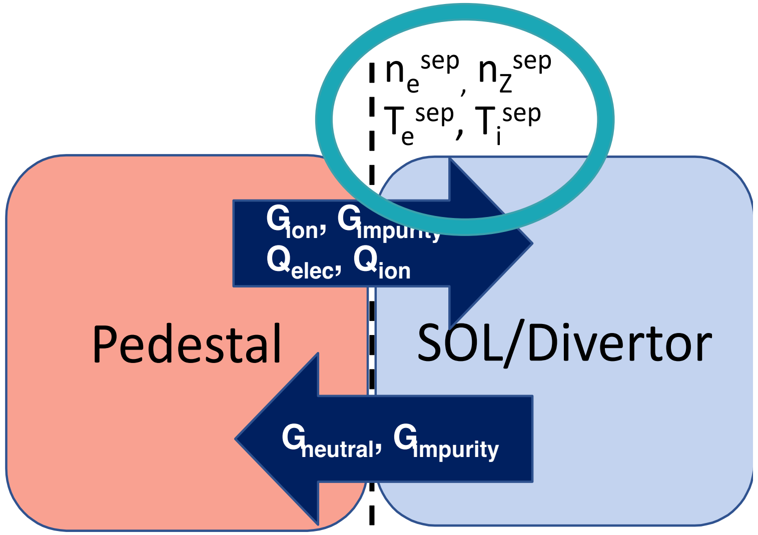


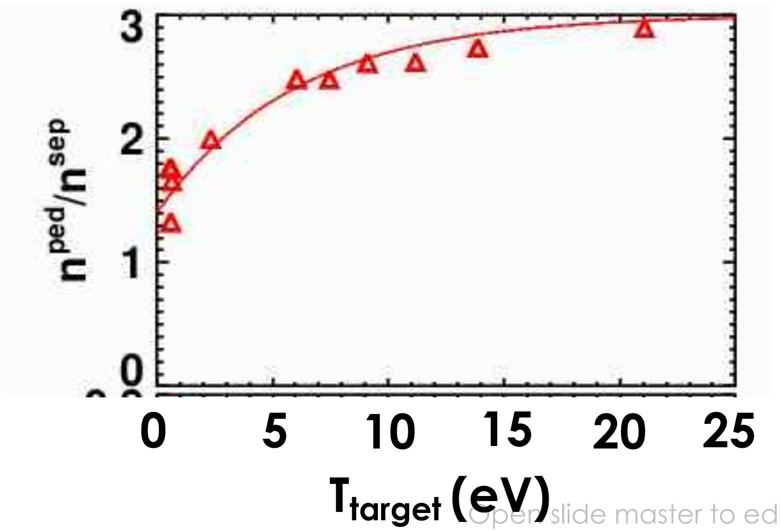


Coupling EPED to SOLPS-ITER for Self-Consistent Prediction of the Pedestal + SOL / Divertor

- Standard EPED: designed to be independently predictive
  - Assumes separatrix conditions are not known (and uses benign values in model equilibria, $n_{e,sep}=n_{e,ped}/4$, T_{sep}=75eV)
- Modified EPED for pedestal-SOL coupled model
  - Flexible separatrix conditions, taking $n_{e,sep}$ and T_{sep} values calculated by SOLPS-ITER
  - In the pedestal, profiles (and transport coefficients for SOLPS) determined by modified EPED, iterate EPED-SOLPS to convergence
- $n_{e,ped}$ remains an EPED input, and can be used as a control or optimization parameter, or
  - Long-term goal to predict it based on separatrix conditions and enhanced EPED model
  - **Present approach for closed-loop workflow: empirical ratio of $n_{e,ped}$ / $n_{e,sep}$ as function of T at target *[J Canik HMWS22]***
- Coupled EPED-SOLPS workflow developed using IPS-FASTRAN framework *[JM Park et al PoP 25 012506 (2018).]*

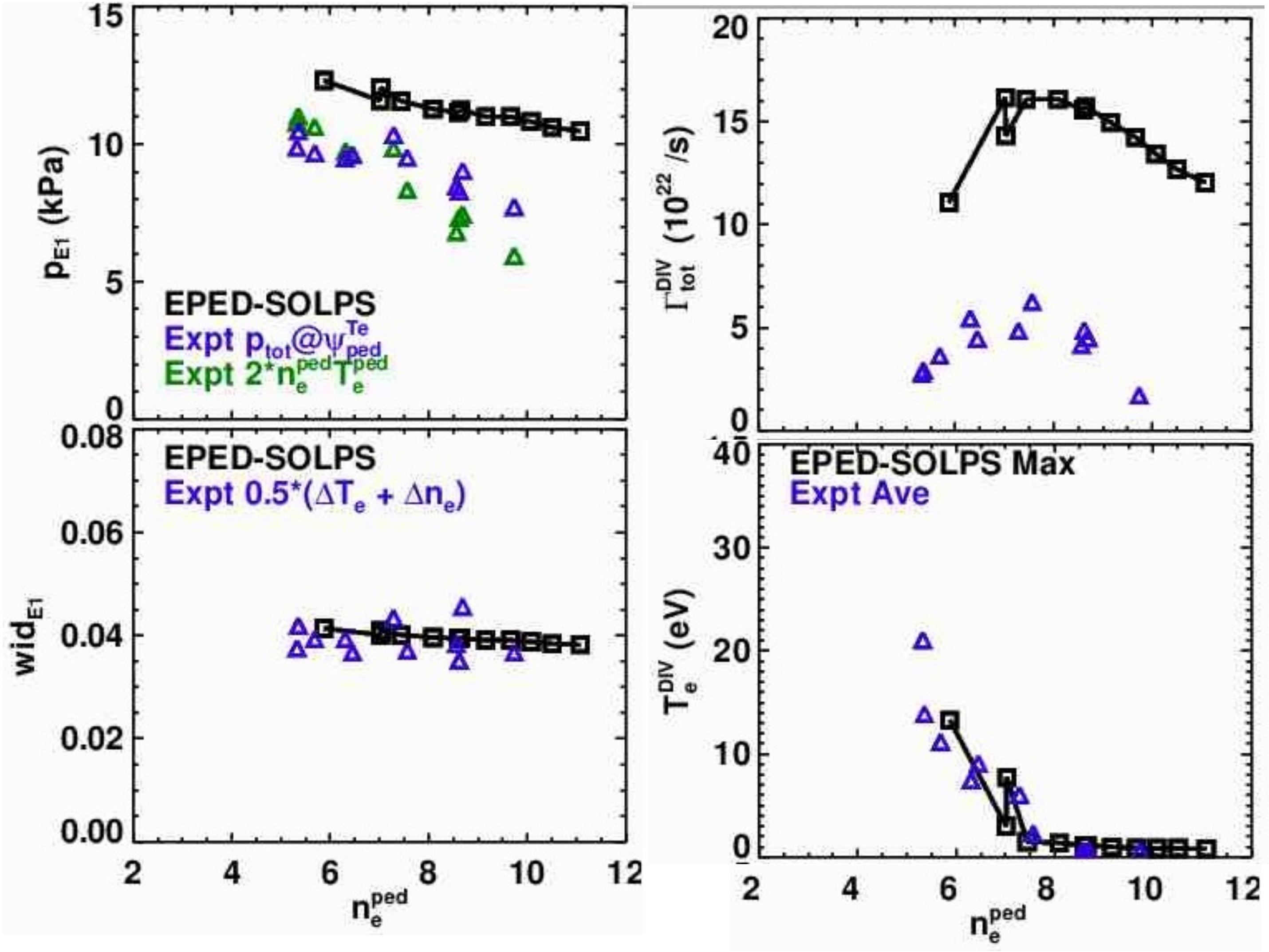
Link via separatrix conditions from SOLPS-ITER





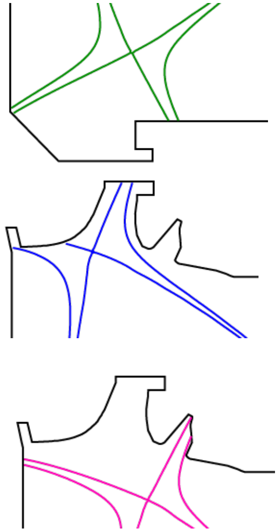
Integrated workflow captures general trends observed during detachment experiments

- Pedestal degradation with increasing density
- Pedestal density at which detachment occurs
  - Rollover of ion flux to divertor
  - Divertor temperature reduction to $T_e < 5$eV
- Caveat: known pedestal physics has not been fully incorporated
  - Pedestal not fully consistent with core plasma
    - In expt β_N drops somewhat at high density, which impacts pedestal
    - Workflow would need to include core simulation to be fully self-consistent
  - Strongly ballooning-limited pedestal (more later) should really use refined model of diamagnetic stabilization
    - Not implemented, will be soon

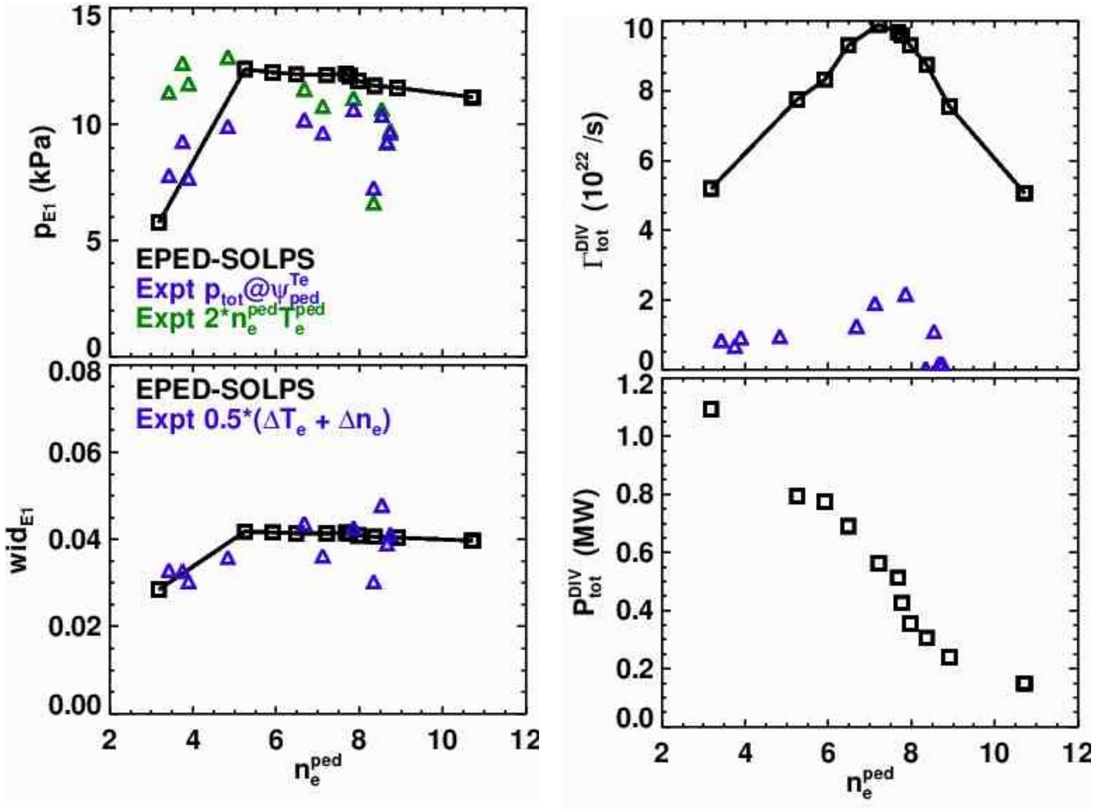


Integrated workflow captures general trends observed during detachment experiments

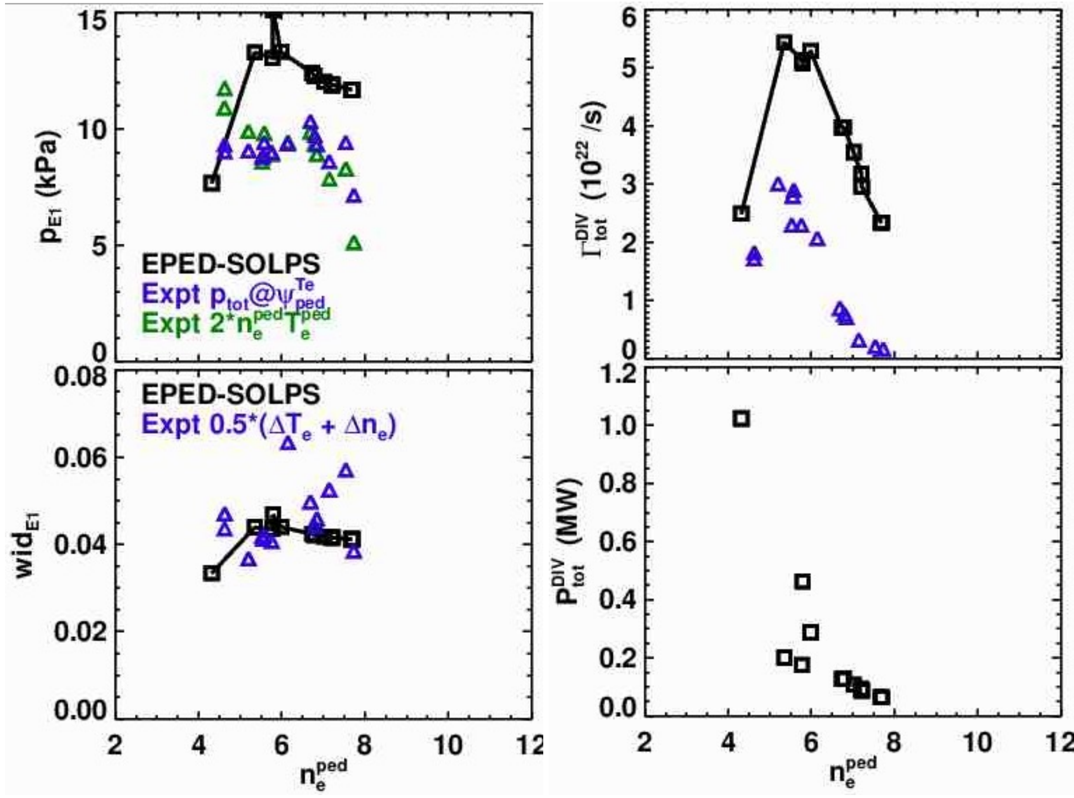
Range of closure:
shelf → upper → SAS



SAS



Upper

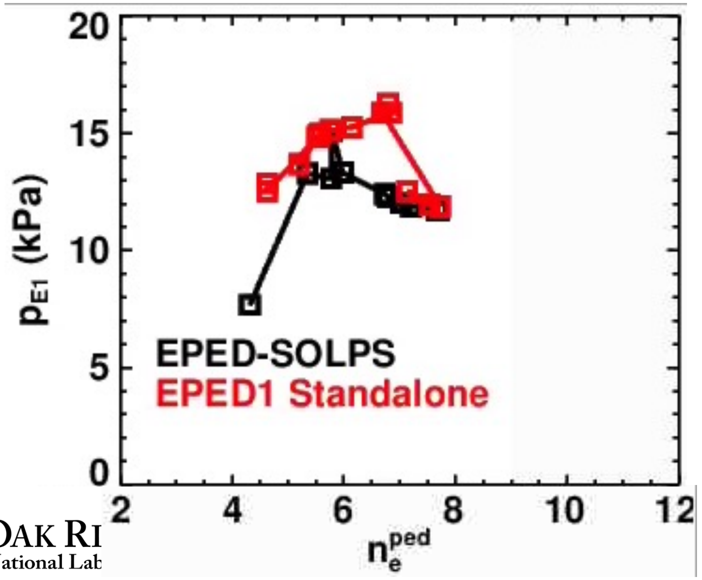


Canik, PSI '22

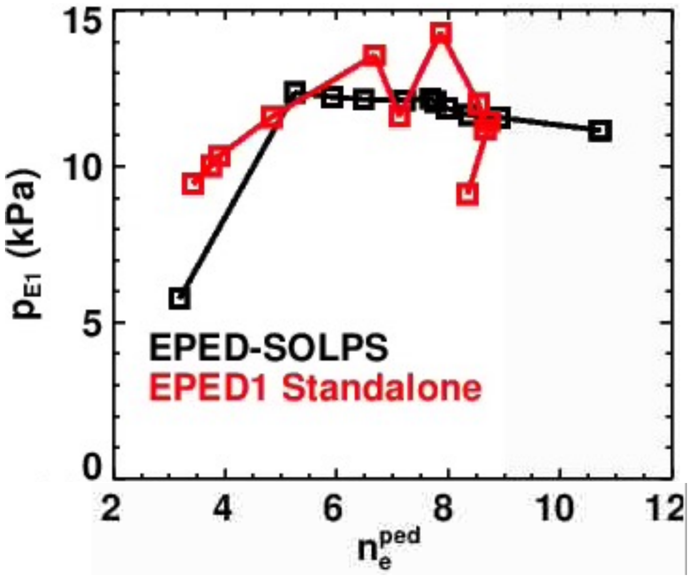
Impact of self-consistency: access to peeling vs ballooning limited pedestal in DIII-D regime

- Accessing peeling-limited pedestal thought to be key to core-edge integration
  - High pedestal pressure at high densities that are favorable for divertor
- Standalone EPED1 calculations show transition from peeling-limited to ballooning-limited as n_e^{ped} is increased, whereas coupled workflow is ballooning-limited throughout
  - Standalone accounts for changes (e.g., β_N) that coupled workflow doesn't (consistency with core plasma)
  - Need to revisit and do full KBM calculations for non-standard separatrix assumptions
  - Need to implement improved diamagnetic stabilization model

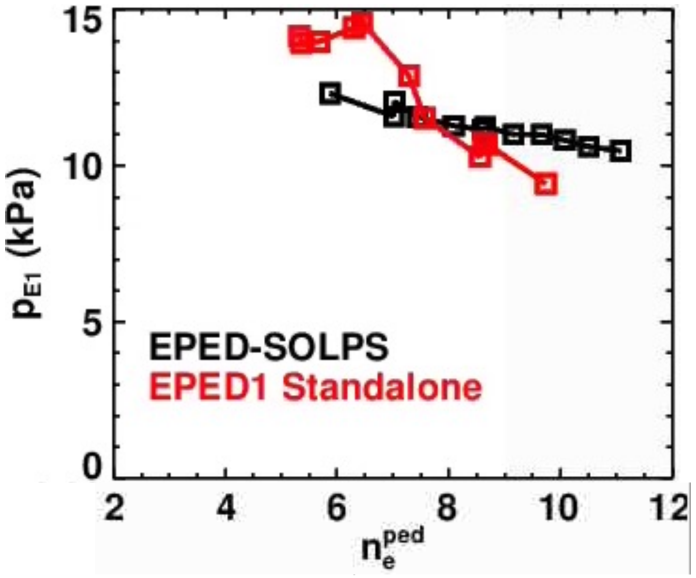
USN



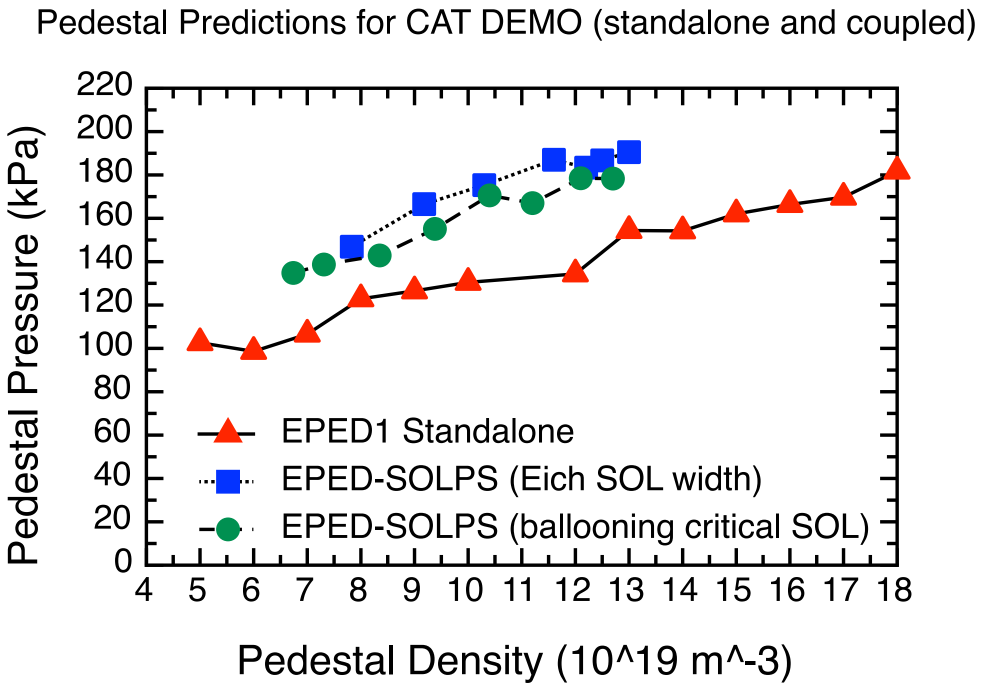
SAS



LSN



Initial EPED-SOLPS Study of Fusion Pilot Plant Conditions



SOLPS-ITER
Eich SOL width

n_{sep19}	n_{ped19}	T_{sep}
4.16	7.83	505
5.09	9.18	463
5.90	10.32	432
7.05	11.55	387
7.46	12.19	371
7.81	12.55	356
8.21	13.04	343

SOLPS-ITER
Ball crit SOL width

n_{sep19}	n_{ped19}	T_{sep}
2.88	6.74	378
3.49	7.31	351
4.22	8.35	327
4.89	9.38	309
5.54	10.42	294
6.11	11.22	283
6.71	12.05	273
7.17	12.69	265

- Study based on CAT-DEMO parameters *R. Buttery, J.M. Park et al Nucl. Fusion **61** 046028 (2021):*
  - Bt=7T, Ip=9.6MA, R=4m, a=1.3m, kappa=2, tri=0.6, β_N=3.6
- SOLPS-ITER n_{esep} and T_{sep} for different SOL models (Eich and ballooning critical alpha~2.5). $n_{e,ped}$ /$n_{e,sep}$ vs T_{target} formula
- Coupled EPED-SOLPS predictions here predict **higher** pedestal temperature and pressure than standalone EPED (in contrast to DIII-D cases)
  - Flattening of density gradient yields less bootstrap current at same pressure gradient, weaker drive for peeling modes
  - Collisionality remains very low because of high predicted separatrix temperature. So no pedestal degradation is predicted due to rising separatrix density (subject to accuracy of SOLPS predictions of Tsep)
  - Pedestal remains peeling limited at full range of density studied (unlike DIII-D or other existing devices)

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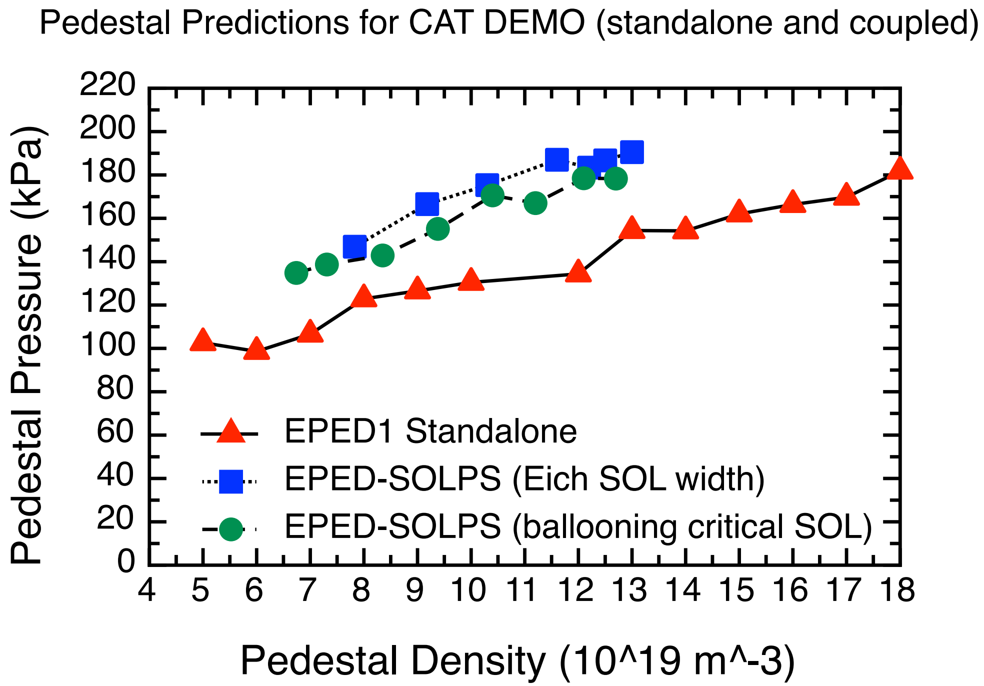

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- SOLPS-ITER n_{esep} and T_{sep} for different SOL models (Eich and ballooning critical alpha~2.5). $n_{e,ped}$ /$n_{e,sep}$ vs T_{target} formula
- This higher predicted pedestal pressure will translate into significantly higher predicted fusion performance for CAT-DEMO
  - Reaches expected parameter regime for a sustained FPP: $\beta_{N,ped}$ ~0.9, $n_{e,sep}$ ~ 8e19 m^{-3}
  - Also promising for QH mode and RMP ELM suppression (both of which appear have peeling-limited pedestals as a necessary, but not sufficient, condition)

Summary and Conclusions

- Simple model (EPED) predicts pedestal height to ~20-25% accuracy in many regimes. Coupling to core models enables initial global confinement prediction
  - Super H and similar regimes enable high T_{ped} and p_{ped}, consistent with high n_{sep} for core-edge integration
  - Initial studies find combination of strong shaping, optimal aspect ratio (R/a~2.3-2.7), density optimized for operation in or near Super H promising for Sustained, Compact Fusion Pilot Plant

- Initial workflow has been developed that couples pedestal (EPED) and SOL/divertor models (SOLPS)

- Self-consistent EPED-SOLPS calculations show promising agreement with experiment
  - Trends in the right direction, many parameters of interest within ~20%
  - More to do to improve model: consistency with core, diamag. stab. model, …
  - In DIII-D conditions, pedestal-SOL coupling raises collisionality near separatrix, transition from peeling-limited to ballooning limited pedestal at lower pedestal density, more pedestal degradation at high density (consistent with observations)
  - In Fusion Pilot Plant conditions (CAT-DEMO), pedestal-SOL coupling substantially **increases** predicted pedestal height and fusion performance. No transition to ballooning limited pedestal due to low collisionality even at high density. Flatter density profile in pedestal reduces bootstrap current, leading to higher pressure limit in peeling-limited regime

- Promising regime identified for EXCITE/FPP with peeling-limited pedestal, cold divertor target
  - Intermediate aspect ratio, high field, and strong shaping
  - Testable prediction that cold target conditions will **improve** pedestal/core confinement in this regime
  - Lots of opportunities for detailed exploration of pedestal/boundary in EXCITE/FPP with BOUT++