

Predicting the Pedestal in a Burning Plasma: Progress and Research Needs

Philip Snyder

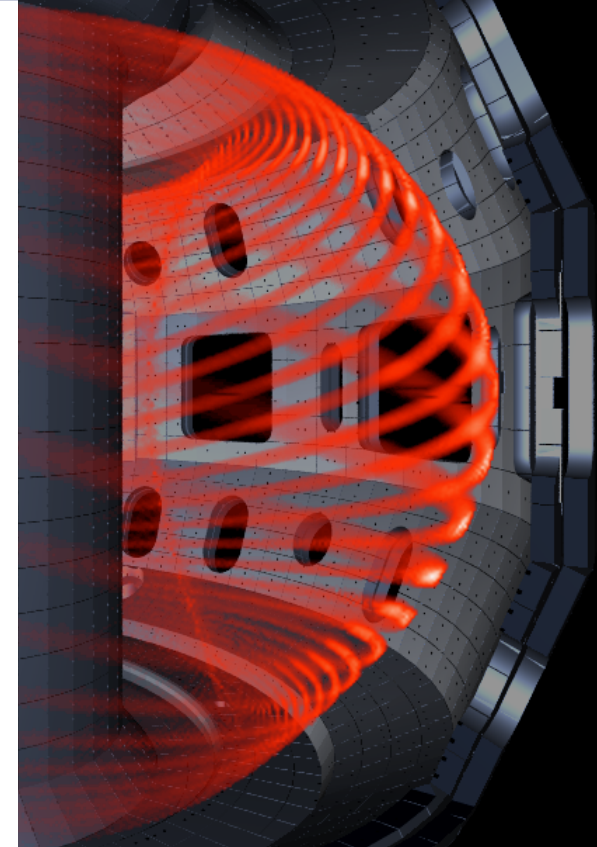
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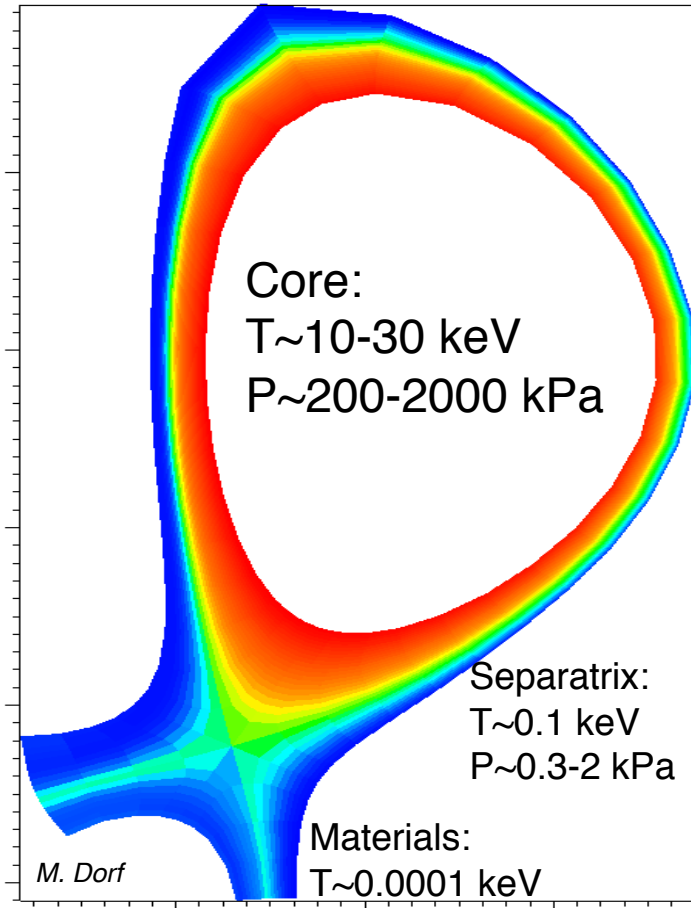


Acknowledgments

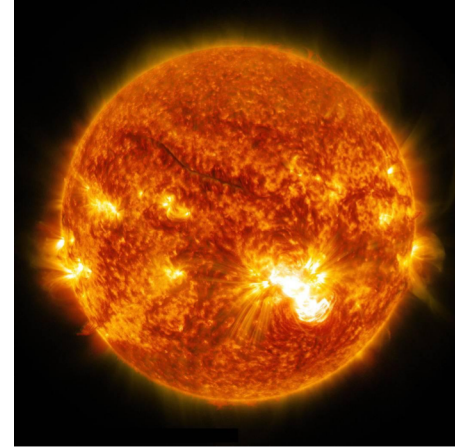
J.W. Hughes, O. Meneghini, T.H. Osborne, W. Solomon, H.R. Wilson, N. Aiba, D. Battaglia, E.A. Belli, M. Beurskens, K. Burrell, J. Candy, J. Canik, C.S. Chang, A. Diallo, D. Dickinson, M. Dorf, B. Dudson, M. Dunne, D. Eldon, M. Fenstermacher, J. Ferron, A. Garofalo, B. Grierson, R.J. Groebner, W. Guttenfelder, D. Hatch, A. Hubbard, G.T.A. Huijsmans, Y. Kamada, A. Kirk, M. Komm, C. Konz, M. Kotschenreuther, B. LaBombard, F. Laggner, L. Lao, A.W. Leonard, M. Leyland, C. Maggi, R. Maingi, W. Meyer, R. Nazikian, D. Orlov, N. Oyama, J.M. Park, S. Parker, C. Paz-Soldan, S. Saarelma, G.M. Staebler, A. Turnbull, H. Urano, E. Viezzer, J.R. Walk, E. Wang, E. Wolfrum, X. Xu, and
the ITPA Pedestal Group



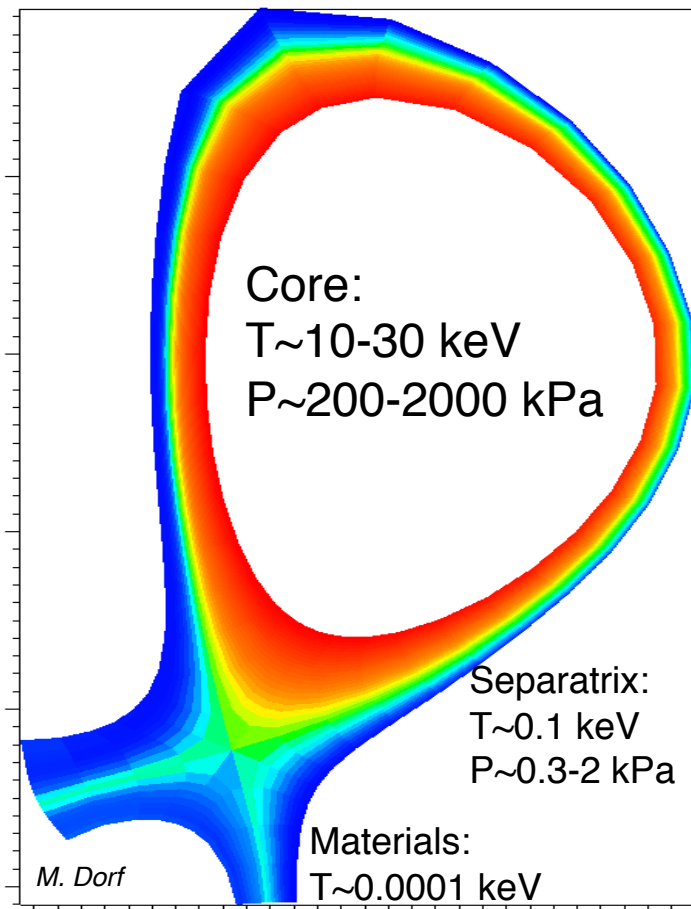
Fundamental Challenge: Fusion Conditions in Core Compatible with Edge/Materials



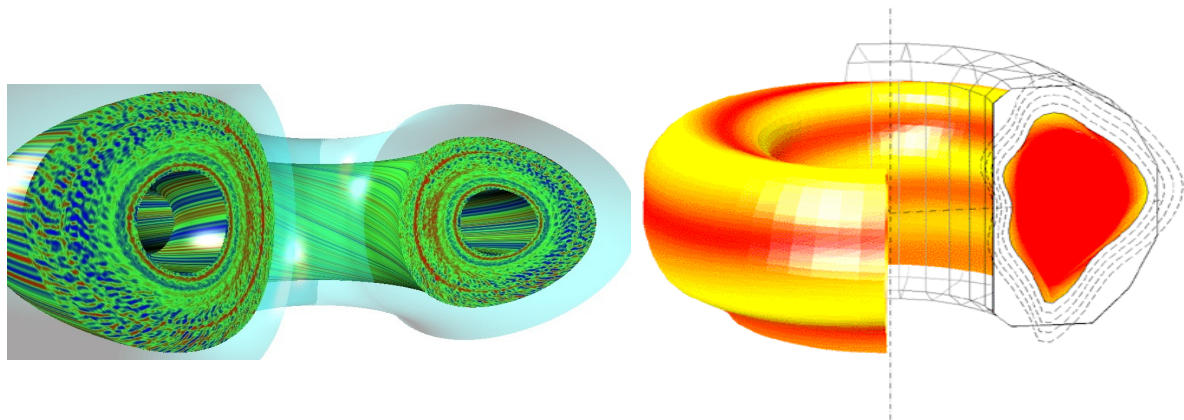
- Core plasma 10x hotter than the core of the sun
- Need increase of $\sim 100\text{x}$ in temperature, $\sim 1000\text{x}$ in pressure to reach fusion conditions in core



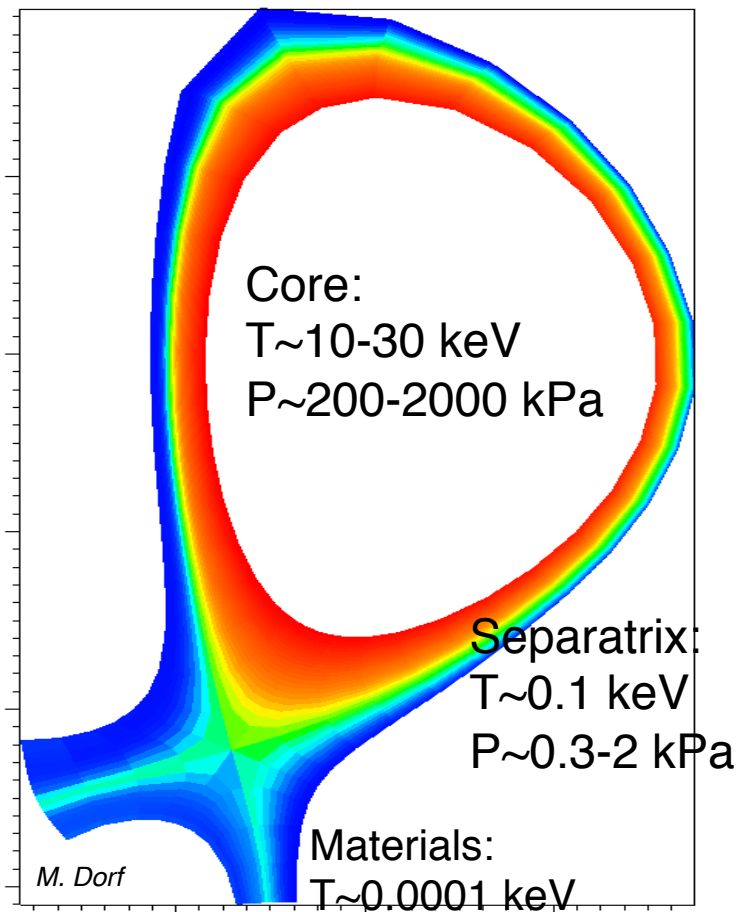
Fundamental Challenge: Fusion Conditions in Core Compatible with Edge/Materials



- **Physics of turbulent transport and large scale MHD instabilities constrain average pressure and temperature gradients**
 - Large normalized size ($aI_p B_t \sim a^2 B_p B_t$) needed, potentially expensive
 - a =minor radius, I_p =plasma current= B_p *circumference,
 B_t =toroidal magnetic field



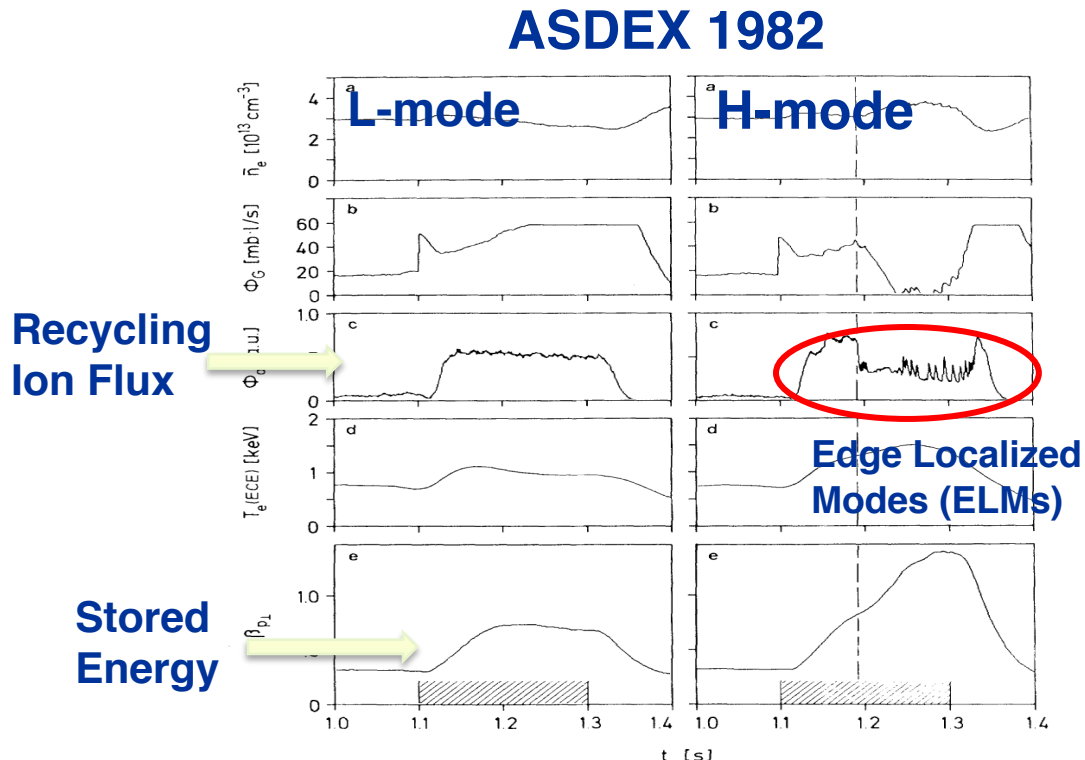
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 - a =minor radius, I_p =plasma current= B_p *circumference, B_t =toroidal magnetic field
- **Ideal solution: Suppress turbulence and build sharp gradients across outermost part of confined plasma**
 - Broad profiles for high global pressure limit, large fusion volume

Sometimes Nature Comes Through: H-Mode and Pedestal

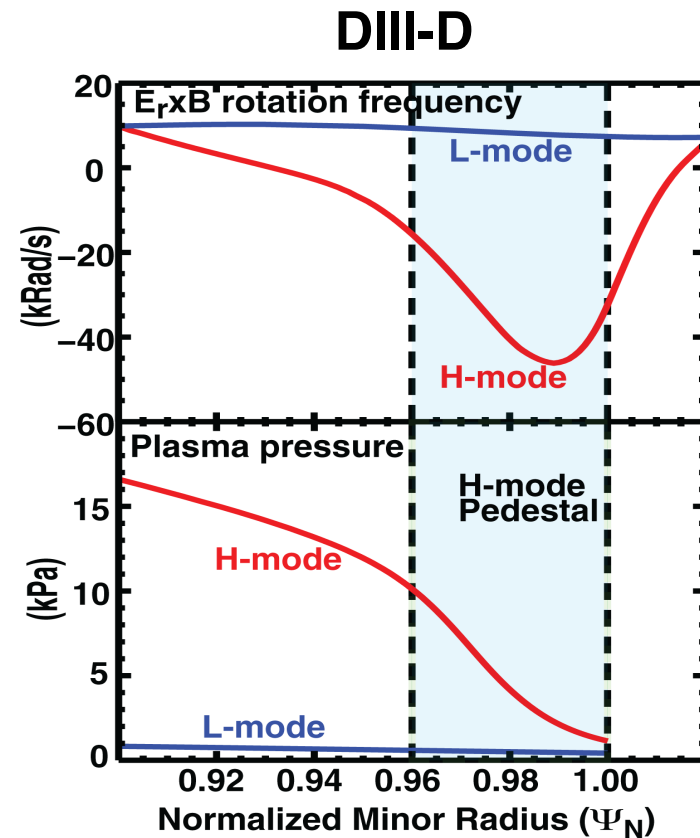
- In 1982 ASDEX reported a new regime named H-mode
 - Later found on numerous tokamaks
- Factor of ~ 2 improvement in confinement and stored energy
 - Bursty events called Edge Localized Modes (ELMs)
- Characterized by suppression of turbulence and high gradients in outer few % of confined plasma



[F. Wagner, *Phys. Rev. Lett.* **49** 1408 (1982)]

The H-mode Transport Barrier is Enabled by Shear in the Edge Rotation Profile

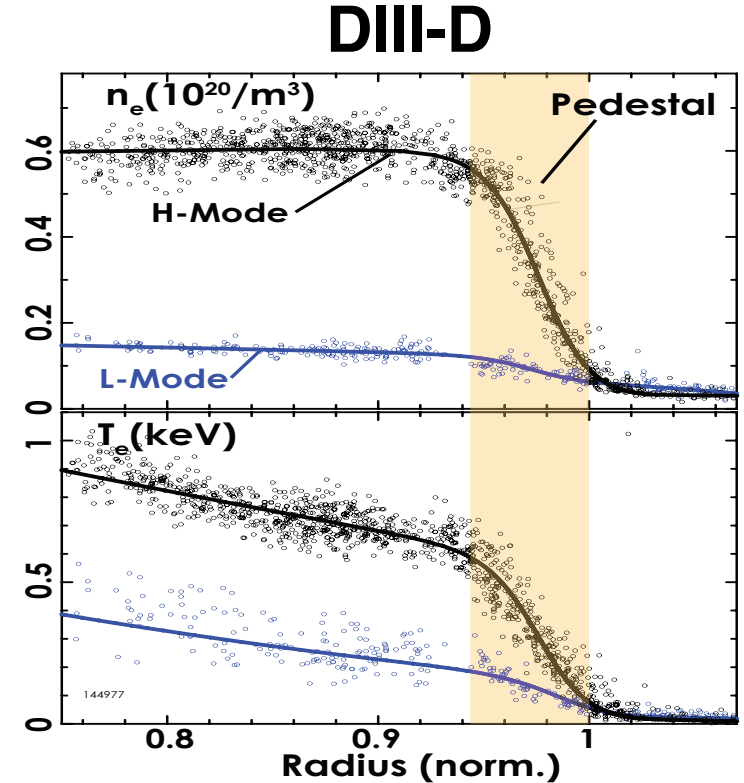
- Driven by auxiliary heating, a spontaneous transition to a higher confinement state
- Shear in perpendicular rotation ($E_r \times B$) suppresses turbulent transport
 - Shears long wavelength turbulence of L-mode, reducing transport, gradients rise
 - Labeled “ E_r well”
- Detailed physics of “L-H” transition complex (*key research need*) – here focus on physics controlling structure of the pedestal



[Courtesy R.J. Groebner]

H-mode Produces a Steep Edge Pressure Gradient

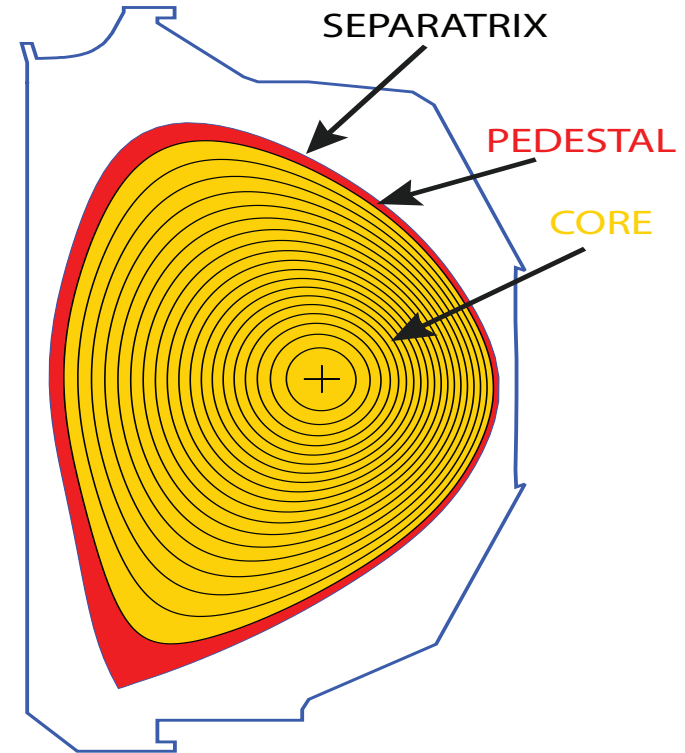
- Narrow edge layer of steep pressure gradient
- High pressure core plasma rests on this “Edge Pedestal”



[Courtesy T.H. Osborne]

The Pedestal is Narrow but Impactful

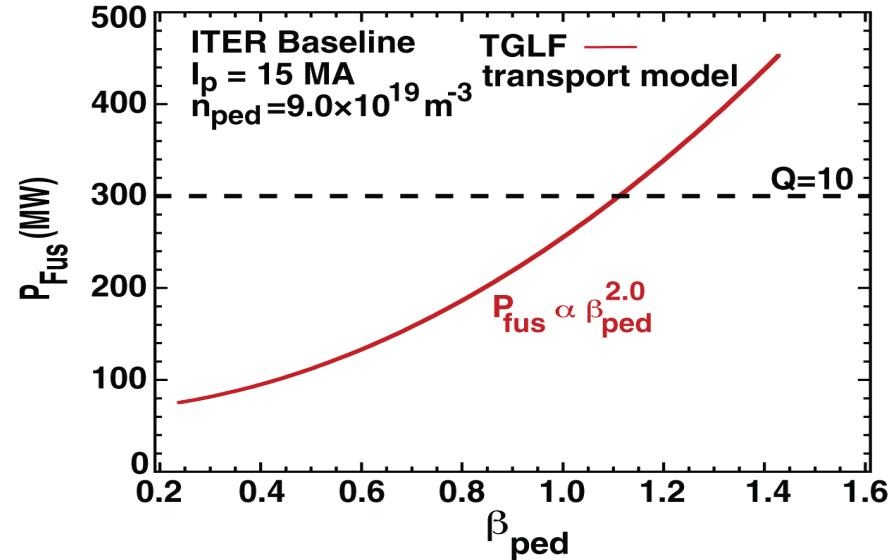
- **Narrow edge layer of steep pressure gradient**
- **High pressure core plasma rests on this “Edge Pedestal”**
- **Can have $>10\times$ increase in T , and $>40\times$ increase in p across this layer**
 - Typically larger relative increase than core



Fusion Performance Rests Upon the Pedestal

- Future burning plasmas rely on maintaining high pedestal pressure
 $P_{\text{fusion}} \propto p_{\text{ped}}^2$
- For ITG limited cores, $T_{i,\text{ped}}$ plays a key role in global confinement
 - On existing devices, optimizing fusion performance a combination of a $T_{i,\text{ped}}$ and p_{ped} optimization
 - However, considering all microinstabilities in core, pressure broadening for global MHD stability, and i-e coupling at reactor scale, p_{ped} generally most important

ITER Fusion Power



[J. Kinsey, *Nucl. Fusion* **51** 083001 (2011)]

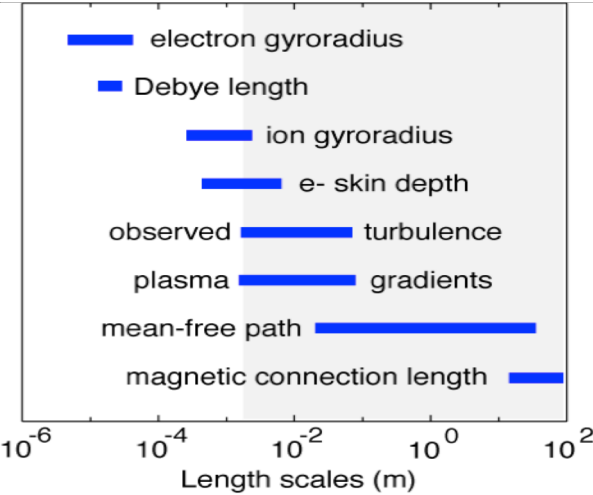
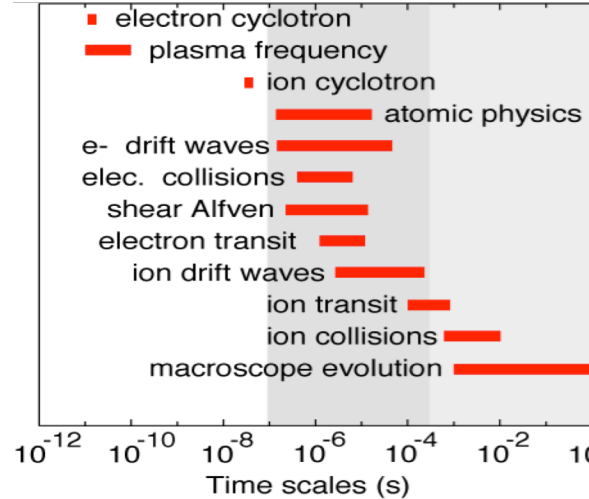
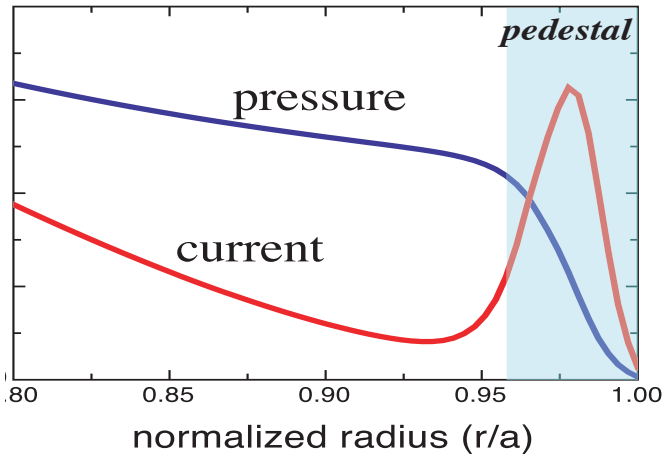
Outline: Pedestal Physics Key to Predicting and Optimizing the Tokamak

- **The Pedestal: What it is and why it matters**
 - Simultaneous improvement of confinement and stability
 - Predictive capability enables fusion power optimization ($P_{\text{fus}} \sim p_{\text{ped}}^2$)
- **Rich physics and computational challenges**
 - Overlap of scales, challenge to methods ($L \sim \lambda \sim \rho$)
- **Physics approaches and experimental tests**
 - Gyrokinetics and neoclassical theory
 - MHD and peeling-ballooning modes
- **Predicting and optimizing the pedestal: The EPED model**
 - Development and testing
 - Coupled core-pedestal prediction fusion optimization
- **Super H-Mode and high fusion performance**
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Very Wide Range of Overlapping Scales in the Edge Barrier Region

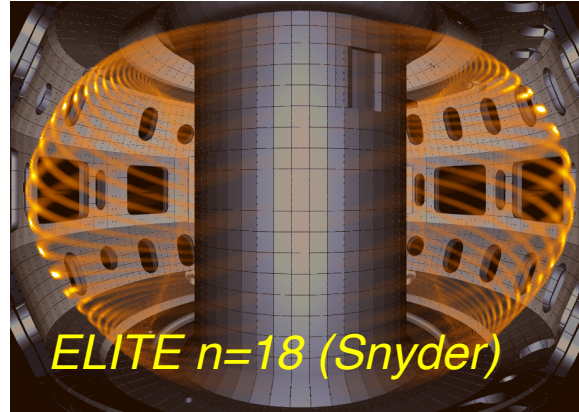
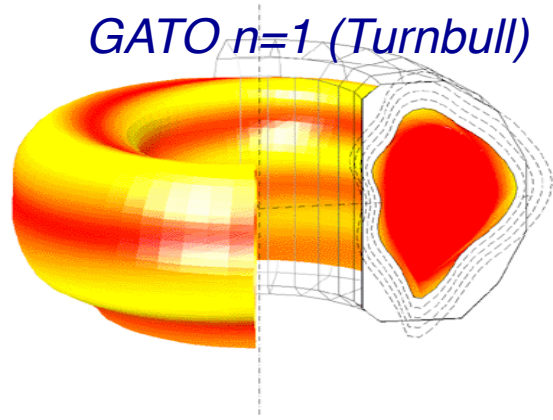


Both time and spatial scales overlap, from microscopic all the way to global

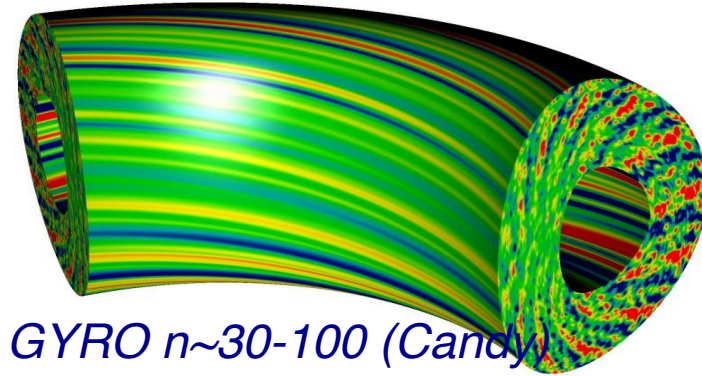
- This wide range (6-7 orders of magnitude) is covered by a **single** equilibrium, key parameters vary by orders of magnitude across the pedestal

Pedestal Physics Challenges Existing Paradigms

GATO $n=1$ (Turnbull)



ELITE $n=18$ (Snyder)



GYRO $n \sim 30-100$ (Candy)

- **Our field traditionally divided into stability ($\lambda \sim L \gg \rho$), transport ($\lambda \sim \rho \ll L$) and source physics** (λ =fluctuation scale, L =equilibrium scale, ρ =drift-/gyro- orbit scale)
 - This separation can break down in the edge barrier
- **Simulations focused on 3D collisional or 5D collisionless equations**
 - Edge barrier is in general both highly collisional and highly collisionless
 - Perturbations can be large, potential problem for δf
 - Electromagnetic perturbations (and 3D fields) and full geometry important

Traditional Transport Theory Requires a Separation of Scales

- Fluctuation scale= λ
- Equilibrium scale= L (eg pressure gradient scale L_p)
- Microscopic scale= ρ (toroidal or poloidal gyroradius)

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

Leading order: gyrokinetic and neoclassical fluxes

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

Equilibrium scale macrostability (MHD) ($L \sim \lambda \gg \rho$)

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

- Can proceed using existing tools to develop physics insight, but must be cautious of limits (in particular the $L \gg \lambda$ approximation can lead to arbitrarily large errors for ion scale modes)

Open issue: Work on extended formulations or 6D simulations by many authors, but practical, rigorous formalism for pedestal remains a challenge

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The Fokker-Planck Equation Provides the Fundamental Theory for Plasma Equilibrium, Fluctuations, and Transport

- $$\left[\frac{\partial}{\partial t} + \vec{v} \cdot \nabla + \frac{z_a e}{m_a} \left(\vec{E} + \hat{\vec{E}} \right) \cdot \frac{\partial}{\partial \vec{v}} + \frac{z_a e}{m_a c} \vec{v} \times \left(\vec{B} + \hat{\vec{B}} \right) \cdot \frac{\partial}{\partial \vec{v}} \right] (f_a + \hat{f}_a) = \sum_b C_{ab}(f_a + \hat{f}_a, f_b + \hat{f}_b) + S_a$$

$f_a, \vec{E}, \vec{B} \rightarrow$ **ensemble-averaged**

$\hat{f}_a, \hat{\vec{E}}, \hat{\vec{B}} \rightarrow$ **fluctuating**

- Separate the FP equation into **ensemble-averaged (A)** and **fluctuation (F)** components.

- $$\mathbf{A} = \left[\frac{\partial}{\partial t} + \vec{v} \cdot \nabla + \frac{z_a e}{m_a} \left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B} \right) \cdot \frac{\partial}{\partial \vec{v}} \right] f_a - \langle C_a \rangle_{ens} - D_a - S_a = 0 \rightarrow \mathbf{DKE}$$

- $$\mathbf{F} = \left[\frac{\partial}{\partial t} + \vec{v} \cdot \nabla + \frac{z_a e}{m_a} \left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B} \right) \cdot \frac{\partial}{\partial \vec{v}} \right] \hat{f}_a + \frac{z_a e}{m_a} \left(\hat{\vec{E}} + \frac{\vec{v}}{c} \times \hat{\vec{B}} \right) \cdot \frac{\partial}{\partial \vec{v}} (f_a + \hat{f}_a) - C_a + \langle C_a \rangle_{ens} + D_a = 0 \rightarrow \mathbf{GKE}$$

- Use the **drift-ordering** to separate **neoclassical** and **turbulent** transport: $\rho_* = \rho_i / L \ll 1$

Leading order, **neoclassical** and **turbulence** separate ($D \Rightarrow 0$).

Gyroaverages of the $O(\rho_*)$ Ensemble-averaged and Fluctuating Equations Give the Drift-kinetic and Gyrokinetic Equations

- Drift-Kinetic Equation:** $\oint \frac{d\xi}{2\pi} A_1 = 0:$ $f_{1a} = \underset{\text{gyroangle-dependent}}{\tilde{f}_{1a}} + \underset{\text{gyroangle-independent}}{\bar{f}_{1a}}$

The first-order (gyroangle-independent) ensemble-averaged distribution is determined by the DKE

$$\mathbf{v}'_{\parallel} \hat{\mathbf{b}} \cdot \nabla \left(\bar{f}_{1a} - f_{0a} \frac{Z_a e}{T_a} \Phi_1 \right) - \sum_b C_{ab}^L(\bar{f}_{1a}, \bar{f}_{1b}) = S_{neo}$$

- Gyrokinetic Equation:** $\oint \frac{d\xi}{2\pi} F_1 = 0:$ $\hat{f}_{1a}(\vec{x}) = -\frac{Z_a e}{T_a} \hat{\Phi}_1 + h_a(\vec{x} - \vec{\rho})$

$$\frac{\partial h_a(R)}{\partial t} + \left(\vec{V}_0 + \mathbf{v}'_{\parallel} \hat{\mathbf{b}} + \mathbf{v}_{da} - \frac{c}{B} \nabla \hat{\Psi}_a \times \hat{\mathbf{b}} \right) \cdot \nabla h_a - \sum_b C_{ab}^{GL}(\hat{f}_{1a}, \hat{f}_{1b}) = S_{turb}$$

The first-order fluctuating distribution in terms of the distribution of gyrocenters $h_a(R)$ is determined by the GKE

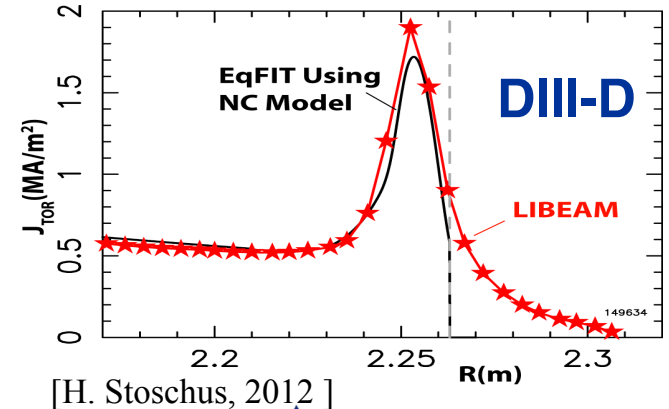
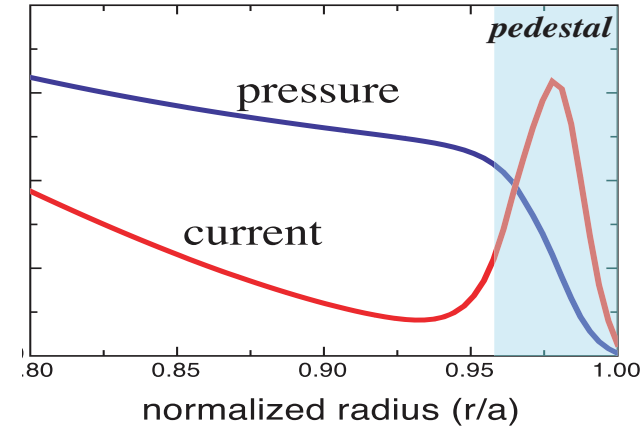
Neoclassical Bootstrap Current in Pedestal Validated Against Observations, Key for Instability Physics

- Pressure gradient gives rise to toroidal bootstrap current

$$j_b \propto \frac{dp/dr}{B_\theta \left(1 + 0.9\sqrt{\nu_e^*}\right)}$$

- Efficient calculation with codes like NEO [Belli9,12] and NEOART [Peeters00], reduced models [eg Sauter99] and neural nets for very fast evaluation
- Experimental validation of pedestal bootstrap current, $\pm 20\%$
- Large bootstrap current reduces magnetic shear and can both stabilize and drive pedestal instabilities

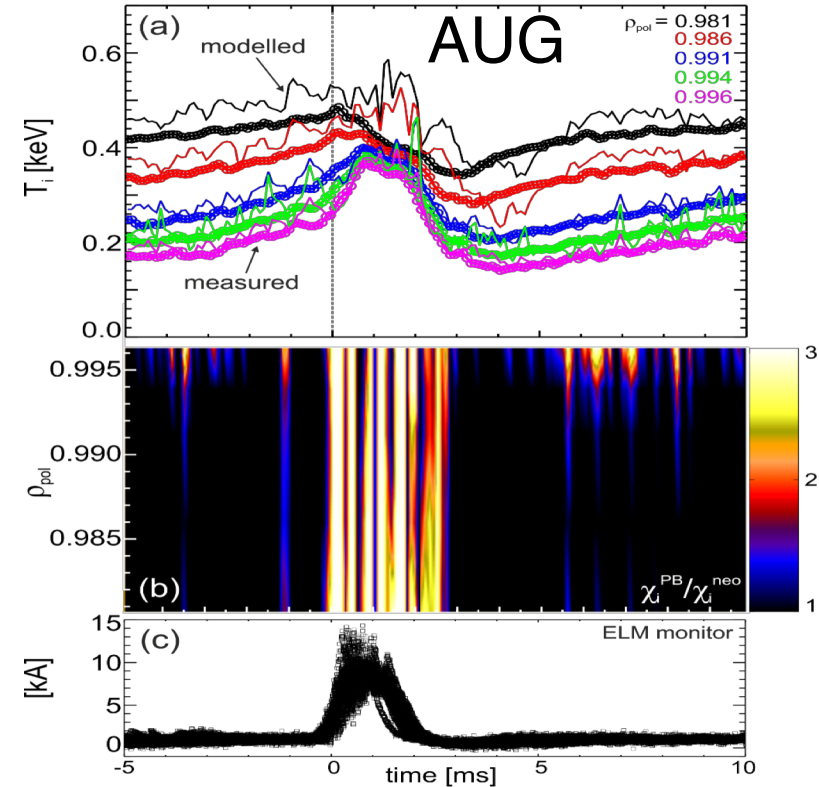
Open issue: Higher order (finite orbit width) effects explored by many authors but theory complexity and exp't validation unresolved



[H. Stoschus, 2012]

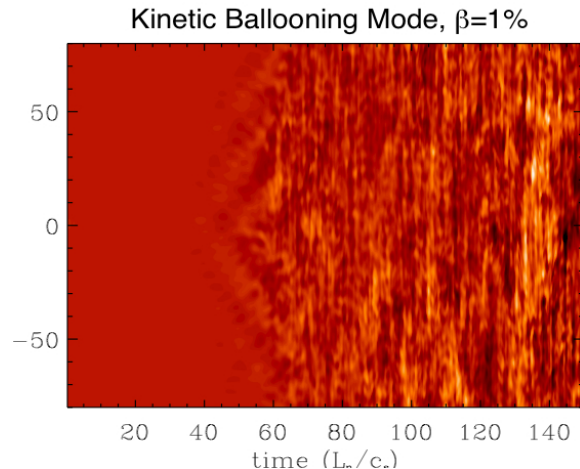
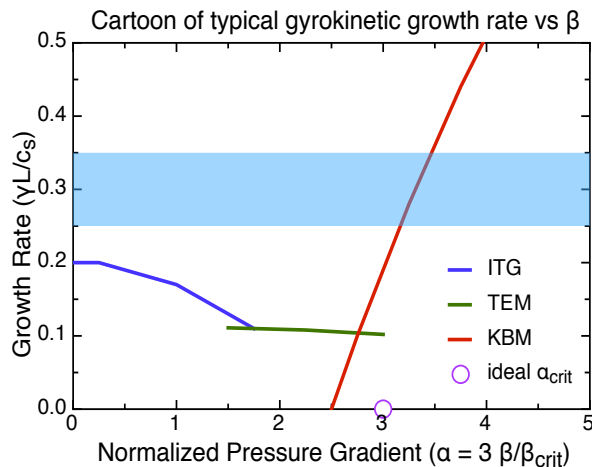
Neoclassical Ion Heat Transport Very Important in the Pedestal

- **High resolution measurements and efficient calculations (eg NEO/NEOART) have confirmed important role for neoclassical ion heat transport**
 - In some cases can account for ~all inter-ELM ion heat flux [ASDEX-U, Viezzer16]
 - Even in cases with strong fluctuations, remains significant
- **While neoclassical particle flux is small in a pure plasma, inward pinch of impurities very important, particularly with high-Z materials**



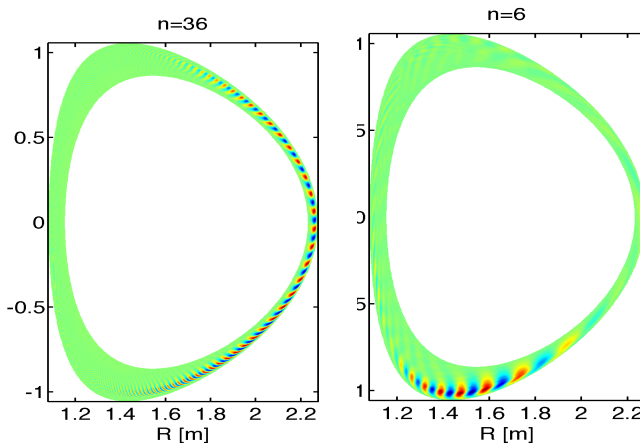
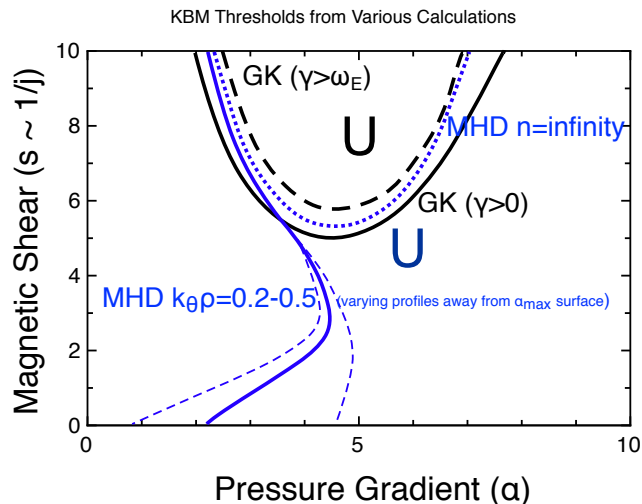
[E. Viezzer, *Nucl. Fus.* **57** 022020 (2017)]

Gyrofluid and Gyrokinetic Edge Simulations Identified Role of Electromagnetic Modes, KBM



- **Electrostatic limit requires (at least) that: (a) β is small, (b) frequency small compared to shear Alfvén frequency, (c) p' far from ideal ballooning limit ($\alpha \ll 1$ or $d\beta_p / d\psi_N \ll 1$)**
 - (c) is nearly always violated in the pedestal due to sharp gradients, and (b) can be violated as well (small k_{par} , drift-Alfvén modes) [Scott98, Snyder99]
- **Kinetic Ballooning mode (KBM) goes unstable just below ideal ballooning mode threshold due to ion drift resonance**
- **Recent studies have assessed effects of multiple species, full collisions [Belli17]**

Consideration of Non-local Effects Key for General Assessment of KBM



Wan, Parker, Chen PRL **109** (2012) 185004

Open issue: Kinetic ballooning mode calculations with full non-locality (including kink term)

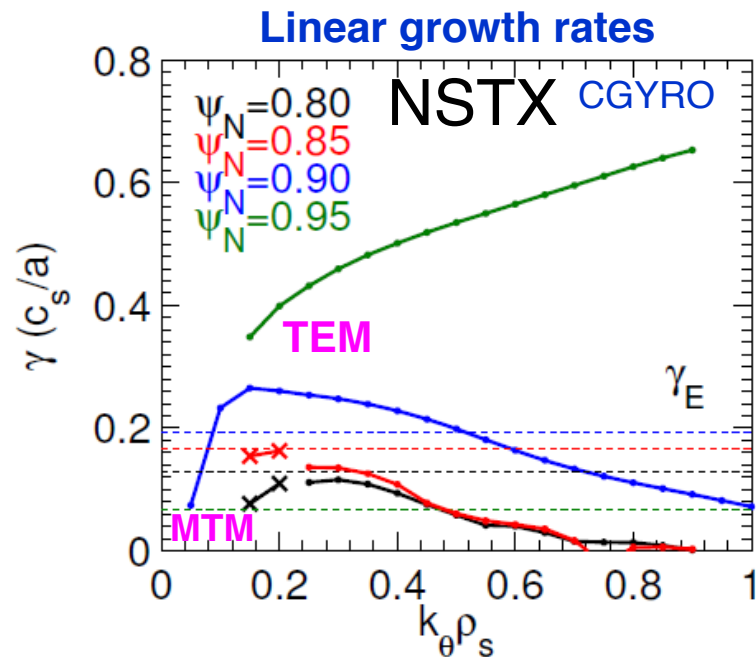
- Purely local (infinite n ballooning, flux tube GK) calculations predict “second stability” for KBM at low magnetic shear (high bootstrap current)
- Finite- n MHD studies find non-local effects close 2nd stability
 - kink term found to be important even at very high n
- Non-local gyrokinetic studies find similar behavior [Wan/Parker12, Saarelma/Dickinson17, Lin16]
 - Mode continues to have finite pressure gradient threshold even at low magnetic shear
 - Generally lack kink and other higher order terms

Variety of Modes in Addition to KBM Contribute to Particle, Heat, Impurity Transport

Strong ongoing effort via DOE/FES milestones this year

- **Electron heat transport driven by a range of instabilities driven by T_e gradients and trapped particles**
Eg, broad spectrum of electron drift waves in NSTX Enhanced Pedestal H-mode, ETG [Gerhardt14,Battaglia17,Guttenfelder19]
- **Microtearing may play a role near the top or inside the pedestal**
Simulations of MAST, NSTX, JET [Dickinson13, Canik13, Hatch17,Battaglia17]
- **Toroidal Ion Temperature Gradient (ITG) Modes Stable, but remnant slab-like ITG remains** [Hatch, Kotschenreuther16]
 - Potentially important mechanism for particle pinch
- **Higher excitation states of TEM/ITG, coupled modes** [Pueschel17, Belli10]
- **Different interactions with flow shear** [Hatch17]

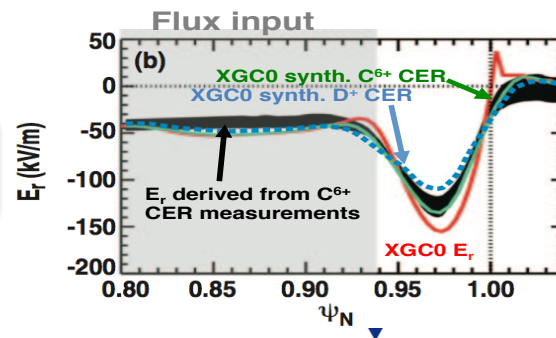
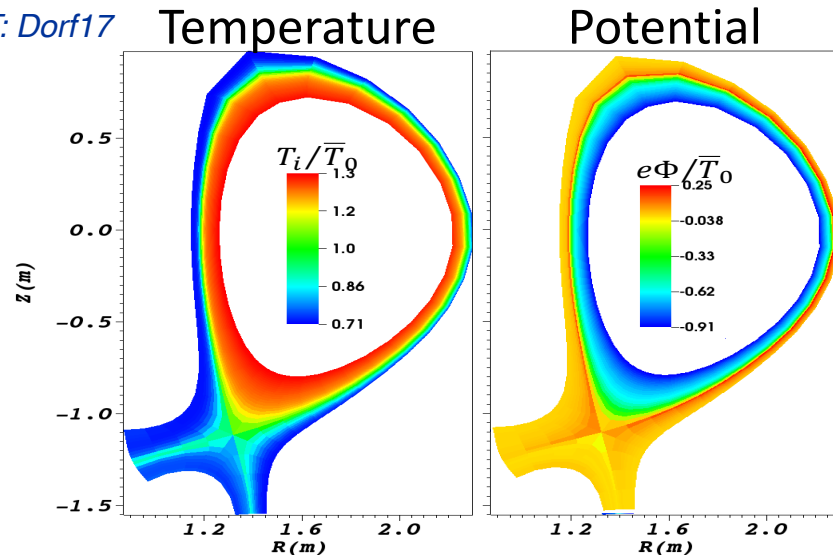
Open issue: Quantitative understanding of full range of instabilities that regulate particle, heat, momentum and impurity transport in the pedestal



Including Cross Separatrix Geometry Important

- Important neoclassical effects associated with ion orbit loss near the separatrix
 - Key role in understanding E_r and possibly L-H transition
 - Interaction with neutrals and sheath
- Electrostatic GK simulations and Electromagnetic GF simulations find strong turbulence, filaments ejected across separatrix [S. Ku/CS Chang17, XQ Xu 17]

COGENT: Dorf17



XGC0:
Battaglia16

ROMICS

Open issue: Electromagnetic gyrokinetic simulations in cross-separatrix geometry highly challenging

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Large Pressure and Current Gradients in Pedestal Drive MHD Instabilities

- **Potential Energy with stabilizing and destabilizing terms**
 - Negative energy implies MHD instability
 - ξ = displacement of plasma fluid, $\mathbf{B}_1$ = magnetic field perturbation

Compression of the magnetic field,
(Fast, magneto-acoustic waves)

magnetic field line bending
(Alfven waves)

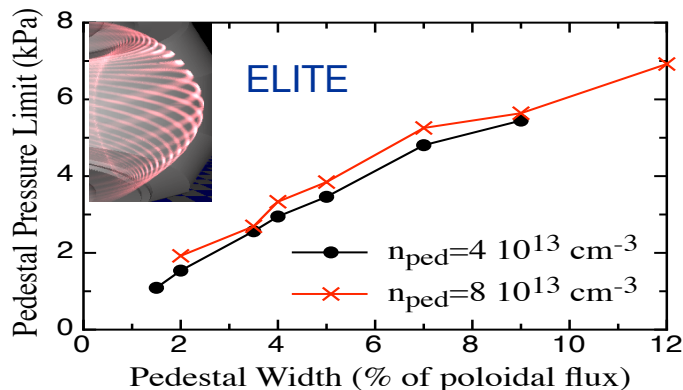
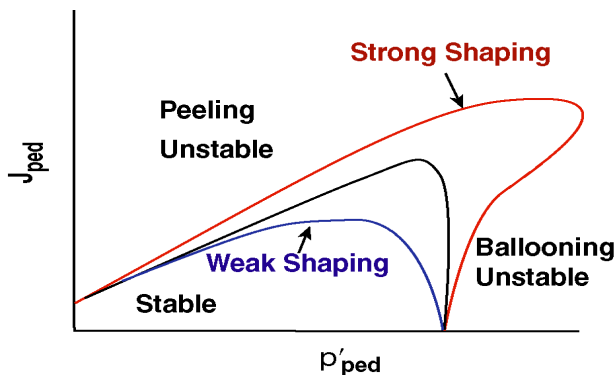
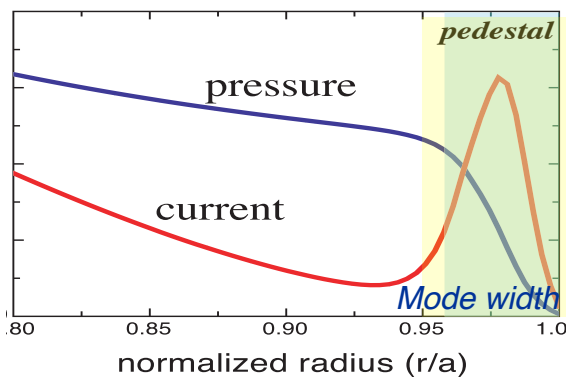
compression
(Slow, magneto-acoustic waves)

$$\delta W = \frac{1}{2} \int dV \left(\left| B_{1,\perp} \right|^2 + B_0^2 \left| \nabla \cdot \xi_{\perp} + 2 \xi_{\perp} \cdot \kappa \right|^2 + \lambda p_0 \left| \nabla \cdot \xi \right|^2 \right) \\ - \int dV \left(2(\xi_{\perp} \cdot \nabla p_0)(\kappa \cdot \xi_{\perp}) + J_{0,\parallel} (\xi_{\perp} \times B_0 / B_0) \cdot B_{1,\perp} \right)$$

pressure gradient destabilizing
(κ =field curvature) **ballooning** drive

parallel current destabilizing
kink/peeling drive

Peeling-Ballooning Modes Drive ELMs and Constrain the Pedestal Height



Pedestal is constrained, and (“Type I”) ELMs triggered by intermediate wavelength ($n \sim 3-30$) MHD instabilities called “peeling-ballooning” modes

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

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

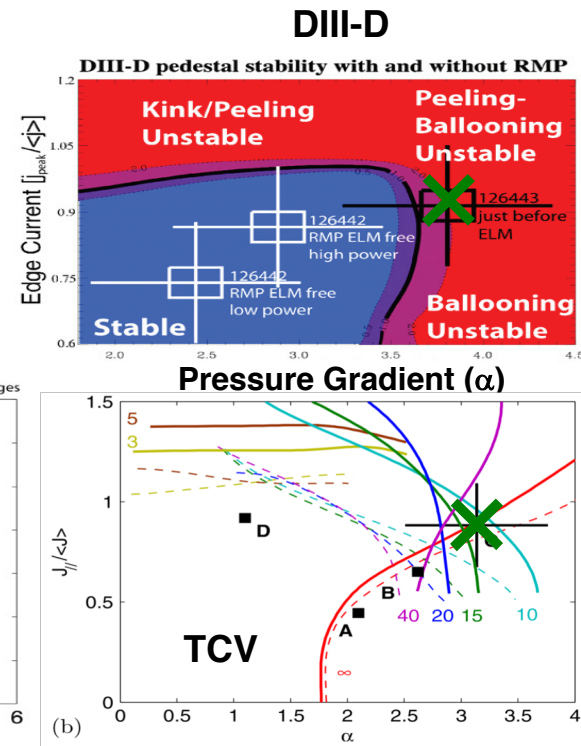
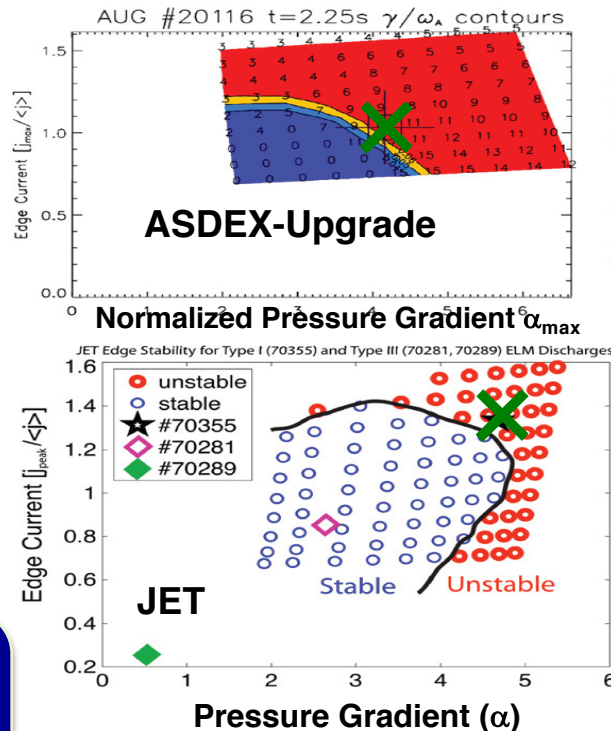
Efficient MHD codes (eg ELITE, MISHKA, KINX) allow accurate computation of the intermediate n peeling-ballooning stability boundary enabling systematic comparison to observations

H.R. Wilson, P.B. Snyder et al PoP **9** 1277 (2002). P.B. Snyder, H.R. Wilson et al PoP **9** 2037 (2002), GTA Huysmans PPCF **47** (2005) B165, S. Saarelma et al PPCF **49** (2007) 31, M.G. Dunne et al PPCF **59** (2017) 025010, A. Merle et al PPCF **59** (2017) 104001 etc

Peeling-Ballooning Model Successfully Applied Across a Range of Tokamaks

- International Tokamak Physics Activity (ITPA) coordinated multi-tokamak analysis
- Validated on all major international tokamaks
- ELM crash within 20% of calculated pedestal stability limit

Open issue: Recent JET metal wall cases sometimes exhibit ELMs below limit. Role of full rotation and extended MHD under investigation



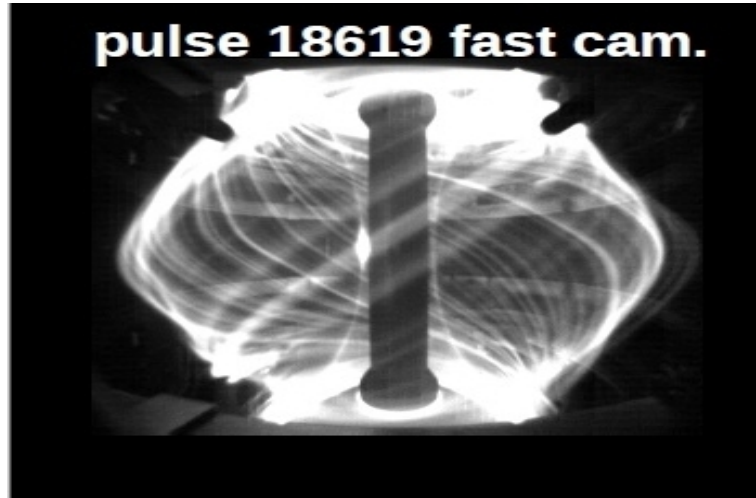
[S. Saarelma 2007, C. Konz 2008, N. Oyama 2005, N. Aiba 2009, P. Snyder NF 2009, A Pitzschke PPCF 2012]

Observed ELM Spatial Structure Similar to Calculated Peeling-Ballooning Modes

Visible Image

MAST

Calculated Mode (JOREK)



[S. Pamela, *Plasma Phys. Control. Fusion* **55** 095001 (2013)]

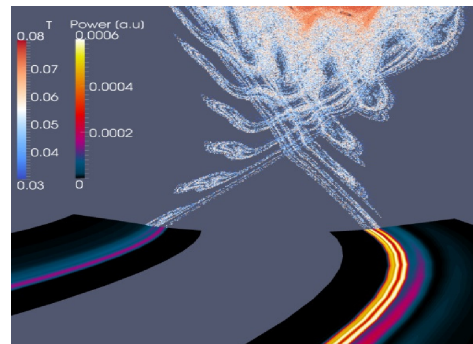
- Complicated structure but mode number similar to that calculated from linear stability

Nonlinear Simulations study ELM Dynamics and ELM Suppression/Control

- **Nonlinear evolution of peeling-ballooning modes complex and can lead to bursting or saturated states**
 - Saturated states (eg Quiescent H-Mode) are a promising technique for avoiding ELMs
 - Quantifying ELM losses is multi-scale, challenging. Being approached with extended MHD and gyrofluid techniques
- **3D perturbations can suppress and mitigate ELMs**
 - Both linear response and nonlinear simulations exploring physics)

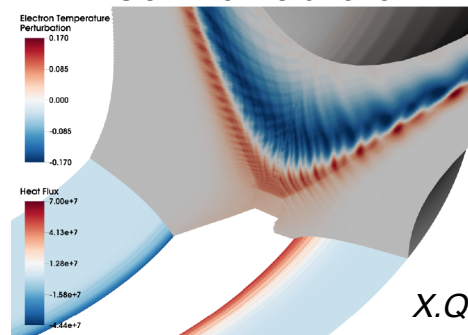
Open issues: Low resistivity leads to fine scale current sheets at computational resolution. Simulating a full ELM cycle with multi-scale physics is a grand computational challenge. Working models exist for RMP ELM suppression and QH mode but detailed quantitative understanding needed

JOREK: JET ELM Divertor



[G. Huijsmans, *Nucl. Fusion* (2013)]

BOUT++ simulations



X.Q. Xu16

Outline: Pedestal Physics Key to Predicting and Optimizing the Tokamak

- **The Pedestal: What it is and why it matters**
 - Simultaneous improvement of confinement and stability
 - Predictive capability enables fusion power optimization ($P_{\text{fus}} \sim p_{\text{ped}}^2$)
- **Rich physics and computational challenges**
 - Overlap of scales, challenge to methods ($L \sim \lambda \sim \rho$)
- **Physics approaches and experimental tests**
 - Gyrokinetics and neoclassical theory
 - MHD and peeling-ballooning modes
- **Predicting and optimizing the pedestal: The EPED model**
 - Development and testing
 - Coupled core-pedestal prediction fusion optimization
- **Super H-Mode and high fusion performance**
- **ITER predictions and future prospects**

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

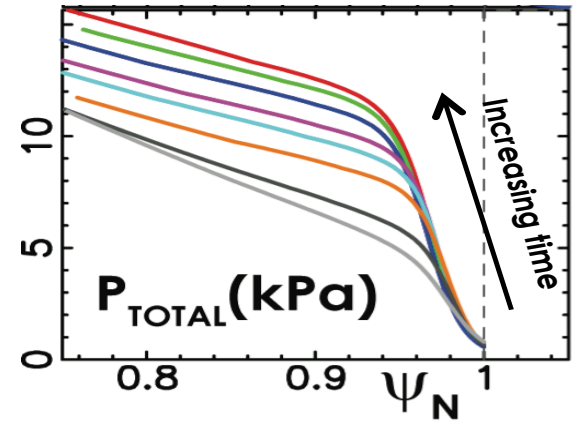
Paradigm: Transport barrier formation starts near separatrix and propagates inward primarily due to diamagnetic E_r

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

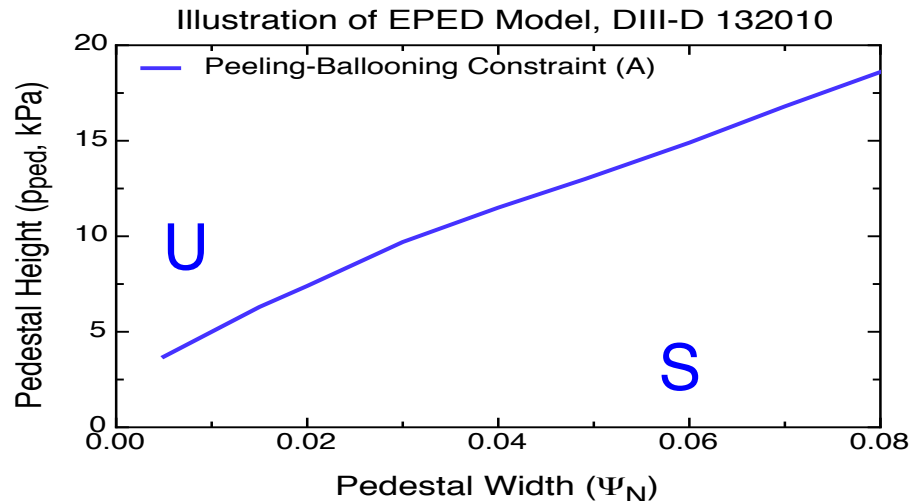
Conjecture: while neoclassical and electron microinstabilities drive transport, KBM commonly provides the final constraint on the pressure gradient.

- Key elements: neoclassical bootstrap current, nearly-local KBM, global peeling-ballooning
- Here take pedestal density as input
 - predicting it is a key goal for future work



Mechanics of the EPED Predictive Model

- **Input:** B_t , I_p , R , α , κ , δ , n_{ped} , m_i , $[\beta_{\text{global}}, Z_{\text{eff}}]$
 - **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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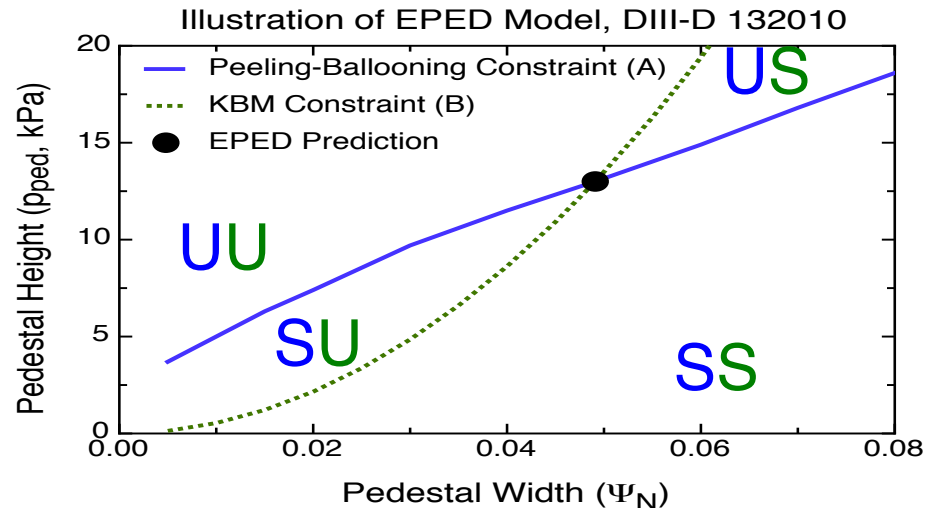
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B. KBM Onset: $\Delta_{\psi_N} = \beta_{p,ped}^{1/2} G(v_*, \epsilon \dots)$

- Directly calculate with ballooning critical pedestal technique

- 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)



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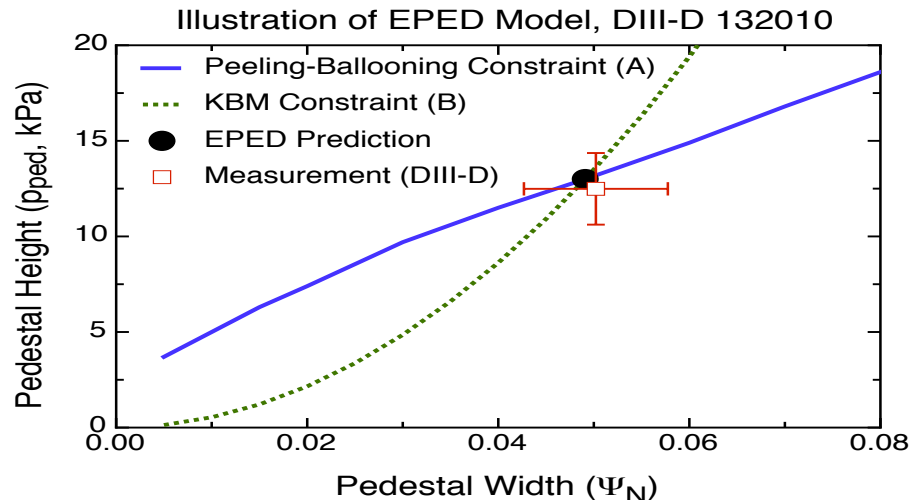
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- can then be systematically compared to existing data or future experiments

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

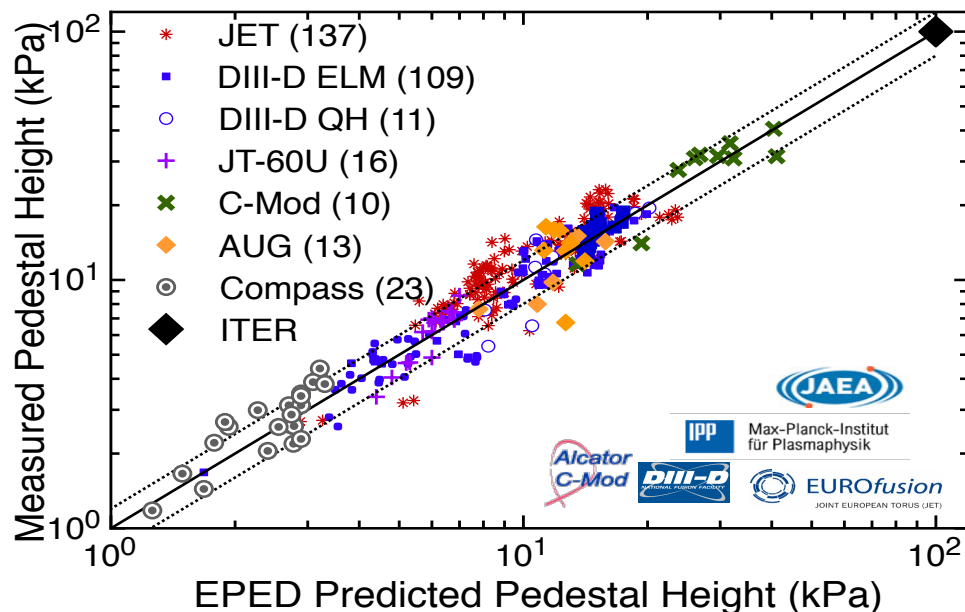
Effect of KBM constraint is counter-intuitive: Making KBM stability worse increases pedestal height and width (eg “wide pedestal quiescent H-Mode.”)



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

Numerous Experimental Tests of EPED Conducted

Comparison of EPED Model to 319 Cases on 6 Tokamaks



Validation efforts coordinated with ITPA pedestal group, US JRT

- >800 Cases on 6 tokamaks
- Broad range of density ($\sim 1\text{--}24 \times 10^{19}\text{m}^{-3}$), collisionality ($\sim 0.01\text{--}4$), $f_{\text{GW,ped}}$ ($\sim 0.1\text{--}1.0$), shape ($\delta \sim 0.05\text{--}0.65$), $q \sim 2.8\text{--}15$, pressure (1.7 - 35 kPa), $\beta_N \sim 0.6\text{--}4$, $B_t = 0.7\text{--}8\text{T}$
- Includes experiments where predictions were made before expt
- Typical $\sigma \sim 20\text{--}25\%$
- Recent work on TCV (Merle, Sauter, Medvedev PPCF17, Sheikh et al PPCF19 etc)

Outline: Pedestal Physics Key to Predicting and Optimizing the Tokamak

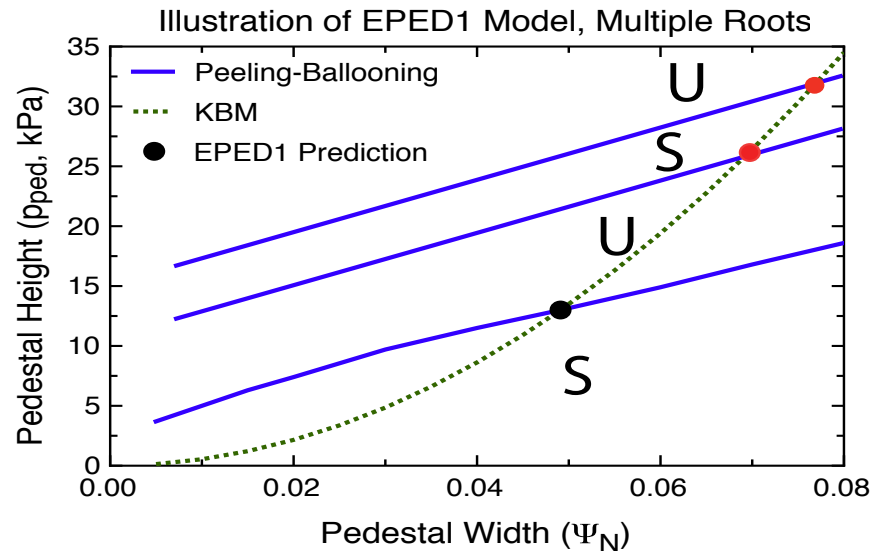
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 - *Skipping in interest of time: Combining EPED with core transport models such as TGLF+NEO enable prediction and optimization of global confinement*
- **Super H-Mode and high fusion performance**
- **ITER predictions and future prospects**

Outline: Pedestal Physics Key to Predicting and Optimizing the Tokamak

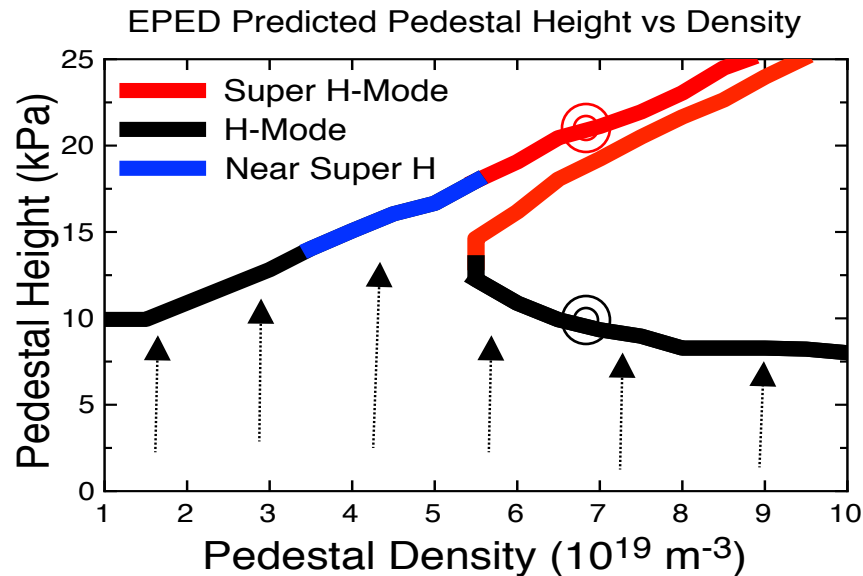
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Thinking Outside the Box: Super H Mode

- EPED model normally predicts a single pedestal solution
- At strong shaping, fixed input parameters (including density), PB mode can go from stable to unstable (pressure driven) and back to stable again with increasing pressure and current: multiple roots for two “equations”, PB and KBM
- Expect only lowest solution to be accessible for these parameters. However, **can move in third dimension** (eg density) to access higher roots (Super H)

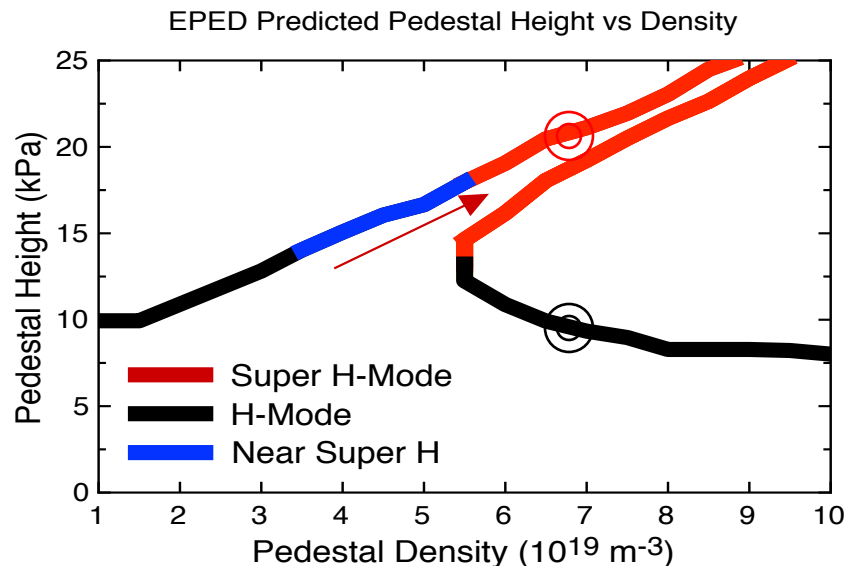


At High Density and Strong Shaping, Solution Splits into H-Mode and Super H



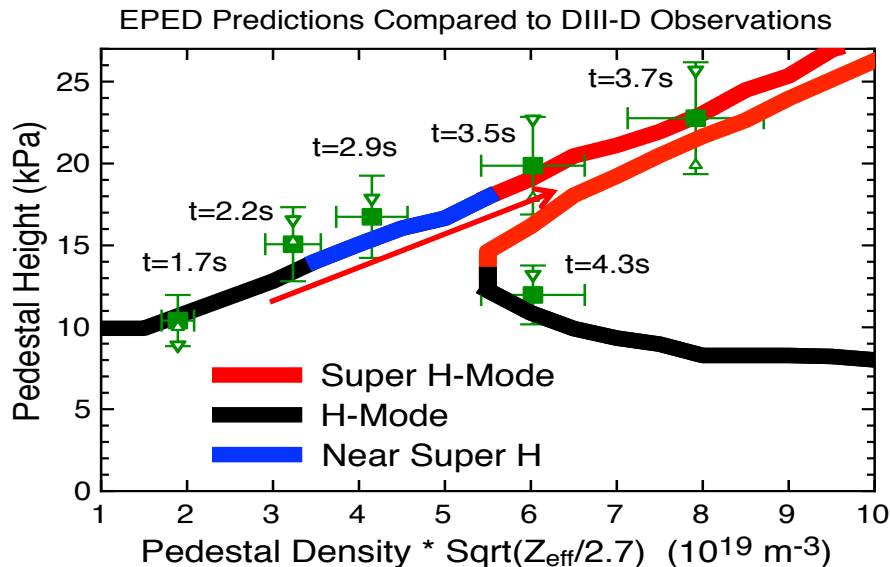
- **Constant density trajectories lead to usual H-Mode solution**
 - Optimal density leads to high pedestal near Super H (blue)
- **Solution above H-mode (red) called Super H-Mode**
 - Much higher pedestal than equivalent H-Mode solution

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).
 - 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



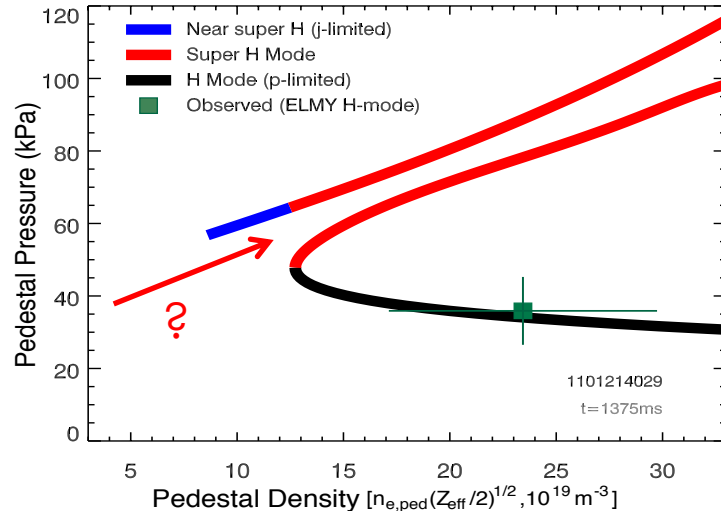
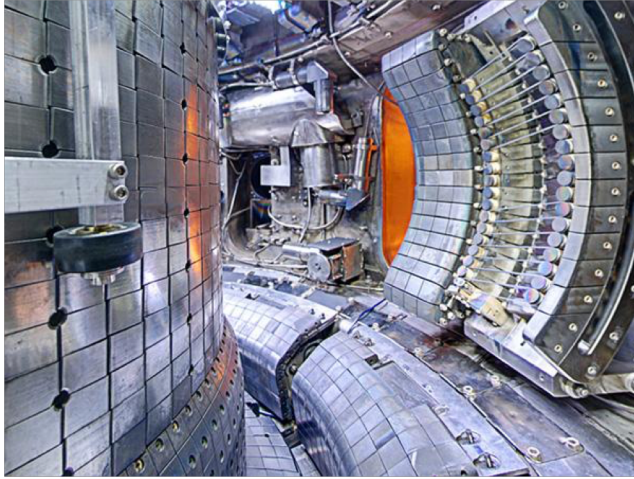
*W. Solomon PRL **113** 135001 (2014)*
*P.B. Snyder NF **55** 083026 (2015)*



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

High peak performance in Super H-Mode experiments

Very High Super H Mode Pressure Predicted for C-Mod

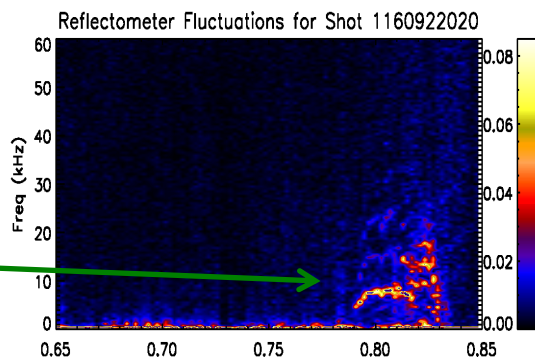
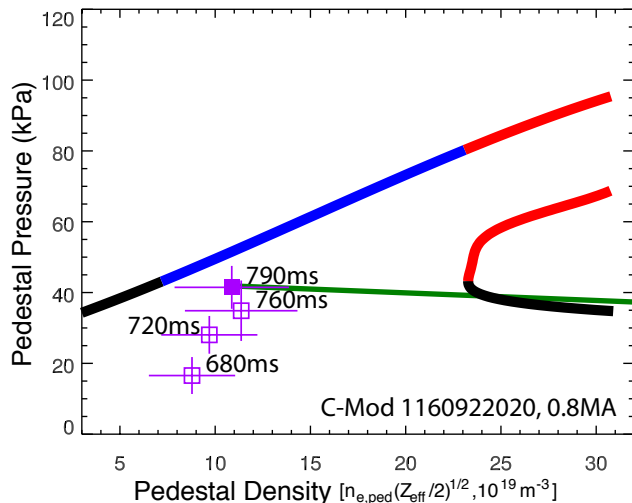


Alcator
C-Mod

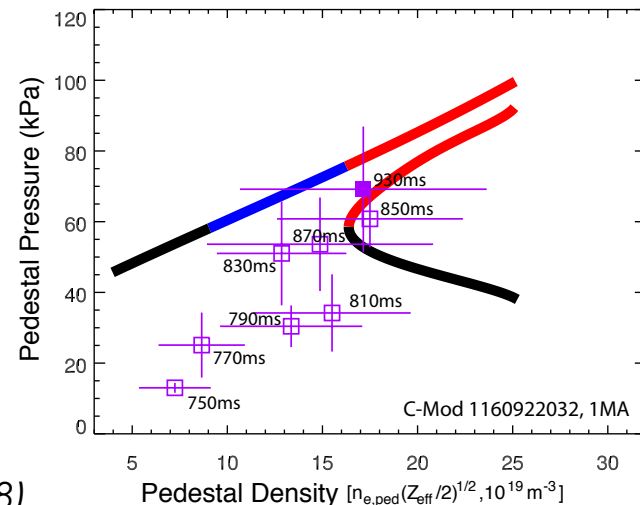
- Alcator C-Mod is a compact, high field device (here $B_t \sim 5.3\text{T}$), capable of high δ
 - After discovery of Super H-Mode on DIII-D, predictions were made for C-Mod (right)
 - Test SH theory at high B_t & B_p , zero injected torque (RF), high Z metal wall
 - Following the right parametric trajectory should enable very high pressure
 - Need to reach densities much lower than typical for C-Mod H-mode to access Super H
 - Challenging to do on a high-Z metal wall device like C-Mod

Alcator
C-Mod

Access to Super H Mode on C-Mod Achieved via L-I-H Transition

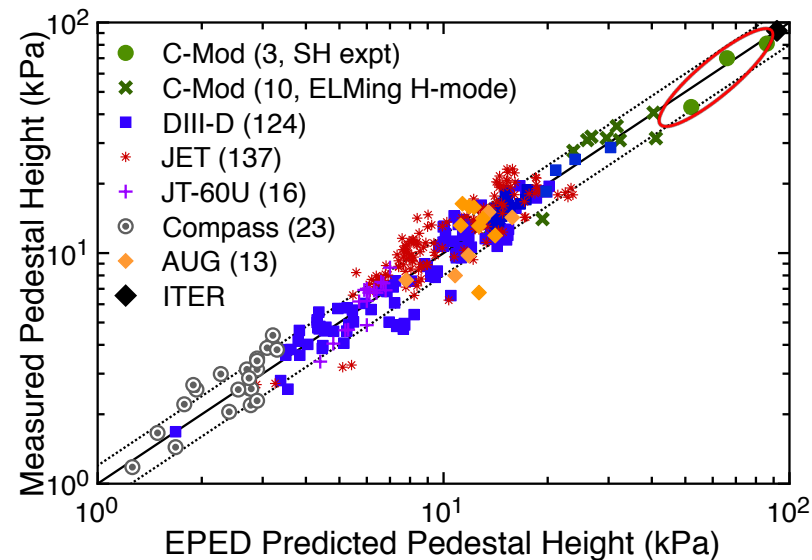
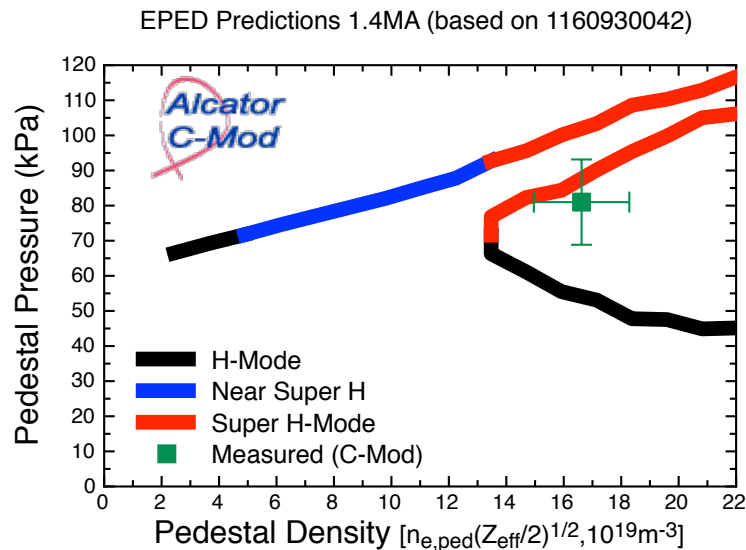


Hughes et al, NF 58 112003 (2018)



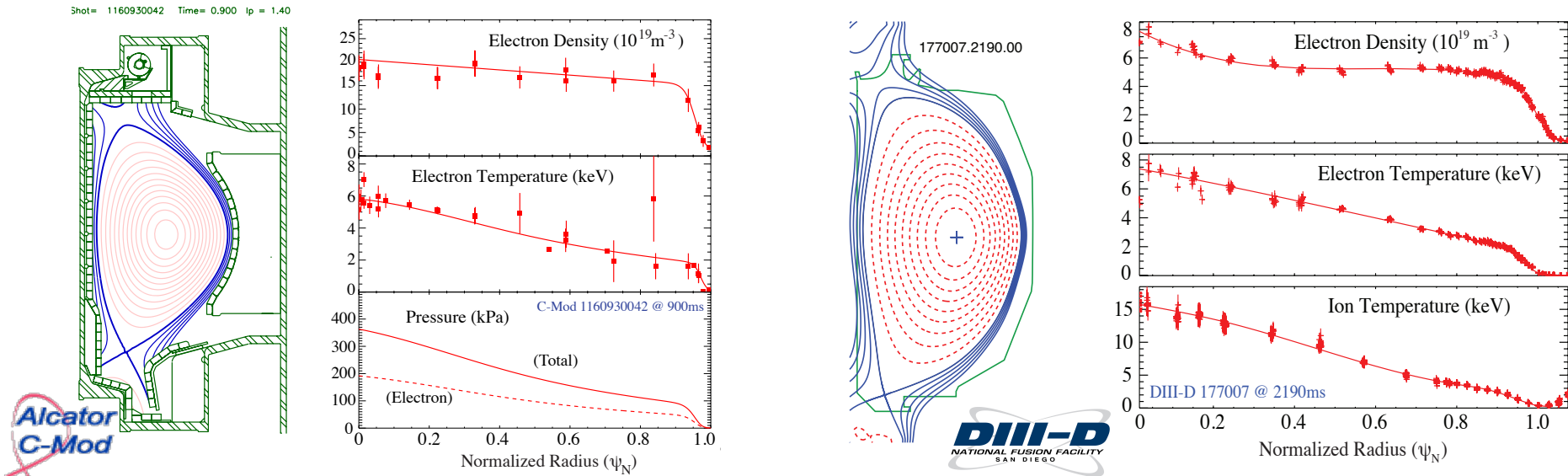
- Transitioning first to I-mode, then to H-mode leads to a low n_e , low impurity H-mode (left)
- As pedestal approaches predicted kink/peeling limit, low n mode observed (center)
- Discharges at 1MA, 5.4T reach SH regime, $p_{ped} \sim 70$ kPa (right)

Super H-Mode Experiments on C-Mod Yield ITER-like p_{ped}



- **Super H-Mode expt at 1.4MA achieved record 81 kPa pedestal pressure on last day of Alcator C-Mod operations, ITER-like pressure at ITER-like field [Hughes NF 2018]**
 - EPED model successfully tested over 2 orders of magnitude in pressure on 6 tokamaks
 - No indication of significant variation of model accuracy with p^* or p_{ped}

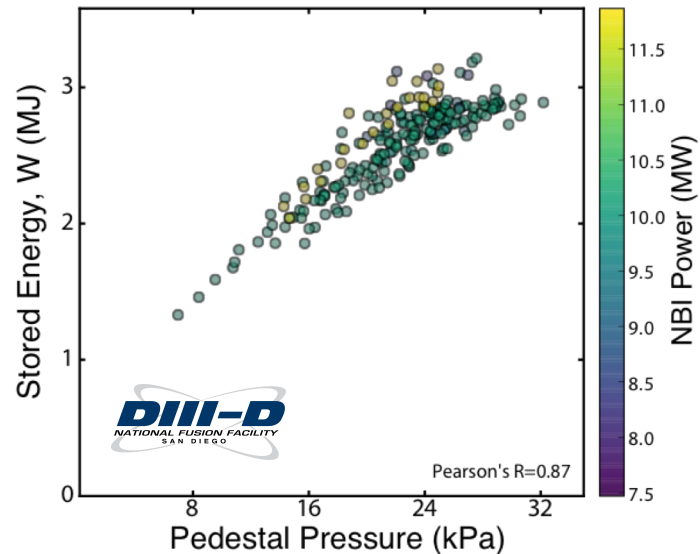
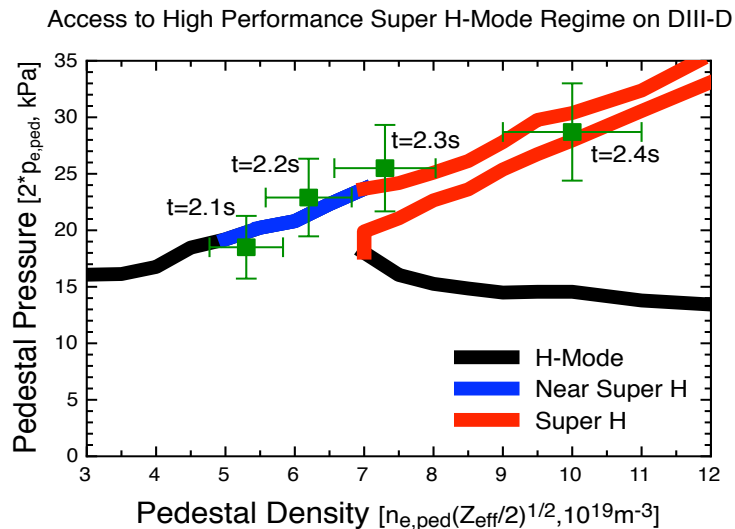
Broad Profiles and High Pressure Obtained in Both C-Mod and DIII-D



- **High pedestal pressure enables good confinement, high global MHD limits**

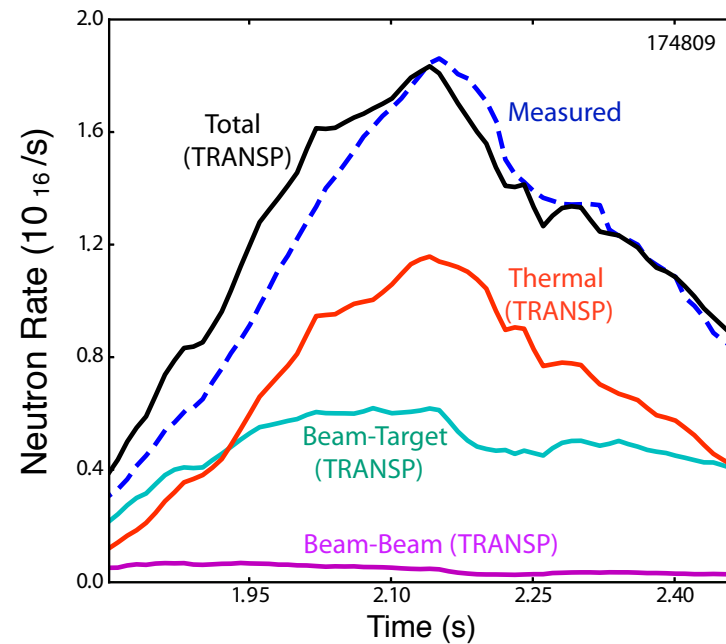
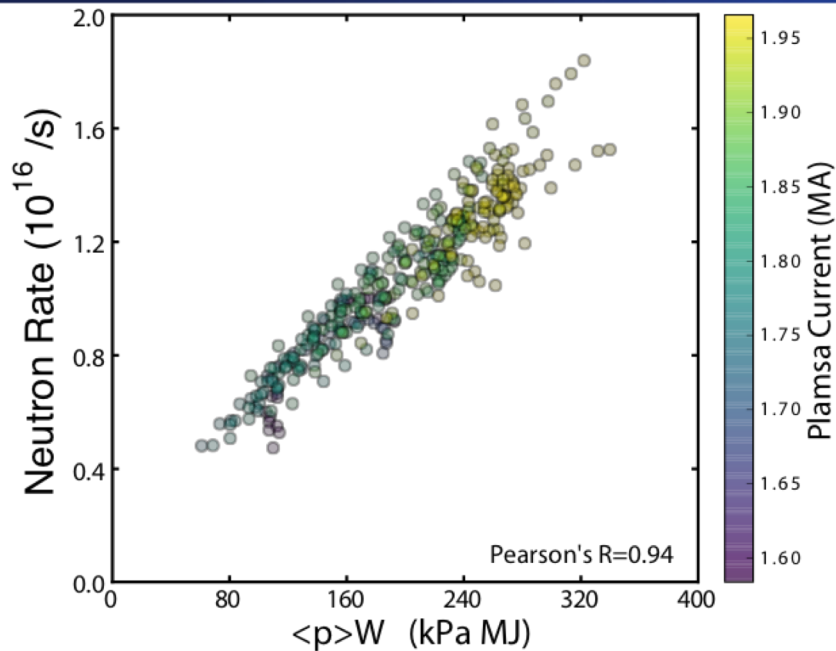
- C-Mod: $B_t=5.3\text{-}5.8\text{T}$, $I_p=0.8\text{-}1.4\text{MA}$, $a=0.19\text{m}$, $R=0.67\text{m}$, $\delta\sim 0.5$
 - $\langle p \rangle \sim 100\text{-}170 \text{ kPa}$, $p_{ped} \sim 50 - 80 \text{ kPa}$
- DIII-D: $B_t=2.1\text{-}2.2\text{T}$, $I_p=1.6\text{-}2.0\text{MA}$, $a=0.6\text{m}$, $R=1.67\text{m}$, $\delta\sim 0.5\text{-}0.7$
 - $\langle p \rangle \sim 70 - 110 \text{ kPa}$, $p_{ped} \sim 20 - 32 \text{ kPa}$, $T_{i,0} \sim 14\text{-}18 \text{ keV}$

Very High Pedestal Pressure, Stored Energy, and Confinement Time in Recent co- I_p Super H-Mode Experiments on DIII-D



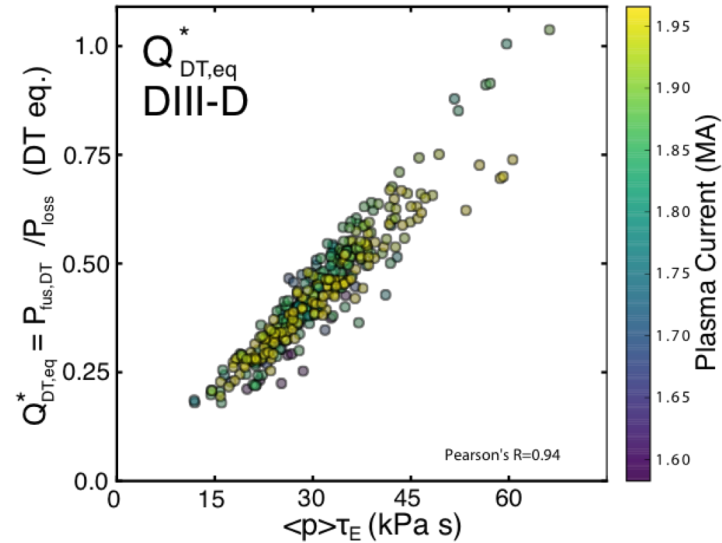
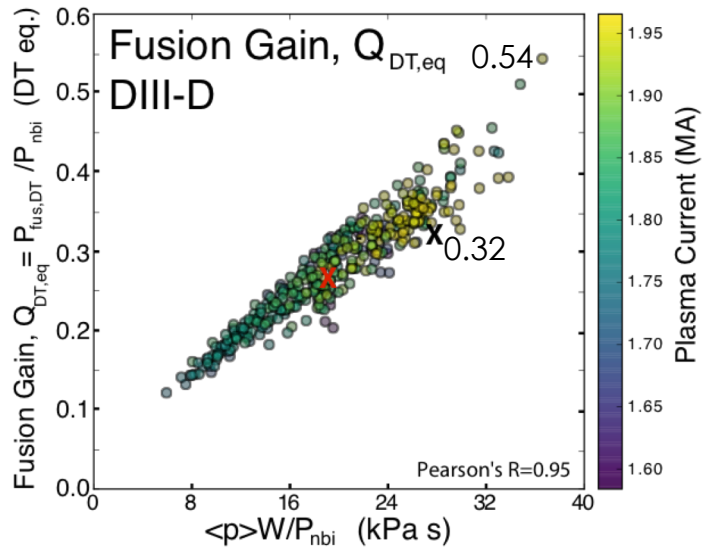
- **Deep access into Super-H regime, good agreement with EPED predictions**
 - $B_T=2.17T$, $I_p=1.6-2.0MA$, $\alpha=0.6m$, $\delta \sim 0.5-0.7$
 - $p_{ped} \sim 30kPa$, $W \sim 2 - 3.2$ MJ (highest in present DIII-D config.) at modest $P_{nbi} \sim 8-12$ MW
 - Peak $\tau \sim 0.4-0.7s$, $H_{98} \sim 2.2-2.9$, $\langle p \rangle_{TE} \sim 30-67$ kPa s, $nT\tau \sim 4 - 8 \cdot 10^{20}$ keV m^{-3} s

High Pedestal Pressure and $T_{i,ped}$ Enable High Peak Fusion Performance on DIII-D



- DD neutron rates up to $1.85 \cdot 10^{16}$ /s
 - ~2/3 thermal, $P_{fus,DD} \sim 22$ kW, $P_{fus,DT,eq} \sim 4.8$ MW (at $P_{nbi} \sim 9$ MW)

High Pedestal Pressure and T_i Enable High Peak Fusion Performance on DIII-D, Record Fusion Gain

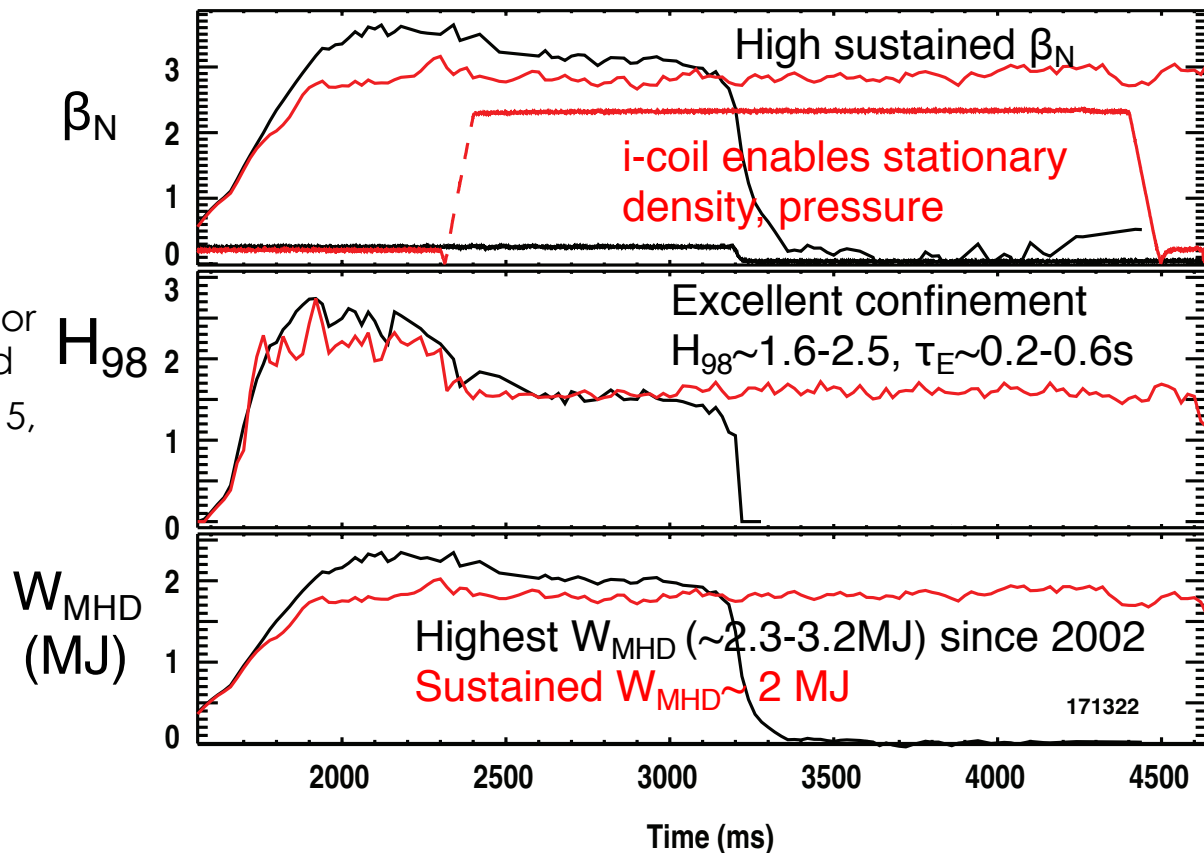


- Equivalent $Q_{DT,eq} = P_{fus,DTeq}/P_{nbi} \sim 0.54$. $Q_{DT,eq}^* = P_{fus,DTeq}/(P_{nbi} - dW/dt) \sim 1$
 - Previous DIII-D record $Q = 0.32$, Lazarus96 in negative central shear discharges with 2.2MA, 22m³
 - Achieved at modest $B = 2.17T$, $I_p = 2MA$, $V = 20$ m³. DT_{eq} Fusion power density ~ 0.2 MW/m³

Appears to be highest $Q_{DT,eq}$ and $\langle p \rangle \tau$ on any medium size ($R < 2m$) tokamak, and highest $Q_{DT,eq}/IaB$ or $Q_{DT,eq}/R^2B^2$ on any MFE device

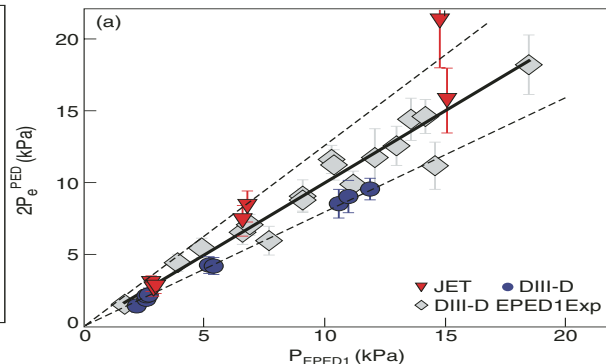
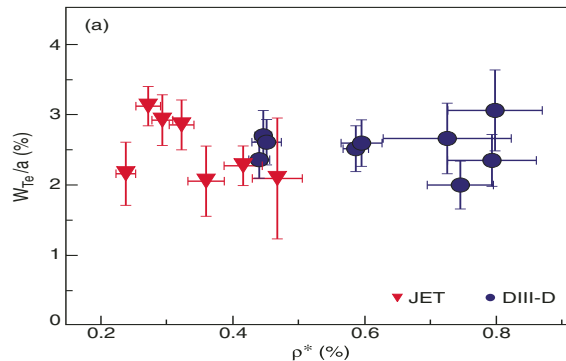
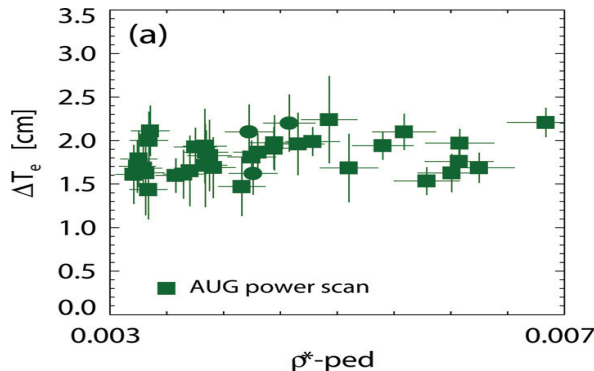
Super H-Mode Sustained Using 3D Magnetic Perturbations to Control Density and Impurity Accumulation

- **High performance condition sustained by applying 3D magnetic perturbation**
 - Controls density and impurity accumulation
 - Feedback control of pedestal or average density demonstrated
 - Sustained $W \sim 1.9 \text{ MJ}$, $Q_{DT,eq} \sim 0.15$, $\tau \sim 0.2 \text{ s}$, $H_{98} \sim 1.6$, $\beta_N \sim 2.9$
 - $\sim 2 \text{ s}$ sustainment (hardware limited)

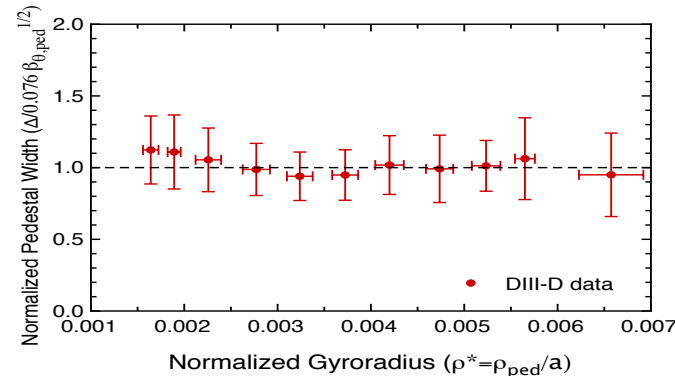


Predictions for ITER, Implications for Compact, High Performance Fusion

Dependence on ρ^* Important for Predictions of ITER

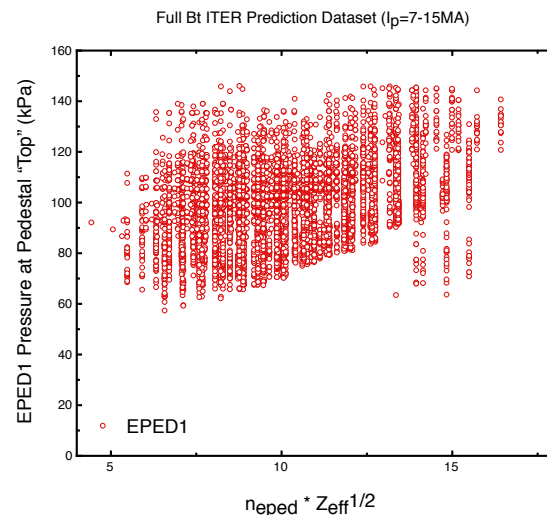
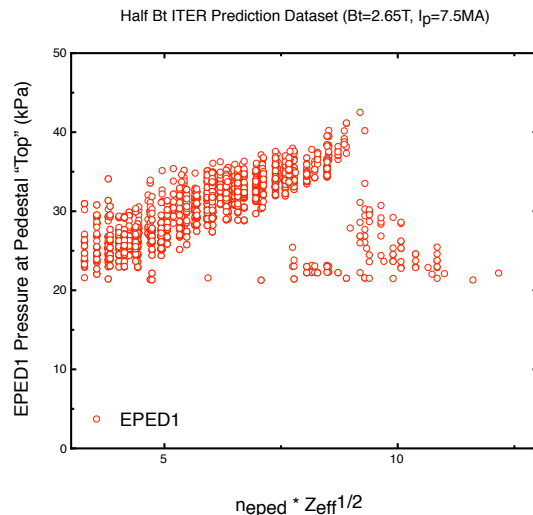


- Key dimensionless parameters for ITER or DEMO reactor matched on existing machines (v^* , β , q , ϵ) except ρ^*
- Argument based on global ExB stabilization of turbulence leads to ρ^* dependence ($\gamma \sim c_s/L$, $\omega_E \sim p/L^2$, $\omega_E > \gamma \rightarrow L < c\rho$)
- EPED predicts ~no ρ^* dependence: front propagation model for barrier formation and broadening
- Observations find little/no ρ^* dependence, including JET metal wall [Beurskens, Osborne PPCF09, Maggi17]



Open issue: Important to continue testing and developing understanding at very small ρ^*

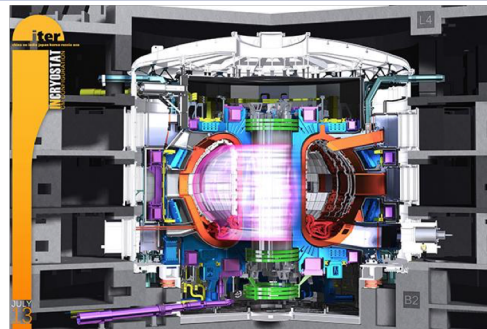
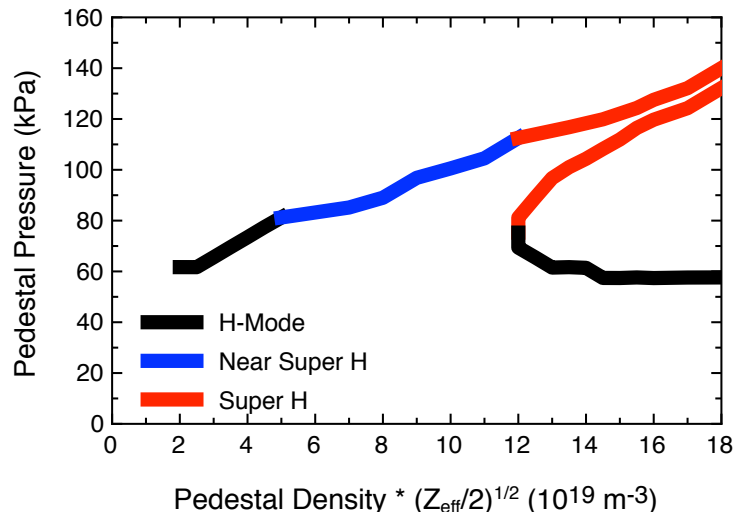
ITER Pedestal Predictions Made for more than 15,000 cases, used to train neural net (ITPA)



- **Fixed:** $R=6.2m$, $a=2m$
- **Varied:** $\kappa=1.7-1.9$, $\delta=0.45-0.49$, $\beta_N=1-3$, $Z_{eff}=1-3$, $m_i=1-3$
- **Three categories:** full (5.3T), half (2.6T), and 1/3 (1.8T) field
 - Full field: $I_p=5-17MA$ (most 7-15MA), $n_{eped}=3-15 \cdot 10^{19}$ (most 6-10.6)
 - Half field: $I_p=2-10MA$ (most 7.5MA), $n_{eped}=3-10.6 \cdot 10^{19}$
- **6 dimensional scan at each of 3 B_t values:** used to train neural net

Super H/NSH Regime Access is Predicted for ITER: DIII-D has Achieved Needed $\beta_{N,ped}$, $n_{e,sep}$, $n_{e,ped}$ Consistently

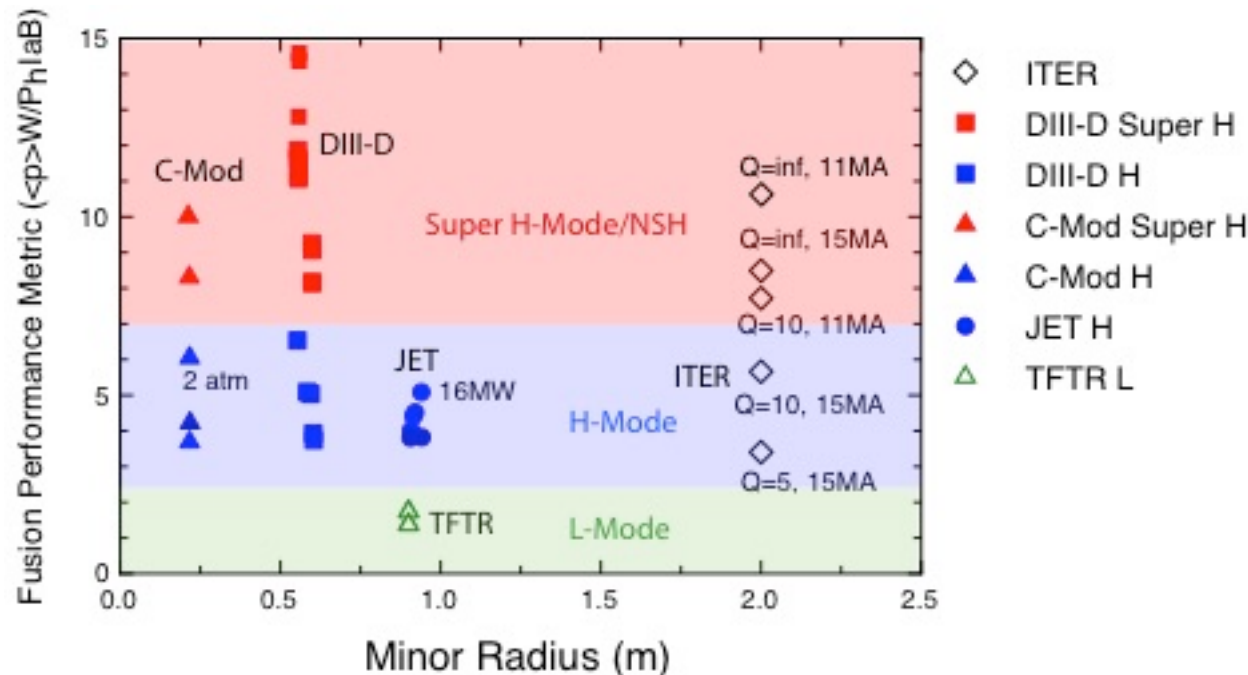
EPED Predicted Pedestal Height vs Density for ITER Baseline



Open issue: Physics of the Greenwald density limit which constrains degree of Super H access and predicted performance for ITER and DEMO concepts

- Core-pedestal simulations find ITER high performance ($Q > 10$) at high n_e [Meneghini16]
- DIII-D SH experiments reproduce many characteristics of the predicted ITER regime, including $\beta_{N,ped} \sim 0.8$, $n_{e,sep} \sim 3-4$, $n_{e,ped} \sim 7-10$. C-Mod produces $p_{ped} \sim 80$ kPa
 - Potential for substantial improvements in ITER performance, consistent with $n_{e,sep}$

Super H and Near Super H Operation Enables Very High Fusion Performance per $I_p a B_t$



Open issues: Challenges for Super H-mode operation include sustainment, impurity control, and ELM control. For JET and ITER, compatibility of strong shaping and nearby metal walls

- **Simple metric of fusion performance (Q or $\langle p \rangle W/P$) per $I_p a B_t$**
 - Colored points are observations ($\langle p \rangle > 50$ kPa), red points are SH/NSH experiments
 - High Q/IaB enables ITER success, and compact, cost attractive pilot plant

Summary: Exciting New Discoveries in Pedestal Physics Leading to Improvements in Fusion Performance

- **Multi-scale nature of pedestal leads to rich physics that challenges traditional analytic & computational approaches**
 - Open issues: formalism, particle & momentum transport, impurities, neutrals, ρ^* , L-H, i-mode & WPQH...
- **Despite challenges, significant progress made via gyrokinetic/neoclassical, MHD approaches, combined with advanced diagnostics**
 - Extensive validation studies on flexible tokamaks with high resolution measurements
- **Simple model (EPED) predicts pedestal height to ~20-25% accuracy in many regimes. Coupling to core models enables initial global confinement prediction**
 - Revolutionary capability for tokamak fusion optimization (many open issues, connection to SOL)
 - Gyrokinetic/neoclassical studies working toward predictive capability for individual transport channels (n, T, v)
- **Super H regime enables high pedestal and high fusion performance**
 - Predictions guided experiments, leading to discovery of new regime
 - Record ITER-like pedestal pressure on Alcator C-Mod, high fusion performance on DIII-D ($Q_{DT,eq} \sim 0.5$)
 - Potential for high performance in ITER, and compact, high performance fusion reactors
 - *ITER predictions made for >15,000 cases, used to train neural net for efficient testing and coupled core-pedestal simulations. Developing accurate methods for incorporating SH solutions as well.*

Acknowledgments

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- *DISCLAIMER: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.*

Extra Slides

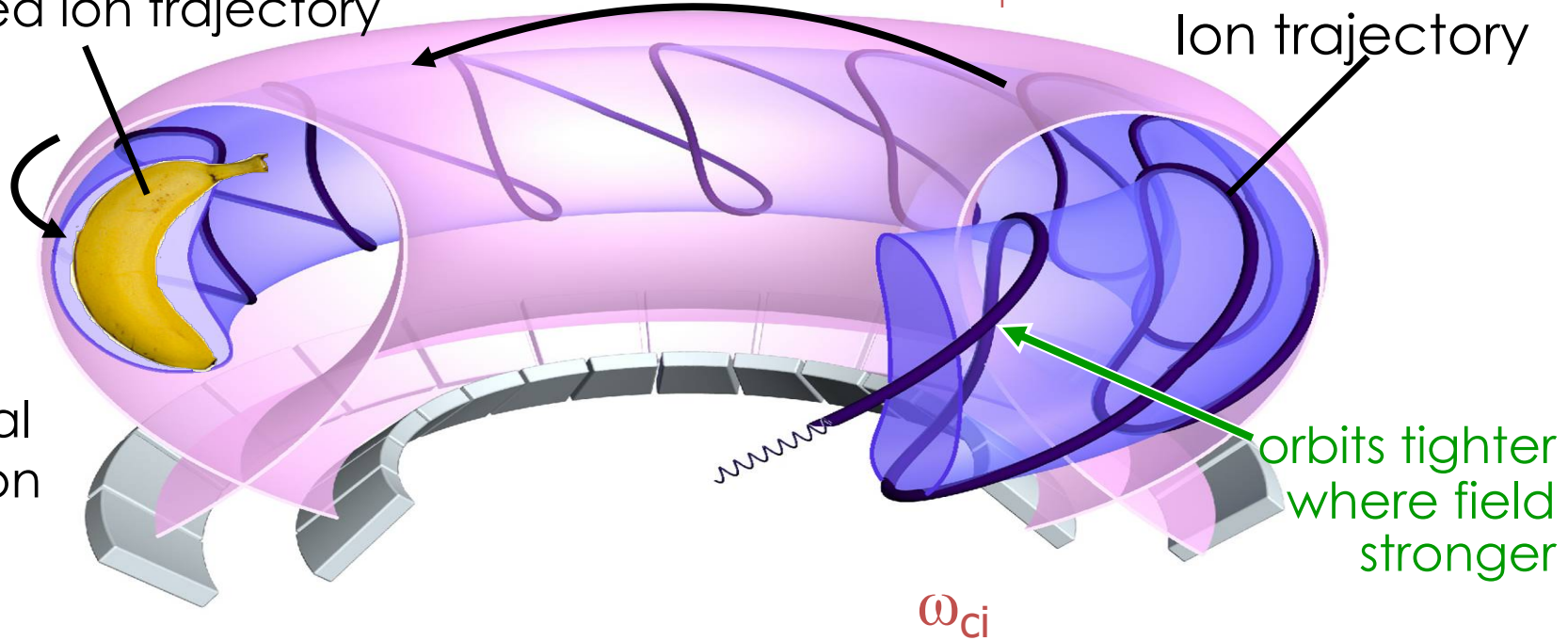
Neoclassical Theory Describes Collisional Transport Associated with Poloidal 'Banana' Orbits

Projection of poloidally trapped ion trajectory

Toroidal direction ω_ϕ

Ion trajectory

Poloidal direction
 ω_θ

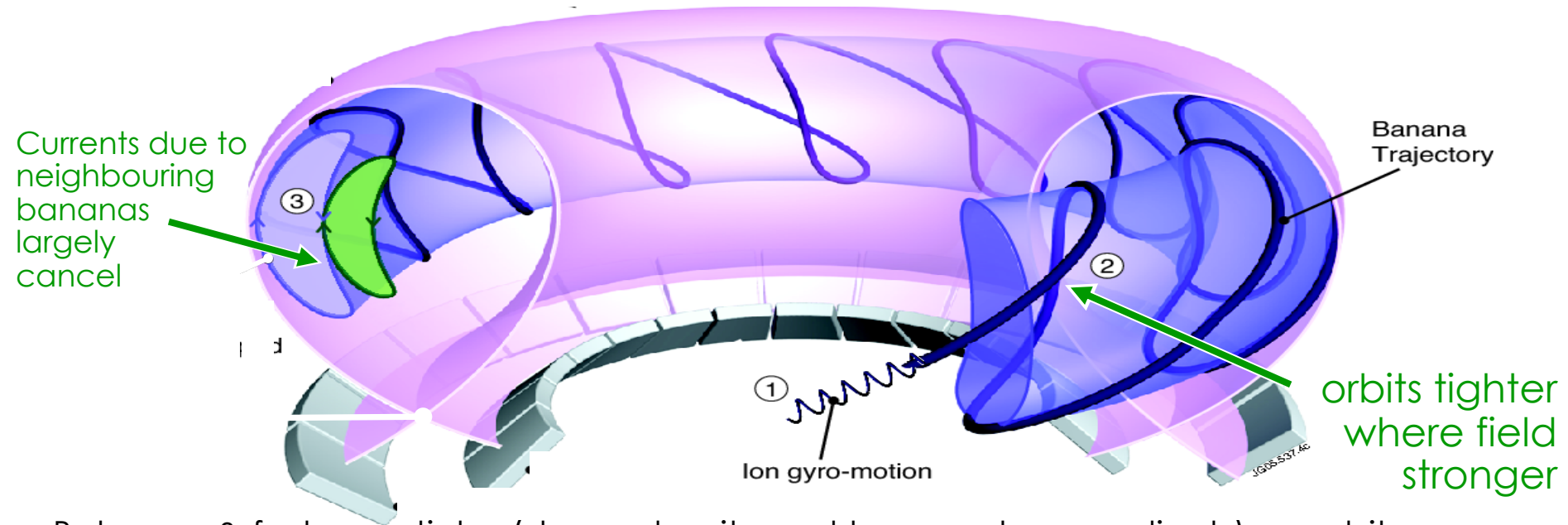


ω_{ci}

Collisions along orbits drive ion heat & momentum and impurity transport

Neoclassical Physics also leads to Large “Bootstrap” Current in Pedestal

Gyro-orbits drift due to non-uniform field $\Rightarrow$ banana orbits



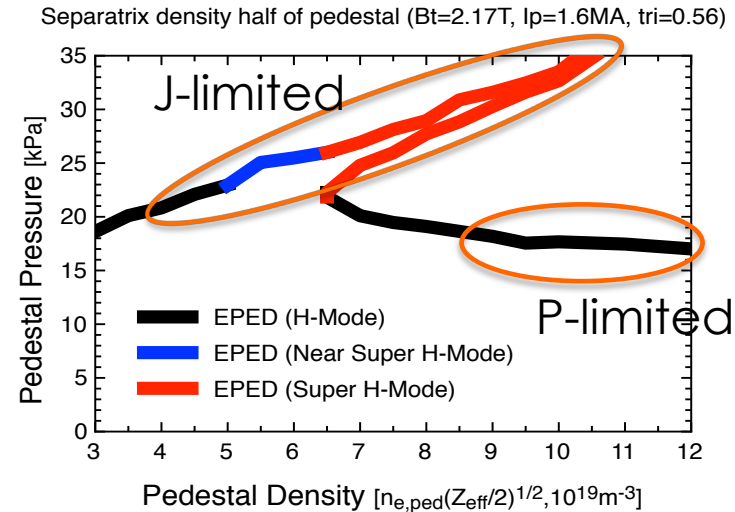
But more & faster particles (strong density and temperature gradients) on orbits nearer the core (green cf blue) lead to a net “banana current”

- this is transferred to a helical bootstrap current via collisions
- Bootstrap current typically dominant in pedestal, major role in instabilities

Sustainment and Core-Edge Compatibility of Super H-Mode Regime

Connecting a High Performance Super H Pedestal & Core to a High Density, Radiative Divertor & SOL

- **Super H (J-limited) solution predicted not to show degradation of pedestal pressure w/ $n_{e,sep}$**
 - P-limited solution degrades with increasing $n_{e,ped}$ and $n_{e,sep}$ (eg high gas puff in JET ILW)
- **Scan D_2 gas rate, and introduce radiative impurities (N_2) into the Div/SOL to test predictions on DIII-D**
 - Use 3D magnetic perturbations (i-coil) to control particle and impurity accumulation in core
 - Use i-coil feedback to maintain ~constant density in pedestal & core as separatrix, divertor and SOL density are increased
 - *Test EPED predictions of sensitivity of pedestal to separatrix conditions*

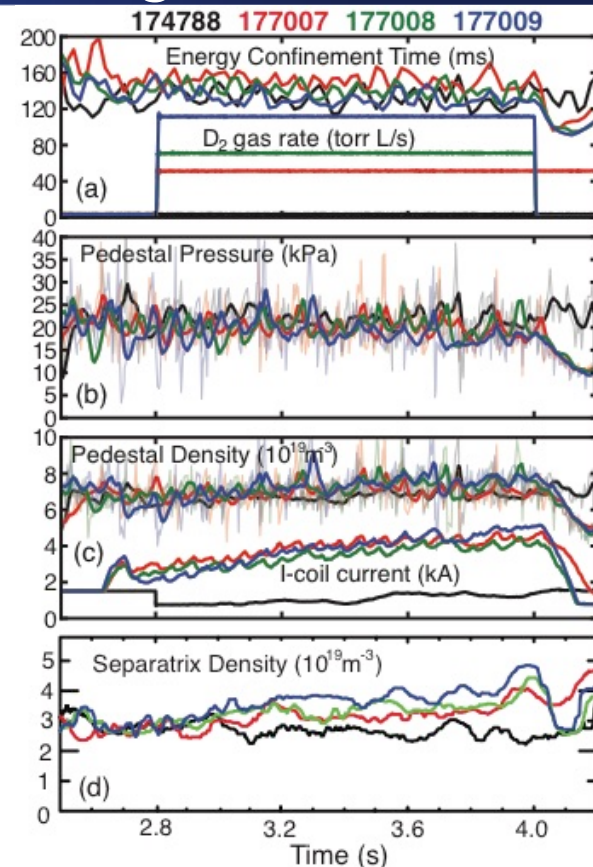


D₂ gas Scan Increases Separatrix and Divertor Density while Pedestal Pressure and Confinement Remain High

- D₂ gas scan in Super H mode experiment at $I_p=2\text{MA}$, $B_t=2.1\text{T}$. Gas rate varied $\sim 30\times$
 - Pedestal pressure and τ_E remain $\sim$ fixed, high
 - i-coil feedback control of $n_{e,\text{ped}} \sim 7\text{--}8 \cdot 10^{19} \text{ m}^{-3}$ successful up to $\sim 110 \text{ torrL/s}$ of D₂ gas
 - Separatrix density rises from $\sim 2.5 \text{--} 4 \cdot 10^{19} \text{ m}^{-3}$
 - Strike point density rises from $\sim 2.5 \text{--} 7 \cdot 10^{19} \text{ m}^{-3}$

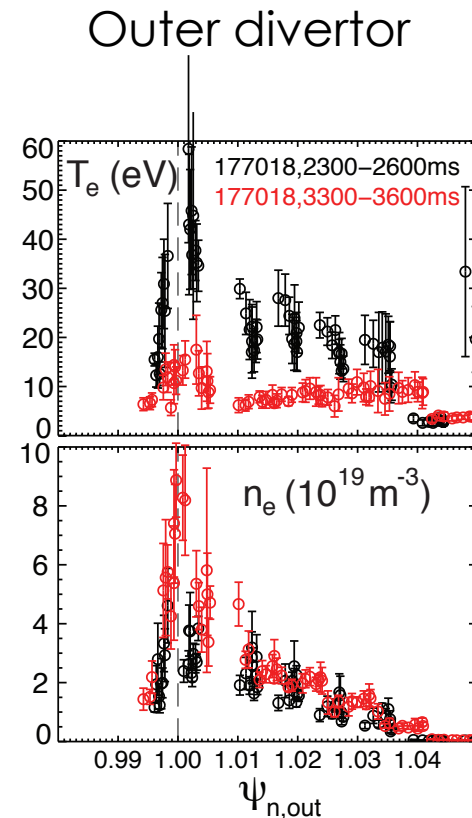
Both pedestal and separatrix density reach ITER values while maintaining high confinement and p_{ped}

Super H-mode compatible with both high fusion performance and high separatrix density for divertor solutions.



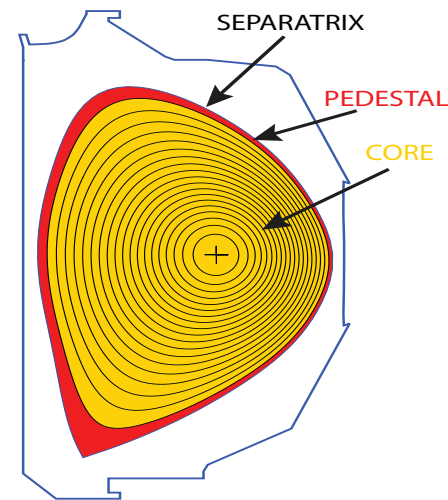
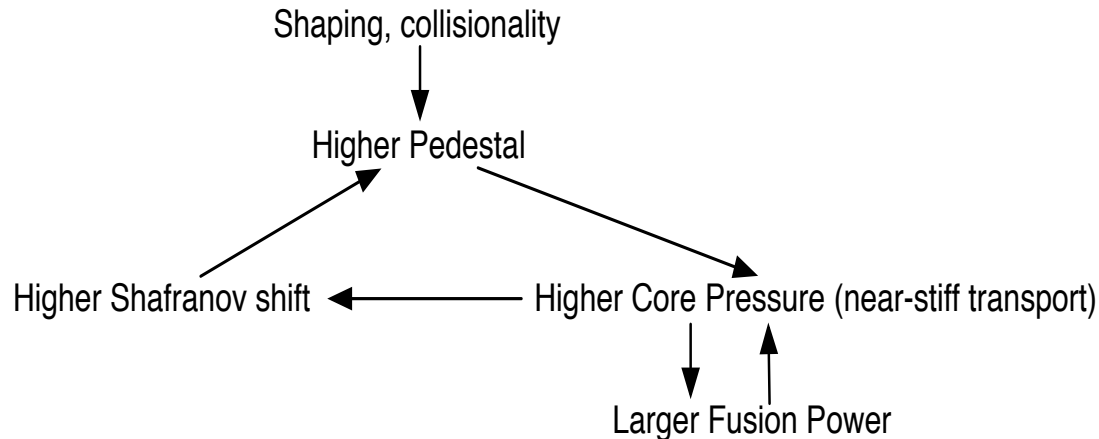
N₂ Injection Effective for Cooling Divertor while Maintaining High Performance Core & Pedestal

- **Significant cooling with ~5MW of divertor radiated power using feedback on N₂**
 - Peak T_e near strike point drops more than 3x
 - Pedestal pressure and confinement remain ~constant
 - Future experiments needed to explore full detachment and impact of closed divertor



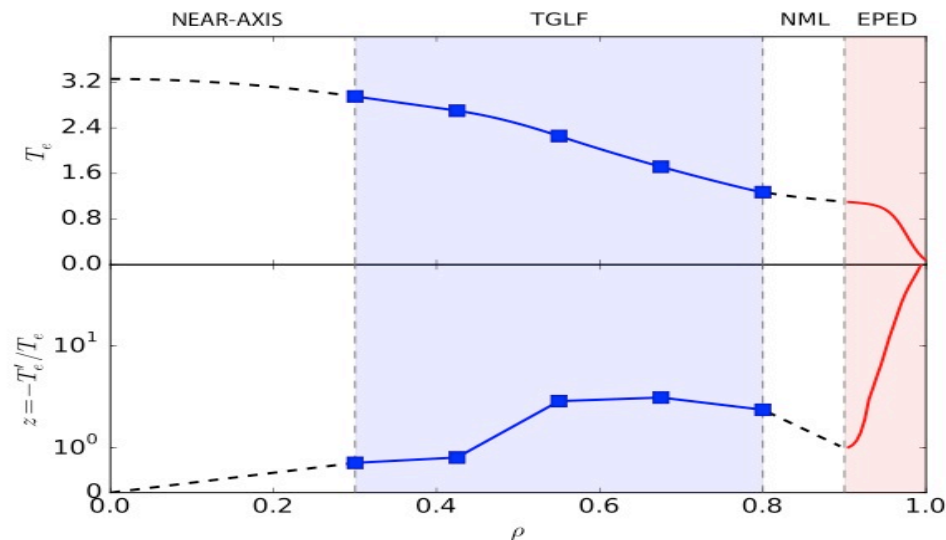
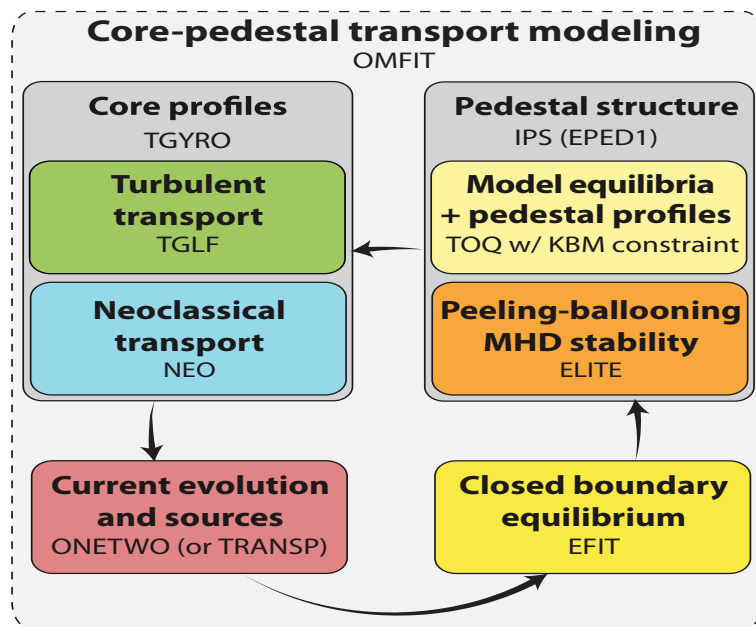
Integrated Modeling Enables Prediction and Optimization of Coupled Core-Pedestal System

- Peeling-ballooning stability is enhanced by the global Shafranov shift, which is proportional to global pressure [Snyder07,Chapman15,Saarelma17]
- Core turbulent transport is gradient scale length driven, 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



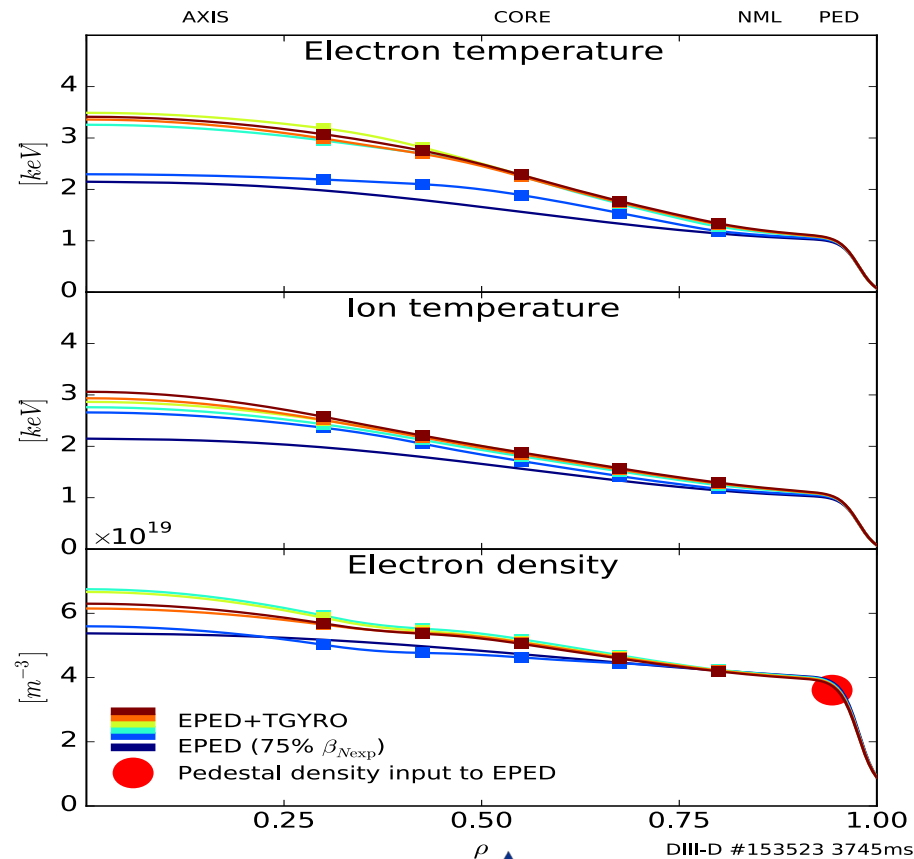
Example: EPED/TGLF/NEO and Core-Pedestal Integrated Modeling: DIII-D ITER-similar Discharge 153523

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



Example: EPED/TGLF/NEO and Core-Pedestal Integrated Modeling: DIII-D ITER-similar Discharge 153523

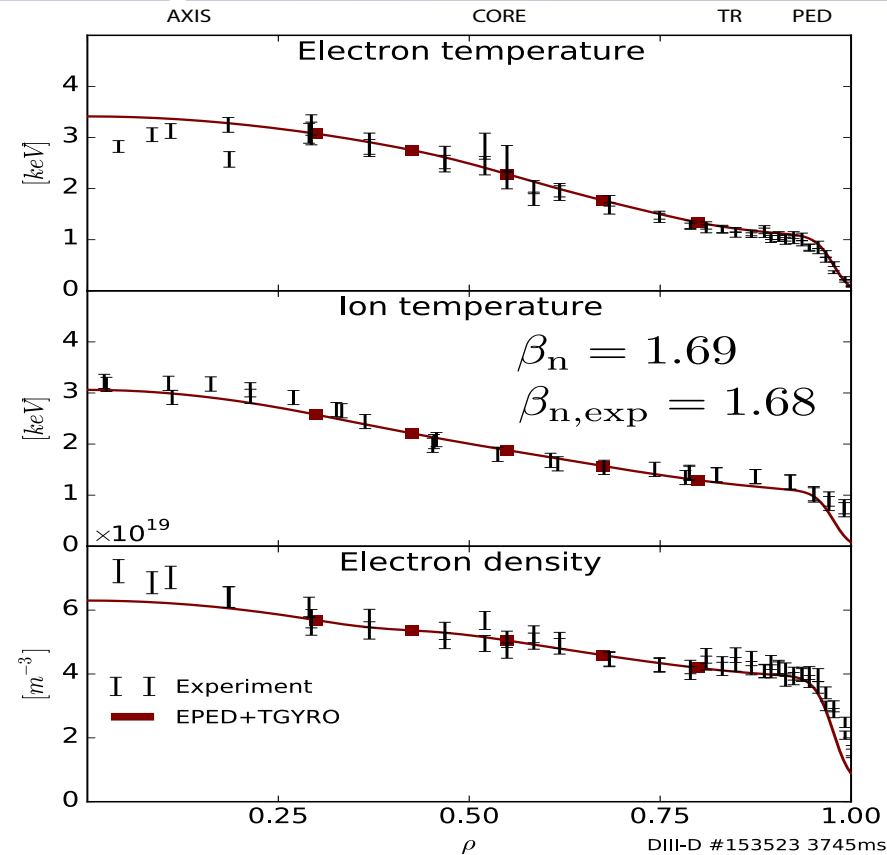
- No measurements of T_e , T_i or pressure input
- Density only input at pedestal
 - Inputs: shape, sources, rot., B_t , I_p , $n_{e,ped}$
 - Predicting T_e , T_i , $n_{e,core}$, β_N
- Step 1: Run EPED
 - Don't yet know β_N so use (poor) initial guess
- Step 2: Run TGYRO using BC from EPED to predict profiles and β_N
- Step 3: Run EPED using updated value for β_N
-
- Iterate to convergence
 - Have predicted profiles for T_e , T_i , n_e and pressure/ β_N
 - Result independent of initial guess



Example: EPED/TGLF/NEO and Core-Pedestal Integrated Modeling: DIII-D ITER-similar Discharge 153523

- **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
 - Statistical accuracy in large studies
- **Revolutionary capability**
 - Predict confinement and stored energy without empirical scalings
 - Employing to predict and optimize the performance of ITER and future devices

Open issues: Predicting L mode and L-H transition. Coupling to open field line region and divertor, material surfaces. Predicting particle and impurity transport through pedestal.



Super H-Mode Experiments on Alcator C-Mod and DIII-D Achieve High Fusion Performance, Record Pedestal Pressure

- Super H-mode (SH) predicted in strongly shaped plasmas: high p_{ped} , increases with n_e [Snyder NF15]
- **Record pedestal pressures** (~80 kPa) achieved in C-Mod SH experiments [Hughes NF18]
 - Successful tests of EPED model up to ~90% of predicted ITER p_{ped}
- **Record DIII-D fusion gain** ($Q_{\text{DT,eq}} \sim 0.54$). $Q_{\text{DT,eq}}/IaB$ and $Q_{\text{DT,eq}}/(RB)^2$ highest reported on any tokamak
- High performance sustained w/ 3D magnetic perturbations to control n_e and impurity accumulation
- **Predicted to enable high performance on ITER, and be compatible with high separatrix density for divertor solutions**

