Pedestals and Thinking Outside the Box

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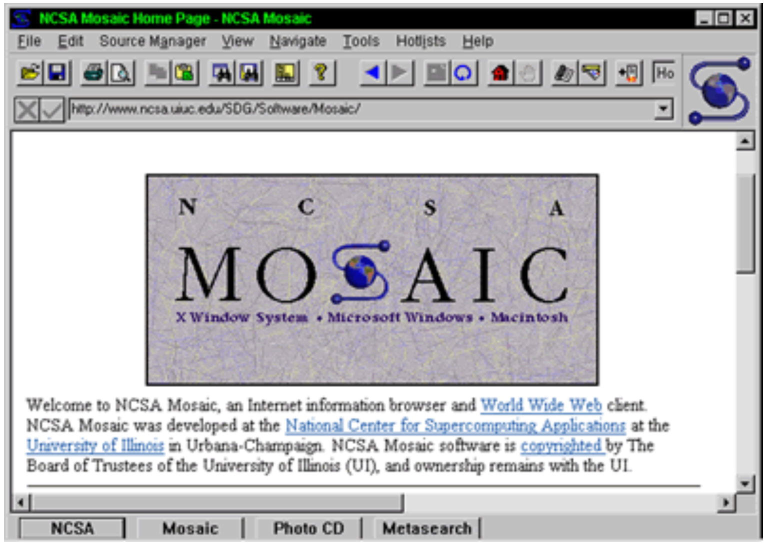
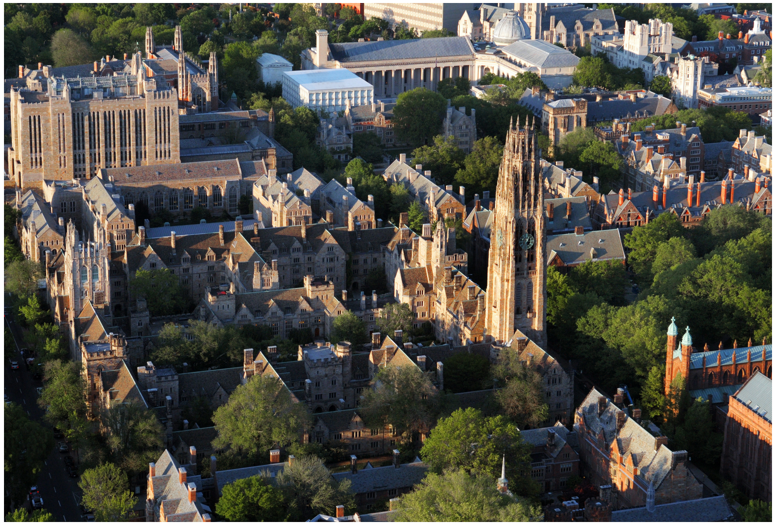
Solved and Unsolved Problems in Plasma Physics
Symposium in Honor of Nat Fisch
Princeton NJ, 28 March 2016

GENERAL ATOMICS

The year is 1992-93....





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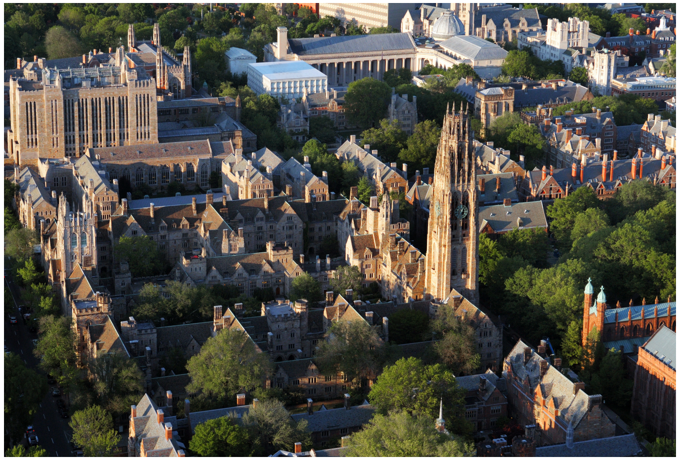
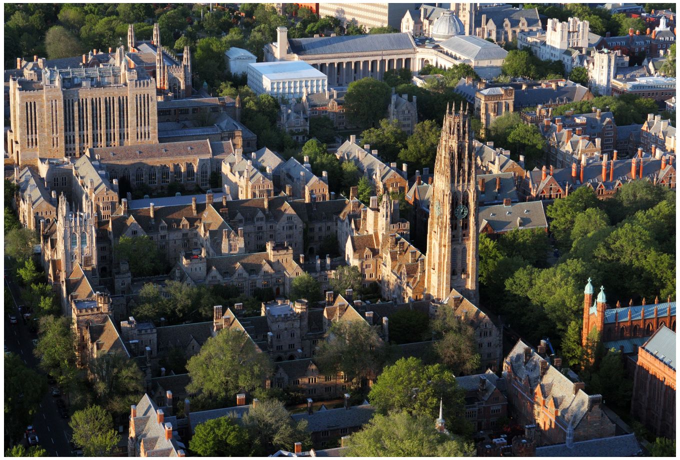
The year is 1992-93….

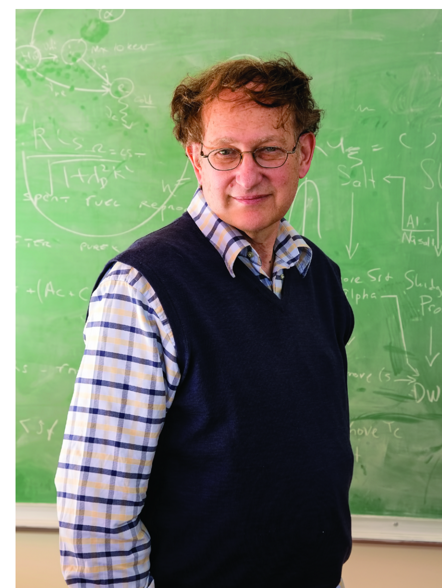


- Computational physics at Yale

The year is 1992-93....



- **Computational physics at Yale**



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PPPL grad program 1993-99

DEPARTMENT OF ASTROPHYSICAL SCIENCES
PROGRAM IN PLASMA PHYSICS
OCTOBER 1994

Standing (left to right): Zhihong Lin, Hui Long, Hong Qin, Qian Qian, Jon Menard, Yi Zhao, Steve Smith, Vladislav Savchenko, Stanislav Boldyrev, Tobin Munsat, Dimitri Uzdensky, Steve Cauffman, Mark Herrmann, Hans Herrmann, Hilary Oliver, Genze Hu.
Seated (left to right): Bob Heeter, Lufeng Leng, Chan Feng, Mike Beer, Yang Chen, John Wright, Mikhail Malyshev, Peter Schwartz, Barbara Sarfaty, Max Karasik, Scott Hsu, Phil Snyder, Bryan Fong, Julian Cummings, Xiaohu Li.
Missing: Ben Chandran, Ed Chao, Gordon Chiu, Wonho Choe, Ted Jones, Ernest Lo, Igor Manuilskiy, David Moore, Jaeyoung Park, Sherrie Preische, Fedor Trintchouk, George Vetoulis, Keith Voss, Zhehui Wang, Yanlin Wu.

Professor Fisch was a strong mentor from the start

- Grad program head, 1st year project advisor, 2nd year project advisor, taught GPP1 (I took and later TA'd), softball team sponsor

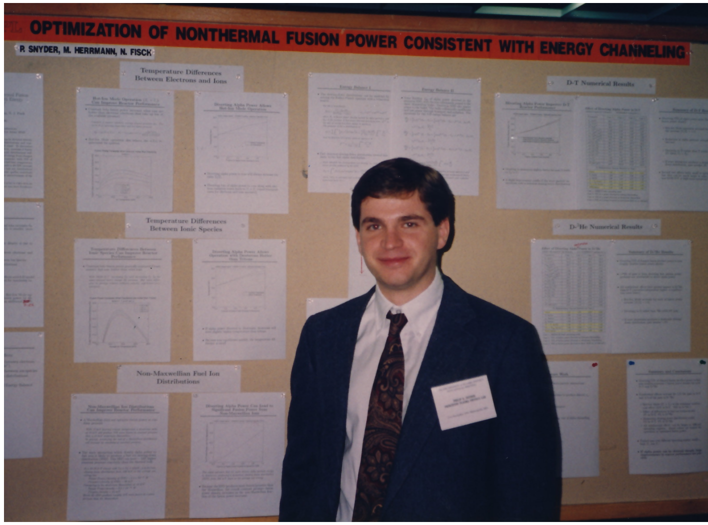
Journal of Fusion Energy, Vol. 13, No. 4, 1994

Optimization of Nonthermal Fusion Power Consistent with Channeling of Charged Fusion Product Energy

P. B. Snyder,[1] M. C. Herrmann,[1] and N. J. Fisch[1]

If the energy of charged fusion products can be diverted directly to fuel ions, non-Maxwellian fuel ion distributions and temperature differences between species will result. To determine the importance of these nonthermal effects, the fusion power density is optimized at constant-β for nonthermal distributions that are self-consistently maintained by channeling of energy from charged fusion products. For D–T and D–^{3}He reactors, with 75% of charged fusion product power diverted to fuel ions, temperature differences between electrons and ions increase the reactivity by 40–70%, while non-Maxwellian fuel ion distributions and temperature differences between ionic species increase the reactivity by an additional 3–15%.

KEY WORDS: Tokamak reactor; non-Maxwellian; alpha channeling; D–T reactor; D–^{3}He reactor.



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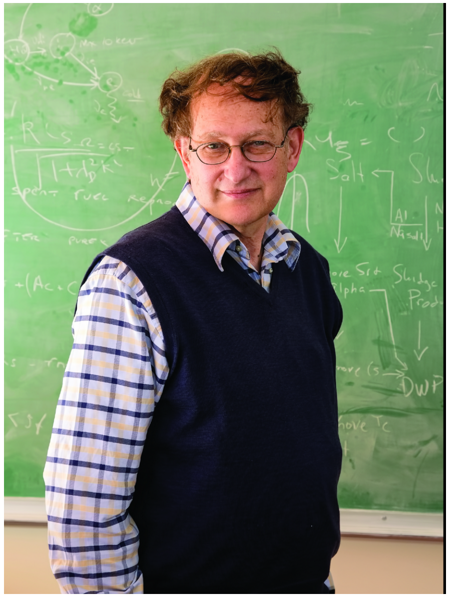
Learned many valuable lessons from Nat

- **The virtues of getting work done after midnight**
- **Think BIG.   Ideas matter.**
  - The fusion problem isn't "done"
- **Think outside the box even if you can't see a way out of it yet**



Turbulence and the Pedestal

- **Went on to study electromagnetic turbulence with Greg Hammett, Mike Beer & Bill Dorland**
  - "finite β" effects become most important near the edge where beta is smallest (but β' is large)
  - Turbulent times in the field (TFTR, GF v GK…)
    - Largely comes down to the edge (pedestal in H-mode… job at GA)

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Turbulence May Sink Titanic Reactor

James Glanz

The $10 billion International Thermonuclear Experimental Reactor project is meant to show that fusion is a practical energy source. But a new set of calculations says ITER will fizzle

DENVER--For more than a decade, hundreds of fusion researchers around the world have been working toward an audacious dream: an enormous machine called the International Thermonuclear Experimental Reactor (ITER). A $10 billion megaproject sponsored by the United States, Russia, Europe, and Japan, ITER is envisioned as a building-sized, donut-shaped device called a tokamak that is threaded with spiraling magnetic fields. The fields would cage million-degree deuterium and tritium ions, long enough for them to fuse and generate abundant power--enough, designers hope, to kindle the world's first controlled, self-sustaining fusion burn. Scientists have struggled for decades to demonstrate that fusion could be a practical source of power. ITER, due to be up and running before 2010 if construction funds materialize, is supposed to prove the case.

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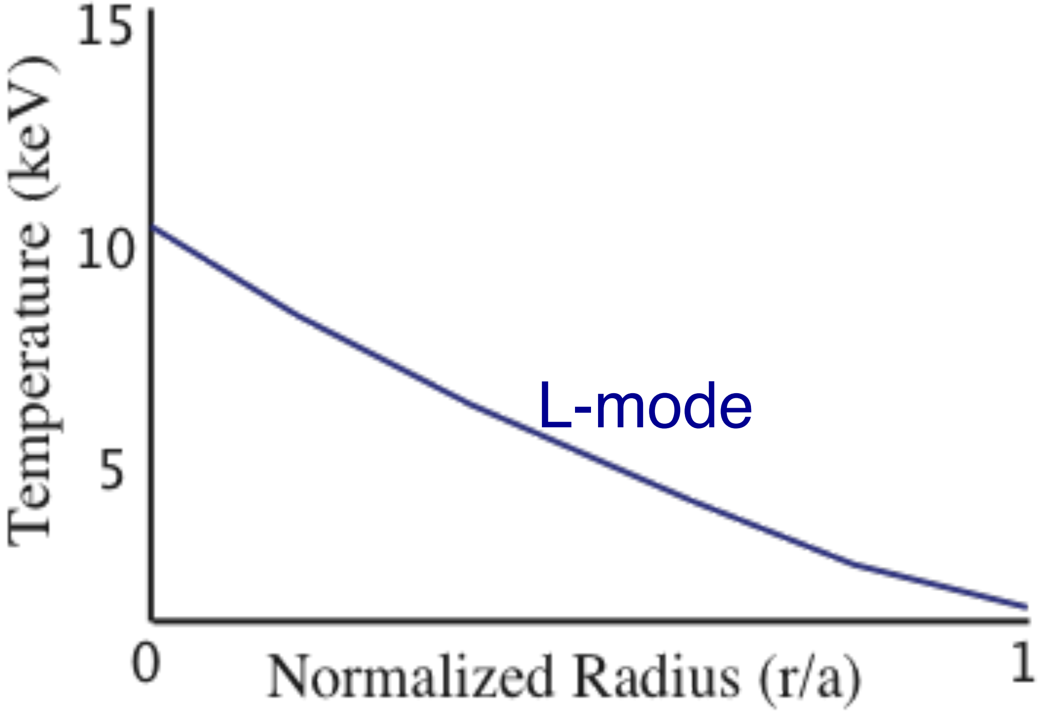
But that grand vision may be colliding with physical reality, in the form of results that have been roiling the fusion community for months and were discussed publicly here at a November meeting of the American Physical Society's division of plasma physics. Two researchers at the Institute for Fusion Studies (IFS) of the University of Texas, Austin--William Dorland and Michael Kotschenreuther--have come up with what Marshall Rosenbluth, a physicist at the University of California, San Diego (UCSD), calls "a remarkable intellectual achievement": a new theory of how turbulence rattles hot, ionized gas caged within powerful magnetic fields in a tokamak. That theory may be bad news for ITER.

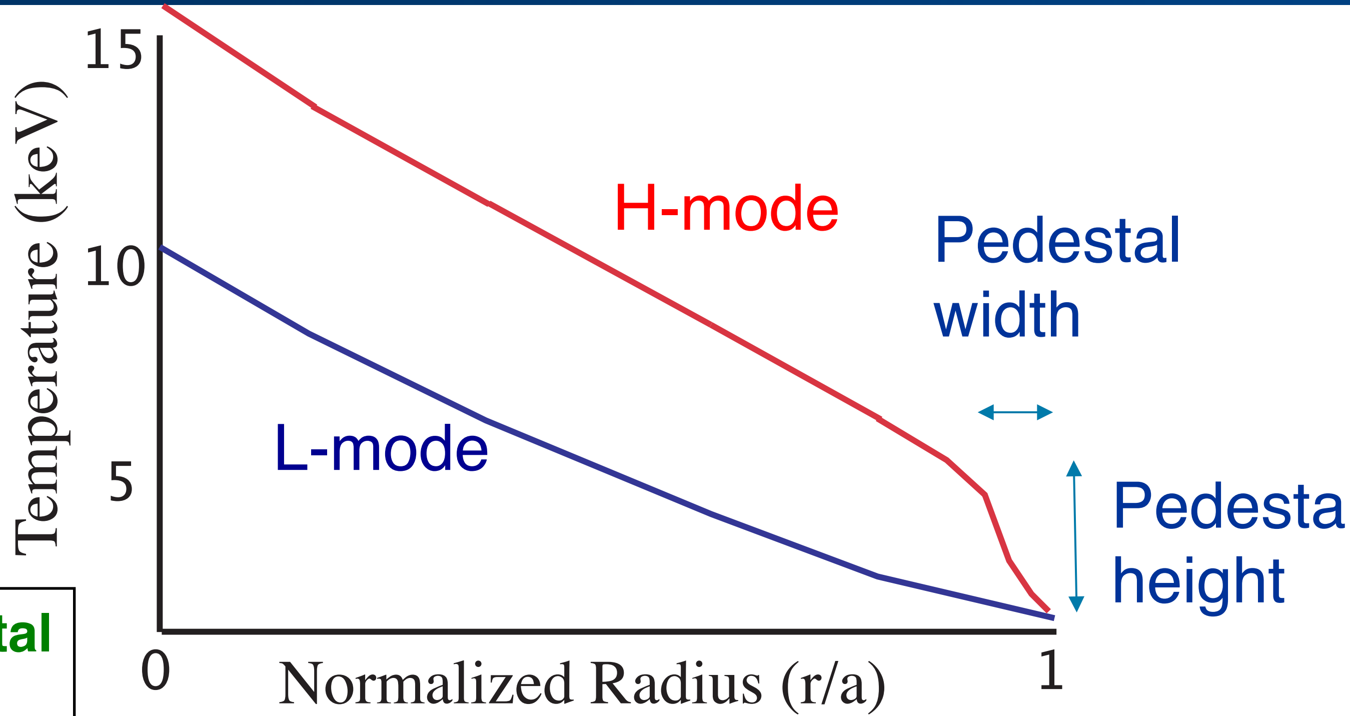
Solved and Unsolved Problems in the Pedestal

High Performance achieved via the Edge Transport Barrier



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

High Performance achieved via the Edge Transport Barrier



- **H-mode pedestal lifts whole profile**
  - "Height" (pressure) of the pedestal key to performance, multiplicative: $P_{fus} \sim p_{ped}^2$
- **Analogous to lifting a statue (core) onto a pedestal, but better, because statue gets higher proportional to pedestal**

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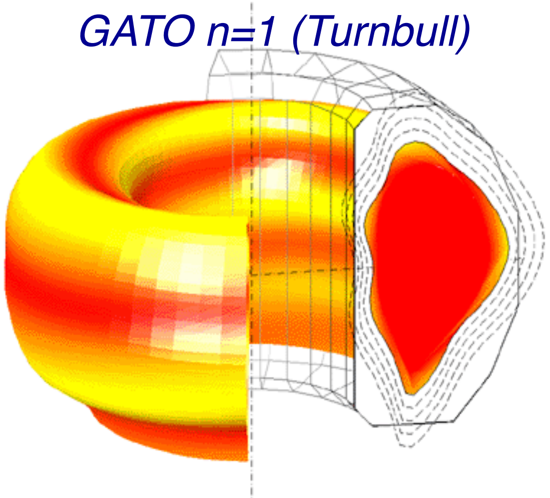
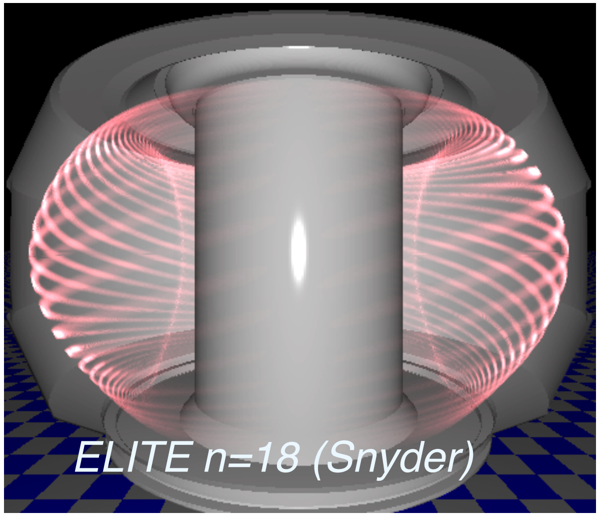
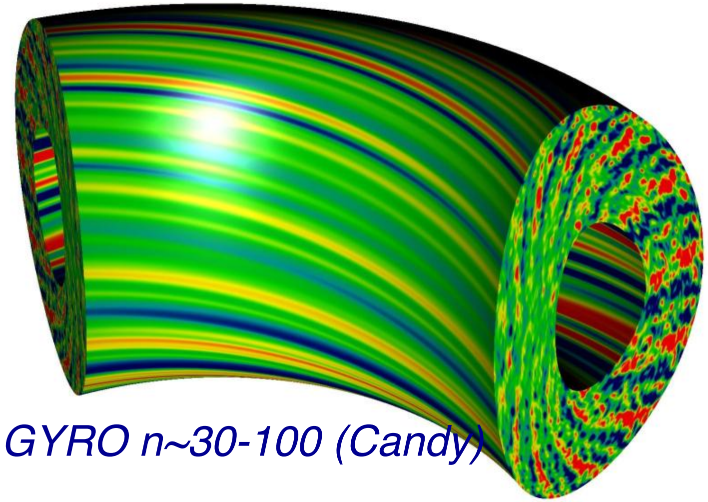
Pedestal Physics Challenges Existing Paradigms







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

Developing a New Paradigm for the Pedestal: Dark Beginnings

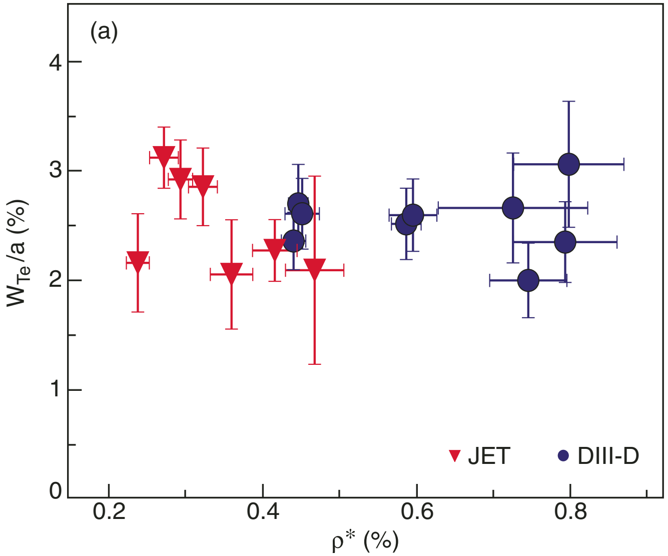
- **In late 1990's early 2000's, approach to pedestal was similar to core**
  - Local GK/GF simulations, ExB shear suppression
  - Simple argument based on diamagnetic ExB shear leads to ρ^* scaling of pedestal width
    - $\gamma \sim c_s/L$, $\omega_E \sim p/L^2$, $\omega_E > \gamma$ -> $L < c\rho^*$
  - Early pedestal measurements also find an observed width which scales with ρ^*

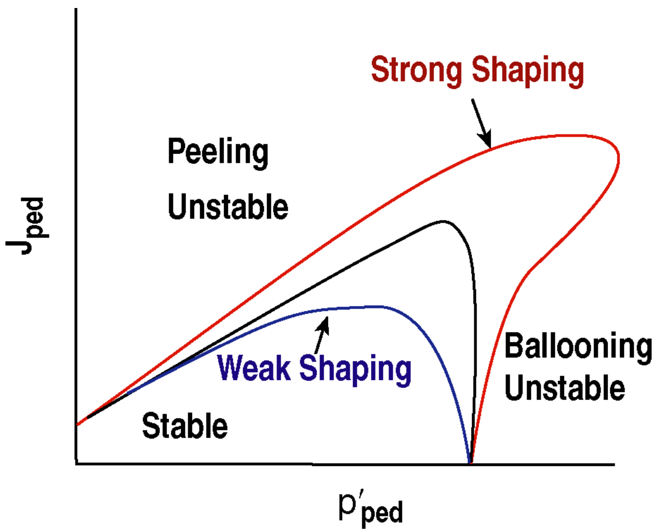
But ρ^* gets very small at reactor scale. Is our H-mode fusion reactor indeed going to sink like the titanic?

Developing a New Paradigm for the Pedestal: A New Hope

Is our H-mode fusion reactor going to sink like the titanic? Maybe not

- **Improved diagnostics and controlled experiments began to find more nuanced dependence**
  - Correlation of pedestal width with $\beta_{p,ped}^{0.4}$ (*Osborne99*), little ρ^* dependence in dimensionless expts (*Urano08, Beurskens09*)
    - Correlation of height with width explains early ρ^* results
- **Peeling-ballooning theory, implemented in efficient codes such as ELITE, provides quantitative constraint on the pedestal** *[Snyder&Wilson02…]*
  - Initially thought of as constraint on p' and j, over time full importance of non-locality (macro scale) appreciated. Little/no ρ^* dependence





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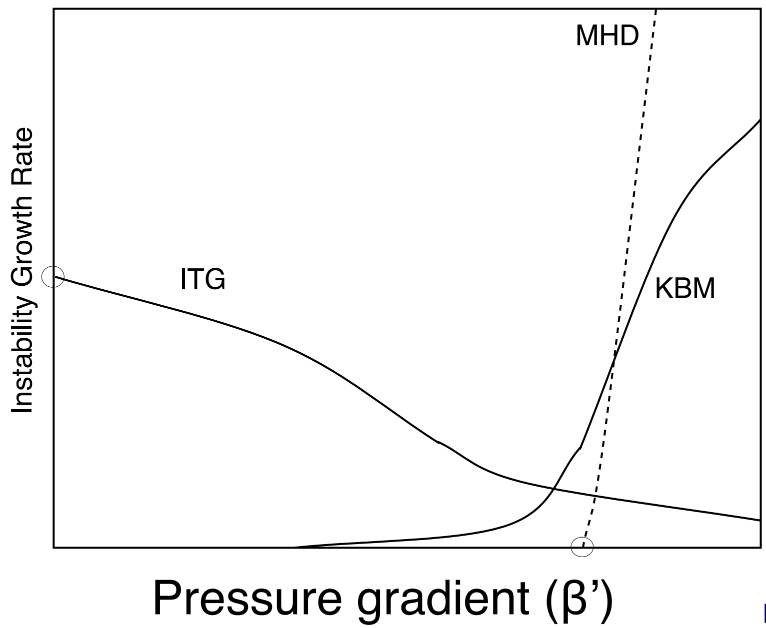
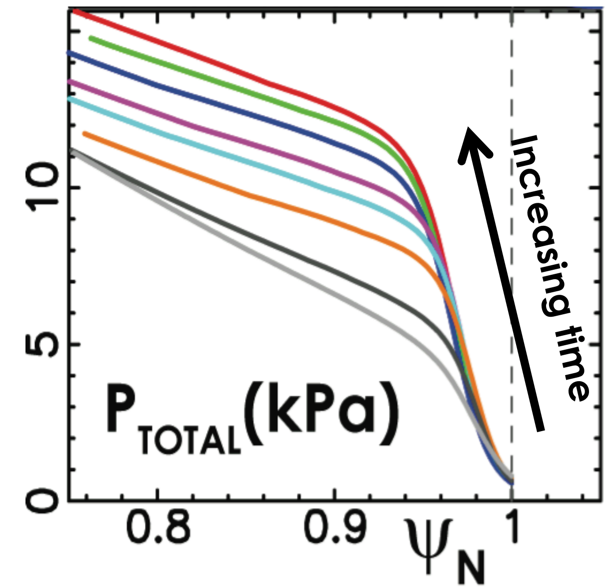
Developing a New Paradigm for the Pedestal: KBM & Front Propagation

- **Observed $\Delta \sim \beta_{p,ped}^{0.4}$ suggests KBM physics (harken back to PhD research)**
- **KBM based argument leads to $\Delta_{\psi} \sim \beta_{p,ped}^{1/2}$. Improving measurements find good agreement with this! (*Snyder PoP 09*)**
- **Key insight: The pedestal is fundamentally about front propagation. Propagates inward due to diamagnetic ExB shear, locked into KBM-criticality behind**
  - KBM criticality can be self-reinforcing. ITG is necessarily stabilized by finite-β' effects at KBM critical gradient
  - At the front, transition from p'_{KBM} to p'_{ITG}, across scale length characteristic of turbulent eddies. $\gamma \sim c_s/L$, $\omega_E \sim p/(L\rho)$, $\omega_E > \gamma$ **no ρ^* dependence**!
  - Peeling-ballooning actually limits the width. Insight on how to control ELMs (RMP & QH)





Putting PB and KBM Physics Together Yields the EPED Predictive Model

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

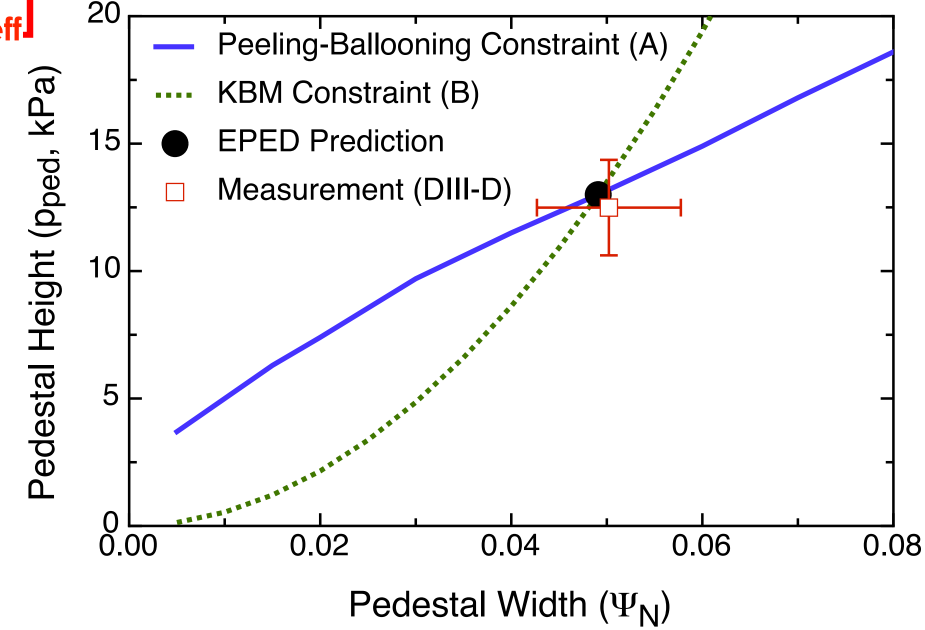
A. P-B stability calculated via a series of model equilibria with increasing pedestal height

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

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

– Directly calculate with ballooning critical pedestal technique

Illustration of EPED Model, DIII-D 132010



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

- **Different width dependence of P-B stability (roughly $p_{ped} \sim \Delta_\psi^{3/4}$) and KBM onset ($p_{ped} \sim \Delta_\psi^{2}$) ensure a solution, which is the EPED prediction (black circle)**

  -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

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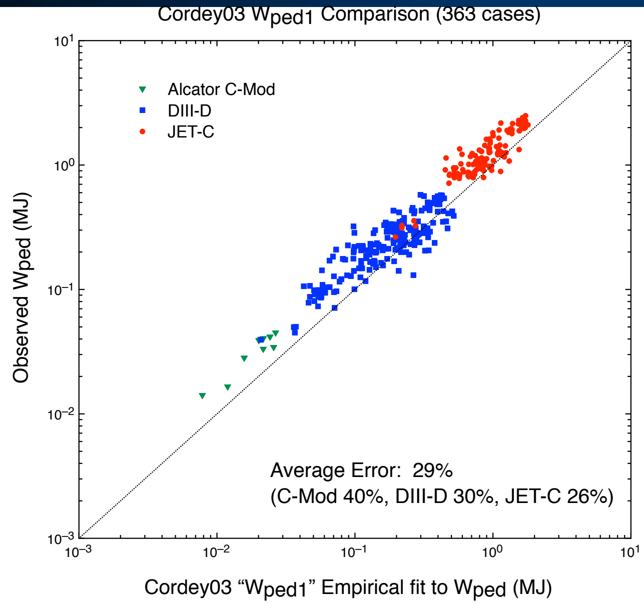
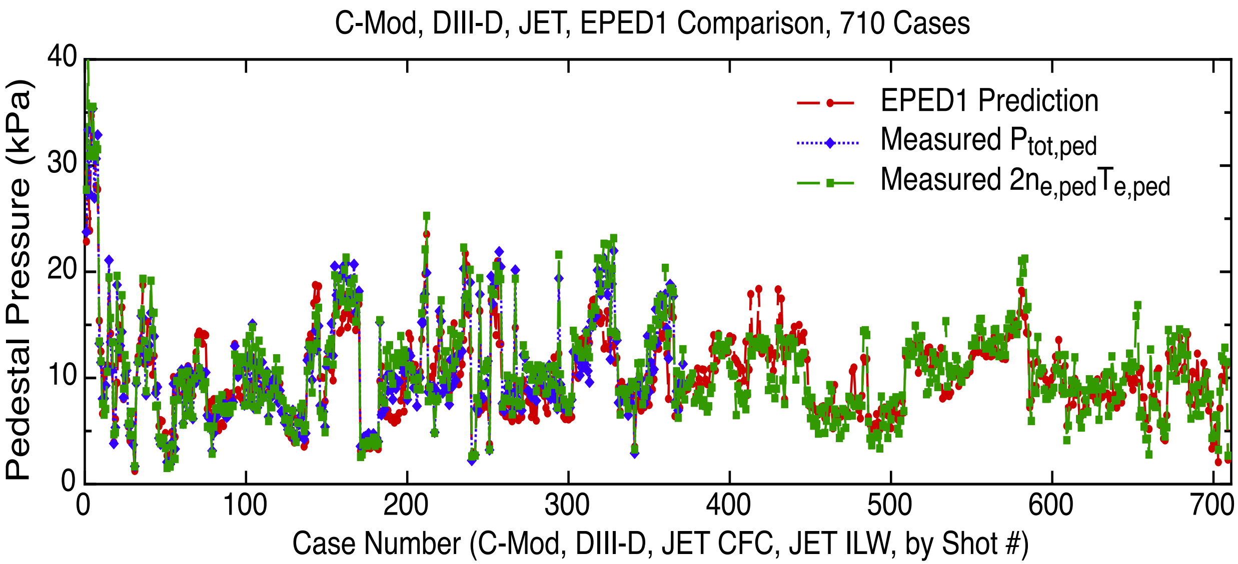
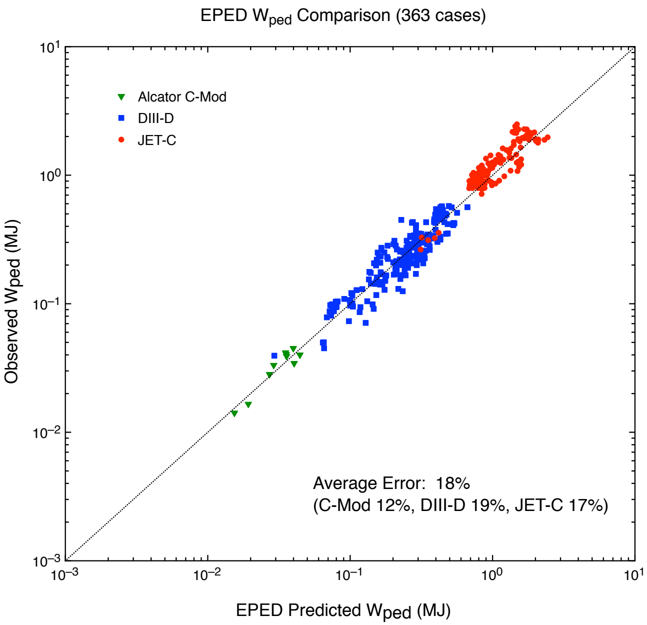
EPED Successfully Tested in Numerous Experiments, Agrees Better than Empirical Models



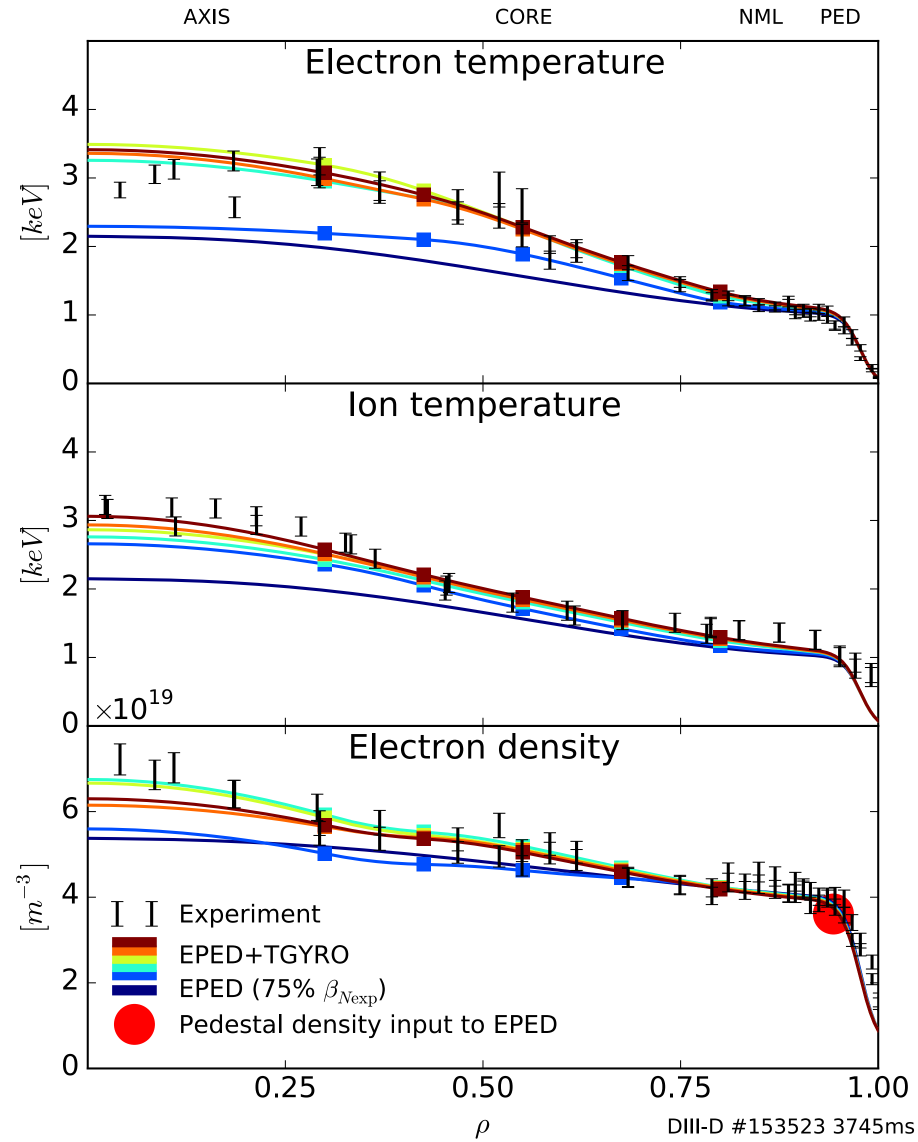




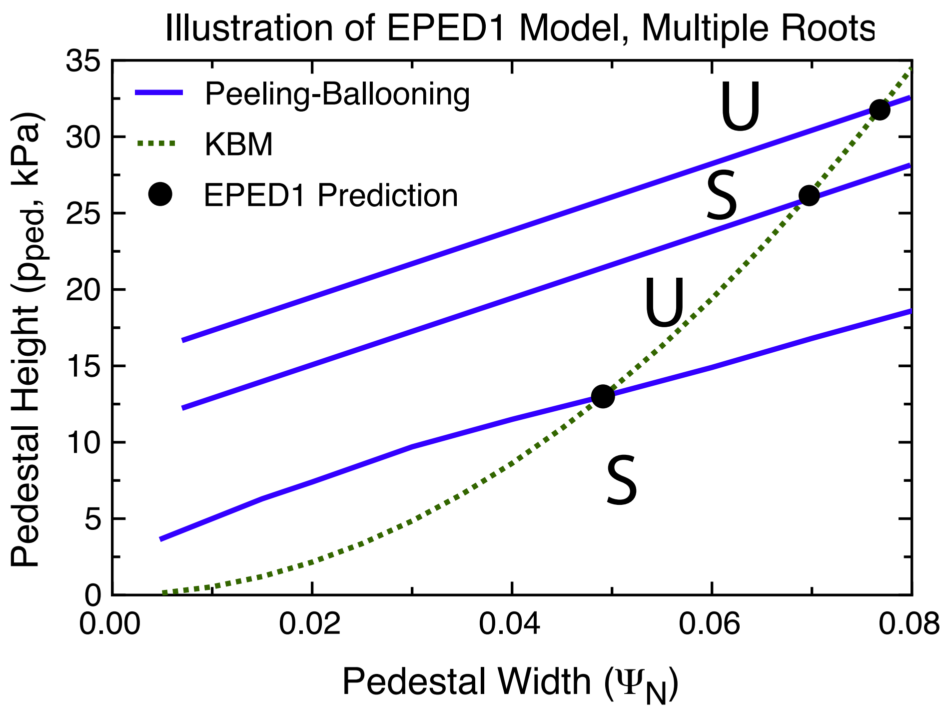
- **710 case study finds agreement with observation to σ~21%, avg error=1.68 kPa, $<|p_E - p_{exp}|>/<p_{exp}>$=16%, correlation coefficient=0.87**
- **EPED theoretical model, with no fit parameters (18% avg error), agrees better than empirical models** *[Cordey NF03]* **with 9 or 10 fit parameters (26-29% avg error)**

Coupling of EPED to Core Simulations (TGLF/NEO) has led to predictive capability for closed flux region

- **New Integrated Simulation SciDAC project (AToM)**
  - Efficient implementation of EPED on HPC resources using IPS
  - Couping to TGYRO/TGLF/NEO via OMFIT
- **Accurately predicts full T_i and T_e profile, core density profile and global beta in initial DIII-D study**
  - Core-pedestal coupling essential
- **Similar workflow applied to ITER and FNSF, optimizing performance as a function of pedestal density and other machine parameters**
- **Direct HPC simulations, such as with GYRO/CGYRO can be used to refine results**
- **Planning to couple to Div/SOL**



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 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)**

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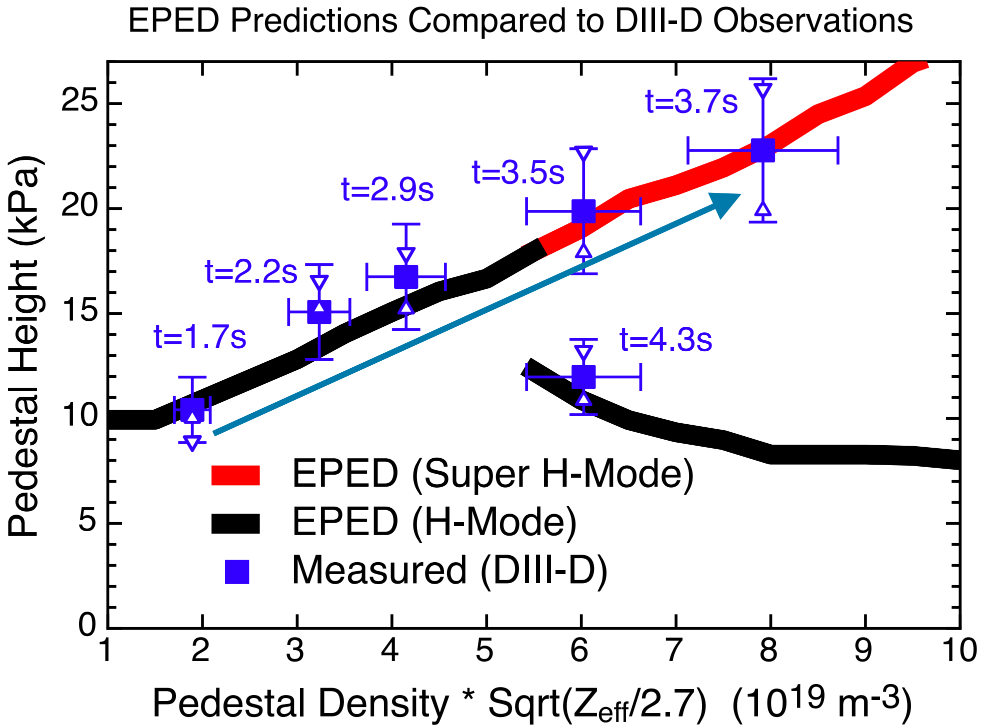
Super-H Mode Regime Accessed on DIII-D



Experiments planned using feedback control of density and global beta

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

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

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Many Important Questions for Future Investigation

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

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

Many Important Questions for Future Investigation

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

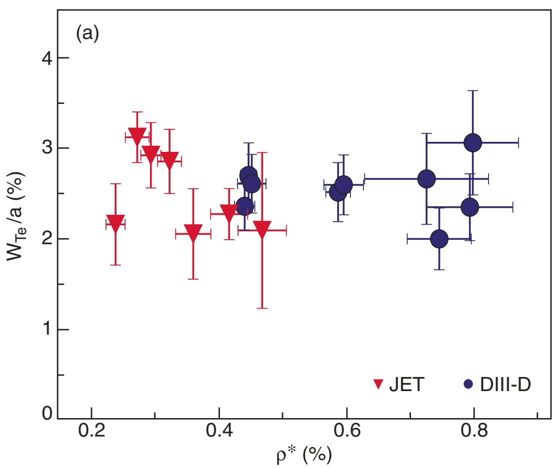
- **Rotation and momentum transport**
  - Can estimate ExB profile within pedestal assuming diamagnetic term is dominant, but need to predict boundary condition on toroidal rotation for core simulations
    - Strong source of intrinsic torque in edge, need to predict its amplitude and coupling to the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

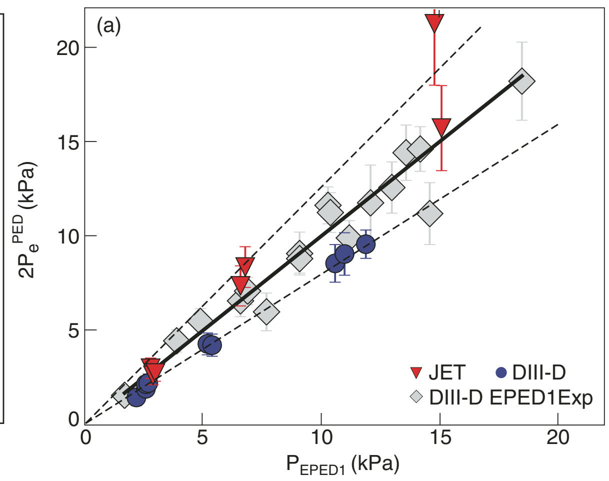
Significant Progress, but Many Interesting Unsolved Problems in the Pedestal

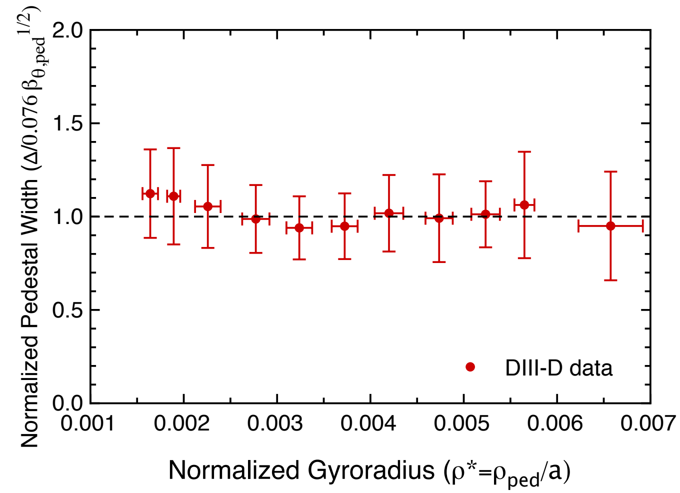
- **Thinking differently about the pedestal led to a new predictive model, EPED**
  - Predicts pedestal height and width to ~20%
  - Predicted a new regime (Super H), later discovered, path to high performance?
- **Insight on how ELM suppression works (stop the front propagation or bring it to a soft landing), but quantitative details of RMP, QH etc not well understood**
- **Process which starts the inward propagating ETB ("L-H transition")?**
  - Role of flows, orbit loss, transition to open field lines, start in ITG regime?
  - Partial transitions (eg I-mode) also not fully understood
- **Just beginning to explore coupling to core, must also study coupling to SOL/ divertor**
- **Detailed structure of density profile and relation to neutral sources is active area of investigation, as are momentum sources and transport**
  - Relation to impurities, divertor detachment
- **Dynamics, including ELMs and ELM impacts on material surfaces**
- **Efficient formalism & numerics for L~λ~ρ (6D, extended GK or GF…)**
  - Does anything new enter at very small ρ* ?

Extra Slides

EPED Agreement with Observations Independent of $\rho*$







- **Validated on dimensionless experiments on JET, DIII-D** *[Beurskens09]*
  - Observed width shows little/no rho* dependence and good agreement with EPED across scan
  - JET ILW discharges agree even better with EPED (same $\rho*$ range)
- **Comparisons with large database show no variation in level of agreement at small vs large $\rho*$**
  - Does something new enter at very small $\rho*$?

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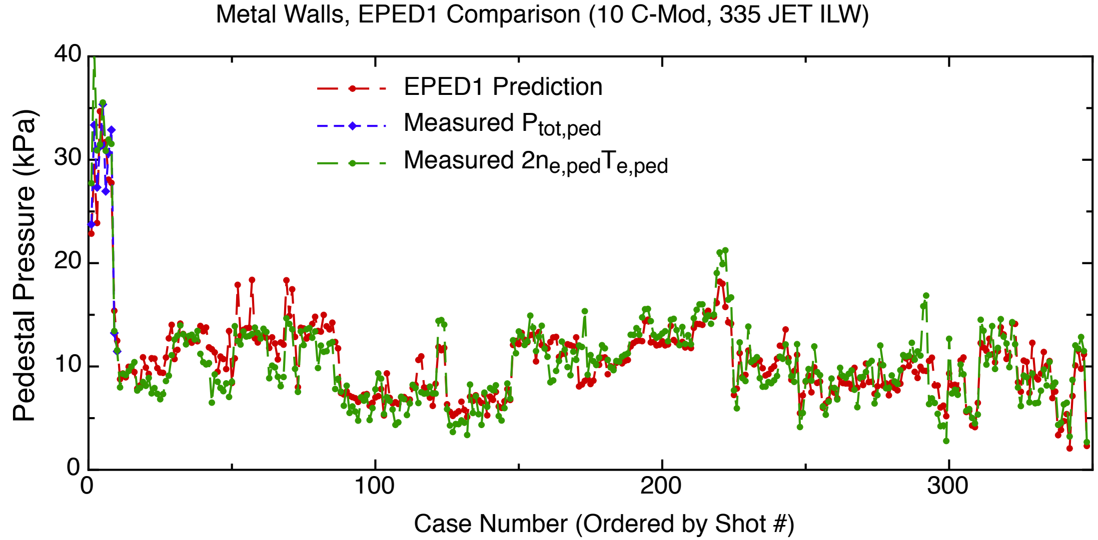
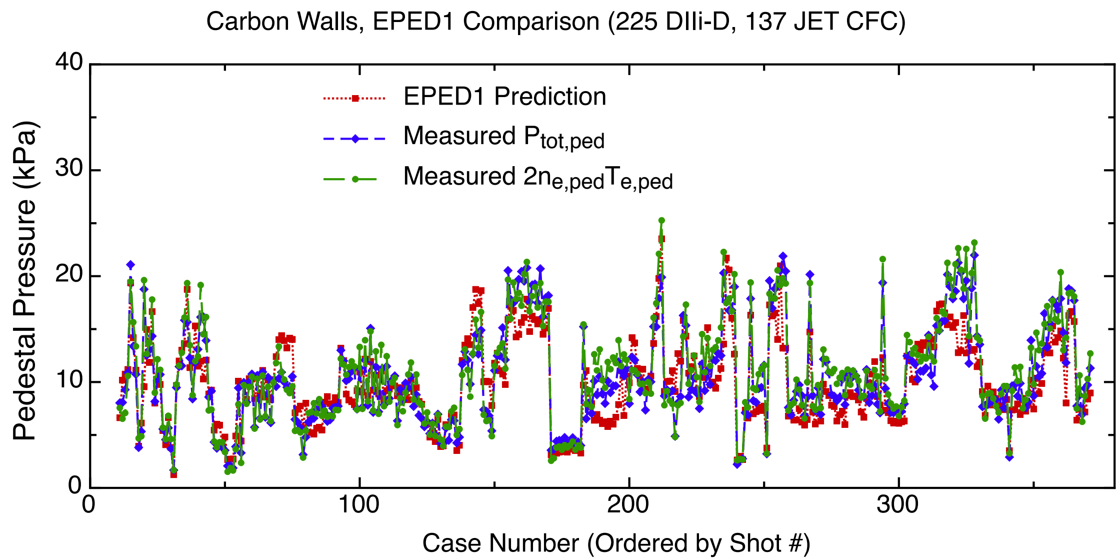
Similar Level of EPED Accuracy with Metal or Carbon Wall

- **Metal: average error=1.46 (14%), correl=0.90, σ=0.19**
- **Carbon: average error=1.88 (18%), correl=0.85, σ=0.22**
- **No indication of strong effect of wall material on *EPED accuracy***
  - JET ILW has lower impurity levels, different operational limits than JET C
  - Studying impact of impurities and gas puffing





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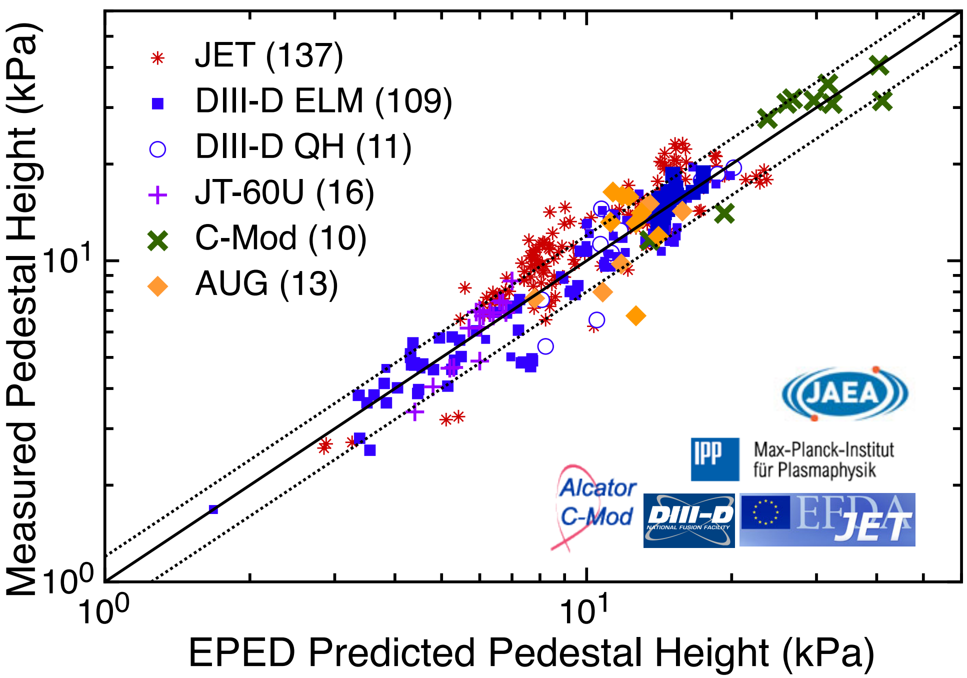
Numerous Experimental Tests of EPED Conducted: Moving to Systematic Uncertainty Quantification

Comparison of EPED Model to 296 Cases on 5 Tokamaks



Validation efforts coordinated with ITPA pedestal group, US JRT

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

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

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

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

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

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

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

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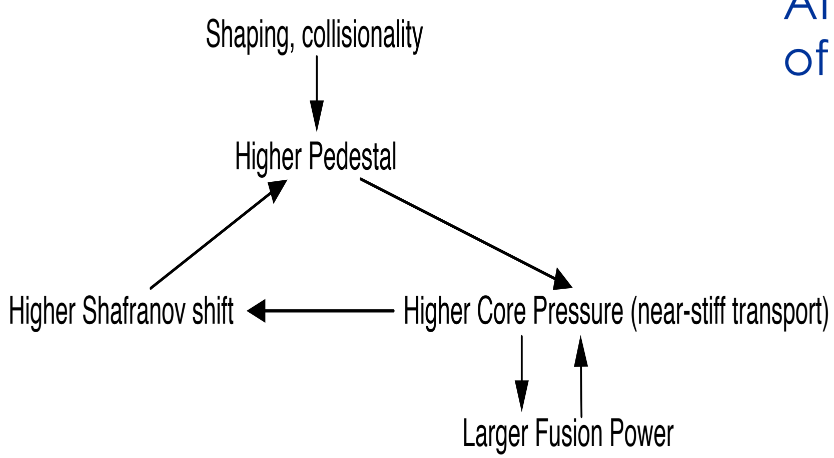
Integrated Modeling Enables Prediction and Optimization of Coupled Core-Pedestal System

- **Peeling-ballooning stability is enhanced by the global Shafranov shift, which is proportional to global pressure** ***[Snyder07]***
- **Core turbulent transport is ~stiff, and hence core profiles depend strongly on the BC provided by the pedestal**

✓ **Potential for a virtuous cycle to strongly enhance performance, but must do self-consistent, coupled pedestal-core modeling**

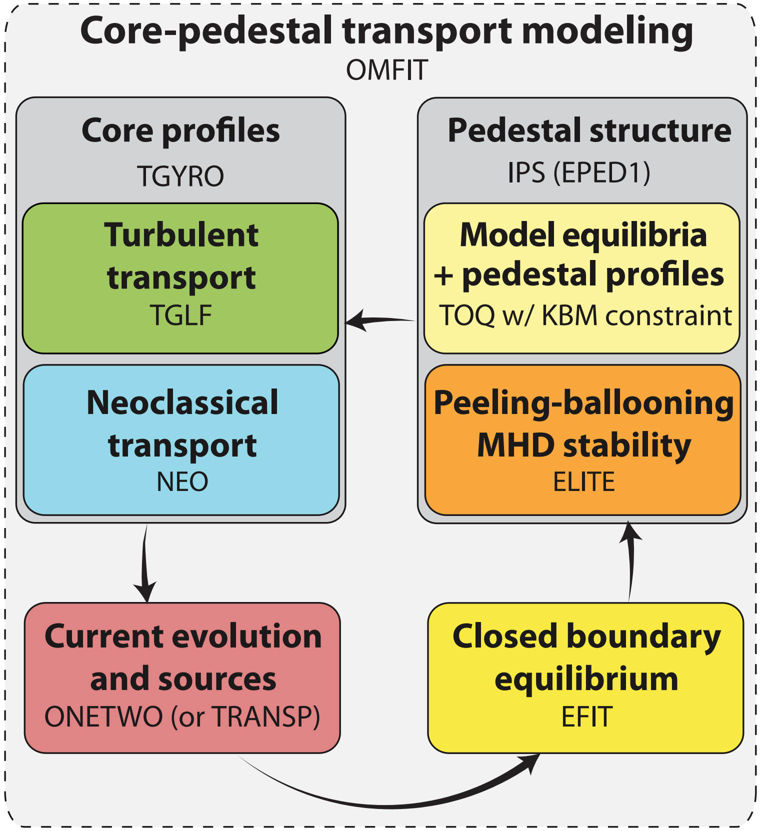


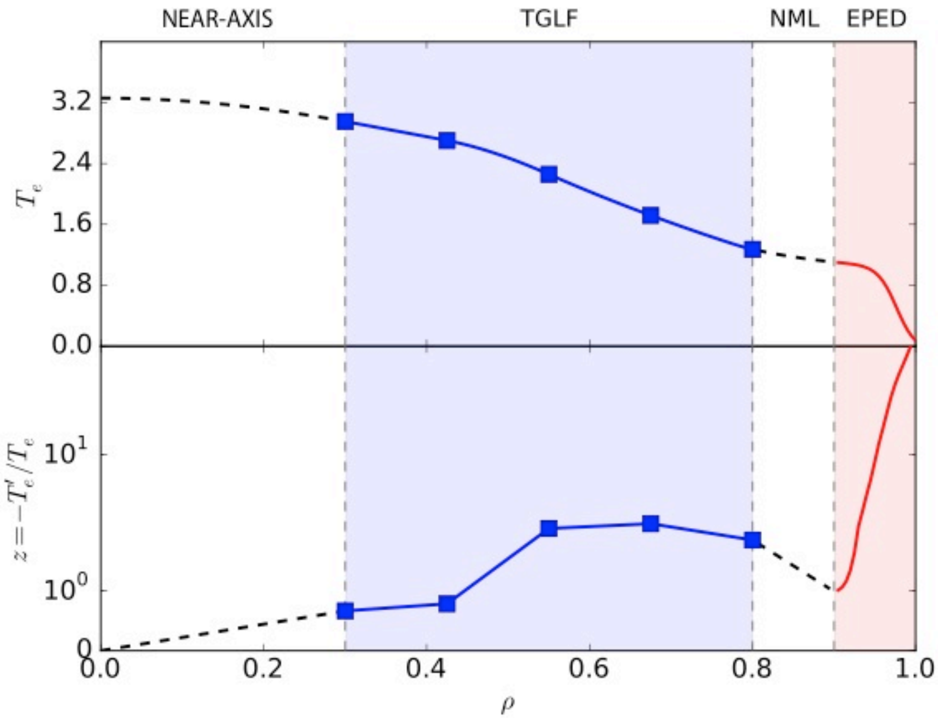
AToM project has enabled dramatic speedup of EPED pedestal model

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

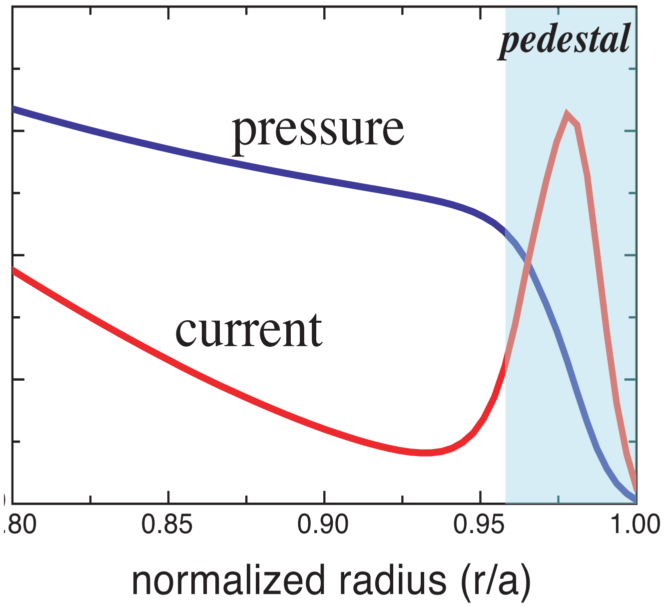
Initial example is EPED/TGLF/NEO and Core-Pedestal Integrated Modeling: DIII-D ITER-similar discharge 153523

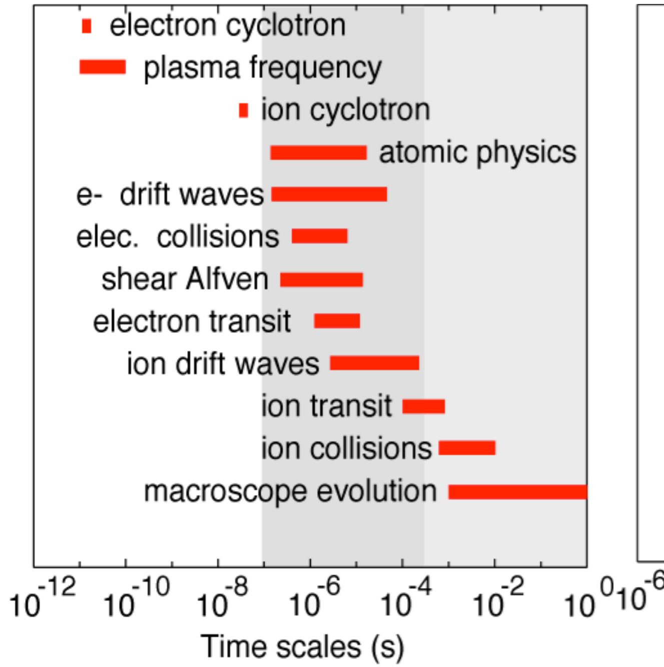
- Divide plasma into 4 regions
- Coupled workflow with OMFIT/IPS

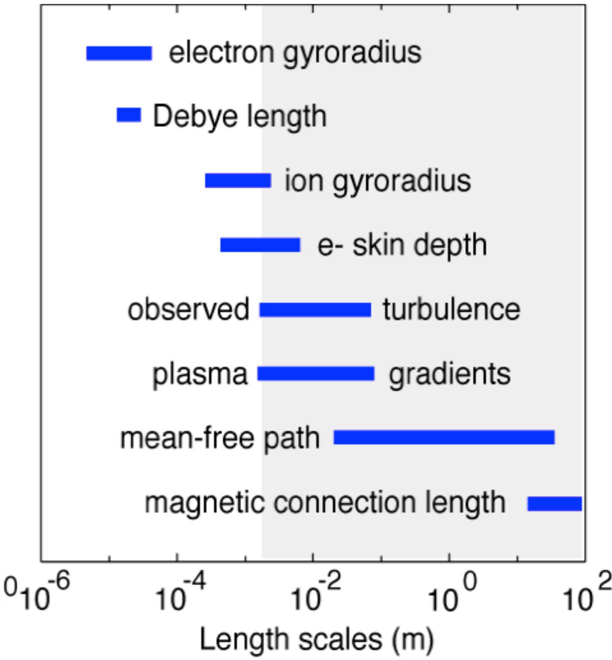




Very Wide Range of Overlapping Scales in the Edge Barrier Region

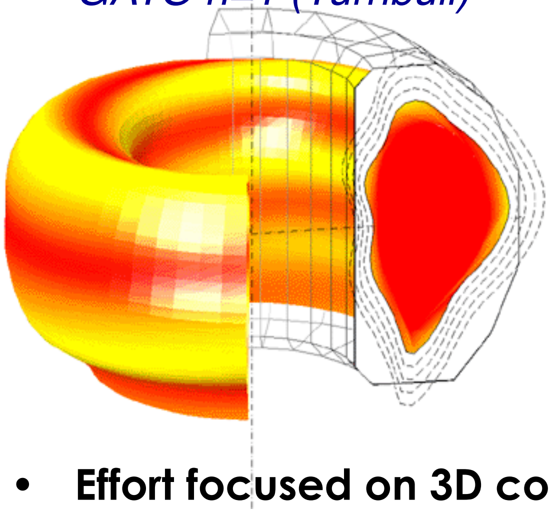


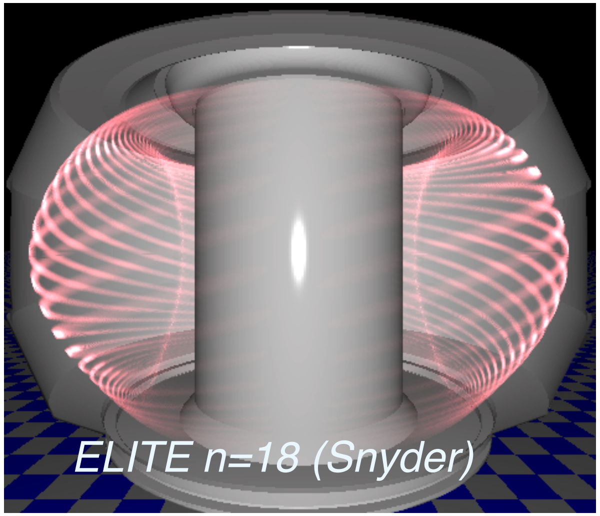


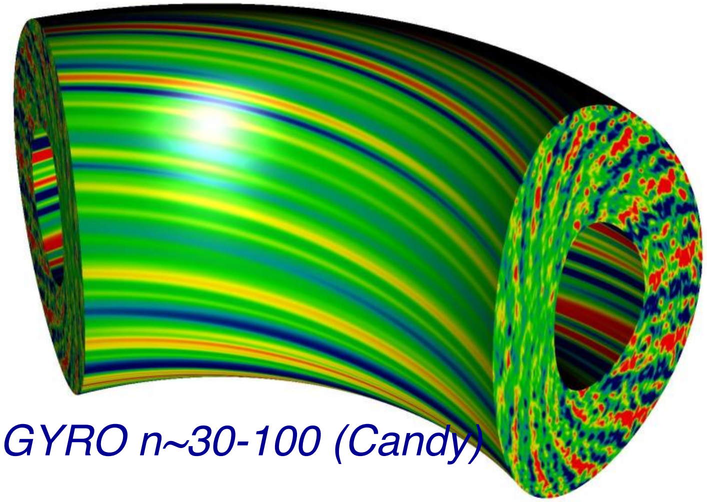


- Both time and spatial scales overlap, from microscopic all the way to global
  - This wide range (6-7 orders of magnitude) is covered by a ***single*** equilibrium, key parameters vary by orders of magnitude across the pedestal
- Pedestal crosses from collisional to collisionless regime
- Equilibrium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

Pedestal Physics Challenges Traditional Approaches to Computation







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

GENERAL ATOMICS

Electromagnetic Fluctuations are Important even though (especially where) β is small

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

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

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

GENERAL ATOMICS

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>> $\lambda \sim \rho$)

Equilibrium scale macrostability (MHD) (L~ λ >> ρ)

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

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

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

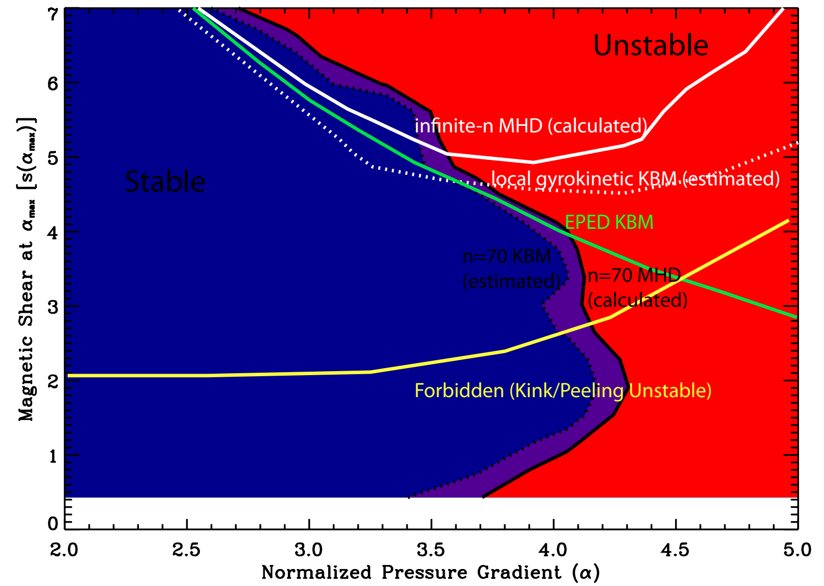
- **If KBM critical gradient were independent of radius, integrating it across the pedestal would yield**

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

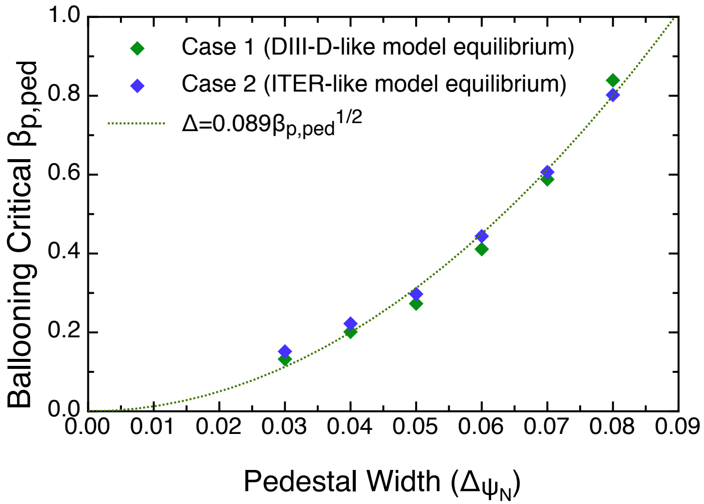
  - Width in normalized poloidal flux increasing linearly poloidal beta at the pedestal

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

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

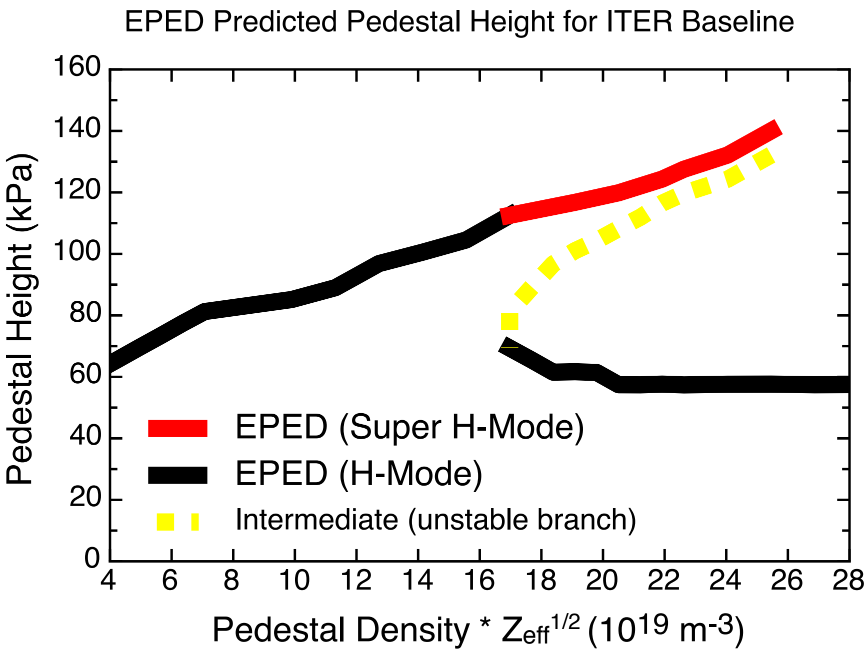


Calculated KBM Constraint using BCP Method



GENERAL ATOMICS

Predicted Super H-Mode Regime Should Enable further ITER Optimization



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

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

GENERAL ATOMICS

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