The Status of Edge Plasma Modeling and Benchmarking

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<u>Thanks for slides and figures to</u>

J. Boedo, C. S. Chang, J. Myra, J. DeBoo, R. Doerner, J. Kinsey, S. Kruger, P. Snyder, X. Xu and their collaborators

Also acknowledge useful discussions with many other individuals

Presented at ARIES Town Meeting, May 21 2010

UCSD

Overview

- **Development of validated modeling capabilities is essential for predicting the performance of ITER and future reactors with confidence**
  - Verification: is your code solving the equations correctly
  - Validation: are you solving the right equations

- **In this talk, I will offer a (incomplete) summary of edge plasma modeling and V&V efforts, from the perspective of someone working on validating core turbulent transport models**
  - My apologies to the many people and groups I have not included or overlooked
  - Emphasize codes/topics in this talk not covered in previous sessions

Start with a proverb from the aerodynamics community…

"No one believes the CFD results except the one who performed the calculation, and everyone believes the experimental results except the one who performed the experiment"

(as relayed in *Fundamentals of Verification and Validation*, P. J. Roache)

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Core Transport Modeling

- **Predicting core profiles requires accurate models of macroscopic ($L \sim a$) and microscopic ($L \sim \rho_i$) instabilities**

- **Have separate analytic models and corresponding codes for each (MHD and gyrokinetics, respectively) which are being separately validated against experiment**
  - Understanding and modeling the coupling between these scales remains a very open area of research (e.g. turbulence effects on NTM stability)

- **In absence of MHD phenomena, microturbulence-based transport models appear to capture many features of observed core profile scalings**
  - Both simplified reduced models and direct nonlinear simulations can now be used to predict core plasma profiles

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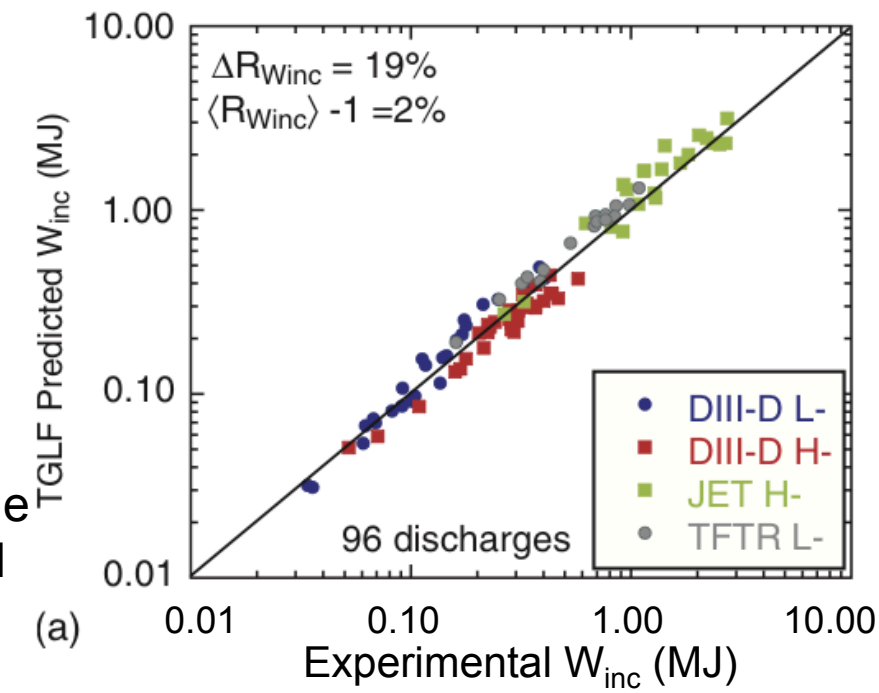
Reduced model example: validation of the TGLF transport model

- **TGLF ((T)rapped (G)yro-(L)andau (F)luid) is a quasilinear transport model which combines linear responses with a semi-analytic spectral weight function (verified against a database of > 150 nonlinear GYRO simulations) to yield turbulent transport predictions**
  - Refs: G. M. Staebler *et al.*, PoP **14** 055909 (2007), J. E. Kinsey *et al.*, PoP **15** 055908 (2008)
  - website: https://fusion.gat.com/theory/TGLF

- **The model has been extensively benchmarked against a wide variety of plasmas from multiple machines with good agreement**
  - ITER projections to be presented at 2010 IAEA FEC

Comparison of incremental stored energy W_{inc} (energy contained inside ρ = 0.84 model boundary) predicted by TGLF against experiment



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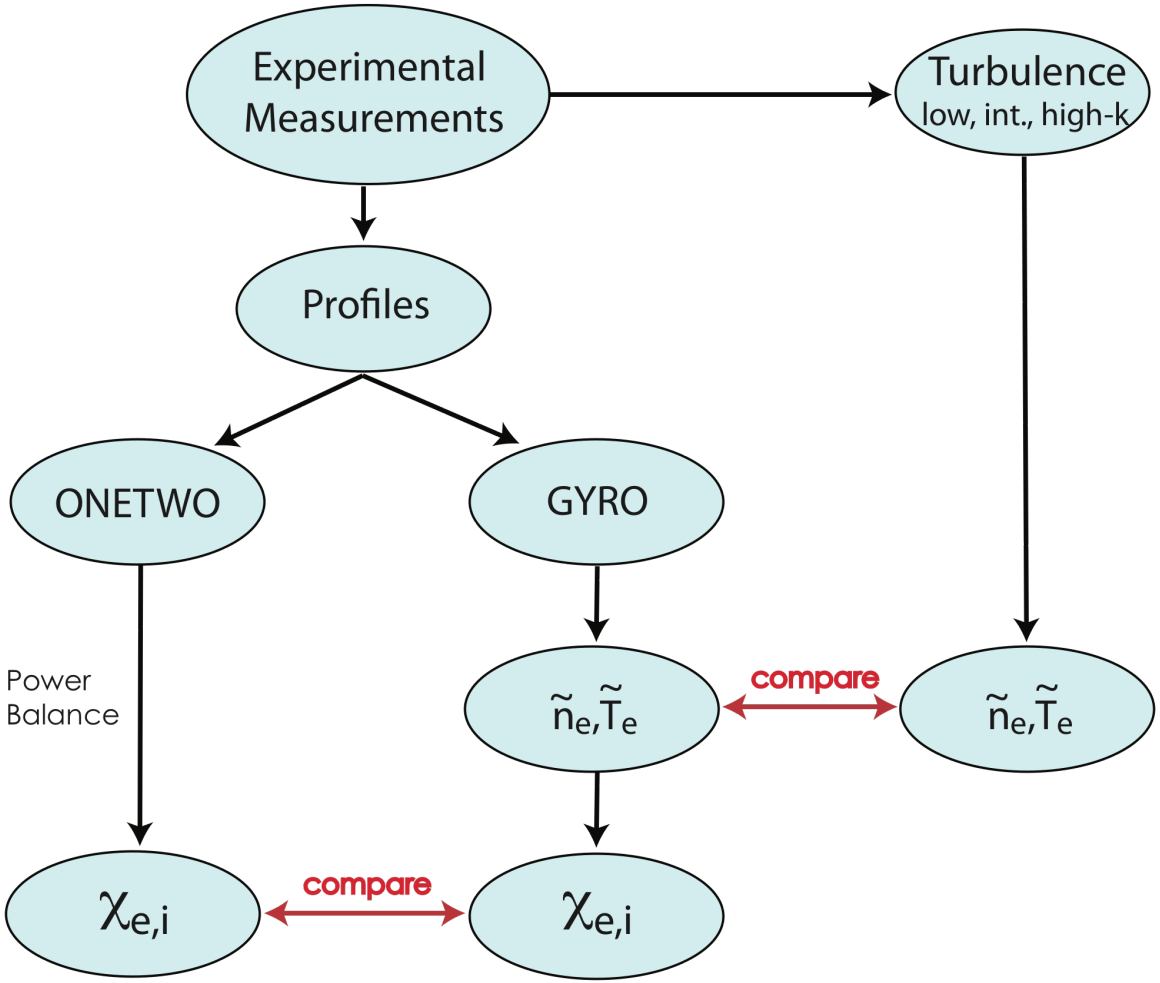
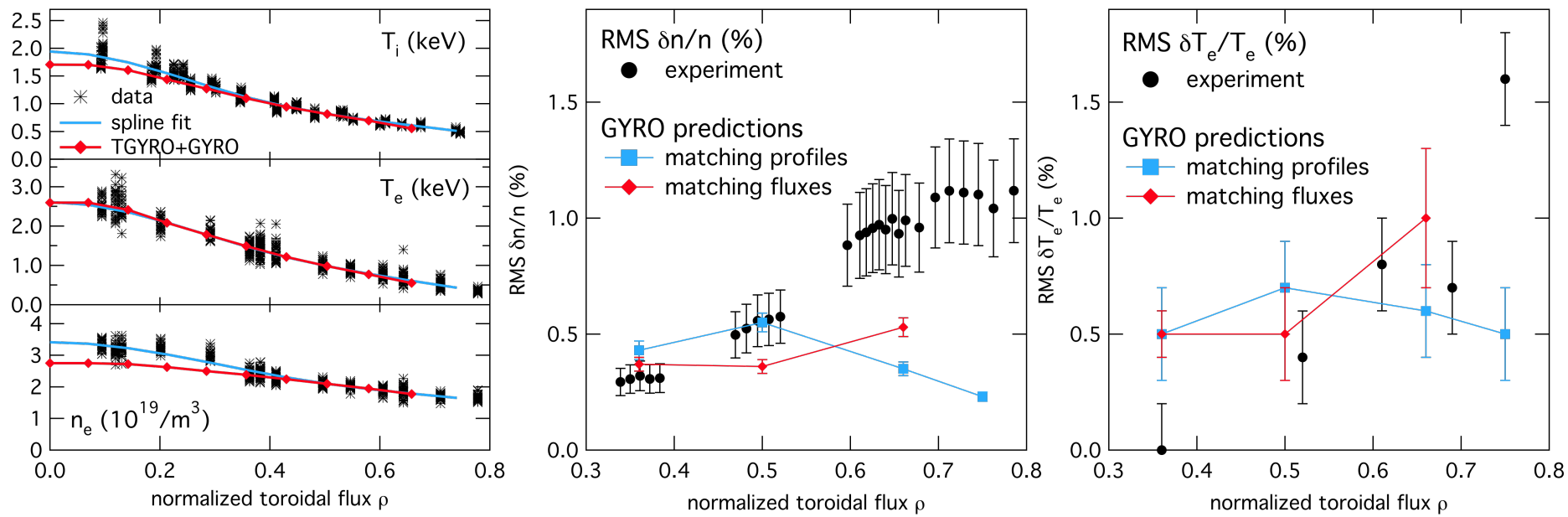
Experiment – Simulation Comparison



Advances in computing power have enabled coupling of transport equations with direct nonlinear simulations of plasma turbulence to predict core profiles

- **Example below: coupling of predictions from nonlinear gyrokinetic code GYRO with TGYRO transport solver to model a DIII-D L-mode discharge (**J. Candy *et al.*, PoP **16** 072305 (2009)**)**
  - Similar efforts underway with GS2/TRINITY codes (M. Barnes *et al.*, PoP **17** 056109 (2010))
- **These simulations allow for validation against measured turbulence characteristics as well as profiles**



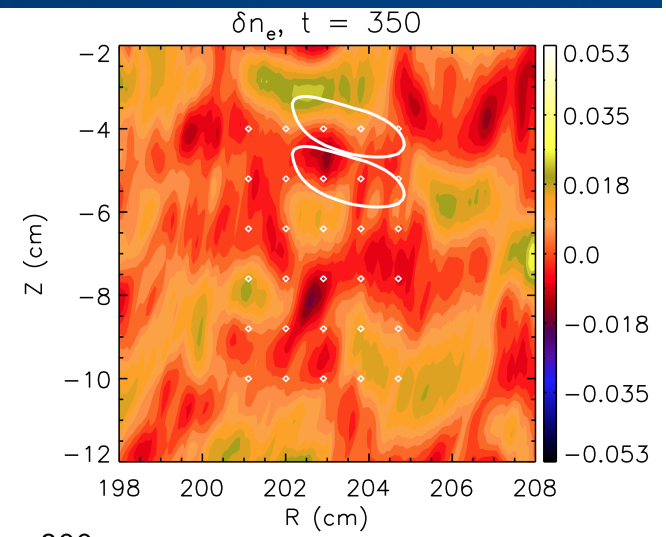
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

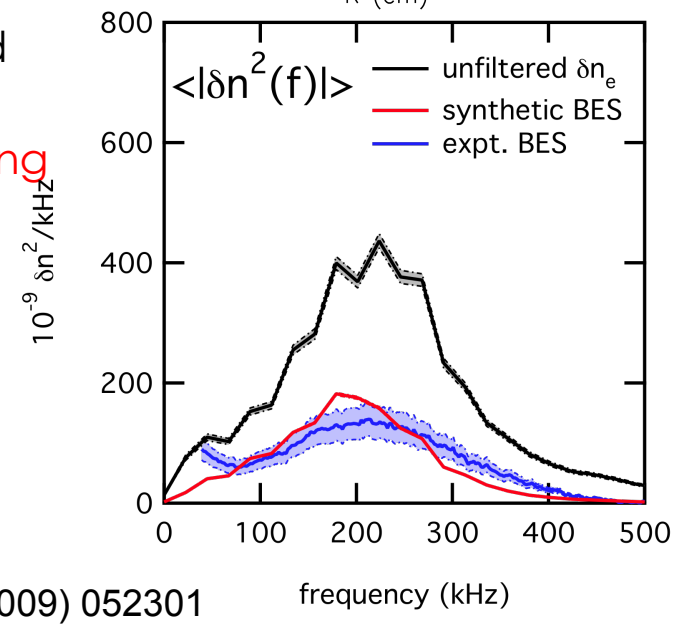
DIIID shot 128913 1500 ms

Synthetic diagnostics essential to meaningful validation studies

- **Figure on top shows contours of density fluctuations from a nonlinear turbulence simulation of an actual DIII-D discharge**
  - White contours show 50% width of BES channel sensitivity functions
- **Bottom plot compares simulated and measured frequency spectra**
  - Grey curve is the "unfiltered" spectra predicted by simulation
  - Red curve is predicted spectrum after convolving with BES sensitivity function
  - Blue curve is experimental measurement
- **Similar effects matter for edge:**

  $(n, \phi, T) \neq (I_{sat}, V_{float}, D_\alpha)$





C. Holland *et al.*, PoP **16** (2009) 052301

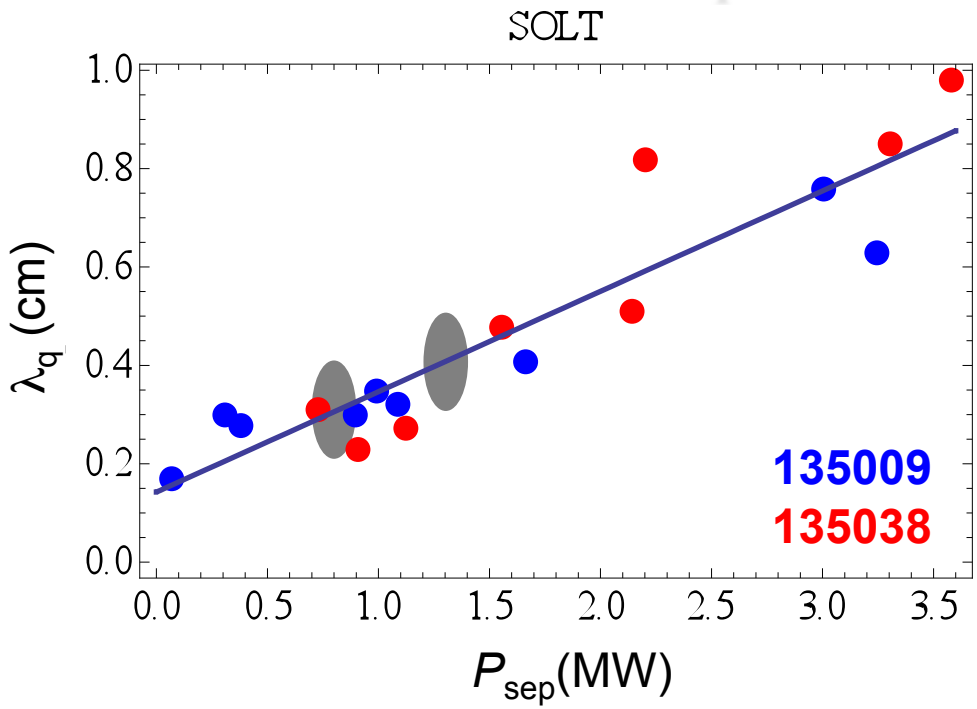
Scrape-Off-Layer Turbulence (SOLT) code

D.A. Russell, D.A. D'Ippolito, J.R. Myra

- physics model
  - 2D fluid turbulence code: model SOL in outer midplane $\perp$ B
    - classical parallel + turbulent cross-field transport
  - evolves n_e, T_e, Φ with parallel closure relations
    - sheath connected, with flux limits, collisional
  - strongly nonlinear: $\delta n/n \sim 1 \Rightarrow$ blobs
  - model supports drift waves, curvature-driven modes, sheath instabilities
  - synthetic gas-puff imaging (GPI) diagnostic
  - flexible sources for n_e, T_e, v_y
- Applications and verification:
  - near SOL heat flux width $q_{||}(r)$
    - compare with reciprocating probe and divertor IR data
  - far SOL blob velocity and size distribution
    - compare with GPI data

Lodestar

Heat flux width λ_q: simulations reproduce data trend



- power scan for low power ELM-free H-modes in NSTX* [J.-W. Ahn]
- λ_q = midplane $q_{||}$ width
- solid line = linear fit to SOLT power scan
- gray ellipses = experimental powers
- absolute predictions not yet possible
- **emphasis on trend verification**
- I_p scan [R. Maingi] not as well described by the physics in SOLT

SOL width: simulation vs. experiment

		NSTX	SOLT
NSTX shot #	P(MW)	$\lambda_{q,mid}$ (cm)	λ_q (cm)
135009	**0.8**	**0.36**	**0.30**
135038	**1.3**	**0.50**	**0.41**

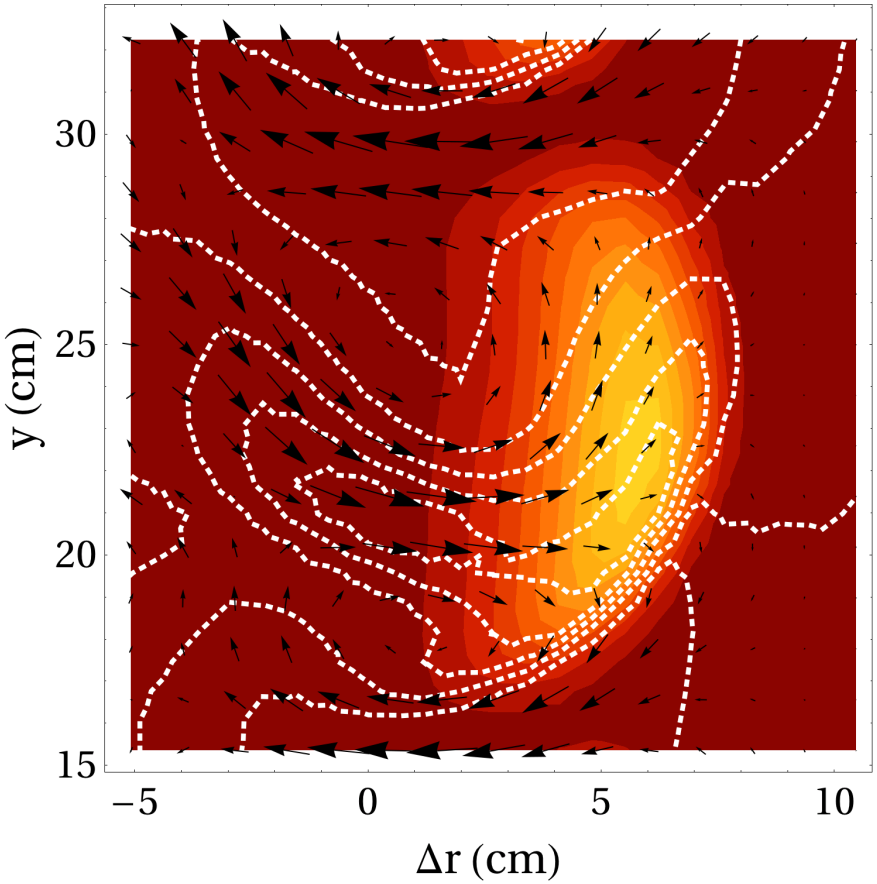
validation of n_e, T_e with midplane reciprocating probe data also done

Lodestar

Myra et al. PSI 2010, paper P3-18

Far SOL blob velocity simulations compared with GPI

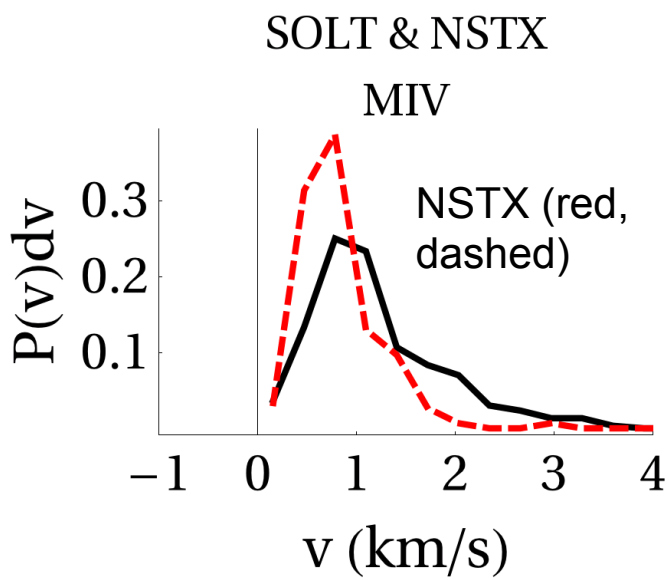
SOLT Simulation
- Synthetic GPI Intensity (orange)
- Pressure (n*T) Contours (white, dotted)
- E x B Velocity (black arrows)



Lodestar

NSTX and SOLT GPI
Image Radial Velocities

For each of 300 frames
the maximum image velocity (MIV):



Optical Flow Analysis:
T. Munsat and Y. Sechrest
NSTX GPI data:
R. Maqueda and S. Zweben

Russell et al. 2010, report in progress

Other groups actively pursing nonlinear edge transport simulations

- **2D fluid ESEL code (Risø)- similar in spirit to SOLT**
  - Emphasis on statistics of intermittency/blobs
  - Have compared simulated interchange turbulence statistics against TCV probe measurements with good agreement found
  - Refs: O. E. Garcia *et al*, PoP **12** (2005) 062309; O. E. Garcia *et al*, PPCF **48** (2006) L1

- **BOUT/BOUT++ (LLNL/U. York)- Braginskii model with realistic geometry**
  - Long history of comparisons to experiment, inc. ELM growth/crash
  - Recent work by P. Papovich (UCLA) to validate key components using linear LAPD device

- **Significant theory work being done to develop rigorous model of edge gyrokinetics**
  - Need to relax e.g. $\delta f/f << 1$ assumptions of traditional core gyrokinetic models
  - Codes: Continuum TEMPEST/ESLCode (ESL), PIC XGC codes (CPES)

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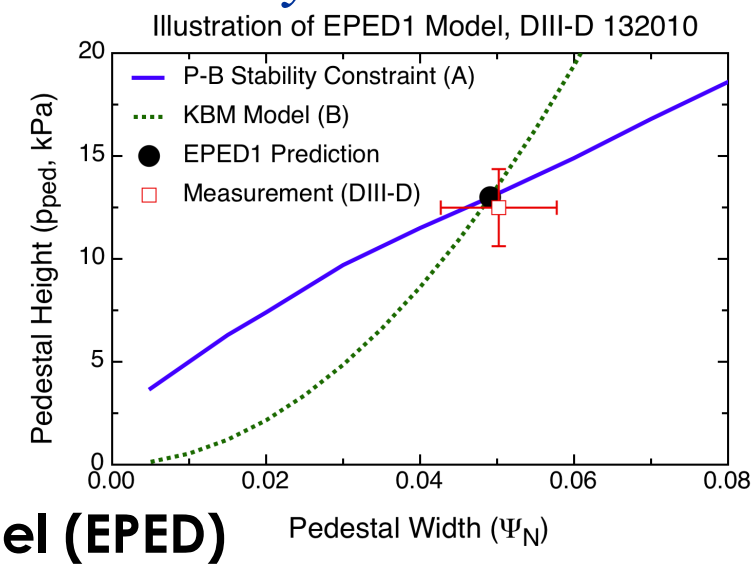
EPED Model Combines Peeling-Ballooning and KBM Physics to Predict Pedestal Height and Width

Develop a model based on two fundamental physics constraints, which are directly calculable, but simple enough to be predictive and easily testable



A. The Peeling-Ballooning Model

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

B. Kinetic Ballooning Mode Onset

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

C. Combine 1&2 to Develop Predictive Model (EPED)

- 2 "equations" for 2 unknowns: pedestal height and width
- Simplified model (EPED1), and present model (EPED1.6)
  - EPED1.6 calculates both P-B and KBM constraints directly for each case
  - ***First principles, no use of measurements in any part of model, but still simple & predictive***

D. Validate Model Against Experiment

- Dedicated experiments on DIII-D and C-Mod, tests on JET and JT-60U
- Validation across wide parameter range, predictions for ITER

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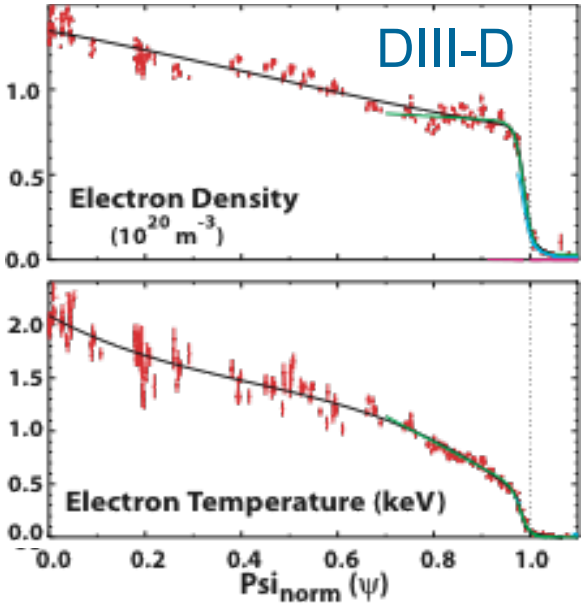
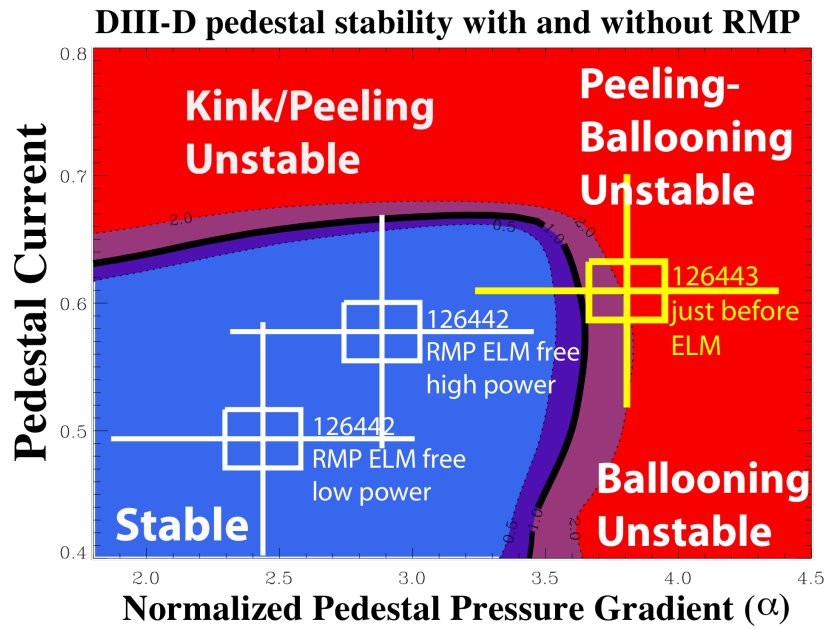
Peeling-Ballooning Model Extensively Validated Against Observation





- **High resolution measurements allow accurate reconstructions and stringent tests of P-B pedestal constraint & ELM onset condition**
- **Onset of each ELM consistently found to correlate to crossing the P-B stability boundary *[Multiple machines, >100 cases studied]***
  - Changing pedestal stability (shape, q, ν^* etc) yields predictable change in the pedestal height
  - Statistical study of 39 recent DIII-D discharges finds good agreement: 1.05 $\pm$0.19
    - Consistent with conclusion the P-B stability limits pedestal height and triggers ELMs

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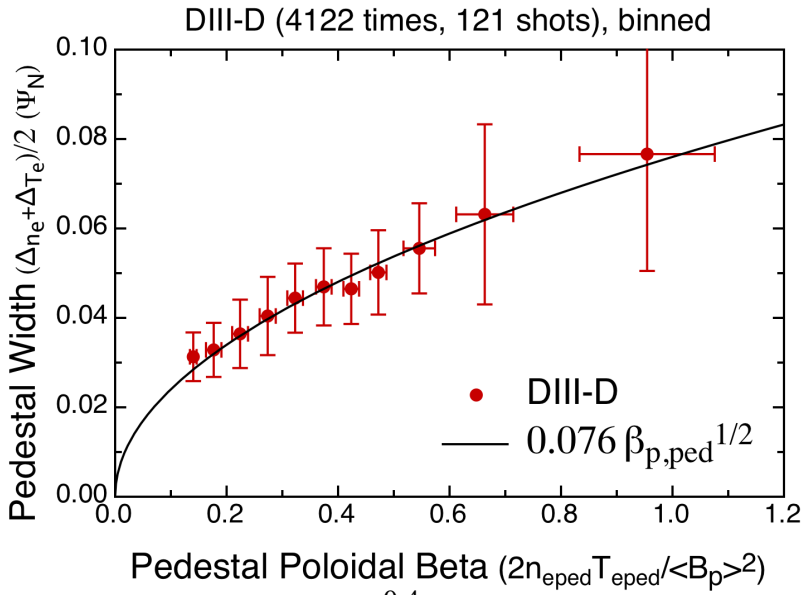
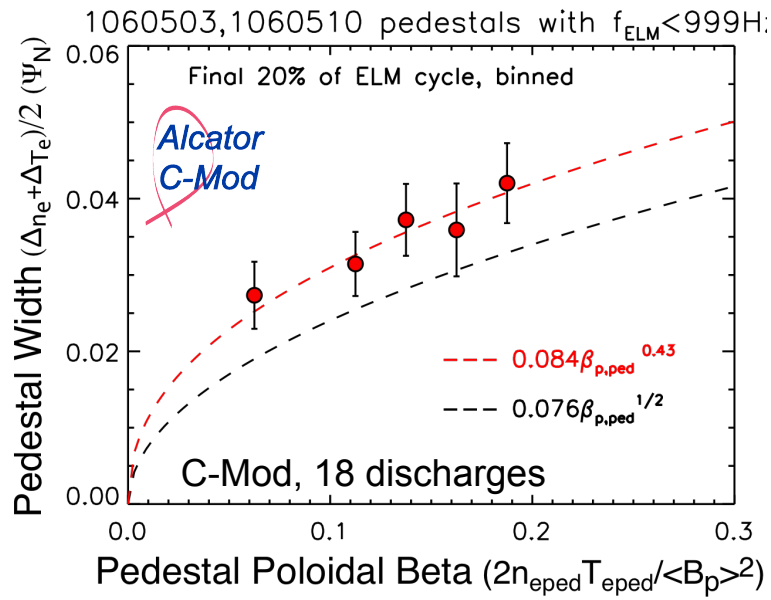
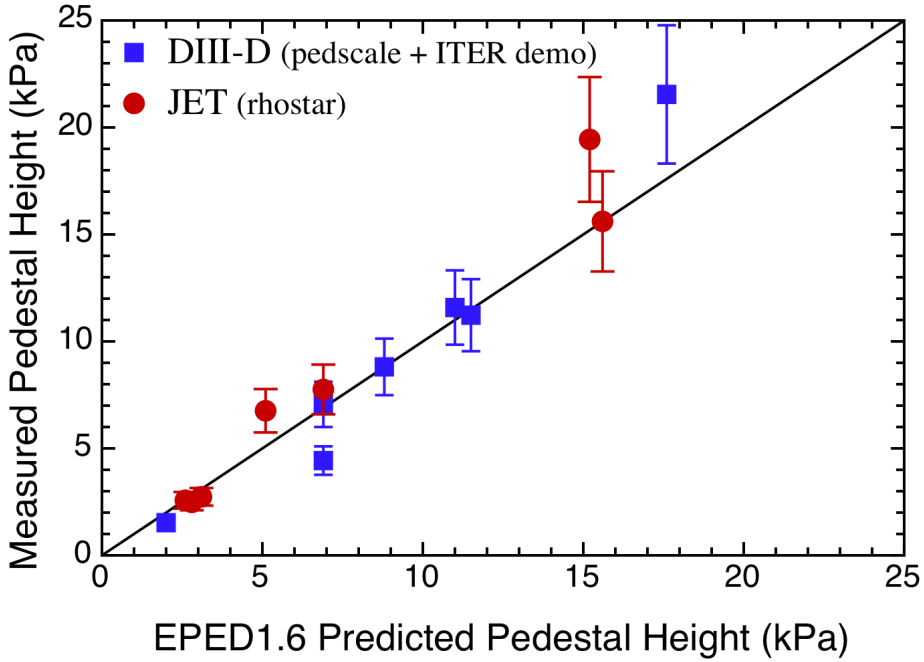
KBM relationship between width and height is consistent with observations





- **Scaling of $\Delta/a \propto \beta_{p,ped}^{0.4}$ first found by Osborne99: recent measurements find similar scaling across many machines**
- **DIII-D, C-Mod, MAST, AUG find $\Delta \sim \beta_{p,ped}^{1/2}$ dependence in T1 discharges**
  - Accounting for this dependence, weak dependence on other parameters (q, ν^*, ρ^*_i, ρ^*_θ, β)
  - KBM calculation: $\Delta_{\psi_N} = 0.09\beta_{p,ped}^{1/2} G(\nu_*, \varepsilon ...)$, <G>=1.0±0.2; data: <G>~0.84 (DIII-D), <G>~0.93 (C-Mod)
- **Isotope variation expts on JT-60U** *[Urano08]*, **DIII-D** *[Groebner08]* **find no dependence of width on mass** (consistent with KBM, inconsistent with gyro or banana radius models)
- **JET - DIII-D rhostar scan expts find no/weak rhostar dependence of the width** ***[Beurskens, Osborne'09]*** (consistent with KBM, inconsistent with gyro/banana radius)

Initial Tests of Full Predictive EPED Model Successful (EPED1.6)



- **EPED1.6 tested on initial set of 7 DIII-D and 7 JET discharges**
  - From pedscale (Groebner08) and ITERDEMO (Doyle08) expts on DIII-D, and ρ_* expt on JET (Beurskens09, Osborne09)
  - Large range of variation in pedestal height (1.6 - 22kPa), ρ_{*ped} (0.24 - 0.7), ν_{*ped} (0.3 - 5), β_{ped} (0.3 - 1.2%)
- **Good agreement in predicted/measured height: 1.02 ± 0.21**
  - Similar level of agreement in width (1.03 ± 0.29) *[no fit parameters]*

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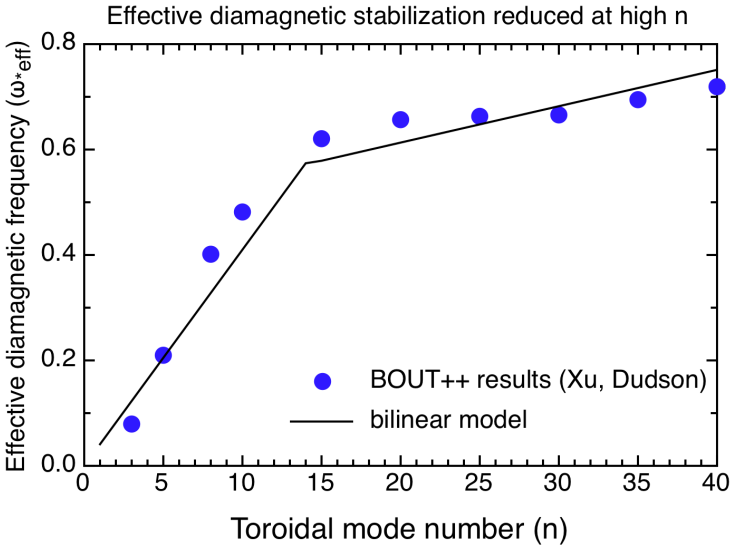
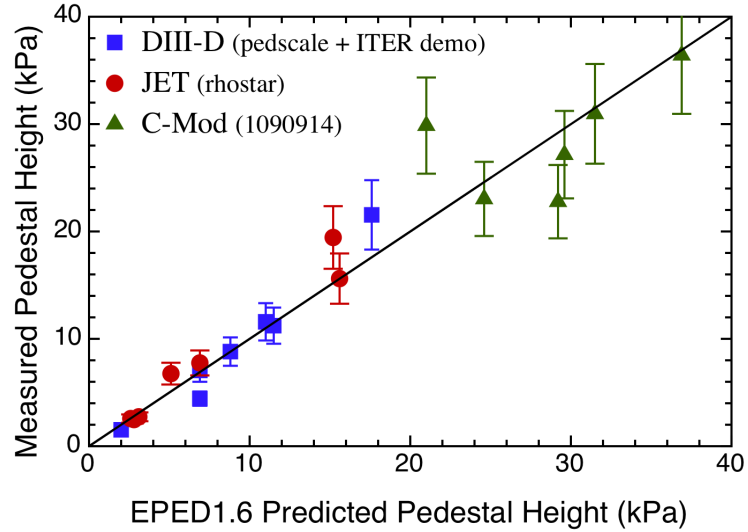
Dedicated Experiment on C-Mod to Test EPED Model in Plasma Current Scan





- **Previous C-Mod studies highlighted importance of ω* stabilization**
  - EPED1 uses simple model: $-\gamma_{MHD}^2 = \omega(\omega - \omega_{*pi}) \rightarrow \gamma_{MHD} > \omega_{*pi}/2$ for instability *[Roberts, Tang]*
  - ω_{*pi} varies rapidly in edge barrier. EPED1 used effective (half max) value, EPED1.6 adds effect of rollover at high-*n* via bi-linear fit using BOUT++ results
- **I_p scan expt on C-Mod, 9/09** *[Hughes, C-Mod team, Snyder, Groebner]*
  - Two values of current (I_p=940 & 680 kA, B_t=5.3T)
  - C-Mod analysis shown here is preliminary, average over arbitrary ELM timing
- **Good agreement in predicted/measured height: 1.02 ± 0.20**
  - 6 C-Mod (1.03±0.19), 7 JET, 7 DIII-D discharges, factor of >20 in ped pressure

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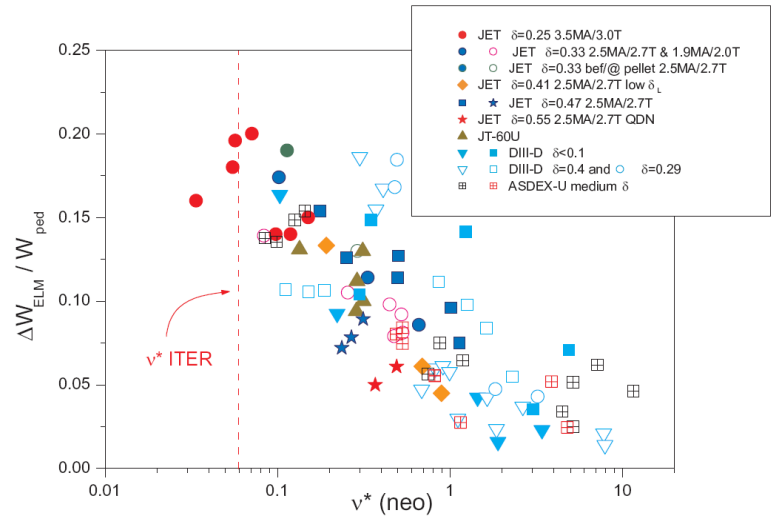
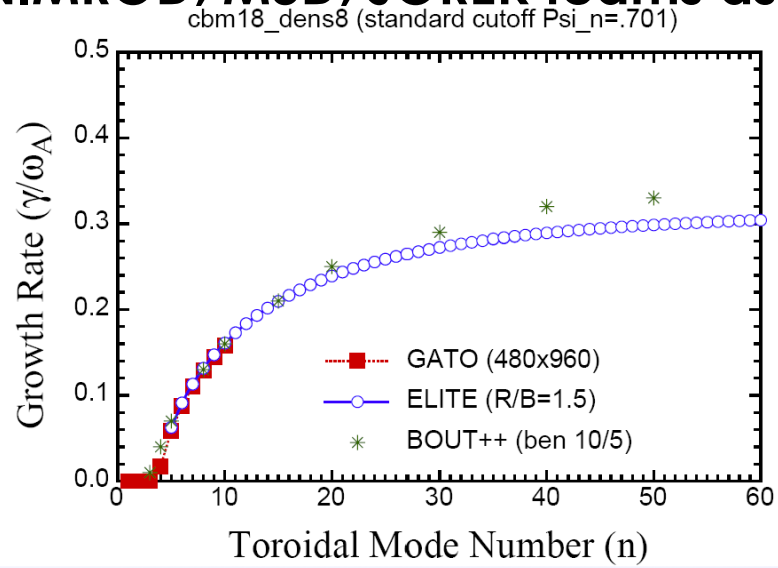
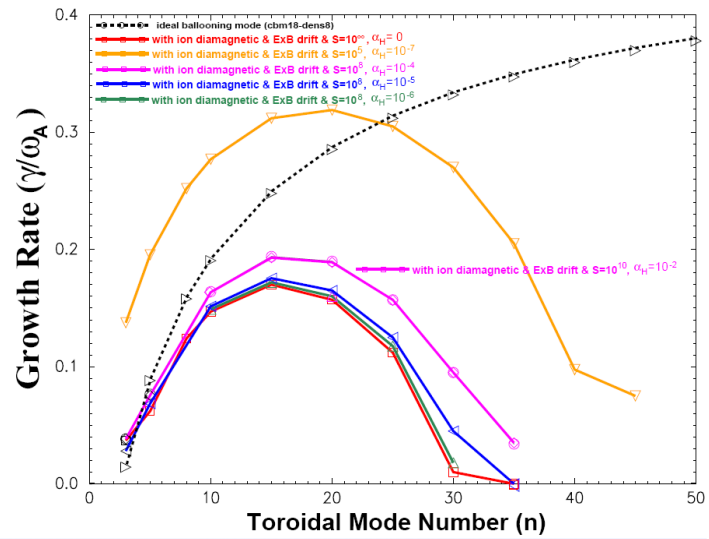
Capturing ν^* scaling of ELM size ΔW_{ELM} may require going beyond resistive MHD

- **Recent BOUT++ simulations by Xu *et al*. find that anomalous electron viscosity μ_e/ hyperresistivity η_h plays key role in nonlinear P-B mode dynamics and ELM crashes**
  - Resistivity, hyper-resistivity both destabilize P-B mode
- **Ongoing work to simulate ELMs by NIMROD, M3D, JOREK teams as well**

A. Loarte *et al.*, PPCF **45** (2003) 1549







THE UNIVERSITY of York

Fusion Energy Program

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A Future Direction:
High-Fidelity Integrated Whole Device Modeling

Examples from two proto-FSP SciDAC projects

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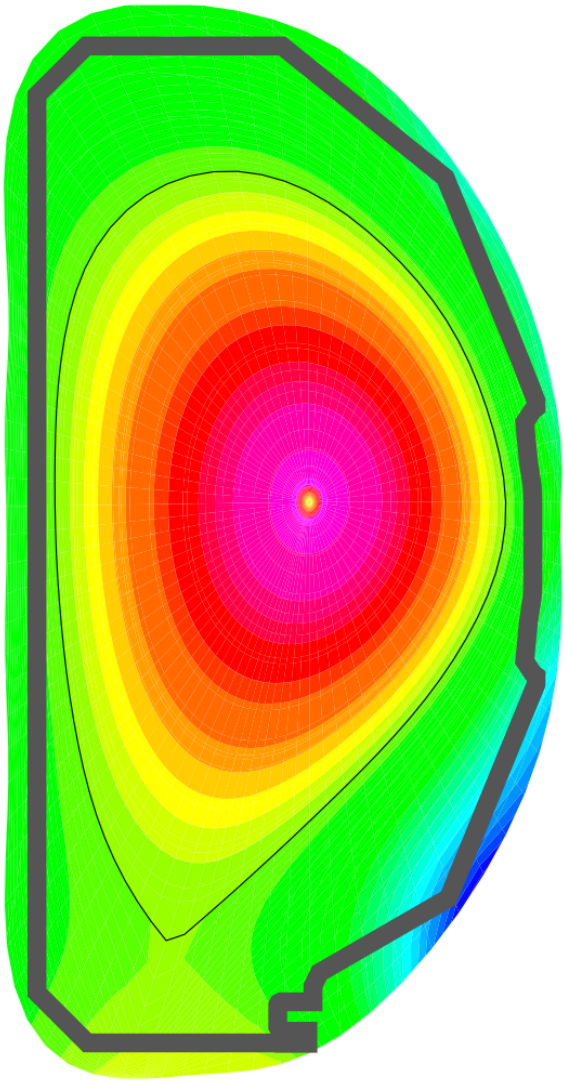
FACETS goal: build a tight coupling framework for core-edge-wall interactions

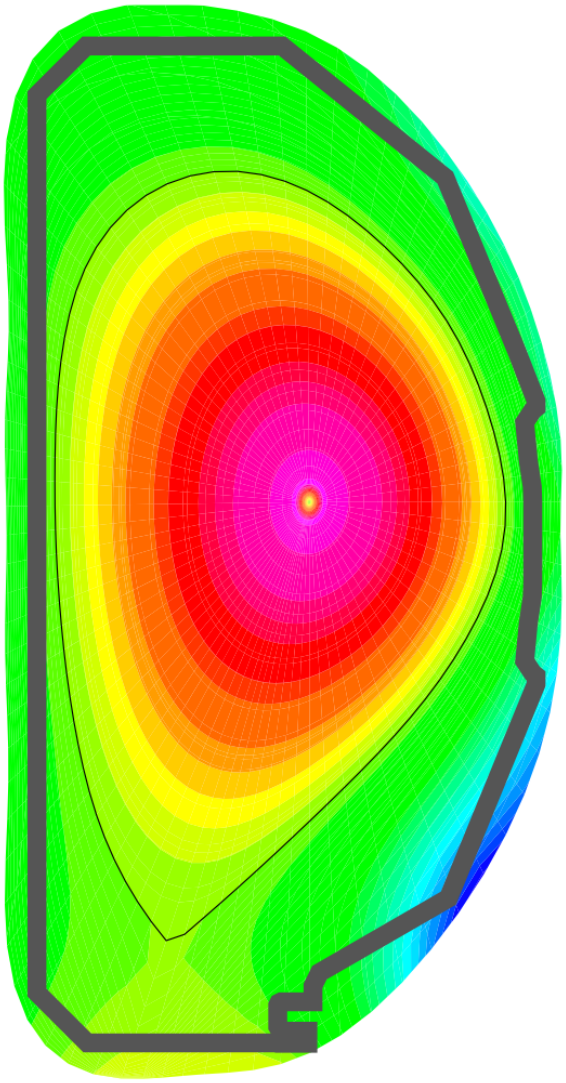


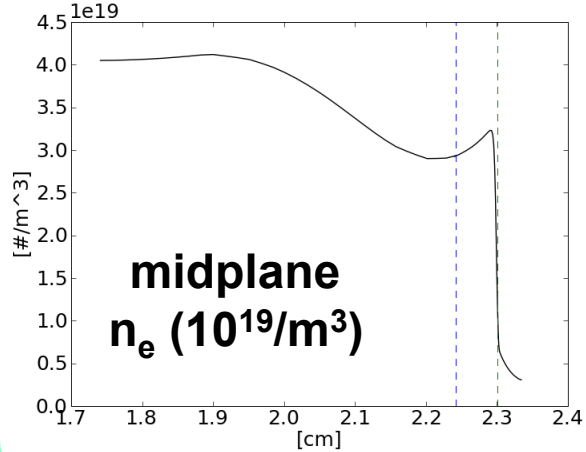
- **Want to build a framework in which users can couple:**
  - **Core transport via e.g. GYRO *or* TGLF**
  - **Edge transport via e.g. BOUT *or* UEDGE**
  - **PMI models like WallPSI (**A. Yu. Pigarov, JNM **390** (2009) 192**)**

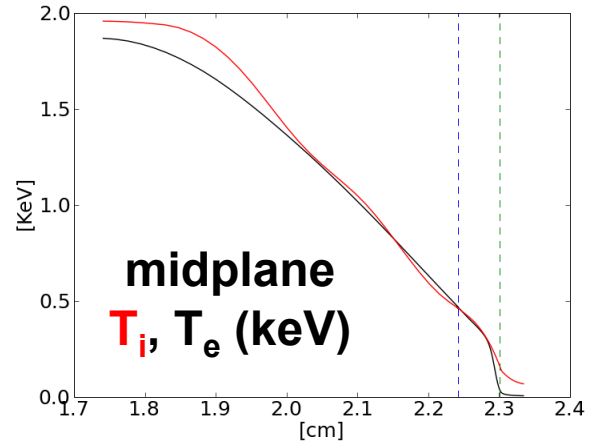
- **First validation test: model DIII-D H-mode buildup including density transport**
  - **Use GLF23 (core), "interpretive UEDGE" edge diffusivities**
  - **Use UEDGE wall recycling model**

TECH-X CORPORATION

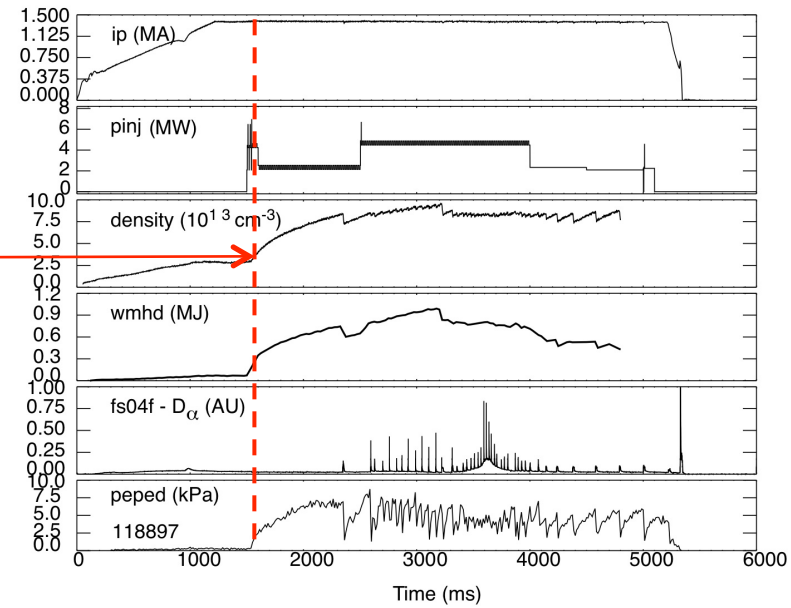
Initial conditions taken from experiment





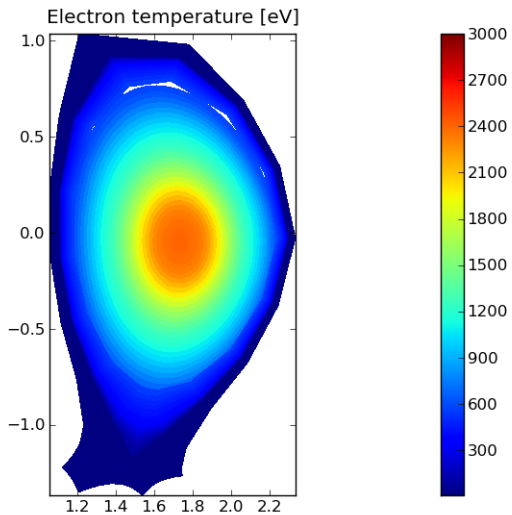


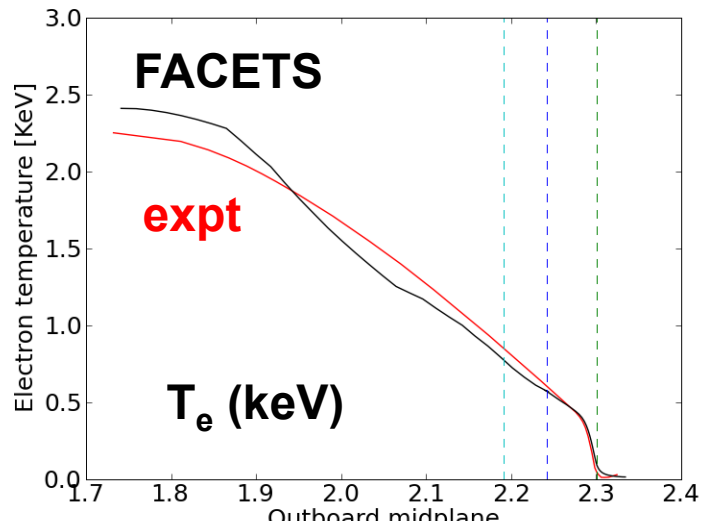
Model early ELM free phase, 1555-1590 ms

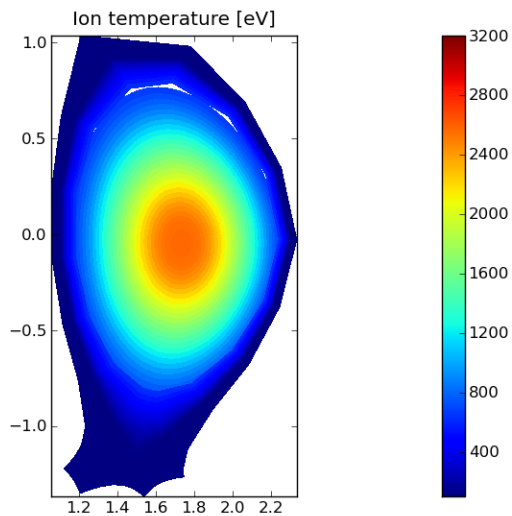


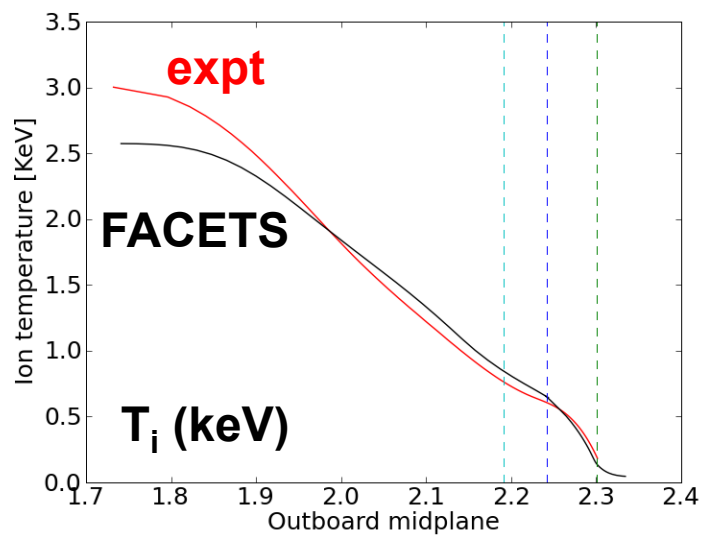
TECH-X CORPORATION

Profiles were evolved for 35 ms and compared with experiments: temperature



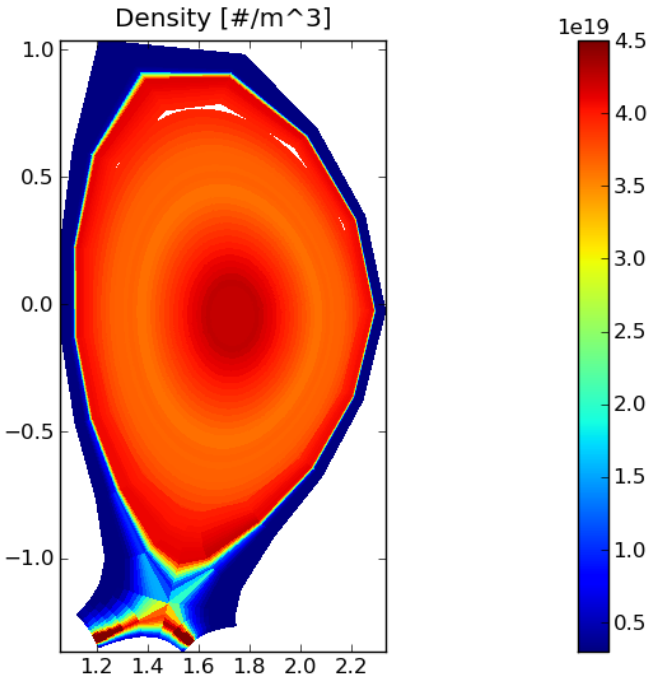


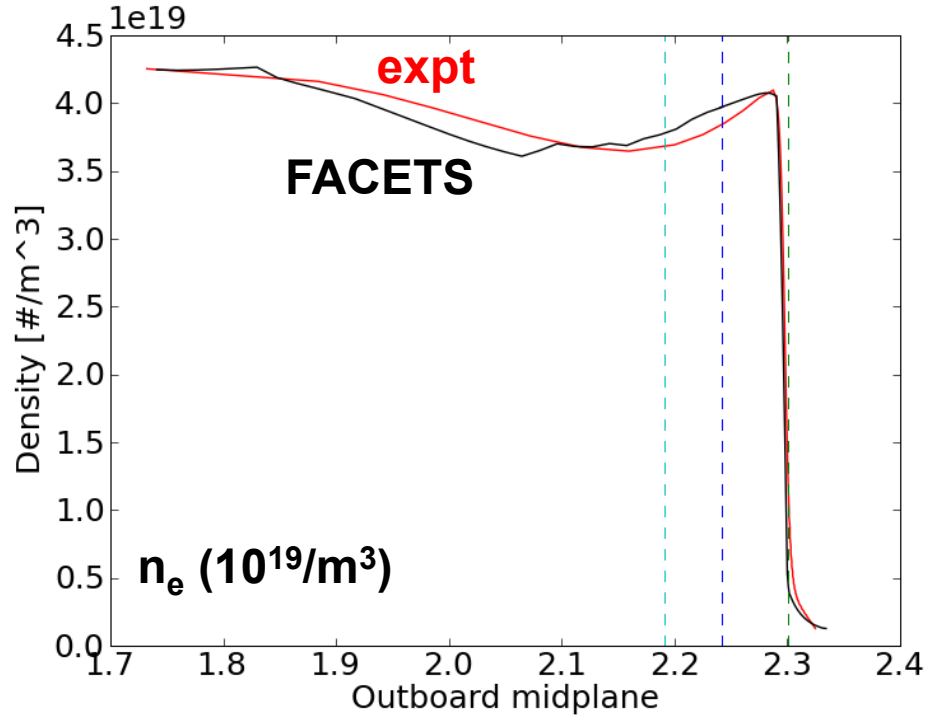




TECH-X CORPORATION

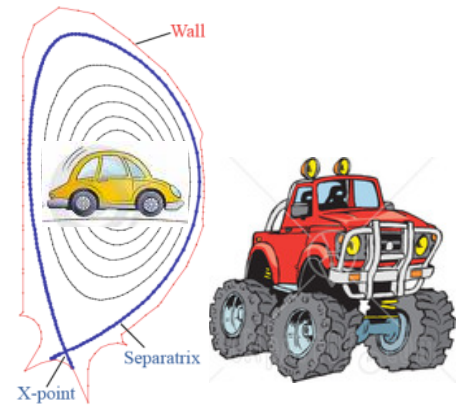
Profiles were evolved for 35 ms and compared with experiments: density





TECH-X CORPORATION

XGC1 full-f gyrokinetic code performs multiscale simulations of turbulence+neoclassical physics in realistic diverted edge geometry



- **X**-point **G**yrokinetic **C**ode: **XGC1**
- Spatial simulation domain
  - Designed for tough edge terrain (cylindrical coordinates)
  - Trivial to extend the domain all the way to magnetic axis
- Pursue more realistic and complete physics
  - Multiscale physics without need for core-edge boundary
  - Particle loss to grounded material wall, including orbit loss
  - Conserving Coulomb collisions
  - Flux driven (heat and momentum source from core)
- Currently, electrostatic turbulence. Soon to be electromagnetic

XGC0 is a one dimensional, drift-kinetic version of XGC1

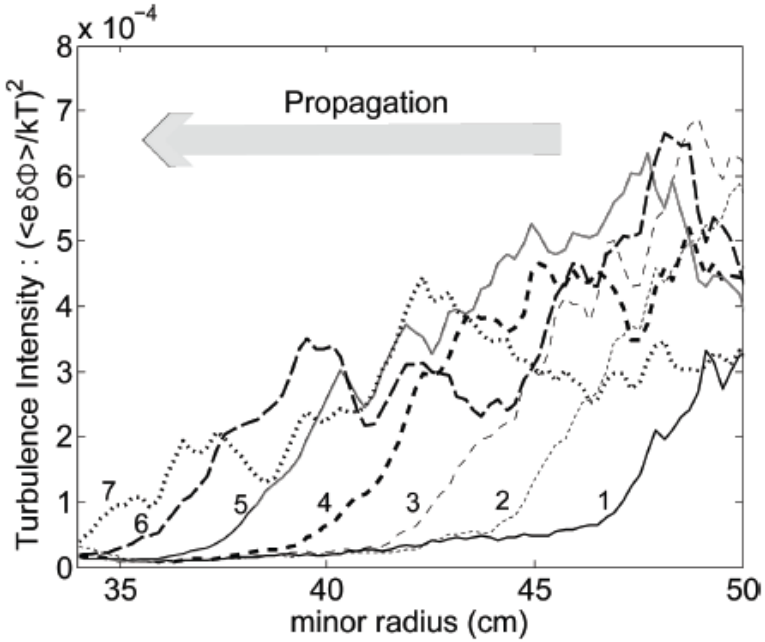
- ~1,000 times faster → kinetic transport modeling in experimental time scale
- Base code in CPES for multiscale integrated simulation of pedestal growth, MHD (Elite, M3D), Neutral Monte-Carlo (DEGAS2), and magnetic reconstruction.

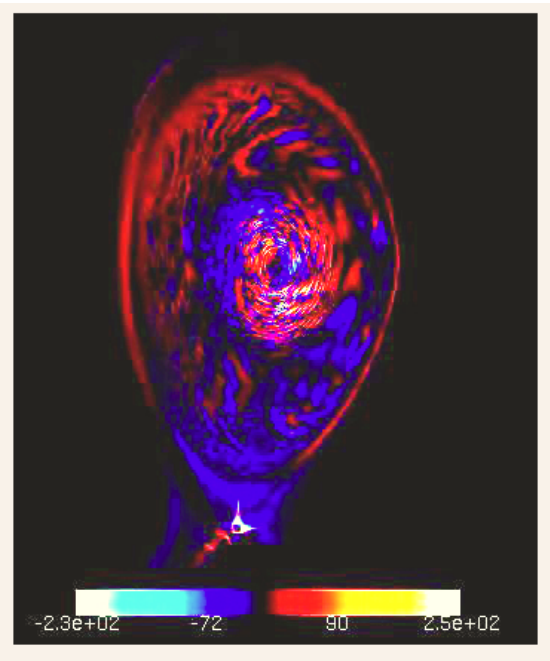
CPES
Center for Plasma Edge Simulation

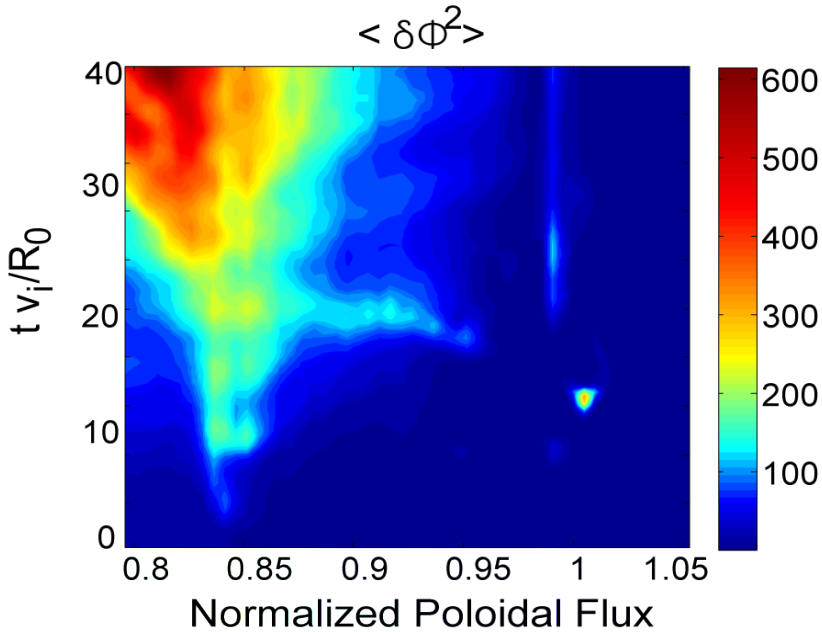
Time behavior of δΦ from ITG turbulence in DIII-D

- **Turbulence source at pedestal top**
- **Spread of turbulence into pedestal (strong ExB region) → Residual turbulence in pedestal**
- **Spread of turbulence into core, modifying core turbulence in miliseconds time scale.**

C. S. Chang *et al.*, J. Phys.: Conf. Series **180** 012057 (2009)





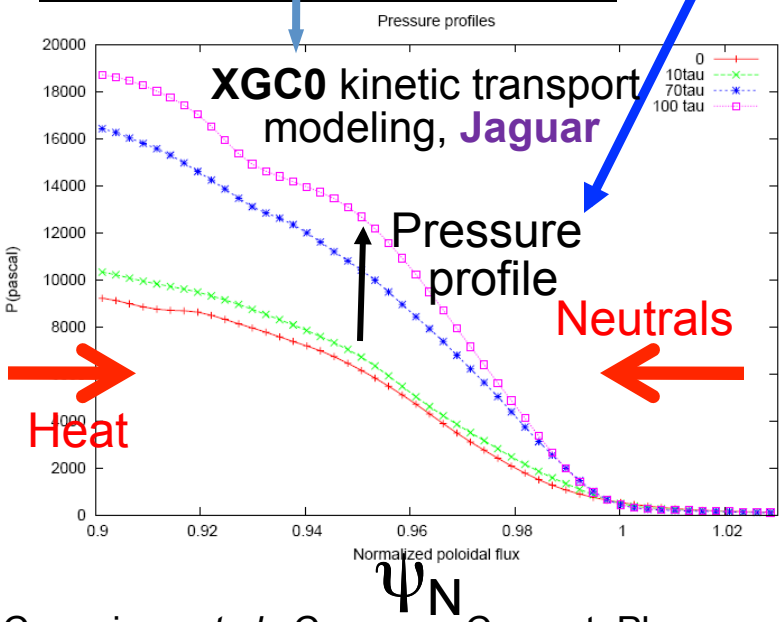


CPES
Center for Plasma Edge Simulation

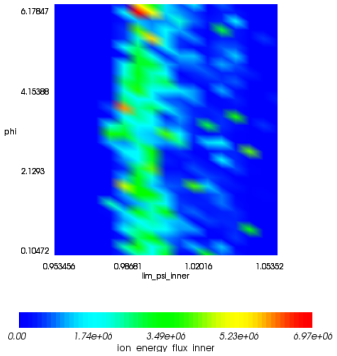
Coupled simulation of XGC0-M3Domp-Elite-M3Dmpp for pedestal-ELM cycle in automated EFFIS framework

Linear stability check (Binary **Elite**) -file coupling

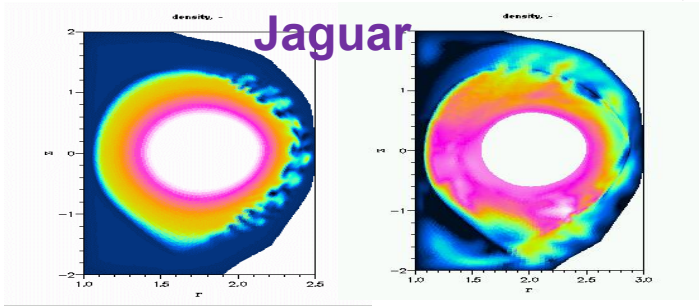
B-reconstruction and mesh interpolation by **M3D-OMP** (file coupling), on **Ewok**



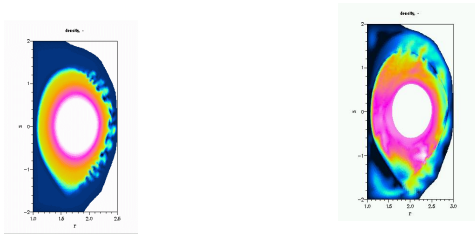
Divertor Heat Load



ELM crash in extended **M3D-MPP,**



Memory coupling



T=76 saturation

T = 496 relaxation

J. Cummings *et al.*, Commun. Comput. Phys. **4** 675 (2008)

CPES Center for Plasma Edge Simulation

Points for discussion

- **Significant progress in developing accurate, first-principles edge transport models**
  - Best on L-mode/inter-ELM transport and pedestal structure
  - WDM, nonlinear ELM crash and RMP effects (not discussed here) still in preliminary stages

- **Developing a predictive modeling capability we can have confidence in requires a robust V&V effort**
- **Some best practices for verification:**
  - Benchmarking against analytic theory
  - Benchmarking against other codes
  - Use of manufactured solutions: adding sources/sinks/forcings to code to impose solutions which test model assumptions
- **Some best practices for validation:**
  - Need to test of range of conditions/operational points- do you get right scalings with location, ν^*, I_p etc.
  - Want a hierarchy of tests: tests of individual components in an integrated model, tests of fluctuations and fluxes in turbulent transport
  - Quantifying agreement with metrics much better than (but can't supplant in my opinion) visual/viewgraph comparisons
  - Need to develop and use synthetic diagnostics for accurate comparisons
  - Need dedicated analysts (independent of code and expt.) to carry all of this out

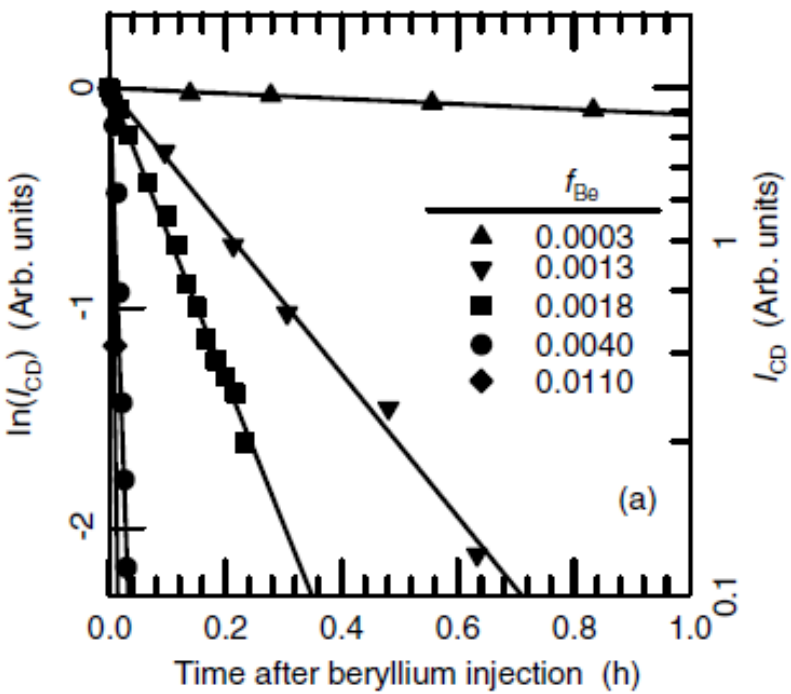
UCSD

Extra Slides

Experimentally, even very small f_{Be} can result in complete suppression of chemical erosion

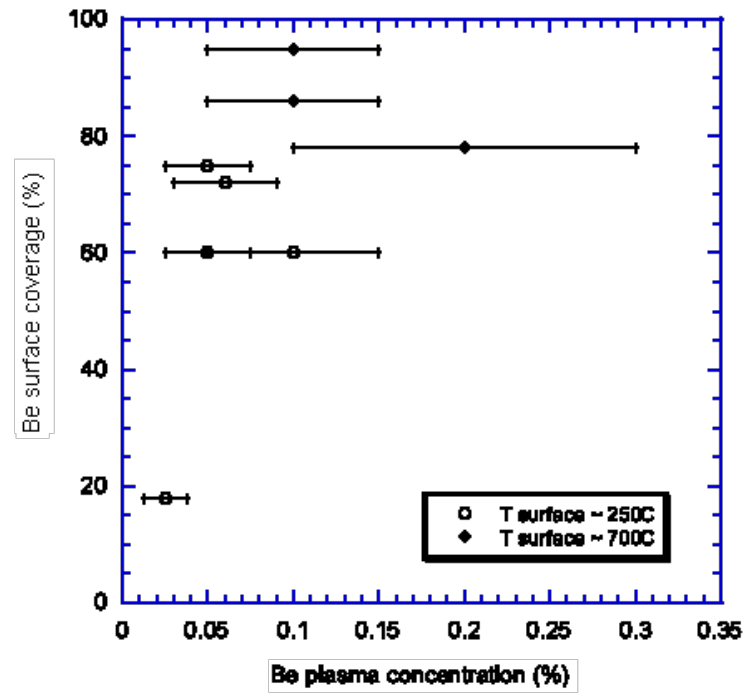
PISCES

PISCES-B D plasma conditions:
Γ_{pl} = 3e18 $cm^{-2}s^{-1}$, 50 eV ion energy, 350ºC



From M. Baldwin et al., NF 46(2006)444.

Equilibrium (3000 sec) Be surface concentration after P-B exposure.



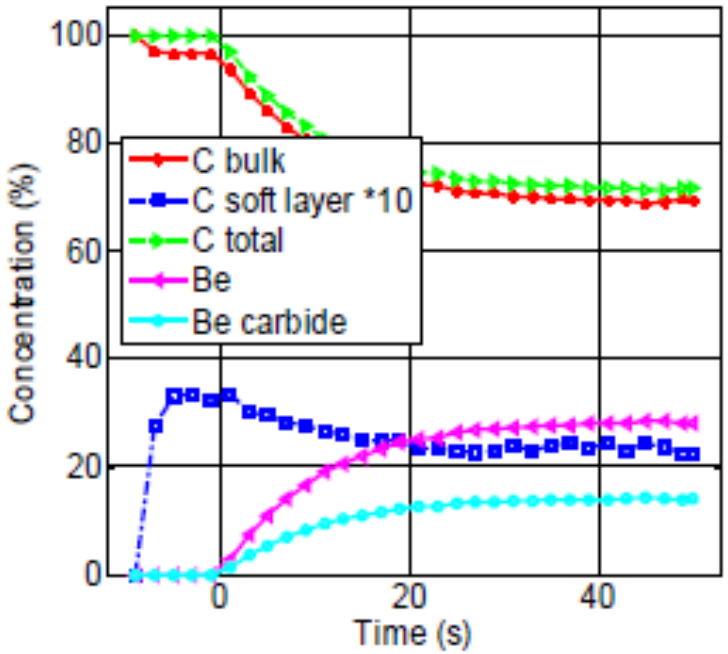
From K. Schmid et al., NF 44(2004)815.

How well do present PSI models predict chemical erosion mitigation?

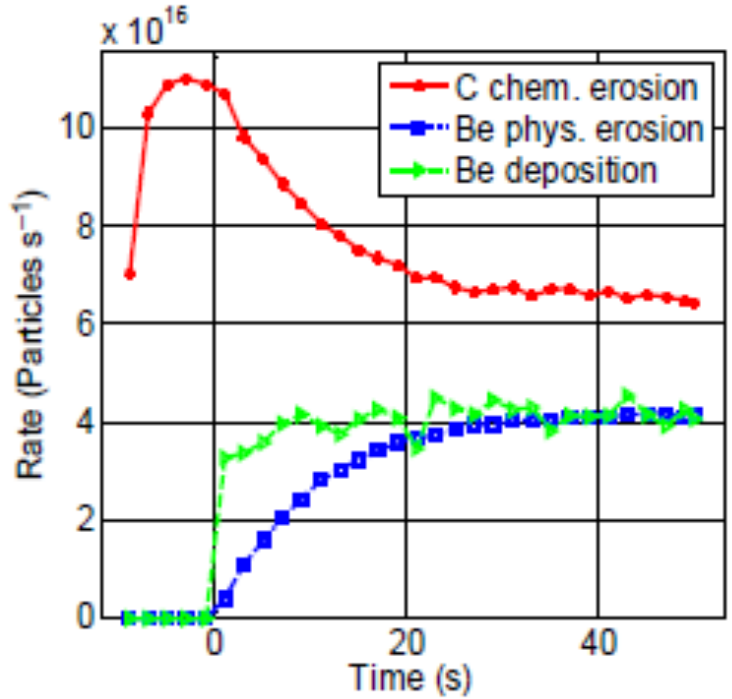
Existing PMI models do not include chemical effects, only simple particle balance

PISCES

Be arrival at surface ~ Γ_{in}*f_{Be} = Γ_{in}*c_{Be}*Y*(1-R) ~ Be leaving surface



Calculated change of surface composition during 1% Be seeding experiment



Calculated change of surface erosion during 1% Be seeding experiment

From D. Borodin et al., Phys. Scr. T128(2007)127.

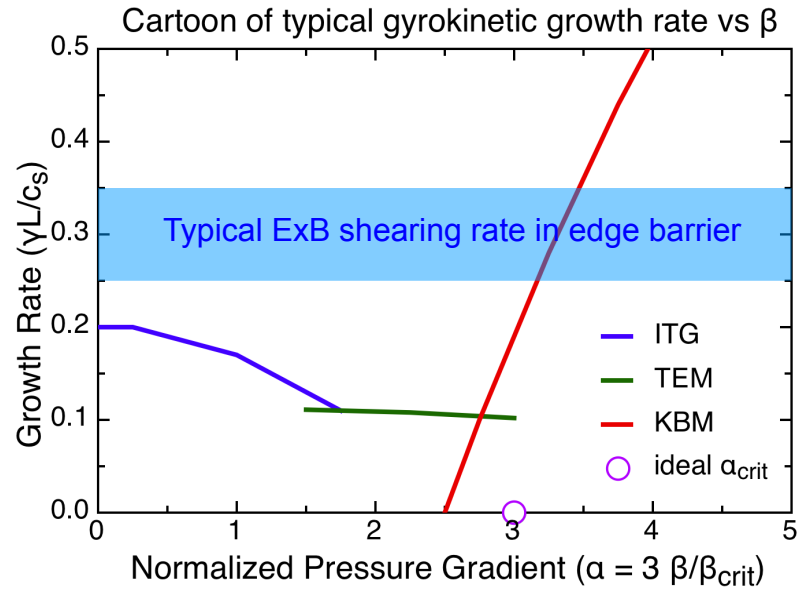
Pedestal Width Theory Has Progressed Slowly, Try New Approach

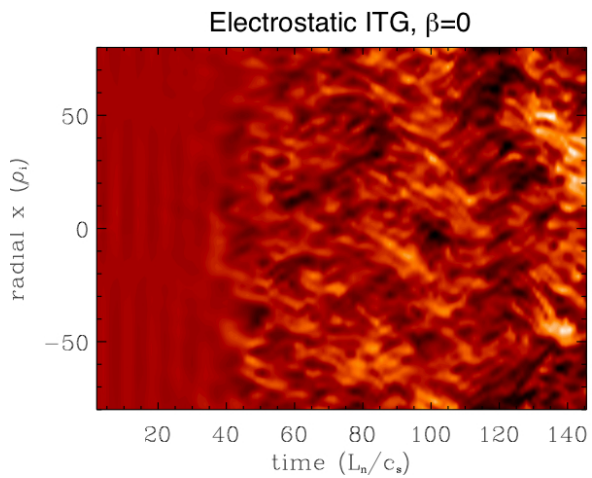
- **Long history of theories of the pedestal width**
  - Most based on ExB suppression of edge turbulence
    - Leads to gyro- and/or banana- radius scaling
- **Problems with that approach:**
  - ***Gyro- and banana- width scaling are not observed***
    - *More on this later…*
  - ExB suppression tells us how barrier formation begins. Want to know what constrains the higher gradients after the barrier is formed
  - P-B stability constrains both height and width (generally no transport steady state)
    - Width can grow up to ELM, can't calculate without ELM physics
  - Need a 2nd (local?) constraint, to accompany "global" P-B constraint
    - ***Many mechanisms cause transport in the pedestal (neo, turb etc), but we're looking the for the one which stops the profiles from evolving***

GENERAL ATOMICS

Propose Pedestal Constrained by KBM Onset near ideal ballooning α_{crit}

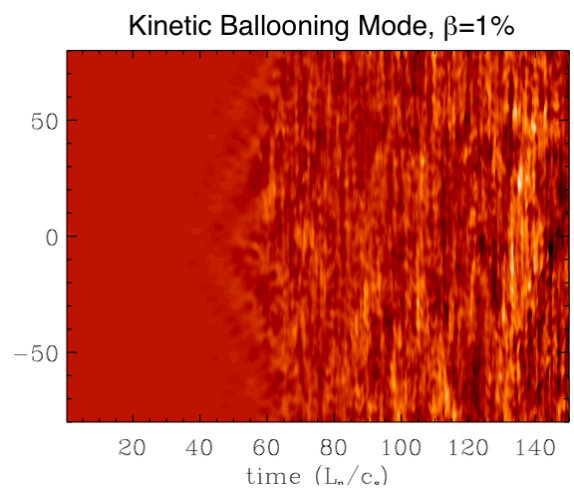
- **EM GF and GK simulations: onset of strongly driven kinetic ballooning mode (KBM) near ballooning α_{crit}**
  [Snyder99, Scott01, Jenko01, Candy05…]
  - Abrupt, strong onset -> profile stiffness
  - kinetic effects drive onset slightly below ideal ballooning (*n*->infinity) boundary α_{crit}
  - ExB shear can impact onset somewhat but not suppress
  - ideal α_{crit} useful marker for KBM
    - onset near nominal α_{crit} even with 2nd stability



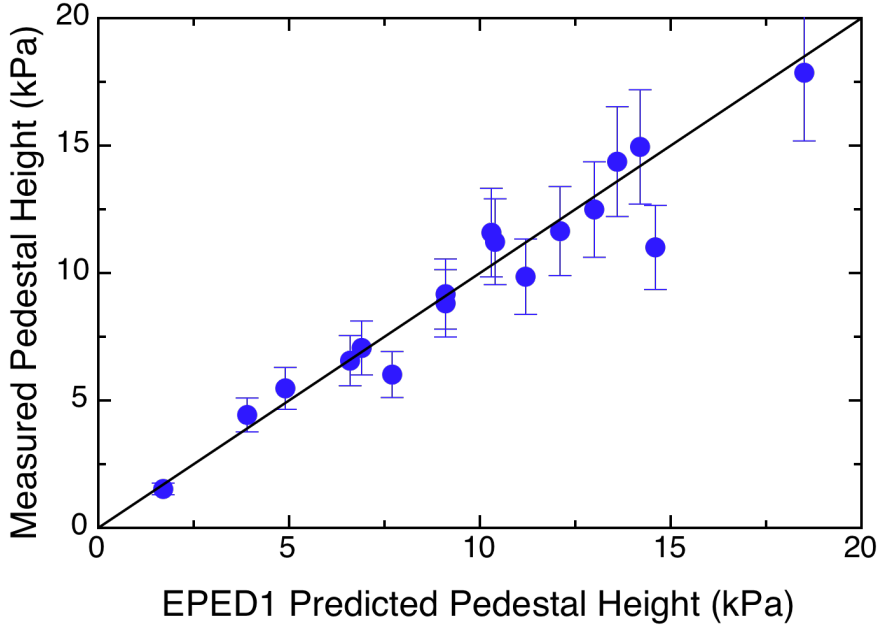


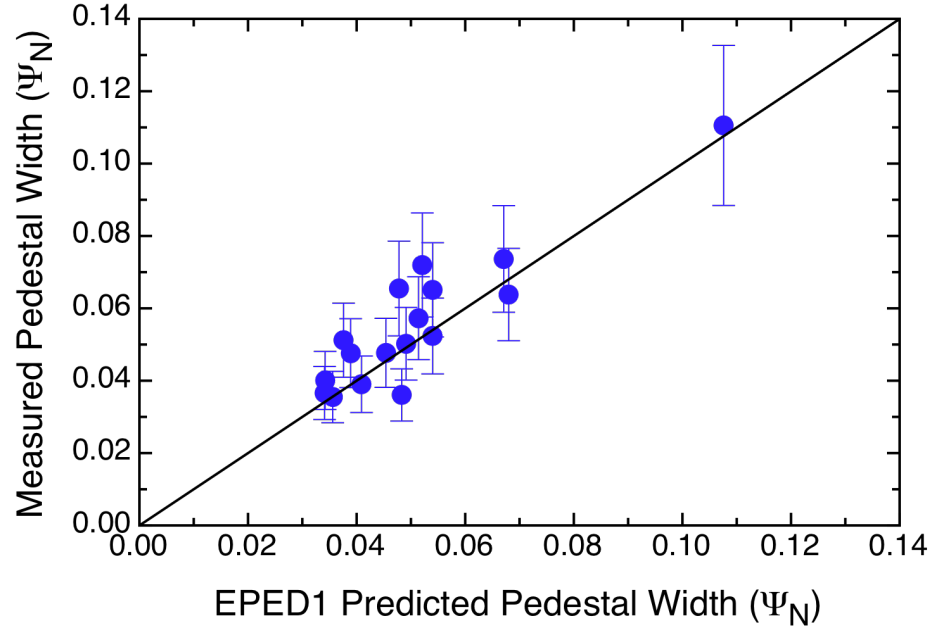
KBM has sharp onset, drives large fluxes. Much shorter correlation time than ITG

Snyder'99,'02



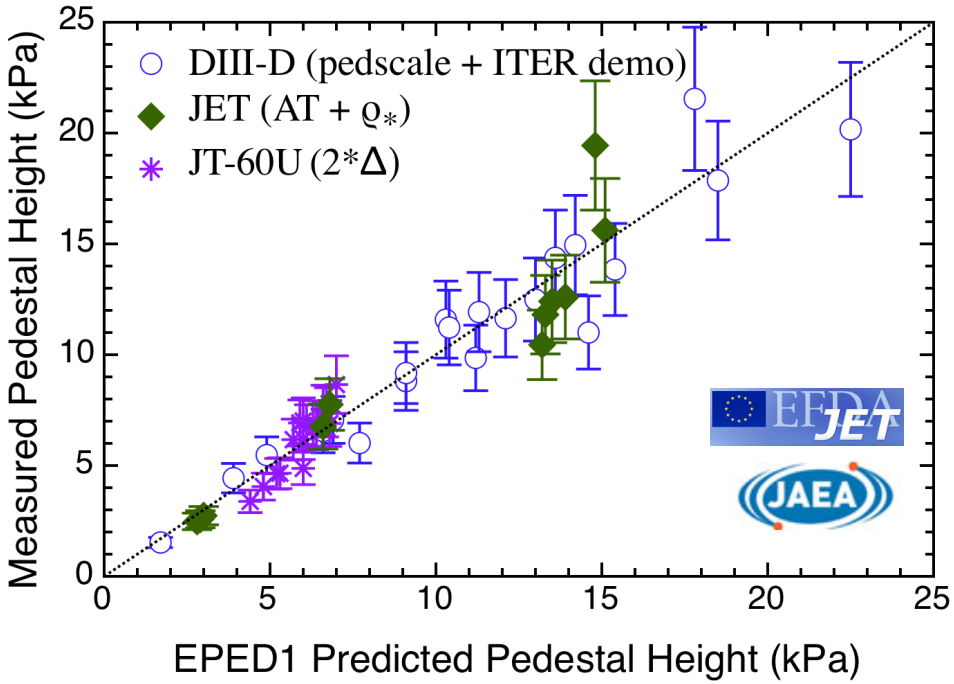
EPED Predictions in Good Agreement with Dedicated DIII-D Experiment (EPED1 Model)

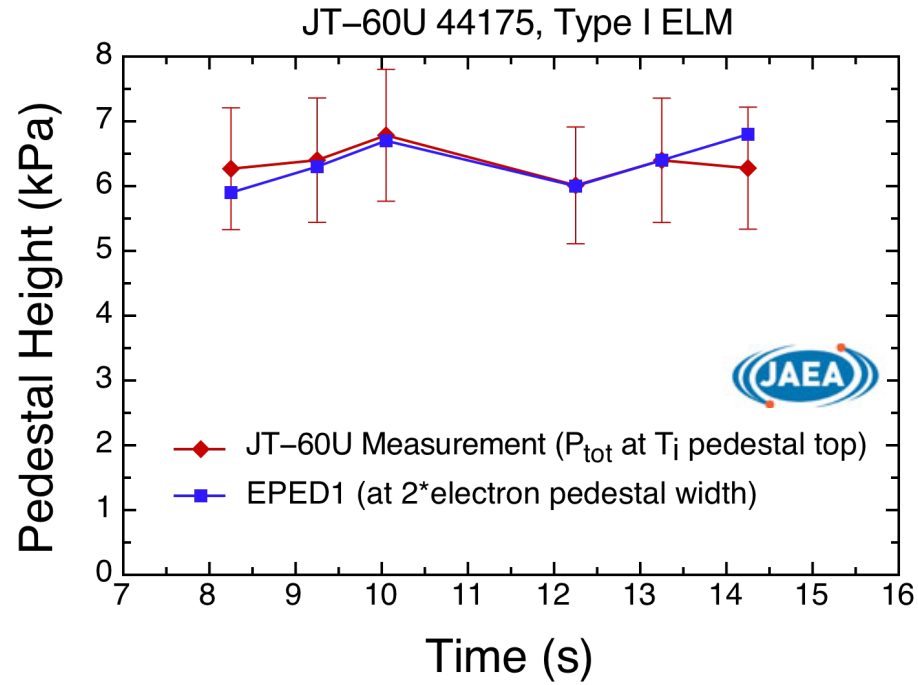




- **Experiment planned to yield large pedestal variation via scans in I_p, B_t and δ (~factor of 3 variations, 17 discharges)** *[Groebner08]*
- **EPED1 predictions made and presented before the experiment**
  - Good agreement, reproduce observed trends
- **Using achieved inputs, find very good agreement in predicted/ measured height 1.03 ±0.13 and width 0.93 ±0.15**
  - Height varied more than a factor of 10, width varied by factor of ~3

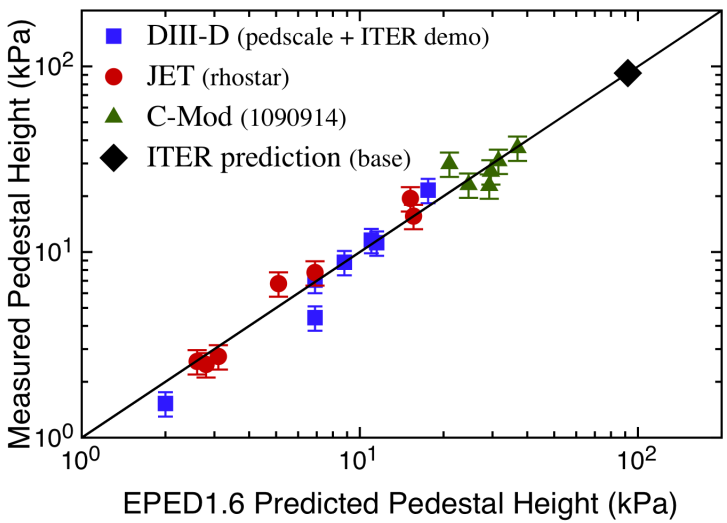
Successful tests of EPED on JET and JT-60U (EPED1 Model)

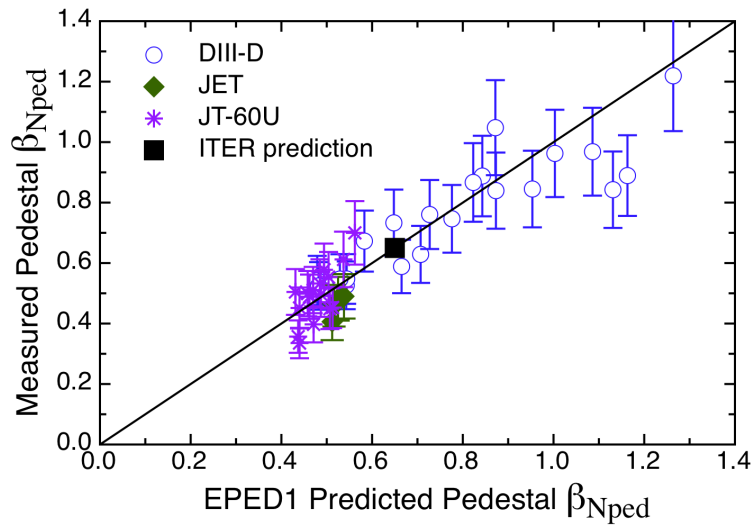




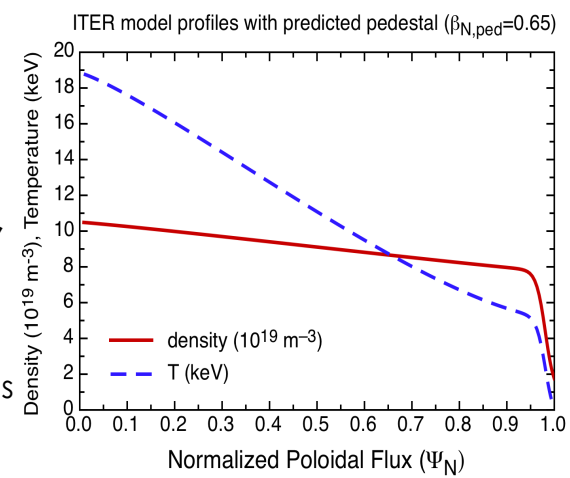
- **Initial test on 11 JET shots, 1.05 ±0.14**
- **Trends with time on JT-60U accurately reproduced**
  - Changes in time of pedestal explained by β_{global} and n_{ped} variation
- **Predicted/Measured pedestal height= 1.02 ±0.14** ***(21 DIII-D, 16 JT-60U,11 JET)***

Pedestal Prediction for ITER

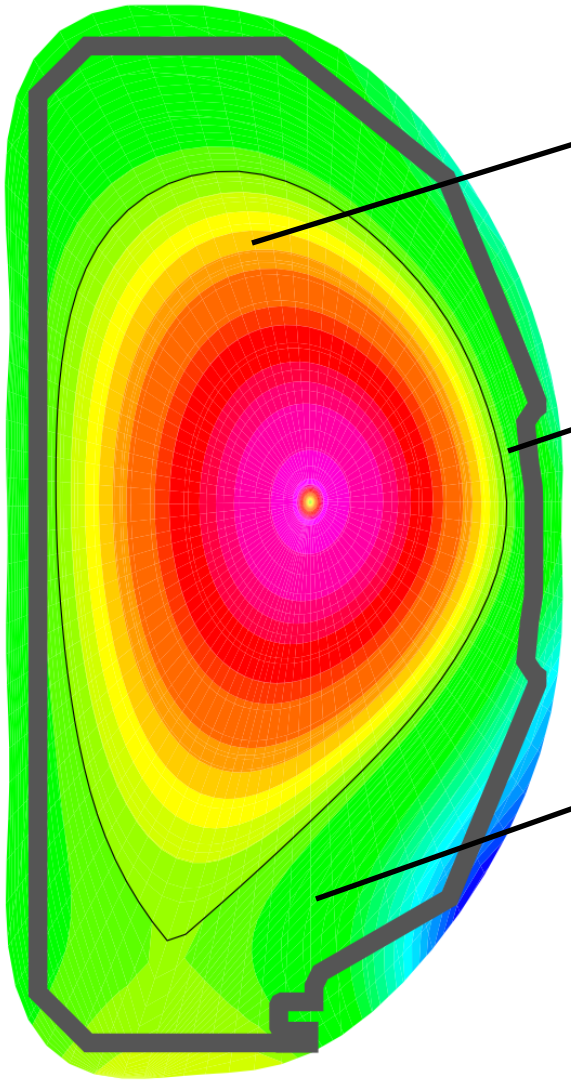




- **$\beta_{N,ped}$ useful metric for predictions**
- **For ITER baseline, EPED predicts a pedestal height of $\beta_{N,ped}$~0.6 and a width Δ_ψ~0.04 (~4.4cm)**
- **At ITER reference density, and typical density peaking, one expects n_{ped}~7x10^{19} m^{-3}, at this density, $\beta_{N,ped}$=0.6 corresponds to T_{ped}=4.1 keV**
  - ***Note***: Predictions are for pedestal top (ψ~0.96, ρ~0.95). Core transport studies often use a BC further in (eg Kinsey ρ=0.86). Using model profiles, our prediction corresponds to roughly $\beta_{N,\rho=0.86}$~0.9, $T_{\rho=0.86}$~5.5 keV, $n_{e,\rho=0.86}$~8x10^{19} m^{-3}



Overview of equations and coupling



$$\frac{1}{V'}\frac{\partial(V'n)}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \rho}(V'F_n^\rho) = S_n$$

$$\frac{1}{V'^{5/2}}\frac{\partial(V'^{5/3}n_s T)}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \rho}(V'F_s^\rho) = S_s$$

$$F^\rho V'/A = F^\rho / < |\nabla \rho| >$$

Particle continuity

$$\frac{\partial}{\partial t}n_i + \frac{1}{V}\frac{\partial}{\partial x}\left(\frac{V}{h_x}n_i u_{ix}\right) + \frac{1}{V}\frac{\partial}{\partial y}\left(\frac{V}{h_y}n_i u_{iy}\right) = \langle \sigma_i v_{te}\rangle n_e n_g - \langle \sigma_r v_{te}\rangle n_i n_g$$

Electron energy density

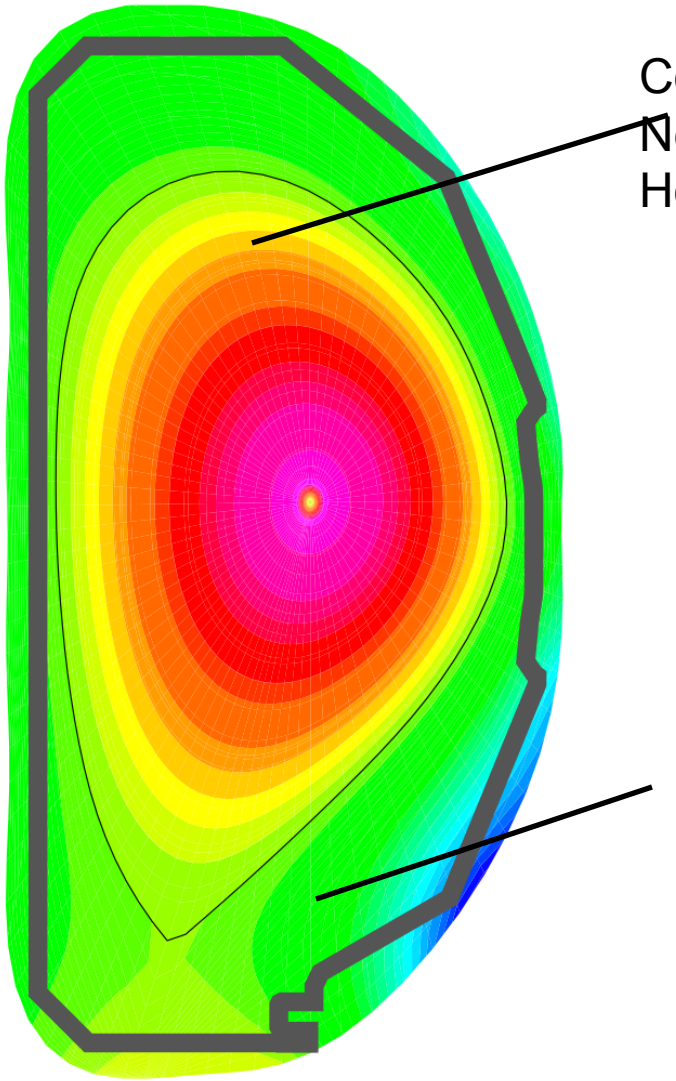
$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_e T_e\right) + \frac{\partial}{\partial x}\left[C_{ex}n_e u_{ex}T_e - \kappa_{ex}\frac{\partial T_e}{\partial x} - 0.71 n_e T_e \frac{B_x}{B}\frac{J_\parallel}{e n_e}\right] + \frac{\partial}{\partial y}\left(C_{ey}n_e u_{ey}T_e - \kappa_{ey}\frac{\partial T_e}{\partial y}\right)$$
$$= -K_q(T_e - T_i) + S_{Ee} + \mathbf{E}\cdot\mathbf{J} + 0 \times \left[u_{ix}\frac{\partial P_e}{\partial x} - u_{iy}\frac{\partial P_i}{\partial y}\right].$$

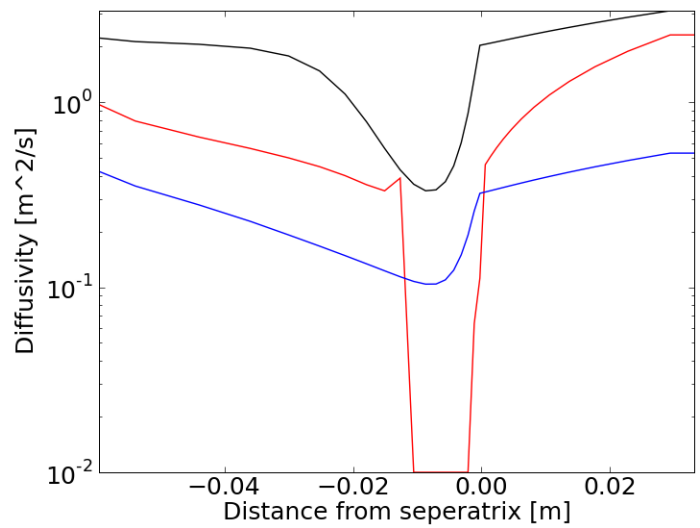
Ion energy density

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_i T_i\right) + \frac{\partial}{\partial x}\left[C_{ix}n_i u_{ix}T_i - \kappa_{jx}\frac{\partial T_i}{\partial x}\right] + \frac{\partial}{\partial y}\left(C_{iy}n_i u_{iy}T_i - \kappa_{jy}\frac{\partial T_i}{\partial y}\right) = 0 \times \left[\mathbf{u}_i \cdot \nabla p_i\right]$$
$$+ \eta_{ix}\left(\frac{\partial v_{ij\parallel}}{\partial x}\right)^2 + \eta_{iy}\left(\frac{\partial v_{i\parallel}}{\partial y}\right)^2 + K_q(T_e - T_i) + S_{Ei} + \frac{1}{2}m_i v_{i\parallel}^2 n_i \nu_{iz}.$$

TECH-X CORPORATION

Overview of flux models in core and edge



Core uses turbulent fluxes from GLF23, Neoclassical from Chang-Hinton and Horton-ETG for on-axis electron transport

Edge used constant diffusivities