A Development Path for a Validated Pedestal Model

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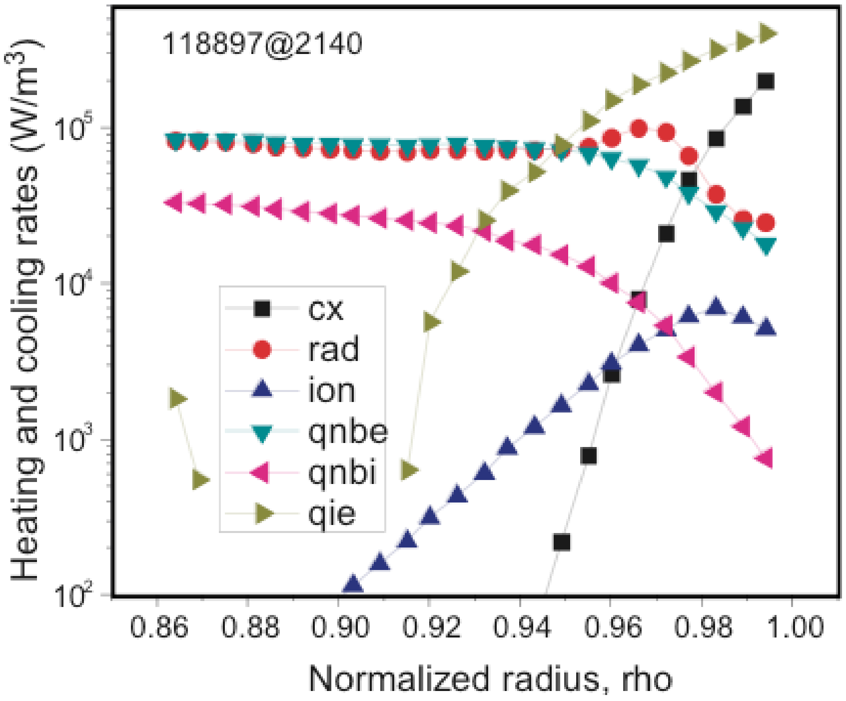
with support from R.J. Groebner, T.H. Osborne, and P.B. Snyder

Presented at the 12th US-EU Transport Task Force Workshop

San Diego, CA

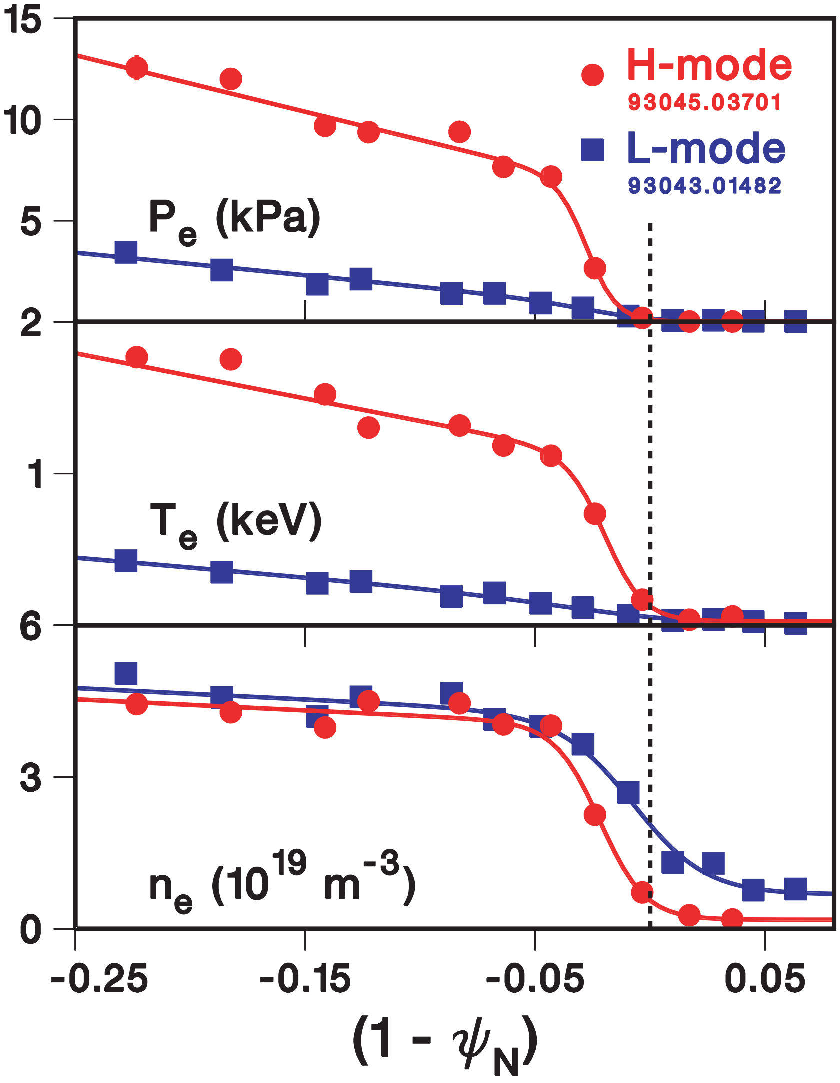
April 17-20, 2007



The Pedestal Remains a Critical Element for Predictive Tokamak Modeling

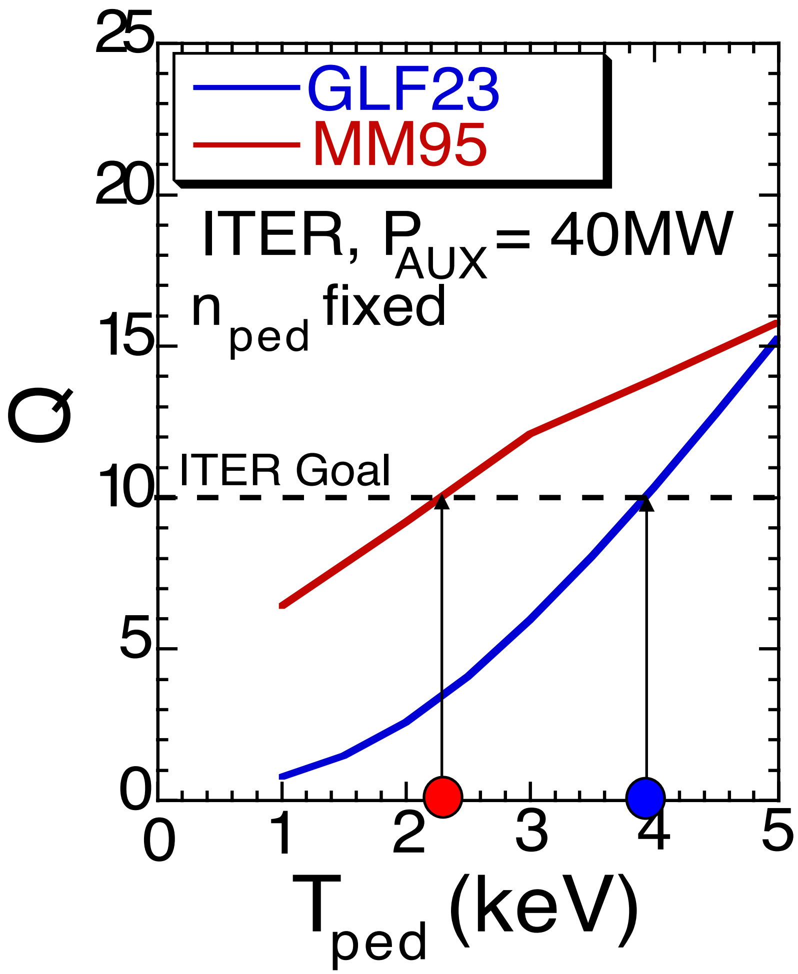
- **The critical dependence of global confinement on pedestal height is well documented**
- **Our uncertainty in predicting pedestal height has not significantly improved in last ~3 years**
- **Several efforts are needed to improve and test our pedestal models**
  - Separate ELMs from transport between ELMS
  - Quantify fluxes through all channels
  - Include time-dependence
  - Account for short scale lengths
  - Extract experimental scaling from correlated parameters
- **Prediction of pedestal pressure height is not the only goal**
  - Particle transport for fueling requirements
  - Momentum confinement for core transport and SOL flows
  - Poloidal variation of fluxes into the SOL

The Pedestal is the Interface Between the Core and Boundary Plasmas



- **The H-mode pedestal results from a transport barrier just inside the separatrix**
- **The pedestal is usually parameterized by a hyperbolic tangent function**

The Edge Pedestal Height is Expected to Strongly Influence ITER Performance

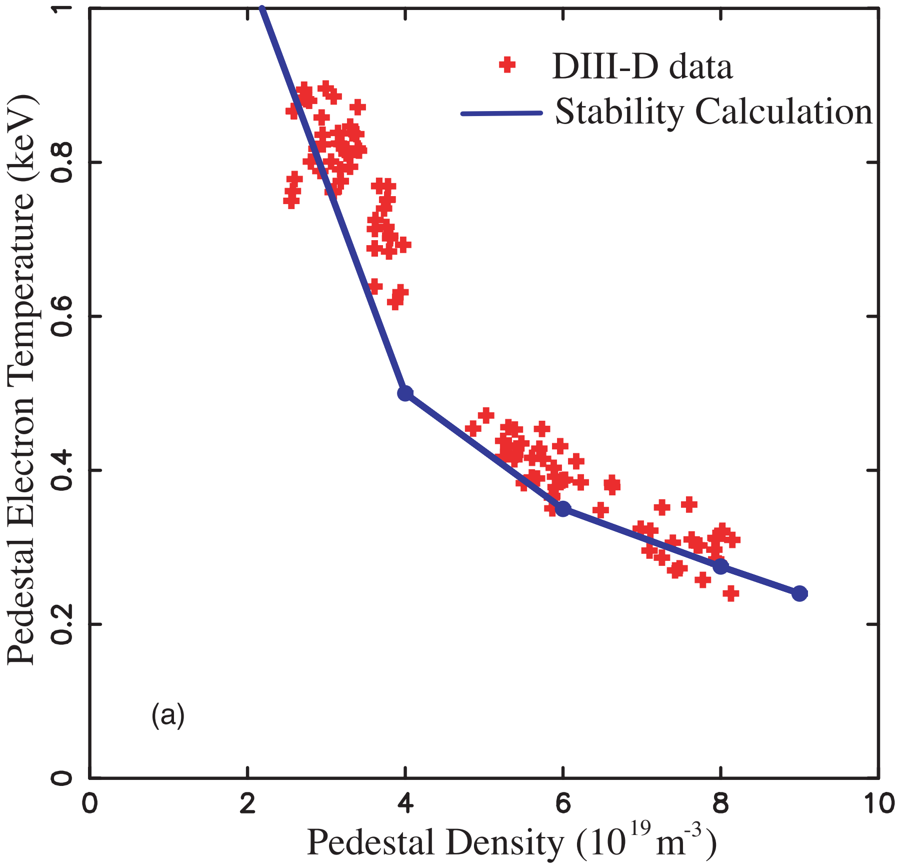


J. Kinsey, IAEA 02

- **For stiff temperature profiles (fixed T/ΔT) core plasma performance improves with increasing pedestal energy**
- **The pedestal often serves as a boundary condition for integrated modeling of tokamak performance**

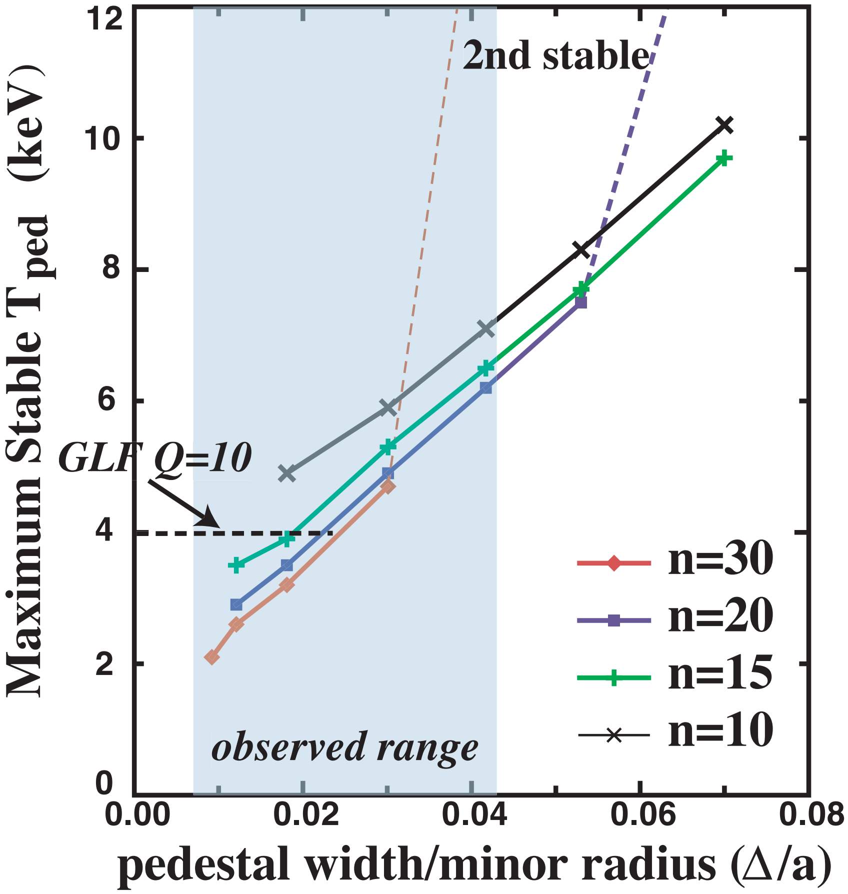
Validated MHD Stability Constraint Shifted Focus to Pedestal Width

Stability limit matches DIII-D Density Scan
(Fixed parameters; pedestal Width, I_p, B_t, etc.



P. Snyder (PPCF 2004)

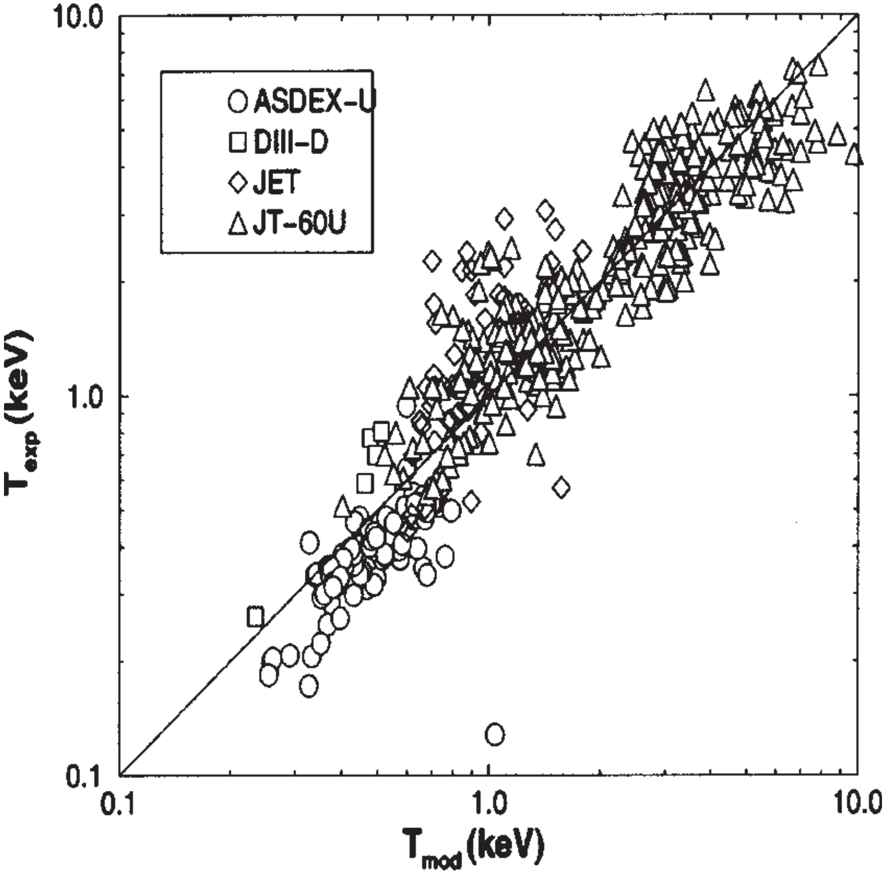
T_{ped} limits for ITER, n_{ped}=7.1 10^{13} cm^{-3}



P. Snyder (Nucl. Fusion 2004)

The ITPA Pedestal Database was Created to Test Pedestal Models

Fit to ITPA Database With Flow Shear Stabilization Constraint



T. Onjun (Phys. Plasmas 2002)

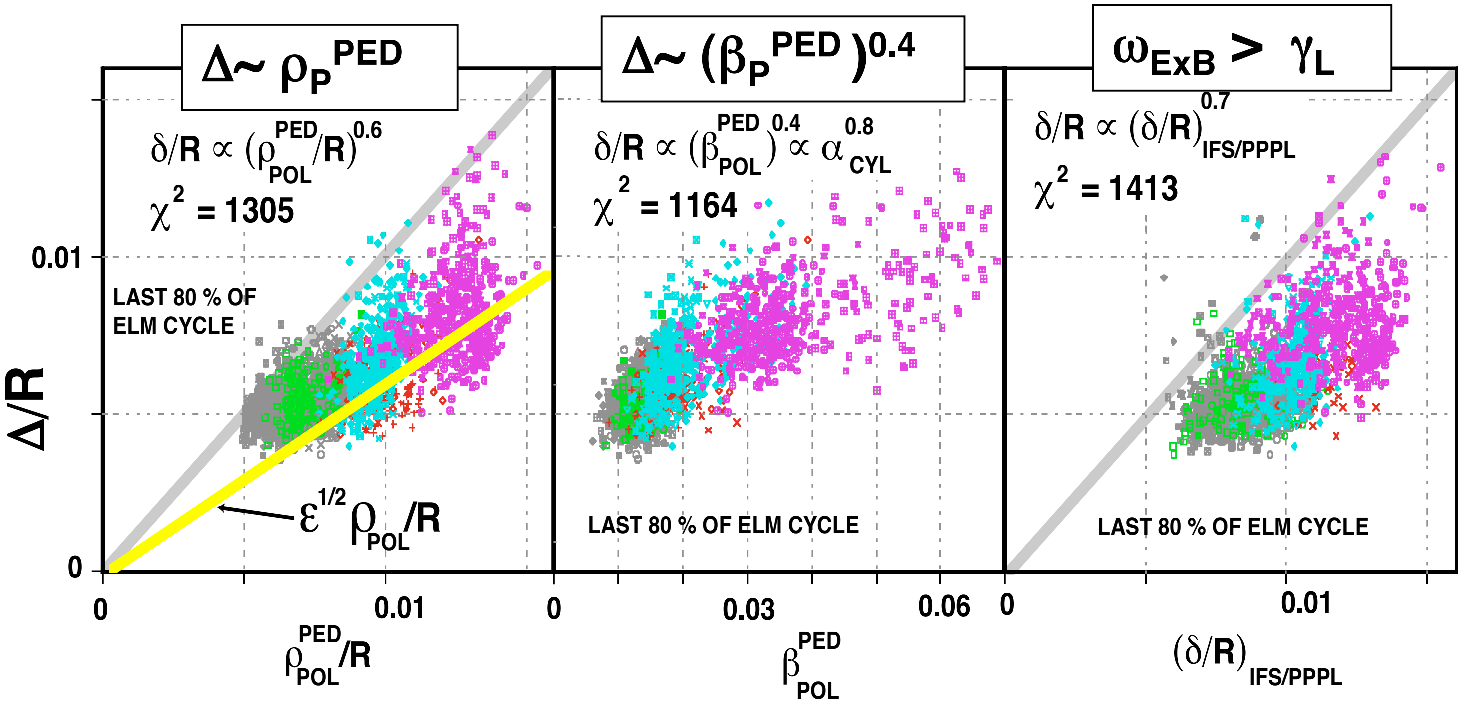
Kritz and Onjun

Scaling	Physical Model	RMSE
$\Delta \propto \sqrt{\beta_\theta} R$	**Poloidal pressure**	33%
$\Delta \propto \rho S^2$	**Magnetic and flow shear stabilization**	32%
$\Delta \propto \sqrt{\rho R q}$	**Flow shear stabilization**	31%
$\Delta \propto \rho^{2/3} R^{1/3}$	**Diamagnetic stabilization**	34%
$\Delta \propto \sqrt{\varepsilon}\, \rho_\theta$	**Ion orbit loss**	34%
$\Delta \propto 1/n_{ped}^{3/2}$	**Neutral penetration**	53%

- **Pedestal widths not generally available-> Fit pedestal top with a stability constraint**
- **The different simple models (ρ^0 to ρ^1) represents a significant range of predicted pedestal pressure**

Even Single Device Scans Exhibit Uncertain Scaling

DIII-D Pedestal Study



- Difficulties arise for a number of reasons; time dependence, correlation with MHD limit, codependent parameters, difficult measurements,...
- We need a different approach than "Try Again, Try Harder"

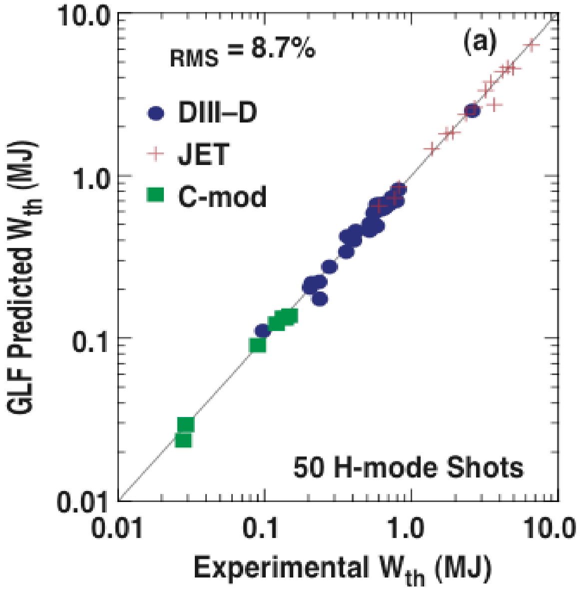
Pedestal Strategy Analogous to Core Transport Model Development

Experiment

- **Measure Profiles**
  - Plasma
  - fluxes (sources)
  - fluctuations
- **Time evolution of profiles**
- **Develop scaling relations**

Theory

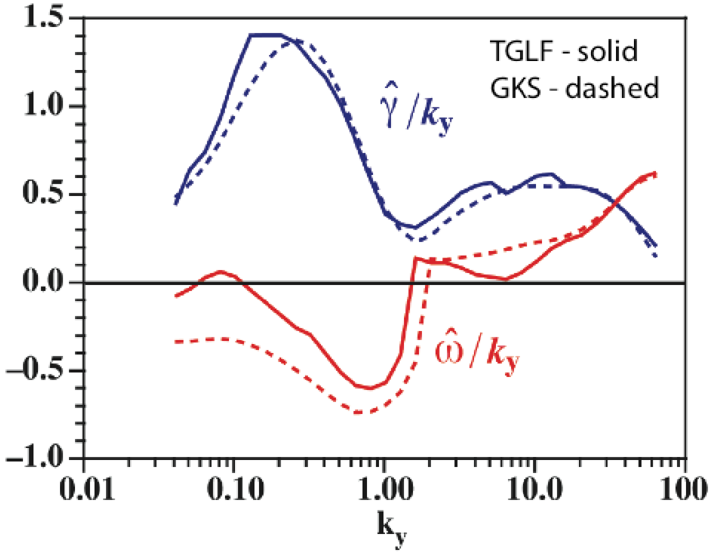
- **From measure profiles predict**
  - Fluxes
  - fluctuations
- **Predict profiles**
- **Models verify observed scaling relations**
- **Predict Burning Plasma Pedestal**



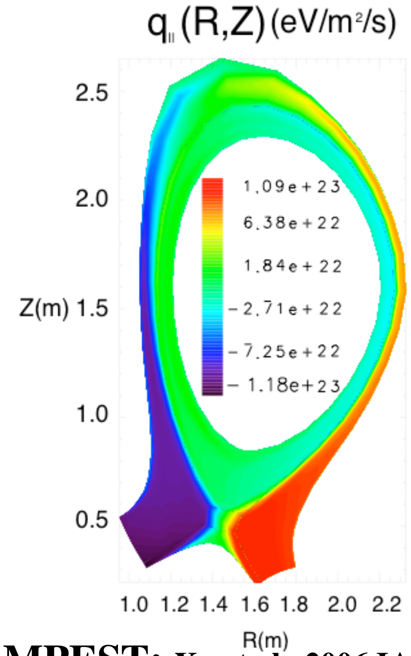
Kinsey et al, 43 NF 1854 (2003)

Several Pedestal Models are under Development

- **TGLF: Quasi-linear approximation to gyrofluid/gyrokinetic simulation is being developed for pedestal conditions**
- **Tempest (continuum) and XGC-1 (particle):Gyrokinetic models, electromagnetic, encompassing pedestal and SOL, neoclassical, ion and electron turbulence,...**
- **Possibility to include other effects such as paleoclassical, etc.**

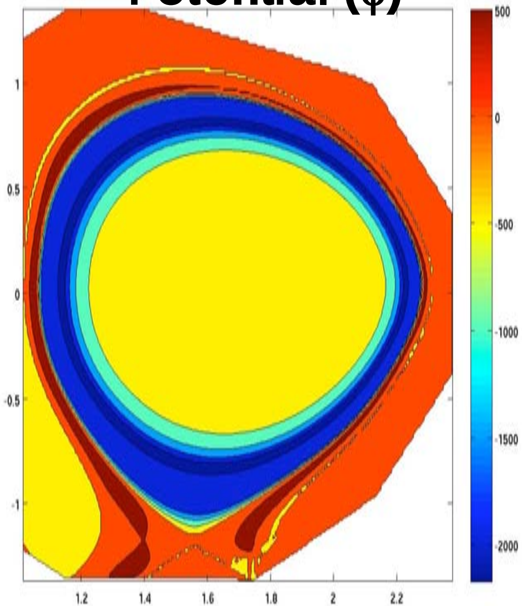


TGLF: Staebler et al., 2006 IAEA



TEMPEST: Xu et al., 2006 IAEA

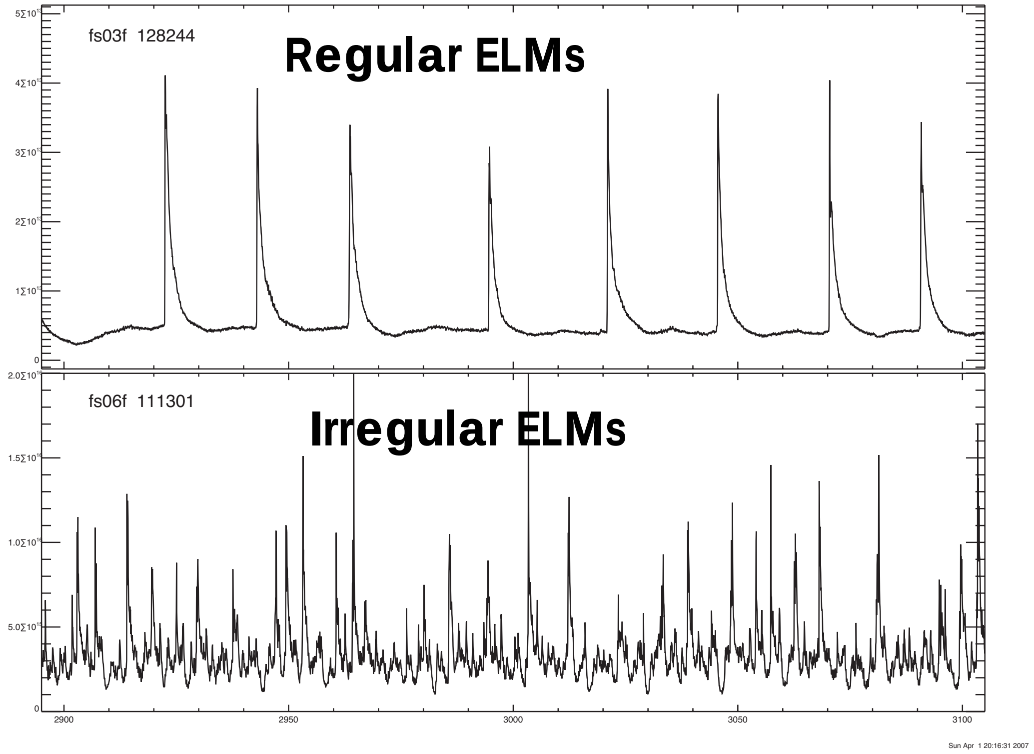
Potential (ϕ)



XGC-1: Chang et al., 2006 IAEA

First Separate ELM transport from Total Pedestal Transport

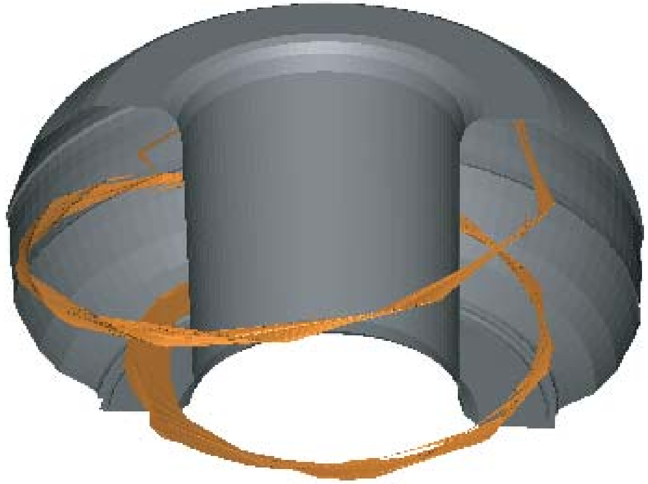
Typical ELMs in DIII-D



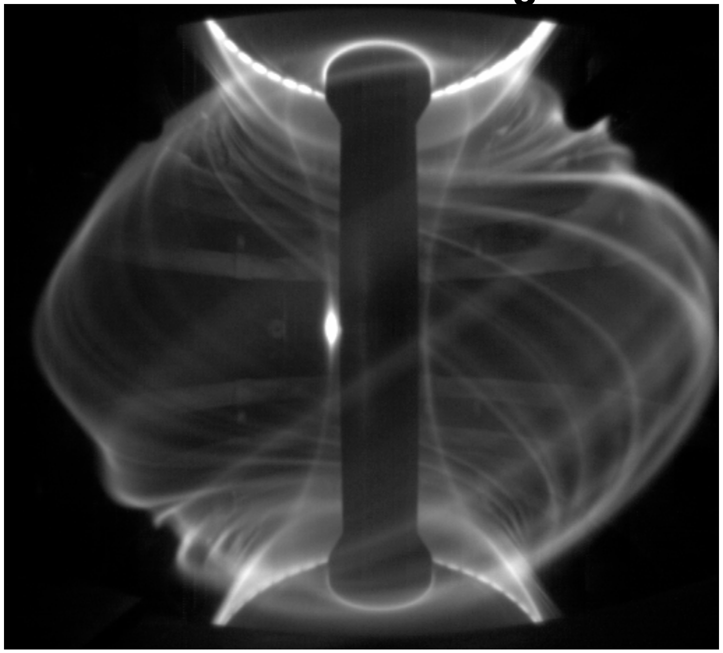
- **Start with clean ELM case**
  - Examine transport between ELMs without large scale turbulence
- **ELM transport is important in its own right.**
  - MHD transport, more global scale instability
  - Work is going forward with non-linear MHD transport

Non-linear ELM Model is Under Development

BOUT Simulation, early nonlinear phase, Surface of constant δn



MAST Visible Image of ELM



A. Kirk (PRL 2004)

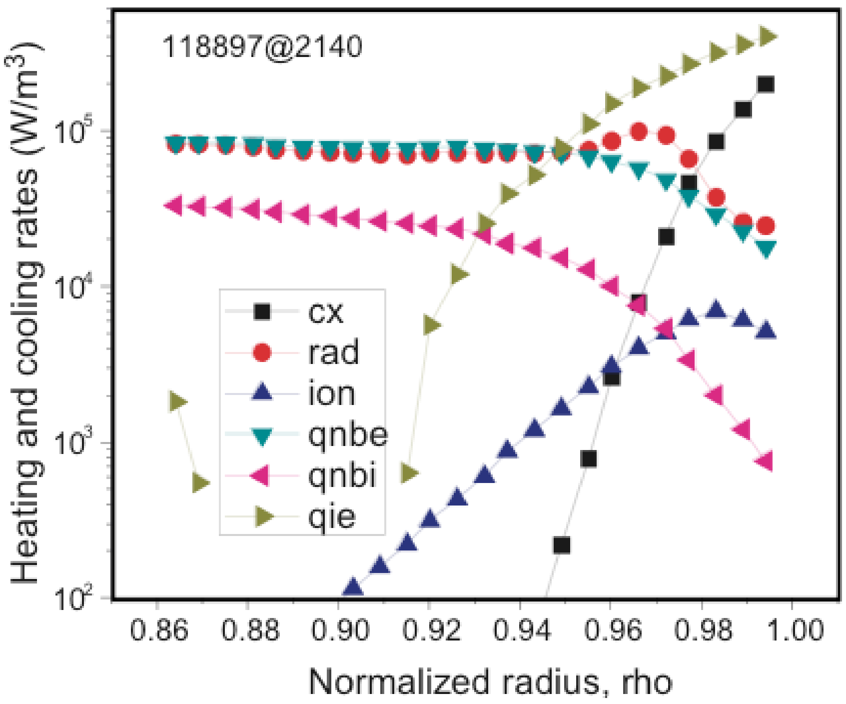
- **Predictions of pedestal loss at each ELM are required to build a time-averaged pedestal model**
  - ELM induced loss of density, temperature and edge current
  - Starting boundary conditions for pedestal evolution

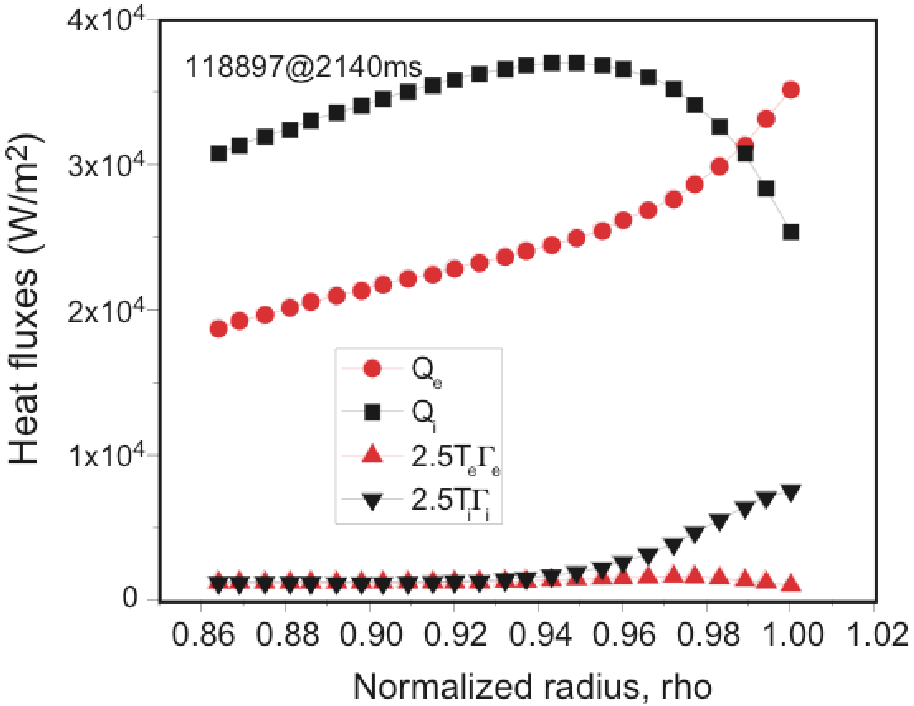
Pedestal Model Development Must Overcome Significant Challenges

- **Energy and particle fluxes through pedestal**
  - Ion source difficult to measure and poloidally asymmetric
  - Possibility of 2D transport
- **Time dependence**
  - Fast diagnostic time resolution
  - Computationally expensive for models
- **Small scale lengths**
  - Diagnostic spatial resolution
  - Theoretical considerations
- **Parametric scaling**
  - Important scaling parameters often experimentally correlated

Adequately Characterizing Pedestal Transport is a Diagnostic Challenge

- **Measurement of fluxes is the most basic and necessary characterization of a transport system**
- **Challenges for pedestal flux measurement**
  - Exchange terms important; Detailed profiles of ions and electrons
  - Ionization source; Significant within pedestal, difficult to measure, 2D





Stacey and Groebner, Phys. Plasmas 14, 012501 (2007)

Diagnostics Need Improvement to Adequately Measure Pedestal Transport

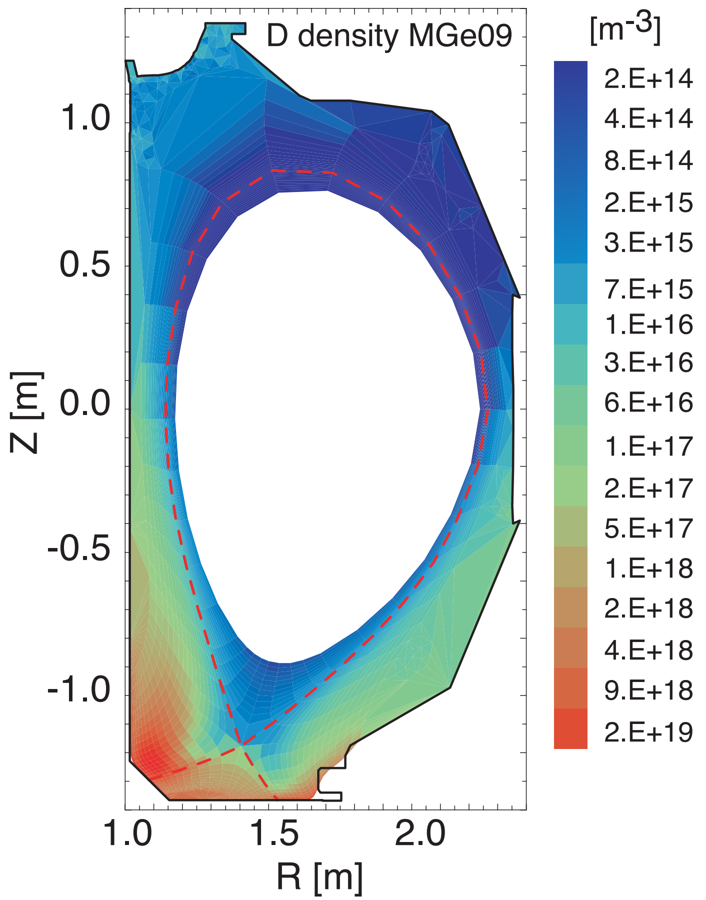
- **All species need high spatial and temporal resolution**
  - Ion and electron density and temperature profiles simultaneously to resolve pedestal structure
  - T_i width may be very different from T_e width
  - Main ion measurements; we rely on impurity ion data
  - Sufficient temporal response to follow evolution between ELMs
- **Ionization source is important and difficult to measure**
  - Hollow profile difficult to invert
  - 2D profile
  - Difficult spectroscopic interpretation
- **Profiles of other parameters needed include**
  - Fluctuations; Most diagnostics fixated on core plasma
  - Rotation; Main ion rotation may be very different from impurities
  - Pedestal bootstrap current; Time dependence is an issue

Interpretive Modeling Approach for the Ion Source 2D Profile

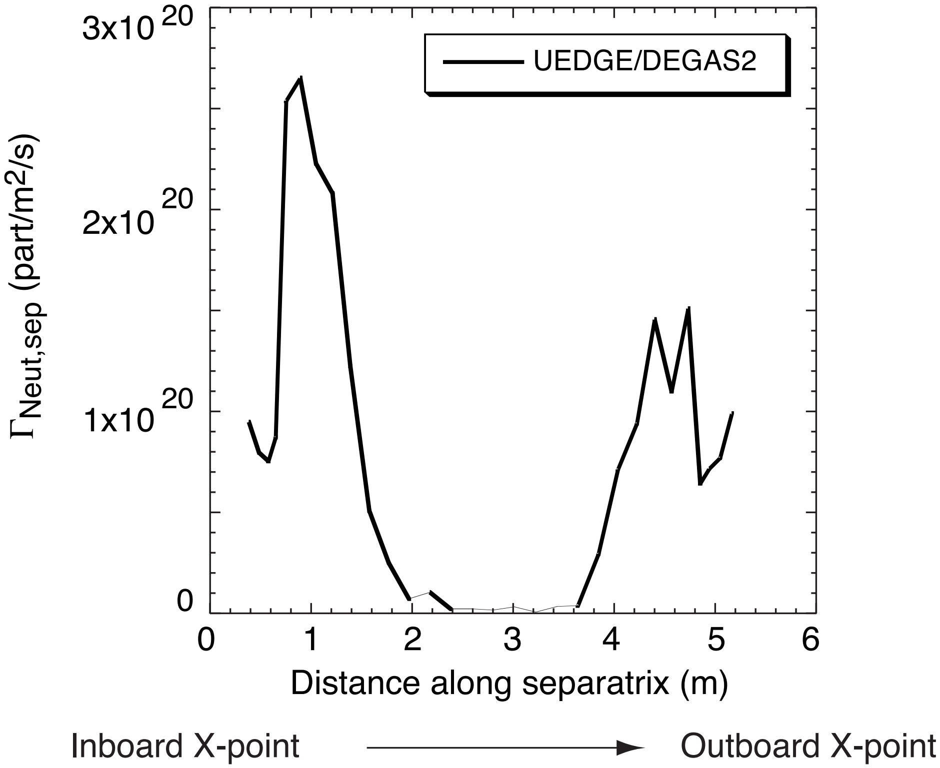
- **Measure ion flux to all surfaces**
  - Use toroidal symmetry and interpolation of sparse measurements to determine profile of wall ion flux
  - Neutral pressure measurements and modeling to determine what fraction recycles
- **Reconstruct plasma background**
  - Interpretive model may be best, but any tool that allows use of all information
  - Build background plasma variations to test sensitivity and uncertainty
- **Launch Monte Carlo neutrals**
  - Uses 2D ion wall flux and reconstructed plasma backgrounds
- **Assess models' sensitivity to pedestal ion source**
  - Help to determine required measurement accuracy

Ion Source in Pedestal May be Strongly Poloidally Asymmetric

- **Divertor neutrals launched into background plasma modeled with UEDGE**



Pedestal neutral flux from Divertor source



- **Role of main chamber ion flux must still be addressed**

2D Transport Analysis May Be Necessary

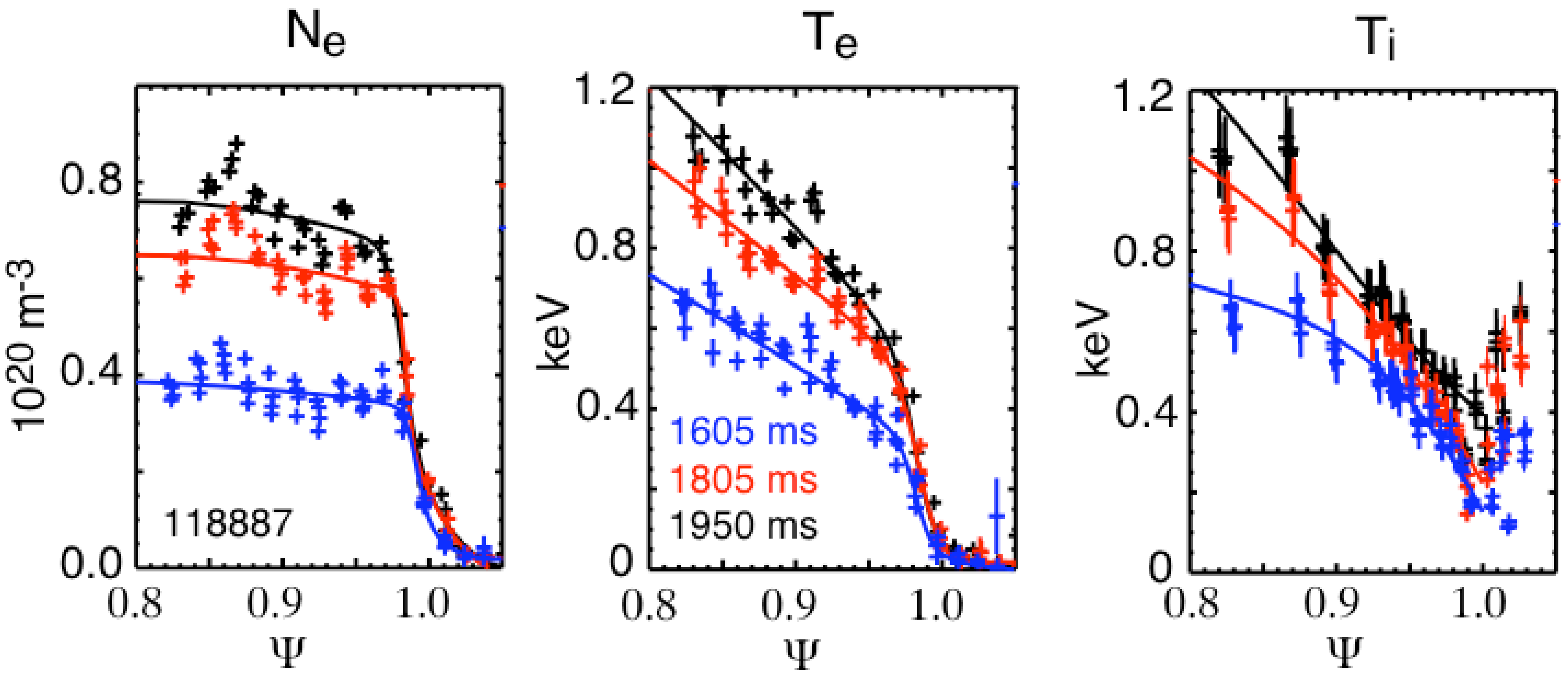
- **Poloidal local ion source can lead to 2D transport**
  - Poloidal variation in density and temperature
  - Parallel ion redistribution flow at sound speed
  - Parallel heat flux to maintain pressure balance
  - Poloidal variation in radial transport
- **Ion distribution can vary on flux surface**
  - Ion orbit loss distribution
  - Inhomogeneous viscous force damping
- **How do we diagnose 2D transport issues?**

Pedestal Transport is Inherently Time-Dependent

- **No examples of steady-state pedestal without applied or intrinsic additional transport**
  - Resonant magnetic perturbations
  - EHO in QH-mode
  - EDA mode
- **Density, temperature, current and/or heat and particle flux evolve from one ELM to the next**
  - ELM cycle terminated by MHD constraint or dropping below H-mode threshold
- **Time-averaging over ELMs will convolve transport with MHD limits**
  - If pedestal width grows between ELMs then time-averaged width will depend on MHD limit

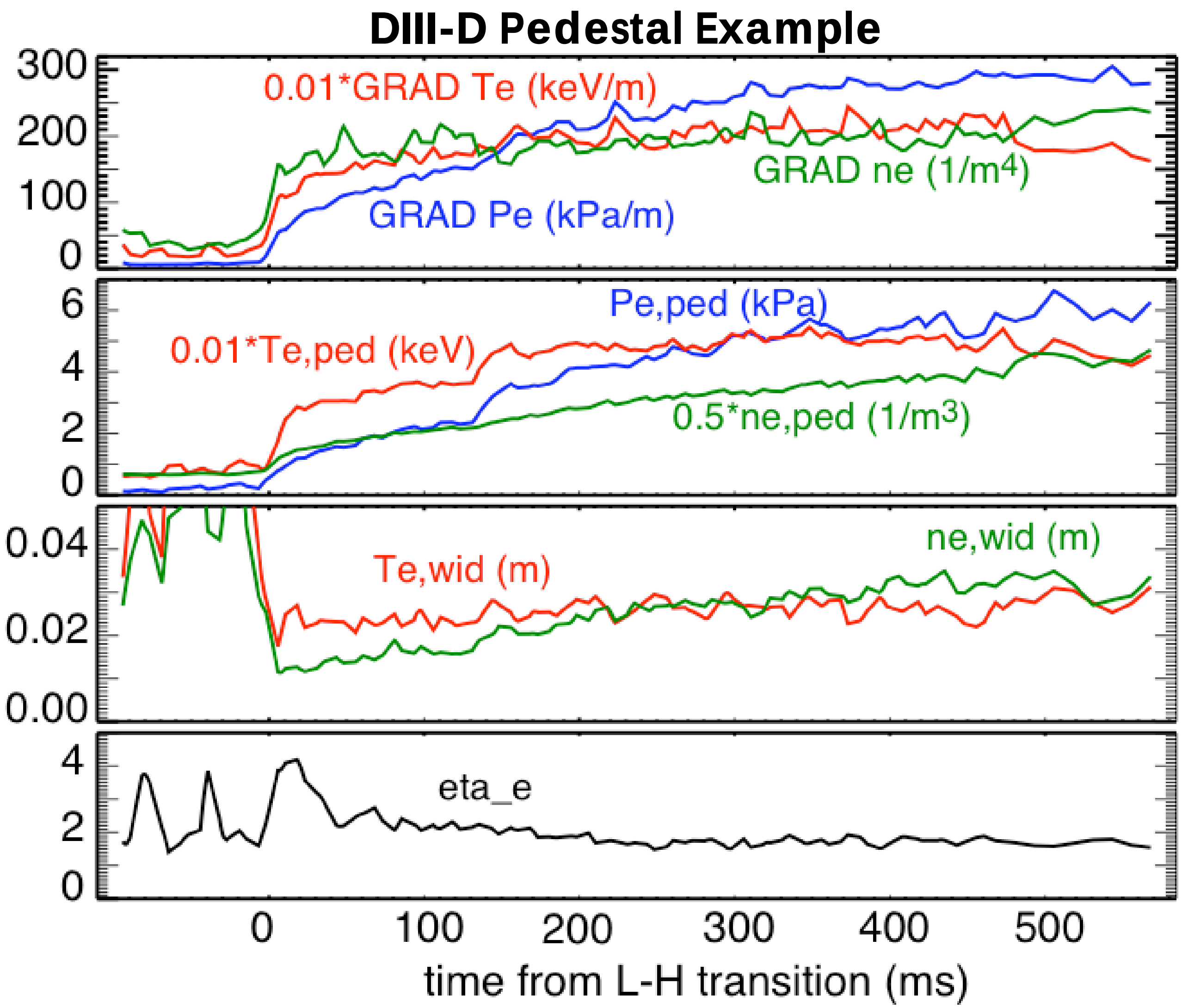
Pedestal Profiles Continue to Build Until the Next ELM

Long ELM-free period in DIII-D



Profiles continue to build until an ELM

Both Widths and Gradients Can Evolve Until the Next ELM



Experimentalists need to Characterize Time Dependence

- **Do pedestal widths for density, Te and Ti grow between ELMs?**
  - Parametric dependence for time behavior of each of these widths is needed
  - Very few published results of pedestal evolution between ELMs
- **Is density transport barrier width same as electron temperature, or ion temperature?**
- **Does turbulence suppression width follow width of density and/or temperature?**

Time Dependence Will be a Challenge for Models

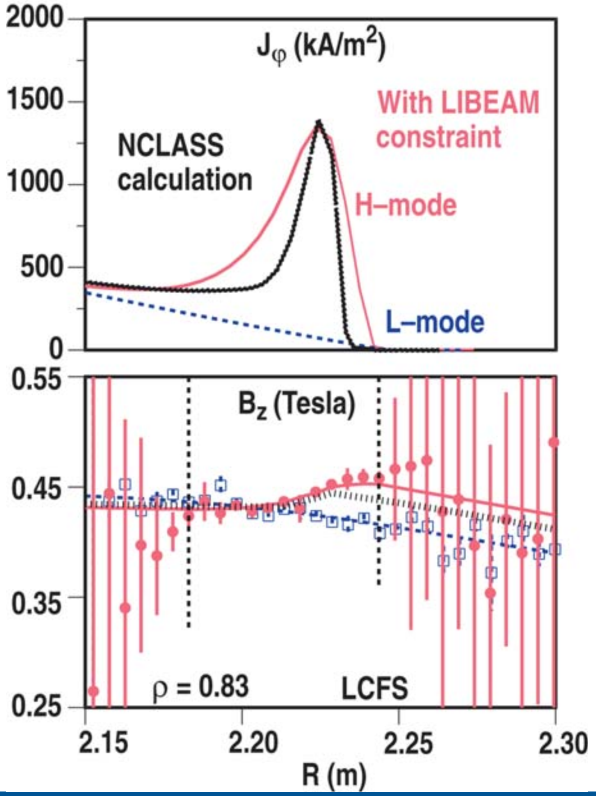
- **Profile evolution takes place over 10s of ms**
- **For codes that follow drift wave turbulence, ELM cycle is a very long time**
- **Profile evolution also expensive for quasi-linear codes**
- **As MHD stability limit is approached, does transport change in character?**

Small Pedestal Scale length Produces Concerns for Theory and Measurements

- **Steep Gradients are hard to measure**
  - Pedestal profile measurements do not typically include all relevant parameters simultaneously; n_e, T_e n_i, T_i, rotation, turbulence, etc.
- **Gradient scale lengths may be similar to turbulence spatial scale**
  - Non-locality of transport, turbulence spreading
  - Quasi-linear codes may not handle non-local transport
  - Can non-local transport be diagnosed?

Neoclassical Effects Require Assessment

- **Neoclassical transport and current may not follow simple models in pedestal**
  - Bootstrap current important for transport as well as MHD limit
  - New codes will address this issue



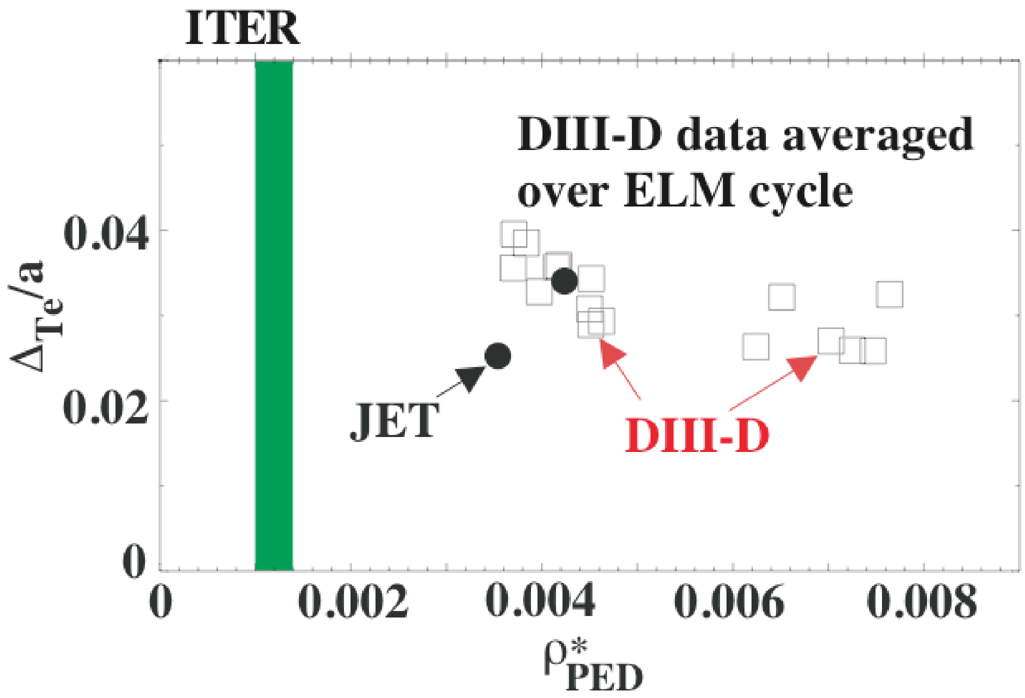
- **Initial measurements encouraging**
- **Time dependence also important**

D. Thomas (Phys. Plasmas 2005)

Experimental Scaling Can Offer Important Insight

- **While global databases have not revealed clear trends in pedestal width, careful selected experiments can be insightful**
  - Rho-star
  - Neutral source
  - Toroidal ripple
  - Toroidal Rotation
  - Beta versus power dependence
  - Shape
- **Models should seek to reproduce experimentally documented trends**

Initial Study Finds Weak ρ^* Dependence for Pedestal Width

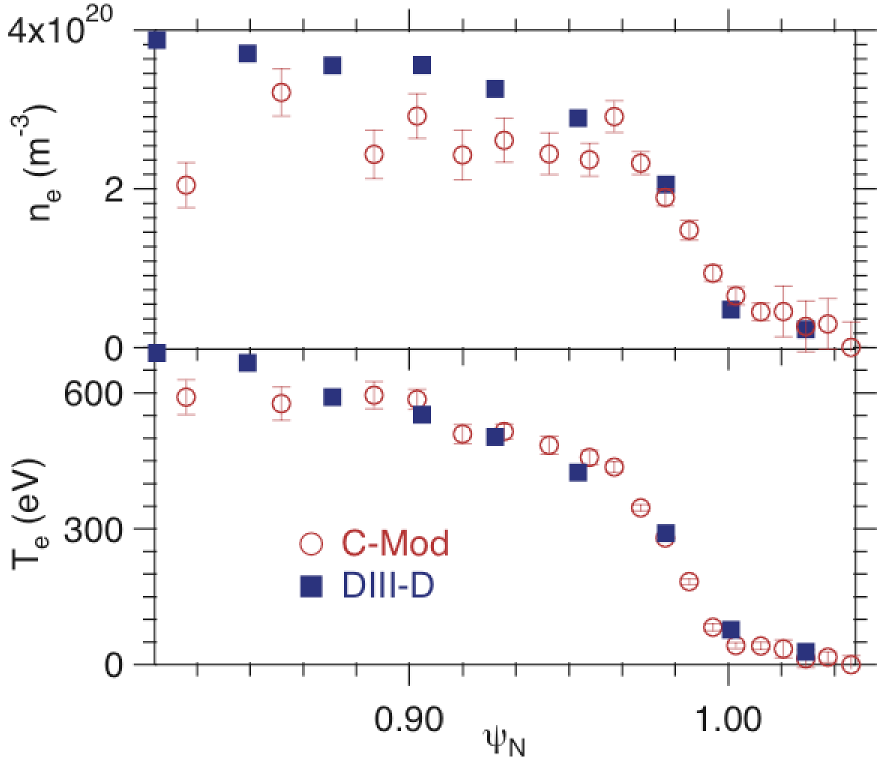


T.H. Osborne, Bull. Am. Phys. Soc. 48, 185 (2003)
M. E. Fenstermacher et al., Nucl. Fusion 45 1493 (2005)

- Generic ExB shearing models predict $\Delta_{ped} \sim \rho_i$, unfavorable for ITER
- Initial results indicate pedestal width constant fraction of minor radius
- Significant implications for ITER
- Plans for factor of 4 ρ^* scan between JET and DIII-D

Pedestal Density Width Correlated with Temperature Width

T_e and n_e pedestals scaled with dimensionless parameters in C-Mod/DIII-D experiment

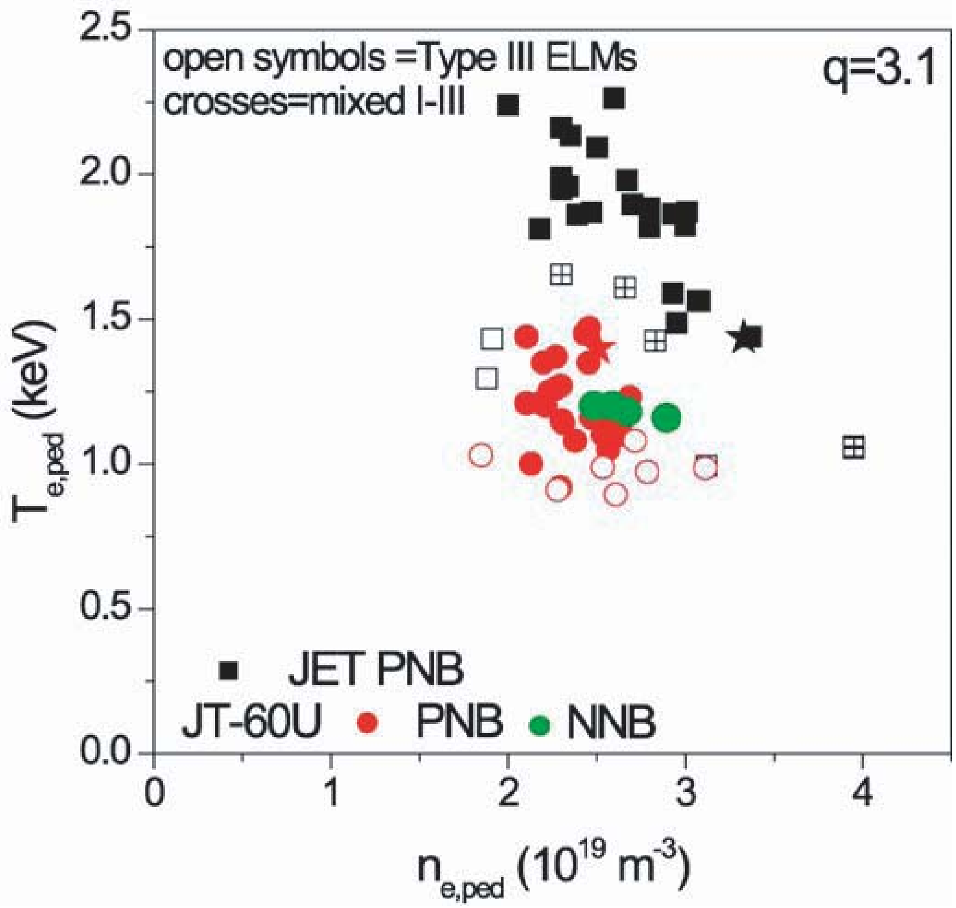


D. Mossessian (Phys. Plasmas 2003)

- **Density profile should be consistent with transport and ion source profiles**
- **DIII-D and C-MOD pedestal match dimensionless parameters. Kinetic modeling indicates consistency with density profile**
- **Interpretation of dimensionless experiments more complicated when dealing with dimensional atomic physics**

Toroidal Ripple or Rotation Cause of JT-60U Pedestal Reduction

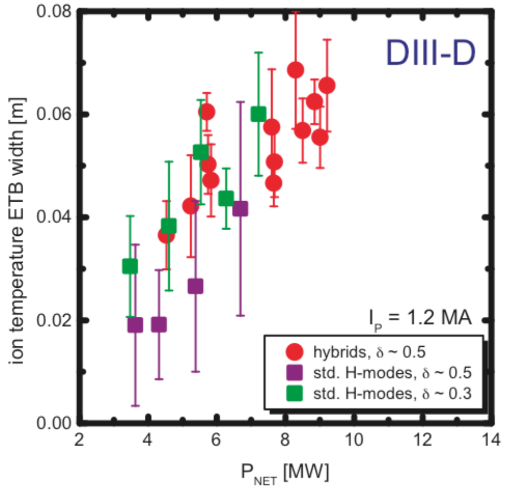
JET / JT-60U
Dimensionally Identical Comparison

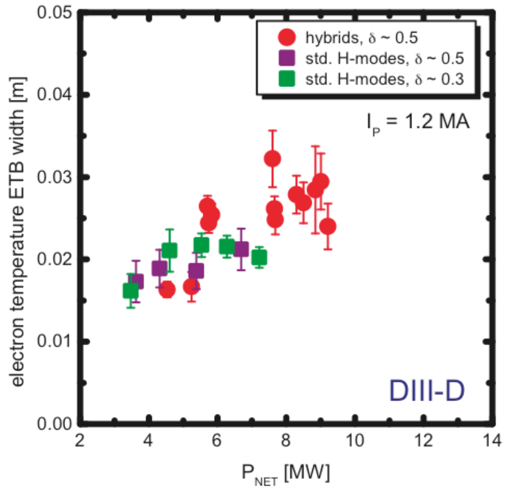


G. Saibene (Nucl Fusion 2005)

- **A dimensional comparison between JET and JT-60U yielded ~30% lower pedestal pressure in JT-60U**
- **Is difference due to ripple induced E_r and rotation profile?**
- **Such discrepancies add uncertainty to multi-machine database analysis**

Pedestal Width Increases with Global Beta and/or Input Power

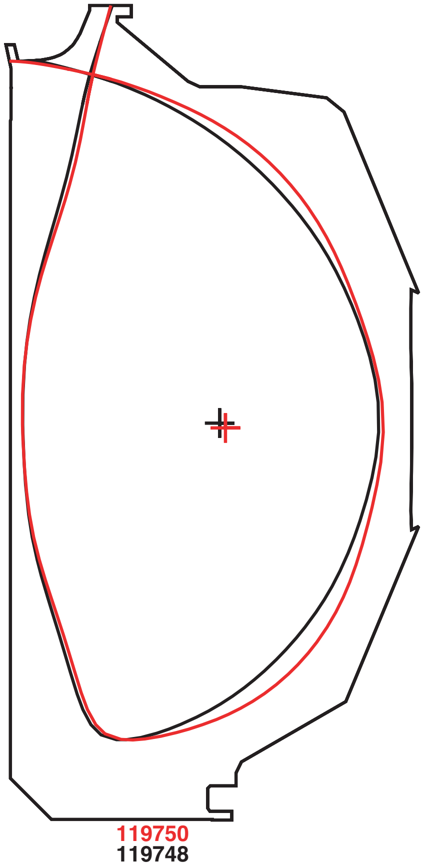


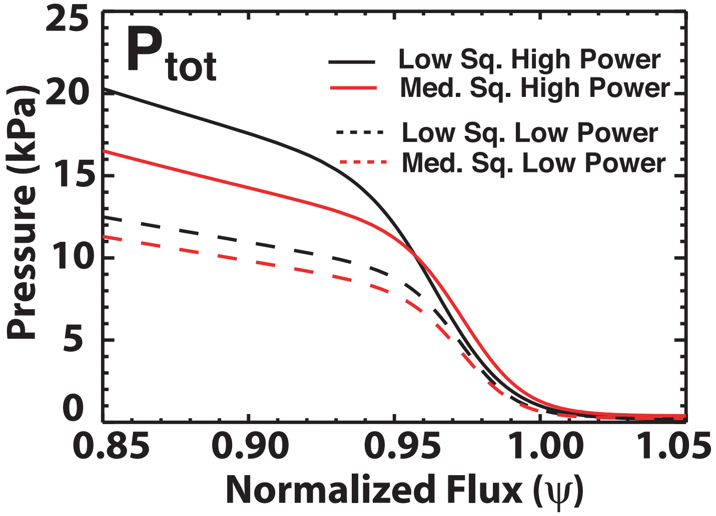


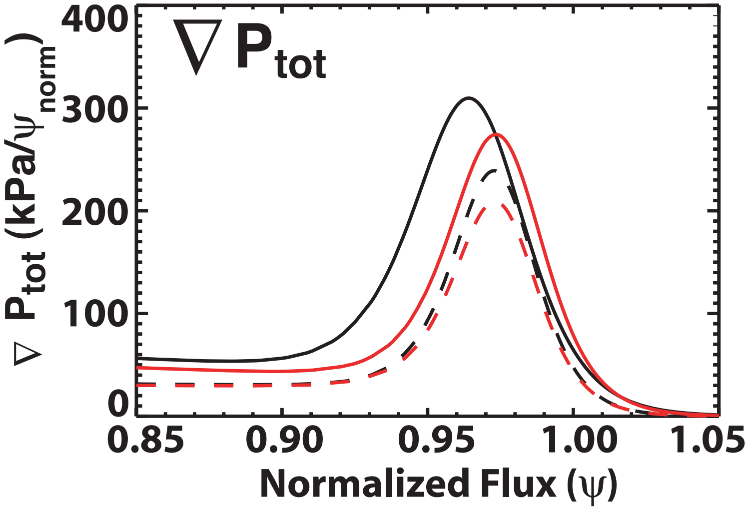
C. Maggi et al, submitted to Nucl. Fusion

- **Pedestal width increases with power and/or beta, observed in several tokamaks**
- **T_i profile more affected than T_e**
- **A transport or MHD stability effect**
- **Power and beta are highly correlated and difficult to separate experimentally**

Shape Can Also Affect Pedestal Width







- **Improved shaping:**
  - Pedestal increases with higher power and/or beta
  - Pedestal increase greater for improved shaping
  - Pedestal pressure gradient consistent with MHD stability
- **Is shape dependence a transport or MHD stability effect?**

Experimental Scaling Studies Offer Insight, but with Challenges

- Careful scaling experiments can isolate and clarify the physics controlling pedestal structure
- Important parameters are often correlated. Careful experimental scans will be required to separate them
- Simultaneous measurement of electron and ion pedestal profiles with adequate time dependence required to interpret scaling results
- Cross machine comparison can produce wider parameter scans, but hidden variables (e.g., ripple, wall material) must be taken into account
- Possible role of neutrals (atomic physics) requires careful assessment of dimensionless scaling arguments

Pedestal Poised for Progress but Critical Issues Need Attention

- **Pedestal clearly a critical issue in predicting global tokamak performance**
- **Some critical questions to address:**
- **How do we extract size scaling (ρ*) from our experiments?**
  - What dimensionless scaling arguments are valid when neutrals may play a role?
- **What role do neutrals play in transport barrier formation and its structure?**
  - How will we measure the 2D neutral profile, and how accurately do we need it?
- **What experimental data and analysis is needed to test the developing models?**
  - Significant lead time to acquire desired data (diagnostic development) and analysis