A Development Path for a Validated Pedestal Model

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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

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

ITER, $P_{\text{Aux}} = 40$ MW, $n_{\text{ped}}$ fixed

J. Kinsey, IAEA 02
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)

Pedestal Electron Temperature (keV)
Pedestal Density (10^{19} m^{-3})

DIII-D data
Stability Calculation

Maximum Stable T_{ped} (keV)

glf Q=10

observed range

P. Snyder (Nucl. Fusion 2004)

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

2nd stable

Pedestal width/Minor radius (\Delta/a)
The ITPA Pedestal Database was Created to Test Pedestal Models

Pedestal widths not generally available -> Fit pedestal top with a stability constraint

The different simple models ($\rho^0$ to $\rho^1$) represents a significant range of predicted pedestal pressure

<table>
<thead>
<tr>
<th>Scaling</th>
<th>Physical Model</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \propto \sqrt{\beta_0 R}$</td>
<td>Poloidal pressure</td>
<td>33%</td>
</tr>
<tr>
<td>$\Delta \propto \rho S^2$</td>
<td>Magnetic and flow shear stabilization</td>
<td>32%</td>
</tr>
<tr>
<td>$\Delta \propto \sqrt{\rho R q}$</td>
<td>Flow shear stabilization</td>
<td>31%</td>
</tr>
<tr>
<td>$\Delta \propto \rho^{2/3} R^{1/3}$</td>
<td>Diamagnetic stabilization</td>
<td>34%</td>
</tr>
<tr>
<td>$\Delta \propto \sqrt{\varepsilon \rho_a}$</td>
<td>Ion orbit loss</td>
<td>34%</td>
</tr>
<tr>
<td>$\Delta \propto 1/n^{3/2}_{ped}$</td>
<td>Neutral penetration</td>
<td>53%</td>
</tr>
</tbody>
</table>
Even Single Device Scans Exhibit Uncertain Scaling

- 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**

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 paleo classical, etc.**

TGLF: Staebler et al., 2006 IAEA

TEMPEST: Xu et al., 2006 IAEA

XGC-1: Chang et al., 2006 IAEA
First Separate ELM transport from Total Pedestal Transport

- **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

**Typical ELMs in DIII-D**

- **Regular ELMs**
- **Irregular ELMs**
Non-linear ELM Model is Under Development

• 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

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

![Graph showing D density (MGe09) and Pedestal neutral flux from Divertor source](image)

- 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

DIII-D Pedestal Example

- 0.01\*GRAD Te (keV/m)
- GRAD Pe (kPa/m)
- 0.01\*Te,ped (keV)
- Pe,ped (kPa)
- 0.5\*ne,ped (1/m³)
- 0.5\*ne,ped (1/m³)
- Te,wid (m)
- ne,wid (m)
- \(\eta_e\)

Time from L-H transition (ms)
Experimentalists need to Characterize Time Dependence

- Do pedestal widths for density, $T_e$ and $T_i$ 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 $\rho^*$ Dependence for Pedestal Width

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

M. E. Fenstermacher et al., Nucl. Fusion 45 1493 (2005)
Pedestal Density Width Correlated with Temperature Width

- 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

- 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

**JET/JT-60U**
Dimensionally Identical Comparison

G. Saibene (Nucl Fusion 2005)
Pedestal Width Increases with Global Beta and/or Input Power

- 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

C. Maggi et al, submitted to Nucl. Fusion
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 clearly a critical issue in predicting global tokamak performance

Some critical questions to address:

How do we extract size scaling (\(\rho^*\)) 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