Physics of the H-Mode Pedestal and the EPED Model

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Outline: Pedestal Physics Key to Predicting and Optimizing ITER

- The Pedestal: What it is and why it matters
  - Simultaneous improvement of confinement and stability
  - Predictive capability enables fusion power optimization

- Physics challenges
  - Overlap of scales, challenge to methods ($L \sim \lambda \sim \rho$)

- Peeling-ballooning modes
  - Global constraint on the pedestal, drive ELMs

- The EPED model
  - Kinetic ballooning modes and model derivation
  - Experimental tests on several tokamaks, statistics
  - Super H-Mode
  - Dynamics and ELM suppression

- Coupled core-pedestal prediction

- Directions for future pedestal research
High Performance achieved via the Edge Transport Barrier

• Stiff transport implies approximately fixed gradient scale length in core
  – 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
- Analogous to lifting a statue (core) onto a pedestal, but better, because statue gets higher proportional to pedestal
Pedestal Key to Fusion Performance because it Strongly Improves both Confinement and Stability

- Raising pedestal pressure dramatically improves global confinement
  - Core transport due primarily to gradient scale length driven microturbulence (ITG, TEM, ETG…)
  - Roughly fixes the pressure gradient scale length ($L_p$) in the core plasma, resulting in $p_{\text{global}} \sim 3 \pm 1 \!\!p_{\text{ped}}$ [“stiff transport”]
  - Higher $p_{\text{ped}}$ -> high $p_{\text{global}}$ -> higher $P_{\text{fus}} \sim p_{\text{global}}^2$
  - This behavior is both predicted by gyrokinetic simulations and broadly observed in expt

Image of graph showing the relationship between $\beta_{\text{pol}}$ and $\beta_{\text{thermal}}$. The graph includes data points from different experiments and simulations, with a trend line indicating a correlation.$\beta_{\text{pol}}$ thermal = $2 \times$ electrons

PB Snyder/ITER School/Dec 2015
Pedestal Key to Fusion Performance because it Strongly Improves both Confinement and Stability

- Raising pedestal pressure dramatically improves global confinement
- However, benefits of high confinement can’t be realized without high stability boundaries (and vise versa)
- Global MHD instabilities are driven by gradients \((p', j')\). Moving gradients as far out as possible (pedestal) maximizes resulting stable pressure (sometimes referred to as profile broadness effect)
  - Also increases wall stabilization effect

Because the pedestal increases both confinement and stability it increases both potential and realizable fusion performance
Motivation: Pedestal Height Critical for ITER Performance Prediction and Optimization

- High performance ("H-mode") operation in tokamaks due to spontaneous formation of an edge barrier or "pedestal"
- Pedestal height has an enormous impact on fusion performance
  - Dramatically improves both global confinement and stability (observed and predicted)
  - Fusion power on ITER predicted to scale with square of the pedestal pressure [Kinsey, NF11]
- Accurate prediction of the pedestal height is essential to assess and optimize ITER performance, and to optimize the tokamak concept for energy production. Optimization must be done with tolerable or controlled ELMs.

Observed Impact of Pedestal Height

Predicted Impact of ITER Pedestal Height
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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 Existing Paradigms

- Our field traditionally divided into stability ($L \sim \lambda << \rho$), transport ($L << \lambda \sim \rho$) 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)
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 $\delta f$

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
Electromagnetic Fluctuations are Important even though (especially where) $\beta$ is small

$$\psi = \beta_i \frac{\omega(\omega - \omega_{*pi})k^2_\perp - 2\omega_d(\omega - \omega_{*pi})}{2k^2_\perp k^2_\parallel - \beta_i 2\omega_d(\omega - \omega_{*pe})} \phi.$$  \hspace{1cm} (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 $\beta_i \omega^2 / 2k^2_\parallel \ll 1$, or $\omega^2 \ll k^2_\parallel / \beta_i$. In unnormalized units this is $\omega^2 \ll k^2_\parallel v_A^2$, 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 $\beta_i \omega_d \omega_{*}(1+\eta_i) / k^2_\perp k^2_\parallel \ll 1$. In the local limit, $\omega_\ast = k_\theta$, $\omega_d = \epsilon_n \omega_\ast$, $k_\perp \sim k_\theta$, and $k_\parallel \sim \epsilon_n / q$, 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 ($\beta_{ic}$), the requirement becomes $\beta_i \ll \beta_{ic}$.

- Derive relationship between magnetic ($\psi$) and electrostatic ($\phi$) potential from GK or GF eqns in simple limit
- Electrostatic limit requires (at least) that: (a) $\beta$ is small, (b) frequency small compared to shear Alfvén frequency, (c) $p'$ far from ideal ballooning limit ($\alpha << 1$ 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)
Traditional Transport Theory Requires a Separation of Scales

- Fluctuation scale = $\lambda$
- Equilibrium scale = $L$ (e.g., pressure gradient scale $L_p$)
- Microscopic scale = $\rho$ (toroidal or poloidal gyroradius)

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

  - Leading order: gyrokinetic and neoclassical fluxes
  - Next order: evolution of equilibrium ($L >> \lambda \sim \rho$)

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

In the pedestal, fluctuation scale overlaps equilibrium and micro scales ($L \sim \lambda \sim \rho$), 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 $L >> \lambda$ approximation can lead to arbitrarily large errors for ion scale modes)
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  – Global constraint on the pedestal, drive ELMs

• The EPED model
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• Directions for future pedestal research
The Peeling-Ballooning Model Explains ELM Onset and Pedestal Height Constraint

Pedestal is constrained, and ("Type I") ELMs triggered by intermediate wavelength (n~3-30) MHD instabilities
- Driven by sharp pressure gradient and bootstrap current in the edge barrier (pedestal)
- Complex dependencies on υ*, shape etc., extensively tested against experiment

The P-B constraint is fundamentally non-local (effectively global on the scale of the barrier)
- Can calculate P-B constraint predictively using sets of model equilibria \( \beta_{N\text{ped}} = f(\Delta_\psi) \)
- P-B limit increases with pedestal width (\( \Delta_\psi \)), but not linearly (roughly \( \beta_{N\text{ped}} \sim \Delta_\psi^{3/4} \))

ELITE code, based on extension of ballooning theory to higher order, allows efficient and accurate computation of the intermediate n peeling-ballooning stability boundary

ELITE Code Efficiently Calculates Peeling-Ballooning Stability

- ELITE implements high order, non-local peeling-ballooning (MHD) theory
- Plasma displacement, $X$, expanded in poloidal Fourier harmonics:
  \[ X = \sum_{m=m_{\text{min}}}^{m=m_{\text{max}}} u_m(x) e^{-im\omega} \]
- Makes use of fact that each $u_m(x)$ is localized about its own mode rational surface where $m=nmq \Rightarrow$ fast and efficient code
- Study coupled peeling/ballooning modes and quantitative constraints on edge gradients and pedestal height. Growth rates and mode structures generated
- High-n ballooning theory reproduced, but quantitatively valid only at very high n, well above FLR cutoff (due to non-locality)
Observed ELM Similar to Predicted Peeling-Ballooning Structure

- Use reconstructed equilibrium just before fast camera image of ELM
  - Most unstable mode n~18
- **Nonlinear simulations** *(eg Snyder ’05, Brennan ’07, recent BOUT++, NIMROD, JOREK, M3D work)* find qualitative agreement in filamentary structure, wavelength, radial propagation
  - Filaments were predicted by simulation and theory before fast camera images

Fast CIII Image, DIII-D 119449  
M. Fenstermacher, DIII-D/LLNL

ELITE, n=18

Peeling-Ballooning Model Extensively Validated Against Observation

• High resolution measurements allow accurate reconstructions and stringent tests of P-B pedestal constraint & ELM onset condition

• Pedestal constraint and ELM onset found to correlate to P-B stability boundary [Multiple machines, >200 cases studied, ratio of $1.05 \pm 0.19$ in 39 discharges]

• Model equilibrium technique used to apply P-B stability constraint predictively

*Can accurately quantify stability constraint [height=f(width)], but need second constraint for fully predictive model of pedestal height and width*
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• **The EPED model**
  – *Kinetic ballooning modes and model derivation*
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• **Coupled core-pedestal prediction**

• **Directions for future pedestal research**
EPED Goal: Cut Through Complexity of Pedestal, Generate Predictive Model to Test and Improve

Paradigm: ETB formation starts near separatrix and propagates inward primarily due to diamagnetic $E_r$

Schematically divide instabilities that impact transport & stability in the pedestal into 2 categories:
A. “Global” modes: extend across edge barrier including significant impact at top
B. “Nearly-local” modes within the edge barrier

Key distinction is between modes that can stop the inward propagation of the ETB (A), and those which only impact gradients within the ETB (B)

Can have similar modes playing both roles
Focus on “high performance” (Type I and QH) H-modes. Allow pedestal density as input, predict pedestal pressure (or equivalently average T), and a single metric of pedestal width

A. “Global” modes: intermediate-n (n~3-30) peeling-ballooning

B. “Nearly-local” modes: KBM, ETG, ITG/TEM, μ T?,…

Make further conjecture that KBM provides the final constraint on the pressure gradient. [ETG constrains $\eta_e$ not $p'$, ITG/TEM weakened by $E_r$ shear, ITG stabilized by $\beta'$]

KBM and P-B together can then provide 2 “equations” for the two unknowns, pedestal height and width

- Numerous complexities: Bootstrap current key (brings in separate T and n dependence), KBM can’t generally be treated as local
- Ongoing development includes multiple impurities, additional transport mechanisms, and fully global KBM calculations (requires strongly nonlocal kinetics)
KBM Constrains Pedestal $p'$ Near Ideal Ballooning

\[ \alpha_{\text{crit}} \sim \frac{d}{d\psi} \frac{\beta_p}{\psi_N} \]

- **Kinetic Ballooning Mode (KBM) is a pressure gradient driven mode**
  - Qualitatively similar to ideal ballooning mode
  - Kinetic effects essential for linear mode spectrum and nonlinear dynamics

- **Linear studies and electromagnetic KBM turbulence simulations find:**
  [Rewoldt87, Hong89, Snyder99, Scott01, Jenko01, Candy05…]
  - Abrupt linear onset, quickly overcomes ExB shearing rate, large QL transport
    - Linear onset near ideal ballooning critical gradient due to offsetting kinetic effects
    - EMGK calcs in edge geometry match expected onset (Dickinson, Wang)
KBM Constrains Pedestal $p'$ Near Ideal Ballooning $\alpha_{\text{crit}} \sim d\beta_p / d\psi_N$

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    - EMGK calcs in edge geometry match expected onset (Dickinson, Wang)
  - Nonlinear: very large fluxes and short correlation times (highly stiff)
    - Flux will match source at gradient near critical

- **Simple model of the KBM can be quantitatively accurate**
  - Stiff onset near MHD ballooning criticality
  - Use model equilibria to “integrate” local constraint

![Cartoon of typical gyrokinetic growth rate vs \(\beta\)](image)

![Kinetic Ballooning Mode, \(\beta=1\%\)](image)
KBM Critical Gradient \((\alpha_{\text{crit}} \sim d\beta_p/d\psi_N)\) Increases Moving Inward

- If KBM critical gradient were independent of radius, integrating it across the pedestal would yield
  \[ \Delta_{\psi_N} \propto \beta_{p,\text{ped}}^{1/2} \]
  - Width in normalized poloidal flux increasing linearly poloidal beta at the pedestal

- However, \(\nu^*\) 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: \[ \beta_{p,\text{ped}} / \Delta_{\psi_N} \propto \Delta_{\psi_N} \]

\[ \Delta_{\psi_N} = \beta_{p,\text{ped}}^{1/2} G(\nu^*,\varepsilon...) \] where \(G \sim 0.07-0.09\) is weakly varying (fixed \(G=0.076\) in EPED1)
Mechanics of the EPED Predictive Model

- **Input:** $B_t$, $I_p$, $R$, $\alpha$, $\kappa$, $\delta$, $n_{\text{ped}}$, $m_i$, $[\beta_{\text{global}}, Z_{\text{eff}}]$
- **Output:** Pedestal height and width *(no free or fit parameters)*

A. P-B stability calculated via a series of model equilibria with increasing pedestal height
   - ELITE, $n=5-30$; non-local diamag model from BOUT++ calculations

![Illustration of EPED Model, DIII-D 132010](diagram)

*P.B. Snyder et al Phys Plas 16 056118 (2009), NF 51 103016 (2011)*
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B. KBM Onset: $\Delta_{\psi_N} = \beta_{p,ped}^{1/2} G(\nu_*, \epsilon ...)$
   - Directly calculate with ballooning critical pedestal technique

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

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**Illustration of EPED Model, DIII-D 132010**

- Peeling-Ballooning Constraint (A)
- KBM Constraint (B)
- EPED Prediction

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- 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 unique 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

- Illustration of EPED Model, DIII-D 132010

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Highly Detailed Tests of EPED Enabled by new High-Res Thomson on DIII-D

DIII-D: $I_p$ varied by a factor of 3 (0.5, 1, 1.5MA)

- $B_t=2.1T$, $\kappa=1.74$, $\delta=0.3$
- “Global” P-B stability increases roughly linearly with $I_p$
- $\beta_N$-like, dependence weakens as $q$ gets low

![EPED1 Model, DIII-D Current Scan (0.5, 1, 1.5MA)](image)
Interaction of P-B and KBM Constraints Predicts Pedestal Height and Width Changes in $I_p$ Scan

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KBM increases with $\sim I_p^2$

Interaction of P-B and KBM leads to height that first rises strongly then stagnates, while width decreases with $I_p$
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**KBM increases with $\sim I_p^2$**

Interaction of P-B and KBM leads to height that first rises strongly then stagnates, while width decreases with $I_p$

- Good agreement with observations at all $I_p$ values
DIII-D Upgrade to Thomson System Allows More Precise Height & Width Comparison to Model

Major Thomson upgrade ~doubles resolution
Dedicated expts to vary pedestal height and width ($I_p$ scan) and compare to models
EPED1 model compared to measured height and width using both pre-expt predictions and post-experiment analysis. Wide range of widths and heights achieved.

Good agreement with EPED1 model (24 cases, 14 shots):
- Ratio of predicted to observed pedestal height: $0.98 \pm 0.15$, corr $r=0.96$
- Ratio of predicted to observed pedestal width: $0.94 \pm 0.13$, corr $r=0.91$
- Ratio of predicted to observed pedestal average $p_{\text{prime}}$: $1.05 \pm 0.16$, corr $r=0.95$
EPED can be Applied to Quiescent H-Mode Discharges

- P-B studies find that EHO is associated with current driven kink/peeling mode, allows prediction of critical density for QH at a given width
- EPED model predicts QH mode pedestal height and width with similar accuracy as ELMing cases (~20%, corr \( r=0.9 \))
  - Very high pedestals can be maintained in QH mode operation with no ELMs
- Gives confidence in prediction that ITER will operate in QH density range. Still quantifying rotation requirements
Numerous Experimental Tests of EPED Conducted: Moving to Systematic Uncertainty Quantification

Validation efforts coordinated with ITPA pedestal group, US JRT
- >700 Cases on 5 tokamaks
- Broad range of density (~1-24 $10^{19} \text{m}^{-3}$), collisionality (~0.01-4), $f_{GW, \text{ped}}$ (~0.1-1.0), shape ($\delta$ ~0.05-0.65), $q$~2.8-15, pressure (1.7 - 35 kPa), $\beta_N$~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)

\[
\bar{f}(\bar{x}) - \bar{y} = f(x + \varepsilon_x) + \varepsilon_f - y - \varepsilon_y \approx f(x) - y + (\bar{s}\varepsilon_x + \varepsilon_f - \varepsilon_y)
\]
ITER Predictions Within Range of Database in terms of Normalized Parameters

Comparison of EPED Model to 296 Cases on 5 Tokamaks

- Existing studies cover 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, $\beta_N$~0.6-4, $B_t$=0.7-8T etc

- Predicted ITER pressure is ~3x beyond existing machines, however predicted $\beta_{N,ped}$, $\beta_{ped}$, normalized width, collisionality, $q$, $a/R$, $f_{GW}$, $\delta$, $\kappa$ within studied range (as are density, $B_t$, but not $\rho$*)

*Note: $\rho$* is most likely a typo and should be $\rho$.
225 case DIII-D study finds agreement with observation to $\sigma \sim 22\%$, avg error=1.7 kPa, $<|p_E - p_{exp}|>/<p_{exp}> = 17\%$, correlation coefficient=0.87

Monte Carlo analysis (using a single Gaussian error to simulate combined expt and parameter uncertainty) finds:
- With perfect measurements, model $\sigma = 22\%$ (algorithmic+structural)
- With $\sigma = 15\%$ for measurements, model $\sigma = 16\%$, (algorithmic+structural)
- With $\sigma = 22\%$ for measurements, model is perfect (limit on measurement uncertainty)

Level of agreement not strongly dependent on $\nu^*$, shape, etc
Large Scale Studies Quantifying EPED uncertainties and accuracy: DIII-D, JET, C-Mod

- 710 case study finds agreement with observation to $\sigma \sim 21\%$, avg error = 1.68 kPa, $<|p_E - p_{\text{exp}}|>/<p_{\text{exp}}>$ = 16%, correlation coefficient = 0.87

- Monte Carlo analysis (using 1 Gaussian error to simulate combined expt and parameter uncertainty) finds:
  - With perfect measurements, model $\sigma$ = 21% (algorithmic + structural)
  - With $\sigma$ = 15% for measurements, model $\sigma$ = 15%, (algorithmic + structural)
  - With $\sigma$ = 21% for measurements, model is perfect (limit on measurement uncertainty)
Similar Level of EPED Accuracy with Metal or Carbon Wall

- Metal: average error = 1.46 (14%), correl = 0.90, $\sigma = 0.19$
- Carbon: average error = 1.88 (18%), correl = 0.85, $\sigma = 0.22$
- 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
- Working to identify any clear dependencies in EPED accuracy
  - help identify where additional physics needed
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Density (Collisionality) is a Powerful Lever for Pedestal Optimization of Shaped Plasmas

- **Density enters primarily through collisionality dependence of bootstrap current**
  - Increasing density moves from J-driven toward p-driven stability boundary
  - Low density (low $\nu_*$): $P_{ped}$ increases with $n_e$; high $\nu_*$: $P_{ped}$ decreases with $n_e$
  - Density dependence weak for weak shapes, stronger at high triangularity

- **Strongly shaped plasmas have a pronounced optimum in density corresponding to the nose of the stability diagram**
  - High performance regimes typically operate near this optimum
Complex Interaction Between Shape and Density Dependence

• At very low triangularity (weak shaping, $\delta = 0$), density dependence is weak
  – Peeling-ballooning coupling strong, no “nose” in J-P diagram (left)
Complex Interaction Between Shape and Density Dependence

- At modest triangularity ($\delta = 0.2$), pedestal height increases, then decreases with density
  - Peeling-ballooning coupling weakens, “nose” in J-P diagram (blue)
Complex Interaction Between Shape and Density Dependence

- At high triangularity ($\delta = 0.5$), pedestal height solution becomes *multi-valued* at high density
  - Peeling-ballooning coupling very weak, “nose” in J-P diagram extends to very high pressure. Effect amplified by KBM, resulting in multiple solutions
At High Density and Strong Shaping, Solution Splits into H-Mode and Super H

- Constant density trajectories lead to usual H-Mode solution
- Solution above H-mode (red) called Super H-Mode
  - Much higher pedestal than equivalent H-Mode solution
  - Intermediate solution (yellow) is dynamically unstable
At High Density and Strong Shaping, Solution Splits into H-Mode and Super H

- Super H-Mode Regime can be reached by dynamic optimization of the density trajectory
  - Start at low density, and increase density over time (red arrow). Avoiding large transients (ELMs) enables smooth traversal of parameter space
  - Very high Super H-Mode pedestal should enable both high confinement and higher beta limit (broader profiles), leading to high fusion performance
Super-H Mode Regime Accessed on DIII-D

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

See also:
P.B. Snyder NF 55 083026 (2015),
W. Solomon PPC/P2-37, PRL 113 135001 (2014)
Predicted Super H-Mode Regime Should Enable further ITER Optimization

- 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 $\text{density} \times Z_{eff}^{1/2}$
    - 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)

See also:
P.B. Snyder NF 55 083026 (2015), W. Solomon PPC/P2-37, PRL 113 135001 (2014)
Outline: Pedestal Physics Key to Predicting and Optimizing ITER

- **The Pedestal: What it is and why it matters**
  - Simultaneous improvement of confinement and stability
  - Predictive capability enables fusion power optimization

- **Physics challenges**
  - Overlap of scales, challenge to methods ($L \sim \lambda \sim \rho$)

- **Peeling-ballooning modes**
  - Global constraint on the pedestal, drive ELMs

- **The EPED model**
  - Kinetic ballooning modes and model derivation
  - Experimental tests on several tokamaks, statistics
  - Super H-Mode (when 2 eqns have >1 solution)
    - *Dynamics and ELM suppression*

- **Coupled core-pedestal prediction**

- **Directions for future pedestal research**
Applying the EPED Model to Develop a Working Model for RMP ELM Suppression

• When ELMs are suppressed by applied 3D fields (Resonant Magnetic Perturbations or RMPs), the discharges are found to hover in the stable region of the peeling-ballooning stability diagram. **WHY? HOW?**
  - Conditions only slightly different between “resonant” ELM suppression, and off-resonant discharges with ELMs (density and gradients similar)

• Can we understand this in terms of the EPED model?
The EPED Model and the ELM Cycle: Understanding Dynamics

EPED is a static model for the pedestal structure, but can be used to interpret dynamics

- Pedestal broadens with time at roughly fixed $p'$ near KBM criticality
- The ELM is triggered by a “global” peeling-ballooning mode (solid blue line), typically followed by a crash, and recovery (with KBM)  [other types of cycle also possible]
- This cycle can be directly measured for low frequency, large ELMs, as in DIII-D 144977 above (single ELM cycle)
The EPED Model and the ELM Cycle: How can (or can’t) ELMs be suppressed?

Reducing the pressure gradient below the initial KBM limit does **NOT**, by itself, prevent the ELM

- **Recovery part of cycle continues to P-B instability, unless it is stopped**
A “Wall” Can Stop the ELM → RMP q windows

- Inserting a “wall” that blocks the expansion of the pedestal can stop the recovery and prevent the next ELM
- In RMP ELM suppression, this “wall” can be a resonant island or stochastic region that drives strong transport and prevents inward pedestal broadening
- Wall location must be precise: too far in will not stop the ELM, too far out will be shielded by very large $\omega_{\perp e}$ in the pedestal (2-fluid response) [15-17]
- Location of “wall” determined by q profile → q windows for ELM suppression
EPED-based Working Model for ELM Suppression Agrees with Observed $q_{95}$ Windows

ELM suppression or mitigation occurs in multiple $q$ windows

- DIII-D 145830, $I_p$ ramp, 2 windows of suppression, 1 sparse (blue)

EPED predicts width of 0.03

- With gradient constrained by KBM, ELM (P-B mode) will be triggered when width exceeds 0.03

- To suppress ELMs, must place the outer edge of the “wall” outside of 0.97
  - Islands can’t penetrate the sharp gradient region: can’t place “wall” any further out than ~0.98

- Predicts 3 windows corresponding to when 12/3, 11/3 and 10/3 islands pass through the proper location (red)
  - Good agreement with observations
EPED-based Working Model for RMP ELM Suppression Agrees with Observed Profile Changes

- If “wall” blocking inward propagation of edge barrier, should be observable in measured profiles (New high-res Thomson system can resolve small changes)

- In ELM suppressed cases, pedestal width is indeed constrained
  - Critical width for suppression is <~3%, in agreement with EPED
  - Pressure gradient inside barrier changes little, as expected from EPED
  - Similar phenomena in pellet-pacing cases
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• Coupled core-pedestal prediction
• Directions for future pedestal research
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 \textasciitilde 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 \textasciitilde 1.5 minutes using ~700 cores. Large dataset run in \textasciitilde 1 hour on 3600 cores (could use \textasciitilde 150,000 cores to get the job done in \textasciitilde 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

```
Core-pedestal transport modeling

OMFIT

<table>
<thead>
<tr>
<th>Core profiles</th>
<th>Turbulent transport</th>
<th>Neoclassical transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGYRO</td>
<td>TGLF</td>
<td>NEO</td>
</tr>
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<table>
<thead>
<tr>
<th>Pedestal structure</th>
<th>Model equilibria</th>
<th>Peeling-ballooning</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPS (EPED1)</td>
<td>TOQ w/ KBM constraint</td>
<td>MHD stability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ELITE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current evolution and sources</th>
<th>Closed boundary equilibrium</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONETWO (or TRANSP)</td>
<td>EFIT</td>
</tr>
</tbody>
</table>
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![Graph showing temperature profiles](image-url)
Initial example is EPED/TGLF/NEO and Core-Pedestal Integrated Modeling: DIII-D ITER-similar discharge 153523

- No measurements of $T_e$, $T_i$ or pressure input
- Density only input at pedestal
  - Inputs: shape, sources, rot., $B_t$, $I_p$, $n_{e,ped}$
  - Predicting $T_e$, $T_i$, $n_{e,core}$, $\beta_N$, ($P_{fus}$)
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- Step 1: Run EPED
  - Don’t yet know $\beta_N$ so use (poor) initial guess
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- **Step 3: Run EPED using updated value for $\beta_N$**
- **Step 4: Run TGYRO using updated BC from EPED**
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- Step 2: Run TGYRO using BC from EPED to predict profiles and $\beta_N$
- Step 3: Run EPED using updated value for $\beta_N$
- Step 4: Run TGYRO using updated BC from EPED
- Iterate to convergence
  - Have predicted profiles for $T_e$, $T_i$, $n_e$ and pressure/$\beta_N$
  - Result independent of initial guess
Initial example is EPED/TGLF/NEO and Core-Pedestal Integrated Modeling: DIII-D ITER-similar discharge 153523

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  - Inputs: shape, sources, rot., $B_t$, $I_p$, $n_{e,ped}$
  - Predicting $T_e$, $T_i$, $n_{e,core}$, $\beta_N$
- Accurately predicts full $T_i$ and $T_e$ profile, core density profile and global beta in this case
  - Core-pedestal coupling essential to achieve this
- Similar workflow can be applied to ITER or 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
Couple Core-Pedestal Workflow can be used to Predict and Optimize ITER Performance

- New TGLF improves treatment of coupling of electron and ion scale turbulence, and nonlinear near-critical physics for ITER [Staebler]
- Iterated coupling of EPED w/ TGLF/NEO enables ITER optimization with respect to pedestal density and current etc. Preliminary density scan

Step 0: “low” density case
Couple Core-Pedestal Workflow can be used to Predict and Optimize ITER Performance

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Final step: “low” density case
Couple Core-Pedestal Workflow can be used to Predict and Optimize ITER Performance

- New TGLF improves treatment of coupling of electron and ion scale turbulence, and nonlinear near-critical physics for ITER [Staebler, APS15]
- Iterated coupling of EPED w/ TGLF/NEO enables ITER optimization with respect to pedestal density and current etc. Preliminary density scan (old TGLF)

Final step: density scan (preliminary)
Fusion power highest at highest density
- Kink/peeling limited pedestal
- At entrance to Super H-Mode
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Many Important Questions for Future Investigation

• Formalism for overlapping scales ($L \sim \lambda \sim \rho$)
  – 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 (more from R. Maingi tomorrow)
  – 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
Is there additional physics that enters at the very small values of $\rho^*$ expected in ITER or a reactor?

- **Absence of strong $\rho^*$ scaling predicted by EPED and observed in today's expts**
  - Both dimensionless expts [Beurskens09] or large database normalized to KBM scaling, show ~no dependence on $\rho^*$

- **Diamagnetic ExB shear stabilization ($\sim p''$) may weaken relative to microinstability growth rates ($\sim \rho^*$)**
  - Becomes independent of $\rho^*$ if transition scale also scales with $\rho^*$
  - Also must maintain high gradients within ETB (low s, high $\beta'$ sufficient?)
Predicting the pedestal is essential for tokamak performance optimization. Presents challenges to traditional theory.

EPED model combines non-local Peeling-Ballooning and near-local KBM physics

- No free parameters, extensive tests on several tokamaks (σ ~0.21, 710 cases)

Platform to predict and optimize pedestal, including core coupling

- Strong dependence on $B_p$, $B_t$, shape, complex dependence on density ($\nu^*$)
- New Super H-mode regime predicted and accessed via dynamic optimization
- Working model for RMP ELM suppression developing (more tomorrow)
- Coupling to TGLF/NEO in core via AToM project enables core-pedestal prediction
  - Pedestal benefits from global Shafranov shift, core from high pedestal (iterate to self-consistent solution)
  - Initial ITER predictions for coupled system, work ongoing to fully optimize & exploit Super H

Many important open/related questions:
- Efficient formalism & numerics for $L \sim \lambda \sim \rho$ (6D, extended GK or GF…)
- Role of impurities and fuelling (neutrals?), prediction of pedestal density & rotation
- $\rho^*$: observed lack of strong dependence consistent with EPED. Limits?
- Connection to SOL and divertor, transient dynamics
- As understanding improves, continue to use it to enable new discoveries
Extra Slides
References (not up to date)

Super H-Mode Access in C-Mod may be possible at lower density

- Calculated based on ELMing H-mode shot with $I_p = 0.908 \text{MA}$, $B_t = 5.39 \text{T}$, $\kappa = 1.54$, $\delta = 0.49$
- Variations of $I_p$ and shape should improve access. Even approaching SH conditions would represent large in $P_{\text{ped}}$
- Consider starting in ELMing H-mode ramp up $I_p$ and triangularity with time
Peeling-Ballooning Theory Derived as an Extension of Ballooning Theory

- Ballooning theory developed in late 1970’s (Culham, PPPL)
  - Expansion in 1/n yields 2nd order ODE, 1D eigenvalue eqn, internal

- H-Mode and ELMs discovered on ASDEX in early 80’s

- High and low n MHD considered as mechanism for ELMs
  [eg Manickam ’92, Turnbull ’86, Ferron ’00]

- Edge ballooning theory allows external current-driven modes [CHTWMH ’96, ’98]
  - Local, external, pure peeling modes
  - Importance of peeling-ballooning coupling

- Extension to next order in 1/n allows quantitative study of edge localized modes [WS ’02, SW ’02]
  - 2D nonlocal, but eliminates 1 component of displacement
  - Coupled p’ and j’ driven modes (still use ‘peeling’ terminology)
  - Extended to include flow shear and compression [SW ’07]
Stability Studies Using Model Equilibria Useful for Predictions in Present and Future Devices

For predictions it is useful to conduct pedestal stability analysis on series of model equilibria

- Simplified shape and profiles, with tanh pedestal and Sauter bootstrap current
- Predict pedestal height as a function of \((\Delta, B_t, I_p, R, \alpha, \kappa, \delta, n_{e,ped}, \beta_p)\)
- Calculations using pedestal width \((\Delta)\) as an input find good agreement with observation (model equilibria capturing important stability physics) \([\text{Snyder04}]\)

Can accurately quantify stability constraint \([\text{height}=f(\text{width})]\), but need second constraint for fully predictive model of pedestal height and width