Theory and Modeling of ELMs and Constraints on the H-Mode Pedestal

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Both theory and experiment indicate a strong dependence of core confinement, and therefore Q on the pedestal height \( (p_{\text{ped}}, T_{\text{ped}}) \).

ELM characteristics strongly impact divertor and wall heat load constraints (large Type I ELMs may not be tolerable in Burning Plasma devices).

Goal is predictive understanding of physics controlling pedestal height and ELM characteristics ⇒ combination of high pedestal and tolerable ELMs.
Pedestal Stability Studies Including Current Lead to New Understanding of ELMs and Pedestal Physics

- Important role of current, as well as pressure, in pedestal MHD stability
- Peeling-ballooning mode stability leads to model of ELMs and pedestal constraints
  - Efficient tool (ELITE) calculates quantitative pedestal stability limits and mode structures

- Model Verified Against Experiment in Two Ways
  - Direct comparisons to experiment
  - Use of model equilibria to assess pedestal limits in current and future devices

- Summary and Future Work

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UKAEA Fusion

DIII-D

GENERAL ATOMICS
Peeling-Ballooning Stability Picture

- Two Principal MHD Instabilities in the Pedestal
  - Ballooning Modes (pressure driven)
  - External Kink or “Peeling Modes” (current driven)

- Bootstrap Current Plays a Complex Role
  - Drives Peeling Modes
  - Opens 2nd stability access to ballooning modes
Two Principal MHD Instabilities in the Pedestal
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Peeling and Ballooning modes couple at finite \( n \)

Intermediate wavelength coupled peeling-ballooning mode often most unstable
- High \( n \)’s second stable or FLR stabilized, low \( n \)’s stabilized by line bending
- High-\( n \) ballooning alone not sufficient

Quantitative stability limits depend sensitively on plasma shape, collisionality, pedestal width, \( q \), etc., and must be tested at multiple wavelengths
- Need an efficient tool
ELITE is a 2D eigenvalue code, based on ideal MHD (amenable to extensions):

- Generalization of ballooning theory:
  1) incorporate surface terms which drive peeling modes
  2) retain first two orders in $1/n$ (treats intermediate $n>\sim5$)

- Makes use of poloidal harmonic localization for efficiency
- Successfully benchmarked against GATO and MISHKA

[H.R. Wilson, P.B. Snyder et al Phys Plas 9 1277 (2002); P.B. Snyder, H.R. Wilson et al Phys Plas 9 2037 (2002).]
ELITE allows quantitative prediction of ELMs, pedestal constraints

- DIII-D model equilibria, self-consistent collisionless bootstrap current. Nominal (zero current) $n \rightarrow \infty$ ballooning limit of $p'=3.1$, exceeded in expt by factors of 2-3, in agreement with calculated $n=10$ limit.

- Demonstrates existence of “second stability” in shaped nonlocal equilibria.

- Good agreement between GATO and ELITE in region of overlap ($4<n<10$).

- Modify current by varying $c_{\text{boot}}$ ($J_{\text{boot}}=c_{\text{boot}} \cdot J_{\text{hirshman}}$): Trends in $p'$ limit and predicted limiting $n$ and ELM size with $J_{\text{ped}}$ agree with observations.
Different n’s and Mode Structures Predicted in Different Regimes

- **Series of JET-like equilibria with self-consistent $J_{bs}$, high $n$ 2nd access**
- **Edge stability limits scanned with ELITE (6<n<30)**
- **Range of unstable n**
- **$n$~6-8 unstable**
- **Higher n modes unstable**

- **$n=13$ peeling**
  - Small ELMS
- **$n=8$, coupled peeling-balloonning mode**
  - Large ELMS

- **$n=6$ marginal**

- **$\beta_N \propto p'_{ped}$**

- **$J_{edge}$**

- **$\psi$**
Peeling-ballooning modes provide a constraint on the edge temperature pedestal, as well as $\beta$

Edge current density increases with edge temperature (Ohmic+collisional bootstrap)

Can consider stability diagram in $\beta_N$-$T_{ped}$ space

MHD stability explicitly limits steady state $T_{ped}$, (for a given width)

Higher triangularity decouples peeling and ballooning modes, allows higher temperature pedestal

$\delta=0.3$  \hspace{1cm} $\kappa=1.6$, $A=3$, $R=3m$  \hspace{1cm} $\delta=0.5$

Stable

\[ \beta_N \sim p'_{ped} \]

\[ \delta = 0.3 \]

\[ \beta_N \sim p'_{ped} \]

\[ \delta = 0.5 \]
Different Types of ELM Cycles can be Envisioned

- ELMs triggered by peeling-ballooning modes, ELM size correlates to depth of most unstable mode and to location in parameter space
- Pressure rises up on transport time scale between ELMs, current rises to steady state value more slowly
- Predict changeover in ELM behavior when $J_{\text{ped}} < J_{\text{peel}}$ \Rightarrow strong density and shape dependence
Verification of Peeling-Ballooning Mode Model for ELMs: Case Study in DIII-D

- $n=10$ growth rate attains significant value just before ELM observed
- Predicted radial mode width consistent with ELM affected area
  - Both extend beyond pedestal
- Mode localized on outboard side, consistent with observations in divertor balance experiments
Three DIII-D shots with varying density studied

- In all 3 cases, peeling-ballooning modes are unstable with significant growth rate just before ELM, even though pedestal height is decreasing with density
  - Consistent with peeling-ballooning modes as ELM trigger

- As density increases, most unstable mode moves to shorter wavelengths, and radial width of mode decreases
  - Due to decreasing bootstrap current and narrowing pedestal
  - Expect smaller ELMs at high density, as observed [Leonard KI2.004]
Direct Comparisons Consistent on Multiple Tokamaks

- **Alcator C-Mod**
  - ELM-free and EDA shots are peeling-ballooning stable
  - Peeling-Ballooning modes consistently unstable just before ELMs
  
  [D. Mossessian KI2.005]

- **JT-60U**
  - Peeling ballooning modes unstable before ELM
  - Broader mode structures in “Giant ELM cases”

[See T. Oikawa QP1.063]
Studies of Model Equilibria Useful for Predicting Trends in Present and Future Devices

- Direct experimental comparisons rigorously test the model, but for prediction of pedestal trends it is useful to conduct pedestal stability analysis on series of model equilibria
  - Compare to observed trends on present devices
  - Predict pedestal height as a function of width, shape, etc in future devices

Sample ITER profiles

![Sample ITER profiles](image)

\[ n_e(\psi) = n_{sep} + a_{n0} \left\{ \tanh \left[ 2 \left( 1 - \frac{\psi_{mid}}{\Delta} \right) \right] - \tanh \left[ 2 \left( \psi - \psi_{mid} \right) / \Delta \right] \right\} + a_{n1} \left[ 1 - \left( \frac{\psi}{\psi_{ped}} \right)^{\alpha_1} \right]^{\alpha_2} \]

\[ T(\psi) = T_{sep} + a_{T0} \left\{ \tanh \left[ 2 \left( 1 - \frac{\psi_{mid}}{\Delta} \right) \right] - \tanh \left[ 2 \left( \psi - \psi_{mid} \right) / \Delta \right] \right\} + a_{T1} \left[ 1 - \left( \frac{\psi}{\psi_{ped}} \right)^{\alpha_1} \right]^{\alpha_2} \]

- Model equilibria, match global parameters \((B_t, I_p, R, a, \kappa, \delta, <n_e>)\)
- Current profile aligned to Sauter collisional bootstrap model in the pedestal
- Width \((\Delta)\) is an input: at each \(\Delta\), \(T_{ped}\) is increased until \(n=8-40\) stability bounds are crossed
Trends in Existing Pedestal Database Can Be Understood Using Stability of Model Equilibria

- Trends with density and triangularity calculated using series of model equilibria, and compared to database
  - Inputs are $B_t$, $I_p$, $R$, $a$, $\kappa$, $\delta$, $<n_e>$, $\Delta$

- Strong increase in pedestal height with triangularity is due to opening of second stability access
  - Bootstrap current plays a key role here. Without it (dashed line) second stability is not accessed at high $n$ and strong $\delta$ trend not predicted

- Trends with both density and triangularity accurately reproduced: indicates both that pedestal is MHD limited and that model equilibria are sufficiently accurate (also find agreement on C-mod)
  - encourages use of this method as a predictive tool for future devices
High $n$ modes limiting at narrow widths, go second stable at wider widths

Pedestal height increases with width, but not linearly ($\sim \Delta^{2/3}$)

Reaches adequate pedestal height for predicted high performance in observed range of $\Delta/a$
  
  - Increase height by optimizing $\delta$, $n_e$, including $\omega_*$ effects
  
  - Scaling of pedestal width remains a key uncertainty [Osborne CT-3]
ELM simulated in BOUT has peeling-ballooning structure

- Additional physics effects (e.g., $\omega_s$, sheared rotation) need to be considered
- Nonlinear BOUT code with current used to simulate peeling-ballooning modes
  - Basic picture of instability remains intact
Rotation and non-ideal effects potentially important

- **Diamagnetic stabilization identified by several authors**
  - Rogers and Drake ‘99 found $\omega_*$ effects significantly stabilizing for ballooning modes -> alternative to 2nd stability to explain $\beta > \beta_c$
  - Hastie, Catto, Ramos ‘00 found strong radial variation of $\omega_*$ diminishes its stabilizing impact. Huysmans ‘01 work with Mishka also suggests reduced impact.
  - Can make simple estimates based on [Roberts ‘62]:
    $$ -\gamma^2_{MHD} = \omega \left( \omega - \omega_{*i} \right) $$
  - Expect reduced ELM sizes for $\omega_*/2 > \gamma$
  - Stronger effect on larger $n$
  - Expect delayed appearance or even elimination of large ELMs in some regimes, first mode to appear will be that with largest $\gamma/\omega_*$
  - Simple model implemented in ELITE:

- **Toroidal rotation shear (and $E_r$ effects in general) also potentially significant**
  - Working to include in ELITE
Summary

- Pedestal current plays an important dual role in stability
  - Drives peeling, 2nd access for ballooning
  - Peeling-Ballooning coupling, intermediate $n$’s often limiting mode

- New tools (ELITE) allow efficient stability calculation for experimental equilibria over full relevant spectrum of $n$

- Model of ELMs and constraints on the pedestal developed based on peeling-ballooning
  - Peeling-ballooning modes as ELM trigger, mode structure correlates to ELM depth
  - Quantitative prediction of $p’$, $J$ limits; $T_{ped}$ limits using self-consistent $J_{bs}$
  - Finite $n$ modes sensitive to pedestal width as well as gradient

- ELM model in agreement with experiment
  - Observed ELM onset consistent with model in multiple tokamaks
  - Pedestal and ELM variation with density quantitatively modeled
  - Trends with triangularity and collisionality consistent, projections made for burning plasmas

- Nonlinear simulations of the boundary region in progress, impact of current included
  - Basic picture of instability remains intact
  - Ongoing work: more complete physics picture and dynamical models

- Many open issues: pedestal width, ELM dynamics, connection to SOL & core...