ELMs and Constraints on the H-Mode Pedestal: A Model Based on Peeling-Ballooning Modes

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Pedestal & ELMs Key to Plasma Performance

- 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 $\Rightarrow$ combination of high pedestal and tolerable ELMs
Pedestal Stability Studies Including Current Lead to New Understanding of ELMs and Pedestal Physics

- Peeling-ballooning mode stability leads to model of ELMs and pedestal constraints
  - 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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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
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- Peeling and Ballooning modes couple at finite $n$
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- Peeling and Ballooning modes couple at finite n

- Intermediate wavelength coupled peeling-balloonning 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 Highly Efficient 2D MHD Code for $n>\sim 5$

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 $n>\sim 5$)
- 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).]
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 ($6<n<30$)

$n=13$ peeling
Small ELMS

$n=8$, coupled peeling-ballooning mode
Large ELMS

$n=6$ marginal

Range of unstable $n$

$\beta_N \propto p_{ped}$

Higher $n$ modes unstable
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 $J_{\text{ped}} < J_{\text{peel}}$ ⇒ 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
Observed Variation with Density Consistent with Model

- 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 [see Leonard EX/P3-06]
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

  [See D. Mossessian EX/P5-04 Saturday morning]

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

[See N.Oyama EX/S1-1, Y. Kamada EX/P2-04]
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

- Model equilibria, match global parameters ($B_t$, $I_p$, $R$, $a$, $\kappa$, $\delta$, $\langle n_e \rangle$)
- Current profile aligned to Sauter collisional bootstrap model in the pedestal
- Width ($\Delta$) is an input: at each $\Delta$, $T_{\text{ped}}$ 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 $B_t$, $I_p$, $R$, $a$, $\kappa$, $\delta$, $\langle n_e \rangle$, $\Delta$

- 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
  - Encourages use of this method as a predictive tool for future devices
Prediction of ITER Pedestal Constraints

- 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 (eg $\omega_*$, sheared rotation) need to be considered
- Nonlinear BOUT code with current used to simulate peeling-ballooning modes
  - Basic picture of instability remains intact
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-balloonning**
  - Peeling-balloonning 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
  - Predicted trends with triangularity and collisionality consistent, projections made for burning plasmas, pedestal width remains a key uncertainty

- **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