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

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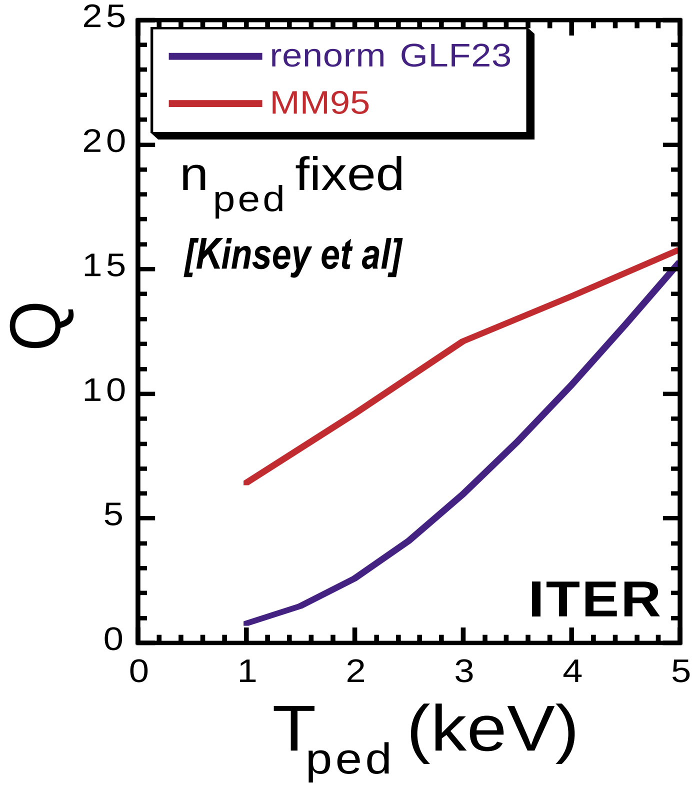
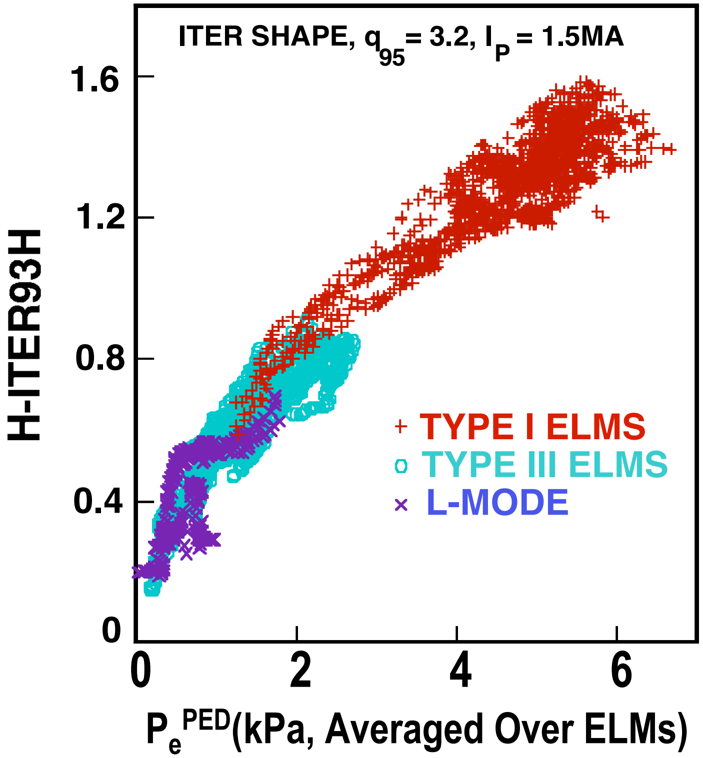
Pedestal & ELMs Key to Plasma Performance

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

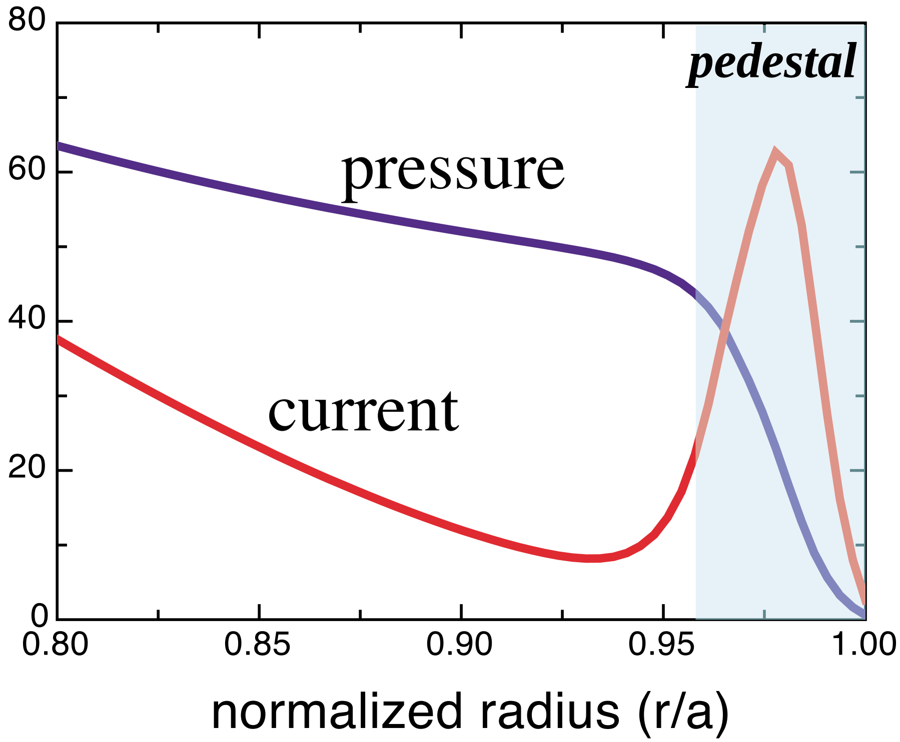




- ELM characteristics strongly impact divertor and wall heat load constraints (large Type I ELMs may not be tolerable in Burning Plasma devices)

➞ 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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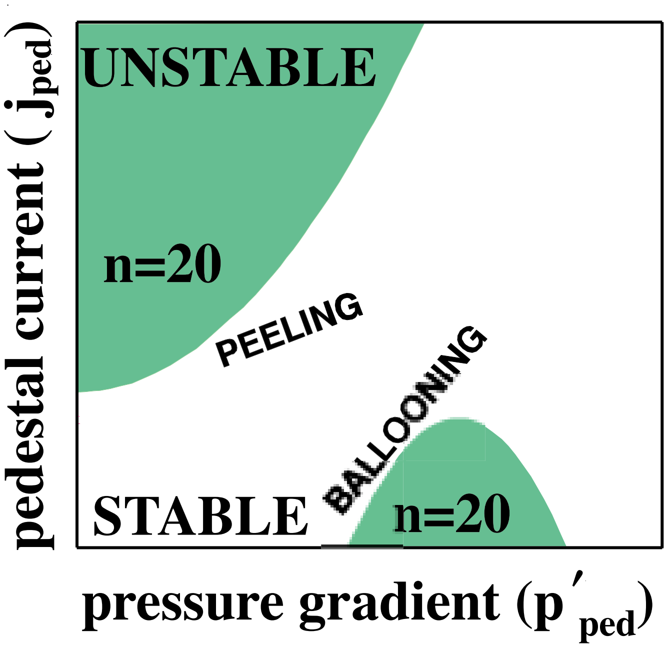
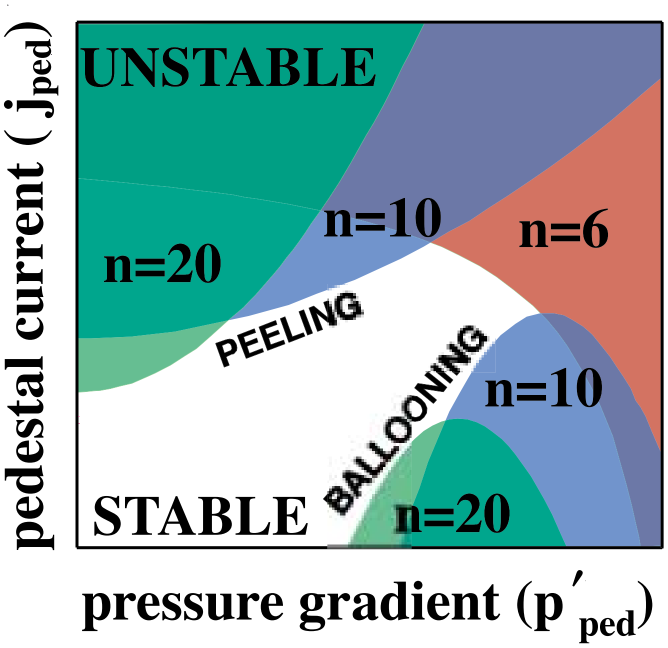
Peeling-Ballooning Stability Picture



- **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

Peeling-Ballooning Stability Picture



- **Two Principal MHD Instabilities in the Pedestal**
  - Ballooning Modes (pressure driven)
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- **Bootstrap Current Plays a Complex Role**
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  - Opens 2nd stability access to ballooning modes
- **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 Highly Efficient 2D MHD Code for n>~5

ELITE is a 2D eigenvalue code, based on ideal MHD (amenable to extensions):

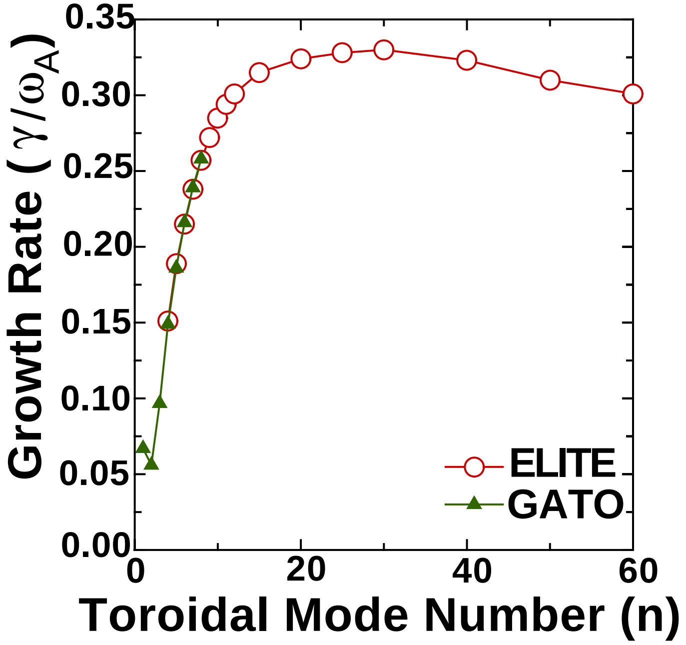
-Generalization of ballooning theory:

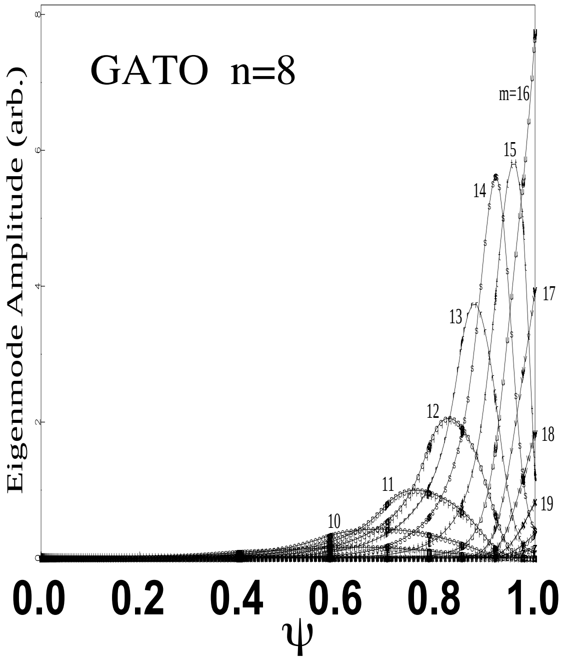
1) incorporate surface terms which drive peeling modes
2) retain first two orders in 1/*n* (treats intermediate *n*>~5)

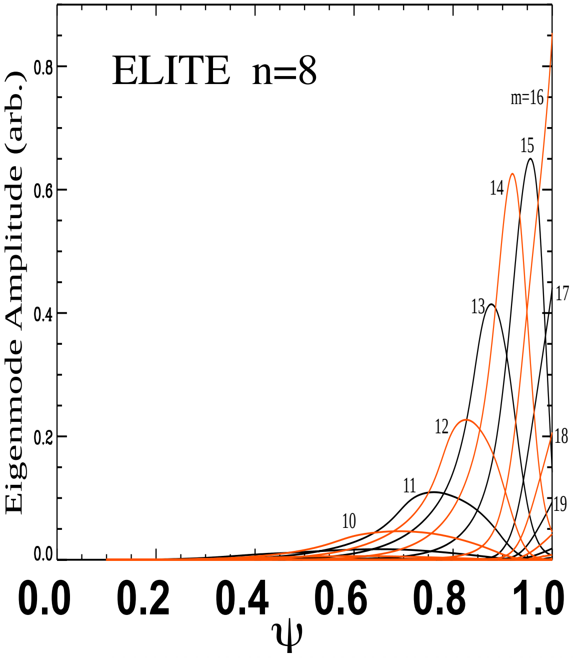
-Makes use of poloidal harmonic localization for efficiency

-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).]*







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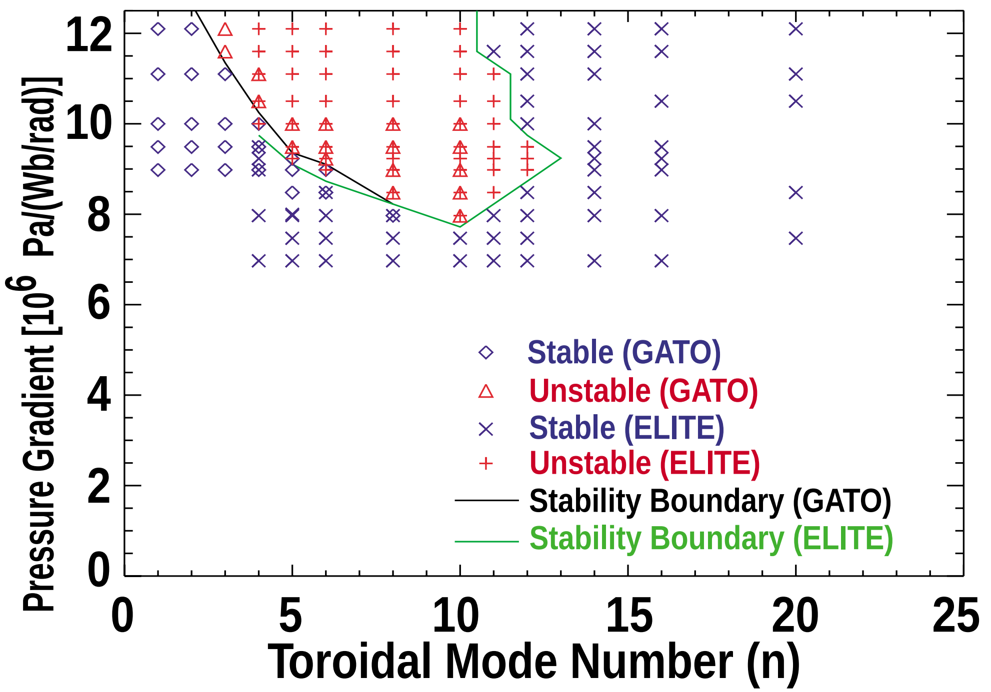
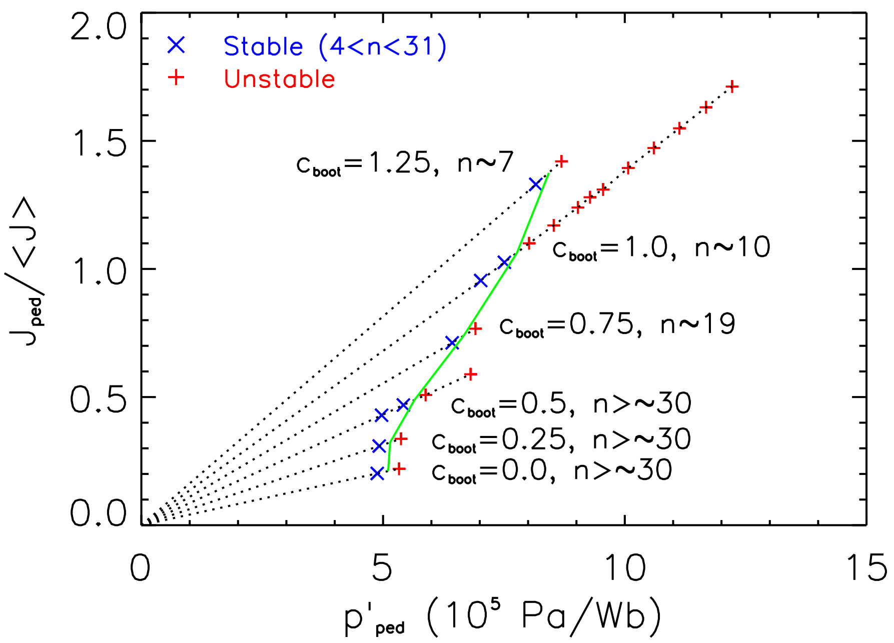
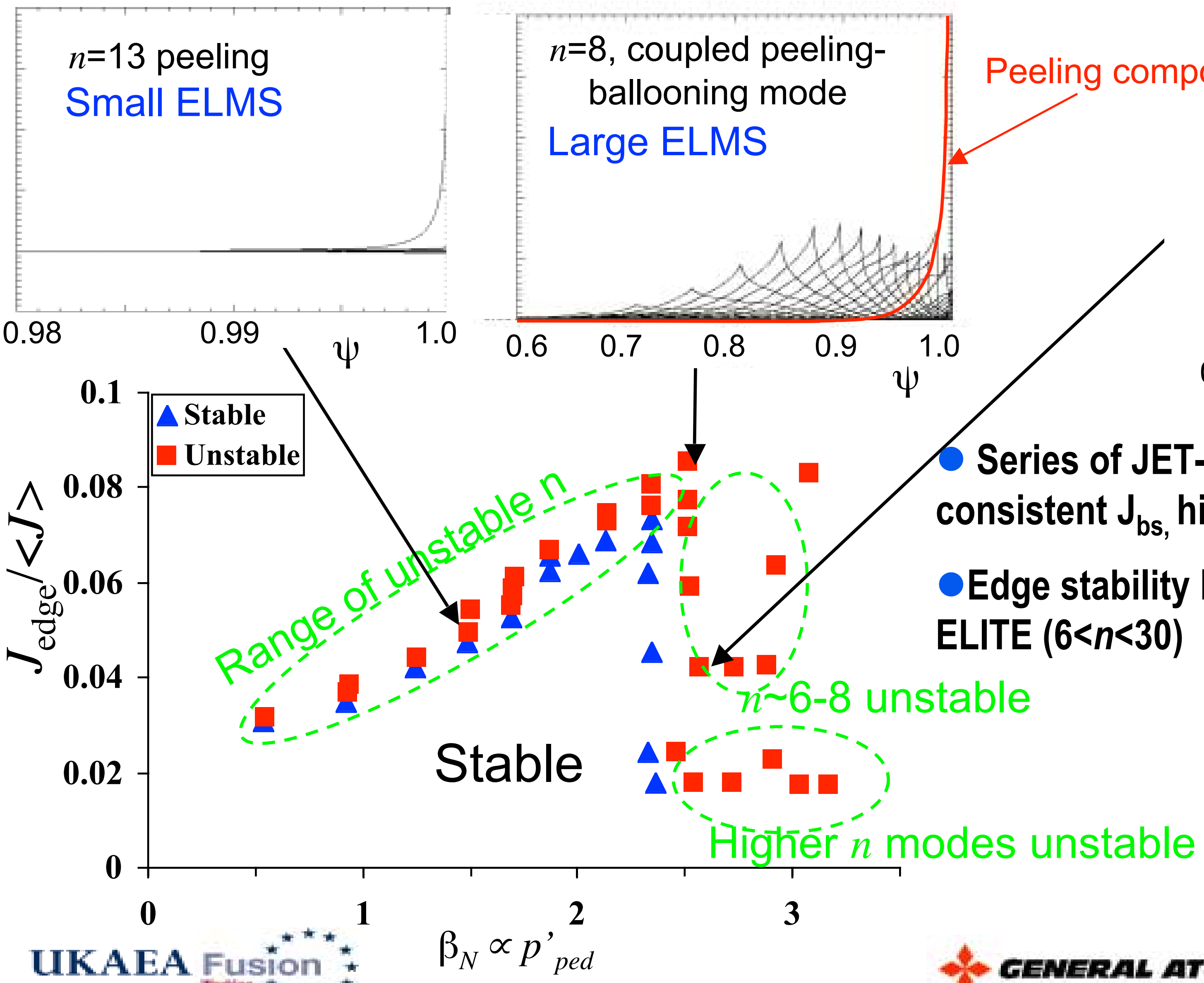
ELITE allows quantitative prediction of ELMs, pedestal constraints

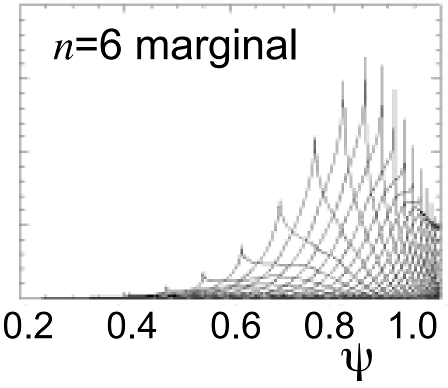




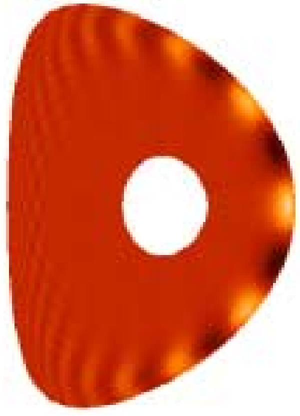
- **DIII-D model equilibria, self-consistent collisionless bootstrap current. Nominal (zero current) $n \rightarrow \infty$ ballooning limit of p'=3.1, exceeded in expt by factors of 2-3, in agreement with calculated n=10 limit**
- **Demonstrates existence of "second stability" in shaped nonlocal equilibria**
- **Good agreement between GATO and ELITE in region of overlap ($4<n<10$)**
- **Modify current by varying c_{boot} ($J_{boot}=c_{boot}{}^{*}J_{hirshman}$): Trends in p' limit and predicted limiting n and ELM size with J_{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)



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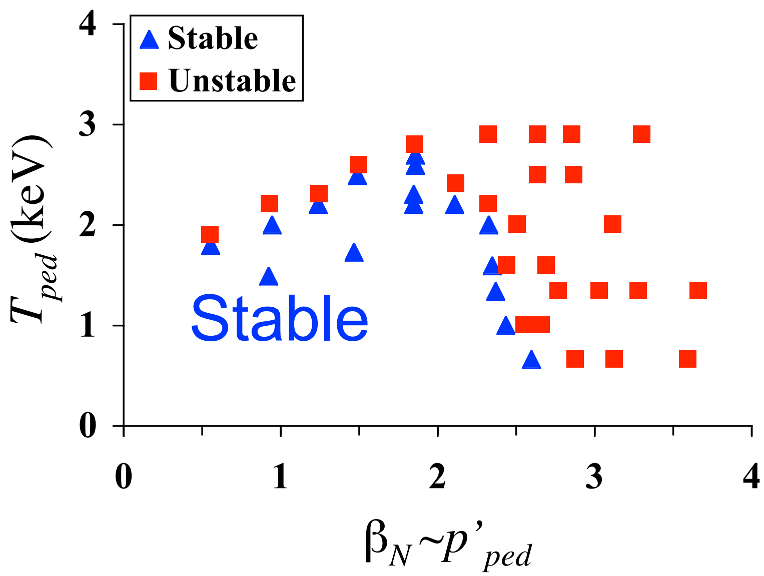
Peeling-ballooning modes provide a constraint on the edge temperature pedestal, as well as β

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

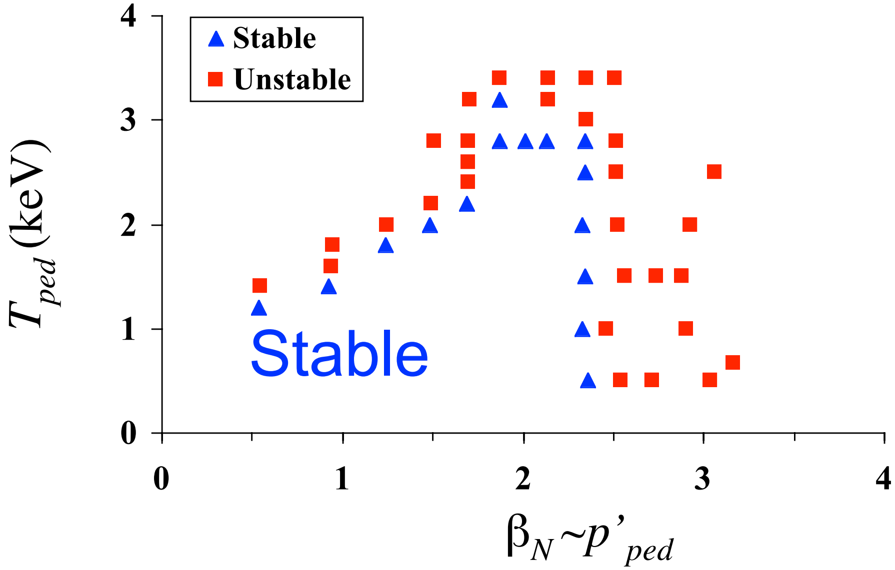
- **Can consider stability diagram in β_N-T_{ped} space**
- **MHD stability explicitly limits steady state T_{ped}, (for a given width)**
- **Higher triangularity decouples peeling and ballooning modes, allows higher temperature pedestal**

κ=1.6, *A*=3, *R*=3m

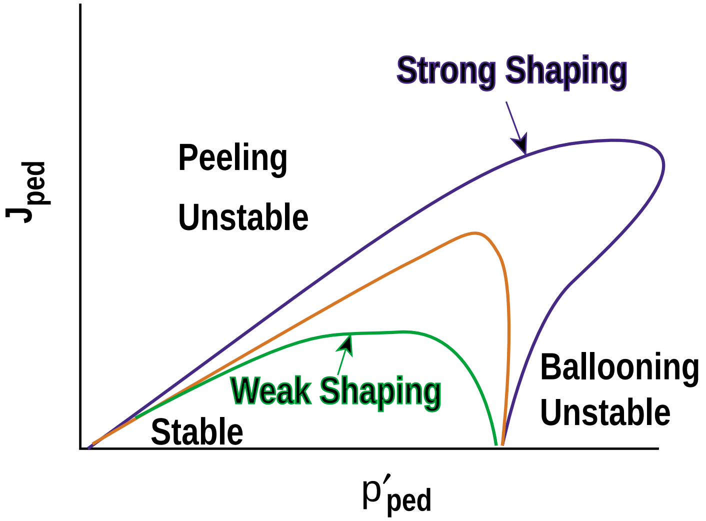
δ=0.3

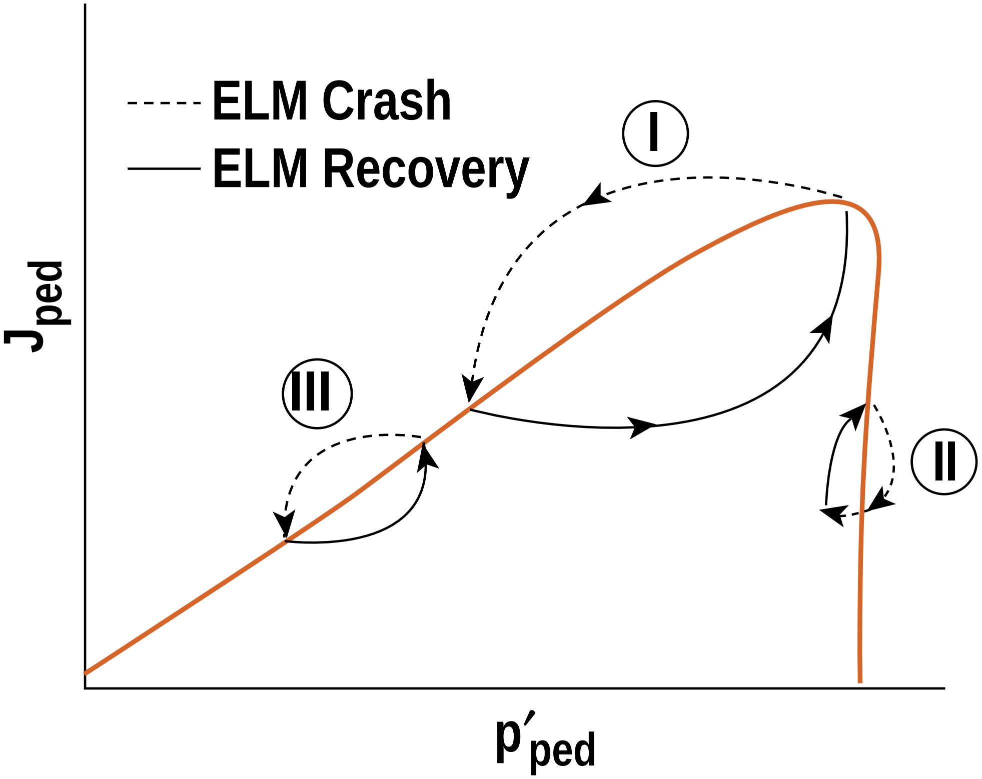


δ=0.5



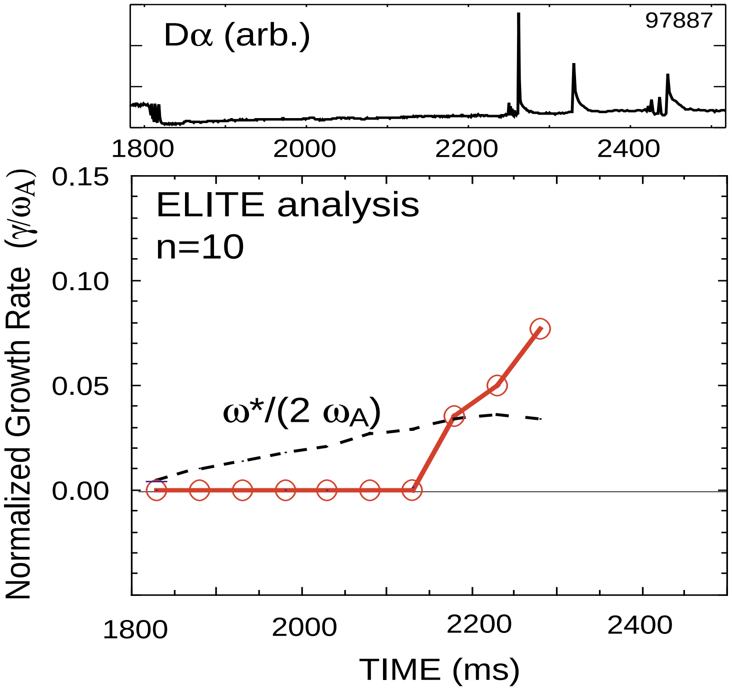
Different Types of ELM Cycles can be Envisioned



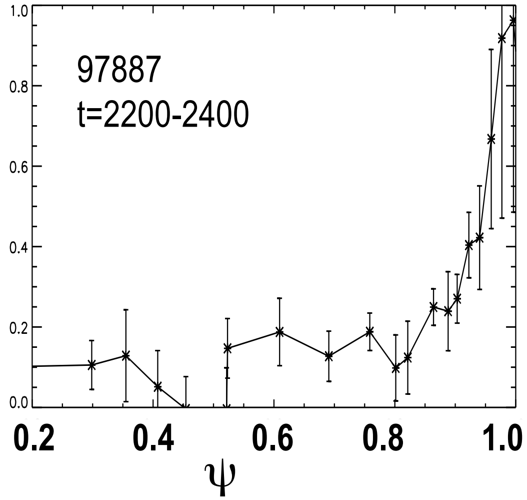


- ELMs triggered by peeling-ballooning modes, ELM size correlates to depth of most unstable mode and to location in parameter space
- Pressure rises up on transport time scale between ELMs, current rises to steady state value more slowly
- Predict changeover in ELM behavior when $J_{ped}<J_{peel} \Rightarrow$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

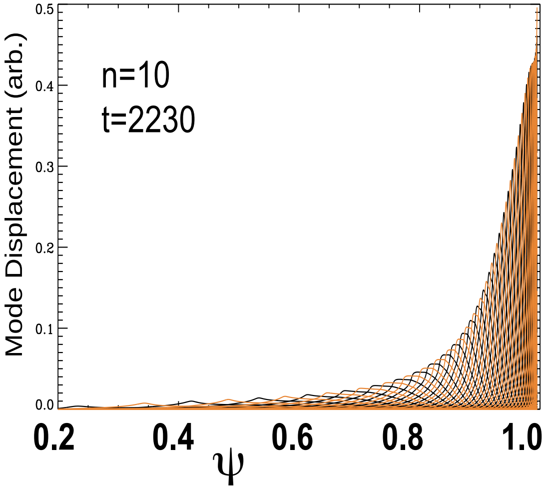
Verification of Peeling-Ballooning Mode Model for ELMs: Case Study in DIII-D

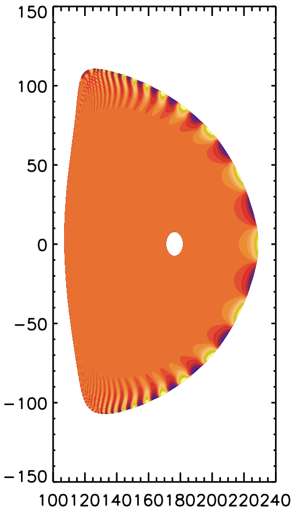


Observed $\Delta T_e/T_e$ across ELMs



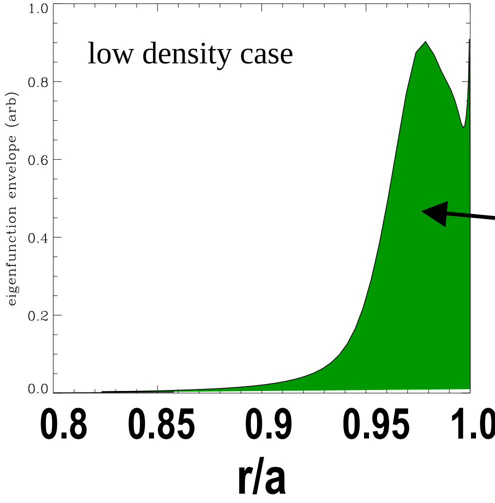
Calculated eigenmode structure

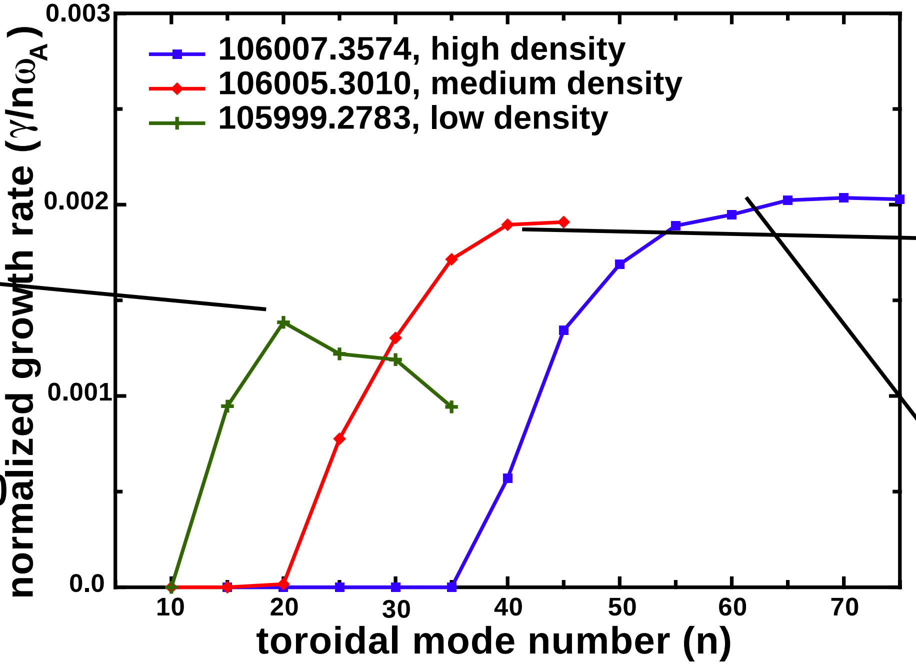


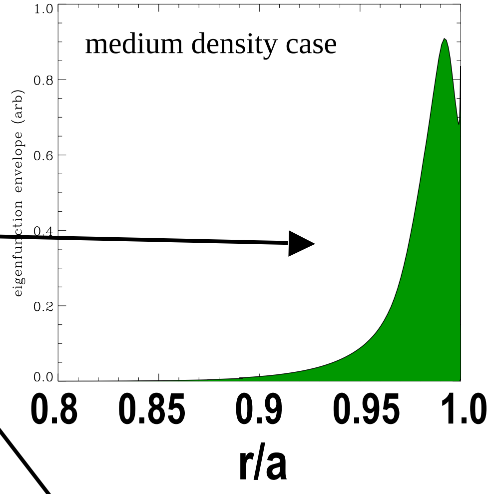


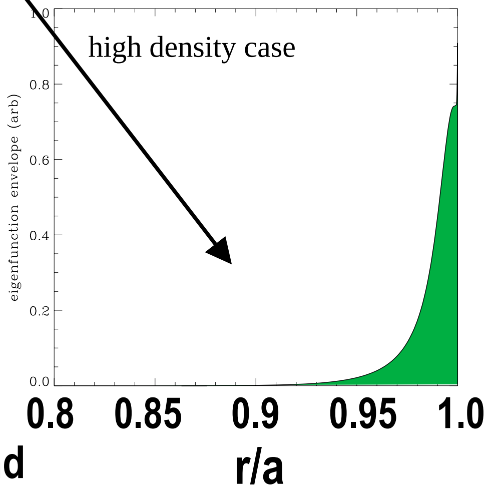
- *n*=10 growth rate attains significant value just before ELM observed
- Predicted radial mode width consistent with ELM affected area
  - Both extend beyond pedestal
- Mode localized on outboard side, consistent with observations in divertor balance experiments

Observed Variation with Density Consistent with Model







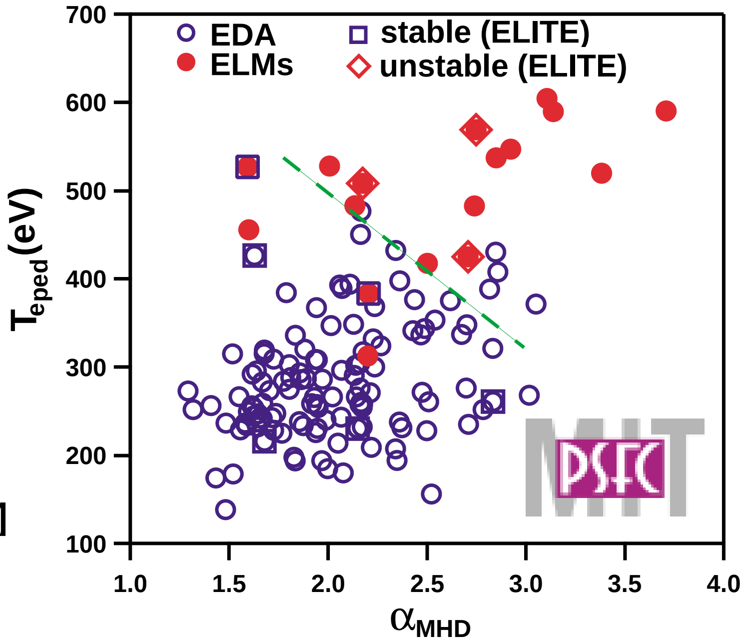


- **Three DIII-D shots with varying density studied**
- **In all 3 cases, peeling-ballooning modes are unstable with significant growth rate just before ELM, even though pedestal height is decreasing with density**
  - Consistent with peeling-ballooning modes as ELM trigger
- **As density increases, 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 ***[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]

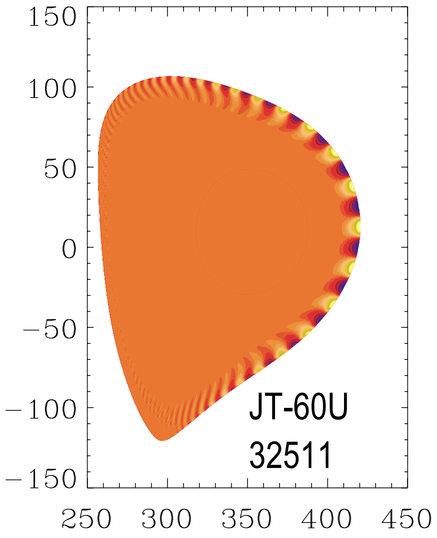


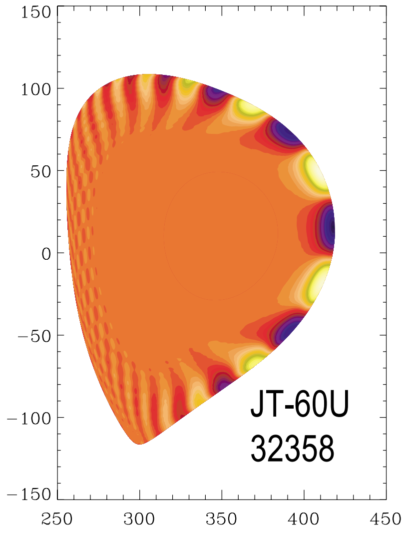
- **JT-60U**

  -Peeling ballooning modes unstable before ELM

  -Broader mode structures in "Giant ELM cases"

Grassy ELMs





Giant ELMs

JAERI

[See T. Oikawa QP1.063]

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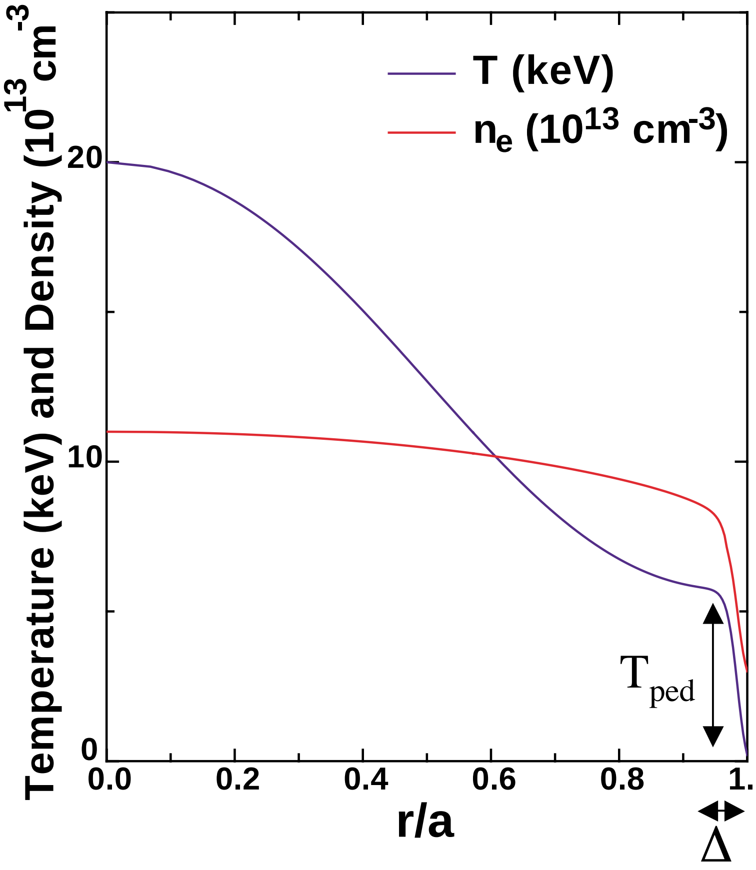
Studies of Model Equilibria Useful for Predicting Trends in Present and Future Devices

- **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

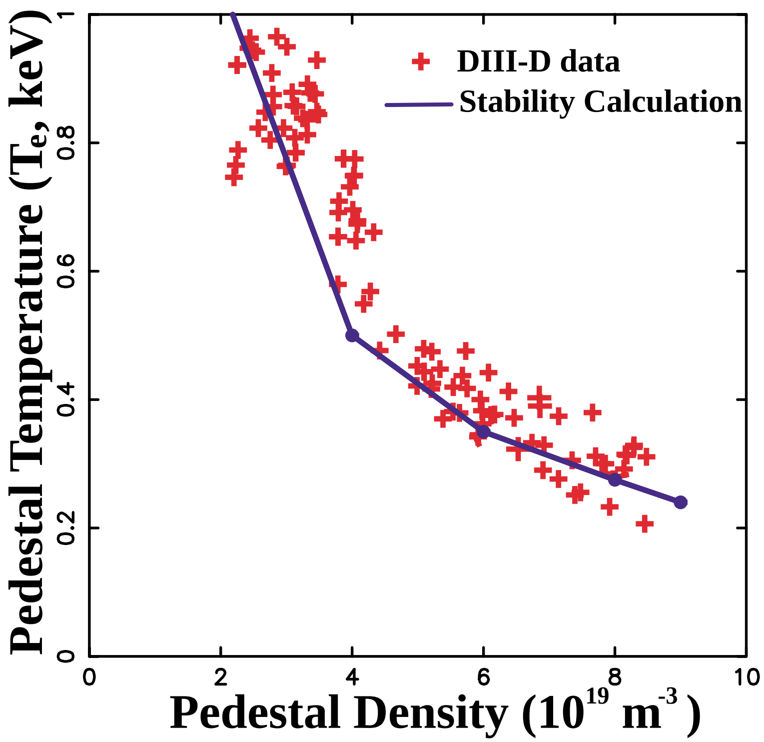


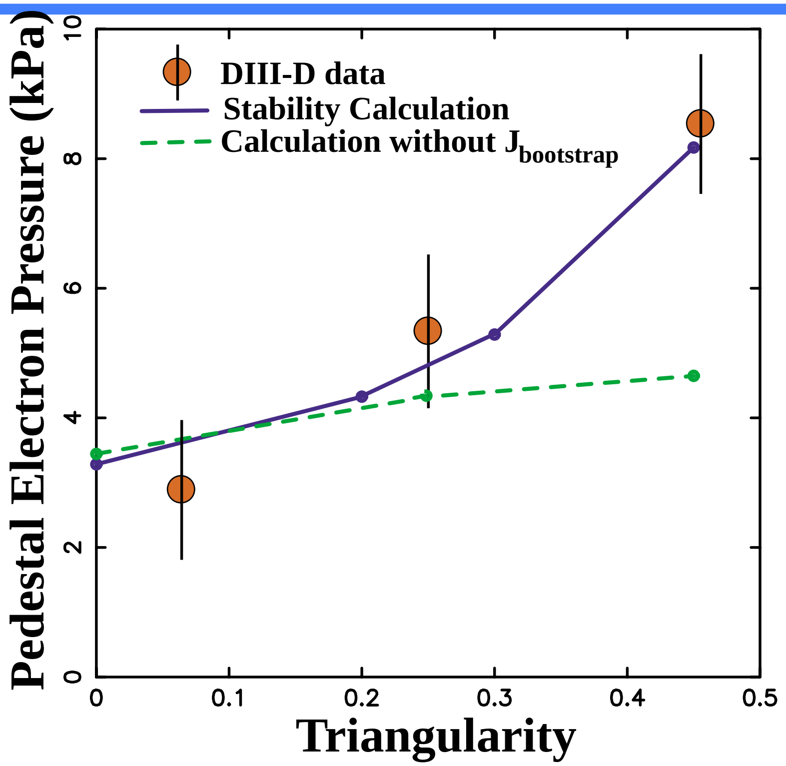
$$n_e(\psi) = n_{sep} + a_{n0}\{\tanh[2(1-\Psi_{mid})/\Delta] - \tanh[2(\Psi-\Psi_{mid})/\Delta]\} + a_{n1}[1-(\Psi/\Psi_{ped})^{\alpha_{n1}}]^{\alpha_{n2}}$$

$$T(\psi) = T_{sep} + a_{T0}\{\tanh[2(1-\Psi_{mid})/\Delta] - \tanh[2(\Psi-\Psi_{mid})/\Delta]\} + a_{T1}[1-(\Psi/\Psi_{ped})^{\alpha_{T1}}]^{\alpha_{T2}}$$

- **Model equilibria, match global parameters (B_t, I_p, R, a, κ, δ, $\langle n_e \rangle$)**
- **Current profile aligned to Sauter collisional bootstrap model in the pedestal**
- **Width (Δ) is an input: at each Δ, T_{ped} is increased until n=8-40 stability bounds are crossed**

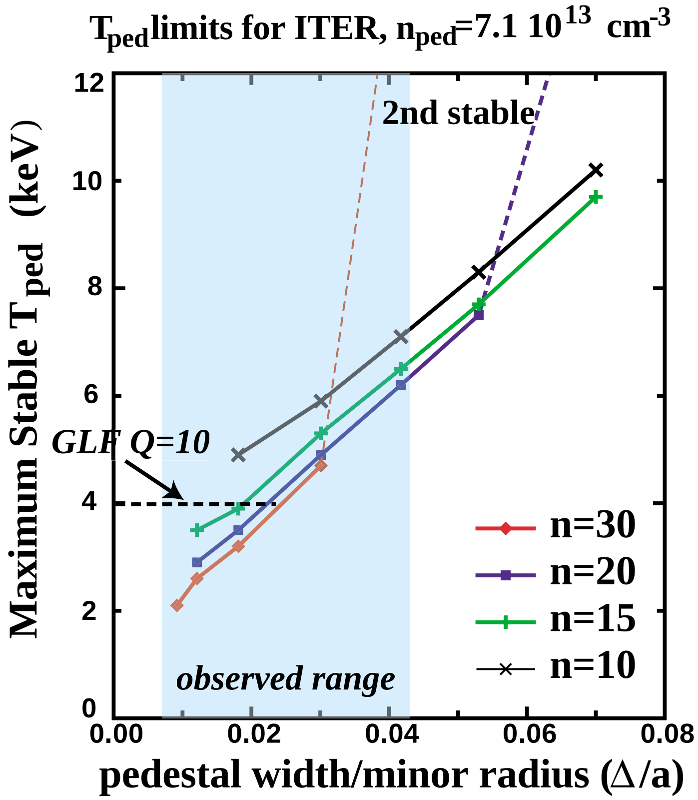
Trends in Existing Pedestal Database Can Be Understood Using Stability of Model Equilibria

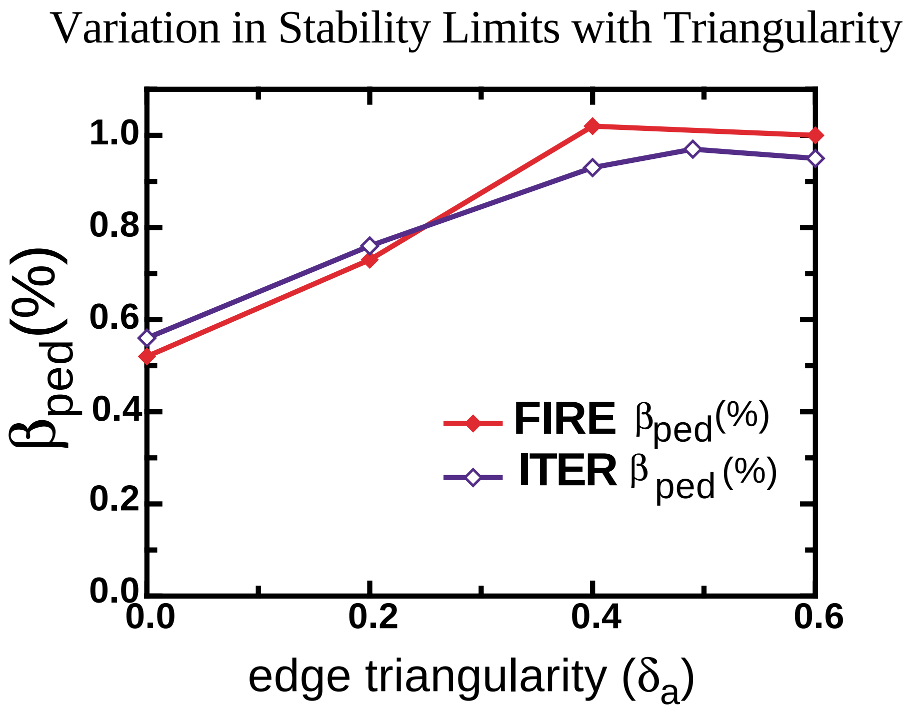




- **Trends with density and triangularity calculated using series of model equilibria, and compared to database**
  - Inputs are B_t, I_p, R, a, κ, δ, $\langle n_e \rangle$, Δ
- **Strong increase in pedestal height with triangularity is due to opening of second stability access**
  - Bootstrap current plays a key role here. Without it (dashed line) second stability is not accessed at high *n* and strong δ 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

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 (~ $\Delta^{2/3}$)**
- **Reaches adequate pedestal height for predicted high performance in observed range of Δ/a**
  - Increase height by optimizing δ, n_e, including ω_* effects
  - Scaling of pedestal width remains a key uncertainty ***[Osborne CT-3]***

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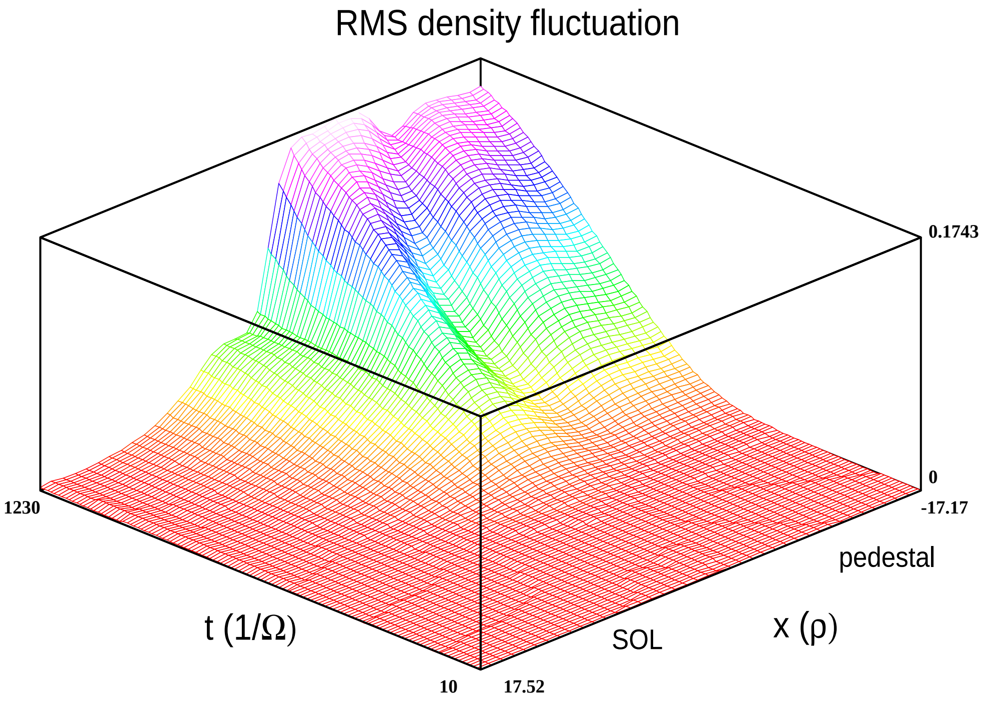
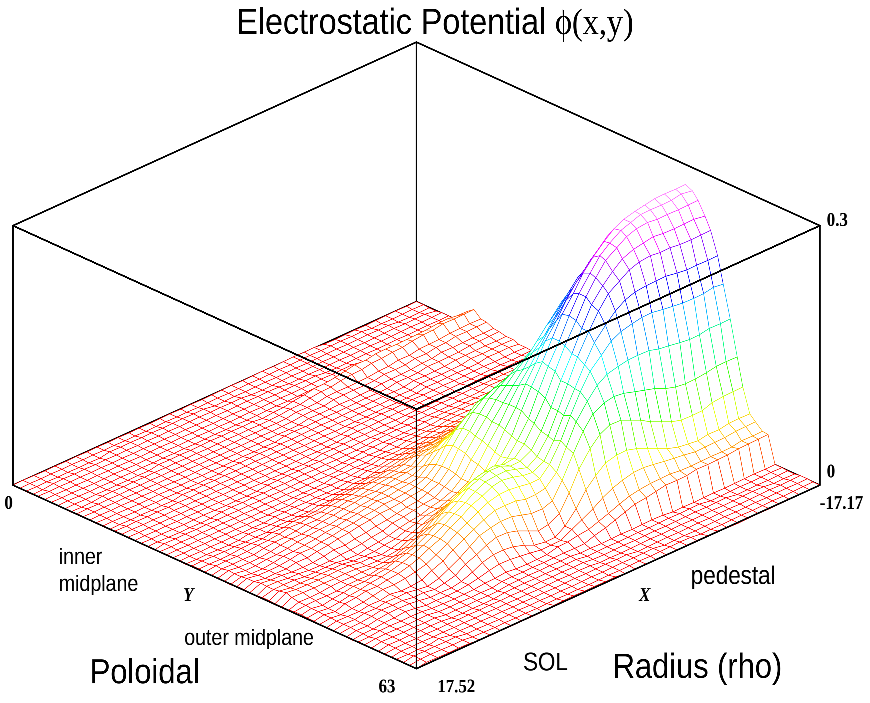
ELM simulated in BOUT has peeling-ballooning structure





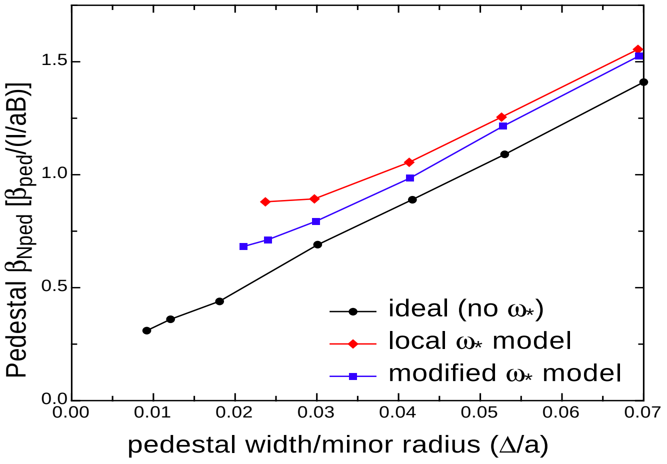
- **Additional physics effects (eg ω_*, sheared rotation) need to be considered**
- **Nonlinear BOUT code with current used to simulate peeling-ballooning modes**
  - Basic picture of instability remains intact

Rotation and non-ideal effects potentially important

- **Diamagnetic stabilization identified by several authors**
  - Rogers and Drake '99 found ω_* effects significantly stabilizing for ballooning modes -> alternative to 2nd stability to explain $\beta > \beta_c$
  - Hastie, Catto, Ramos '00 found strong radial variation of ω_* diminishes its stabilizing impact. Huysmans '01 work with Mishka also suggests reduced impact.
  - Can make simple estimates based on [Roberts '62]:
  - 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 γ/ω_*
  - Simple model implemented in ELITE:

$$-\gamma_{MHD}^{2} = \omega(\omega - \omega_{*i})$$

$$nqA\frac{\rho_i}{L_p}\sqrt{\beta} > 2\frac{\gamma_{\mathrm{MHD}}}{\omega_A}$$



Impact of ω* models on ITER pedestal stability

- **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…**