ELMs and Constraints on the H-Mode Pedestal:

A Model Based on Peeling-Ballooning Modes

P.B. Snyder,[1] H.R. Wilson,[2] J.R. Ferron,[1] L.L. Lao,[1]
A.W. Leonard,[1] D. Mossessian,[3] M. Murakami,[4]
T.H. Osborne,[1] A.D. Turnbull[1], X.Q. Xu[5]

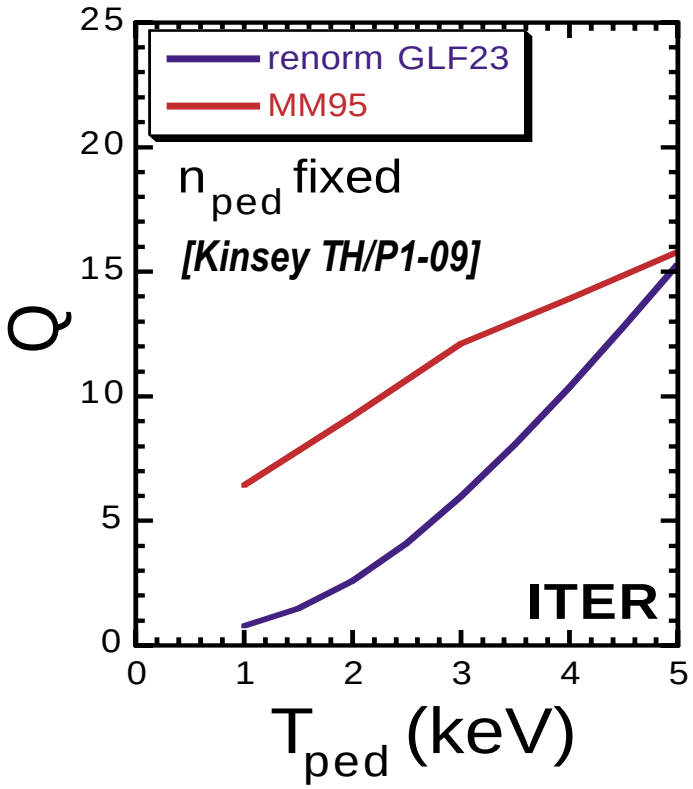
[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA
[2]EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon UK
[3]Massachusetts Institute of Technology PSFC, Cambridge, Massachusetts 02139, USA
[4]Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
[5]Lawrence Livermore National Laboratory, Livermore, California 94550, USA

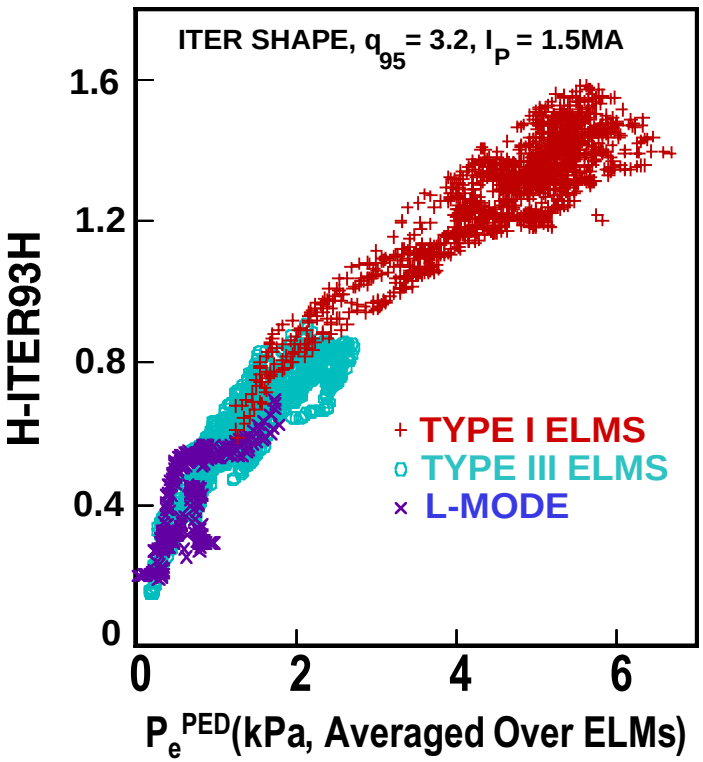
19th IAEA Fusion Energy Conference

Lyon, France, 14-20 October 2002

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)

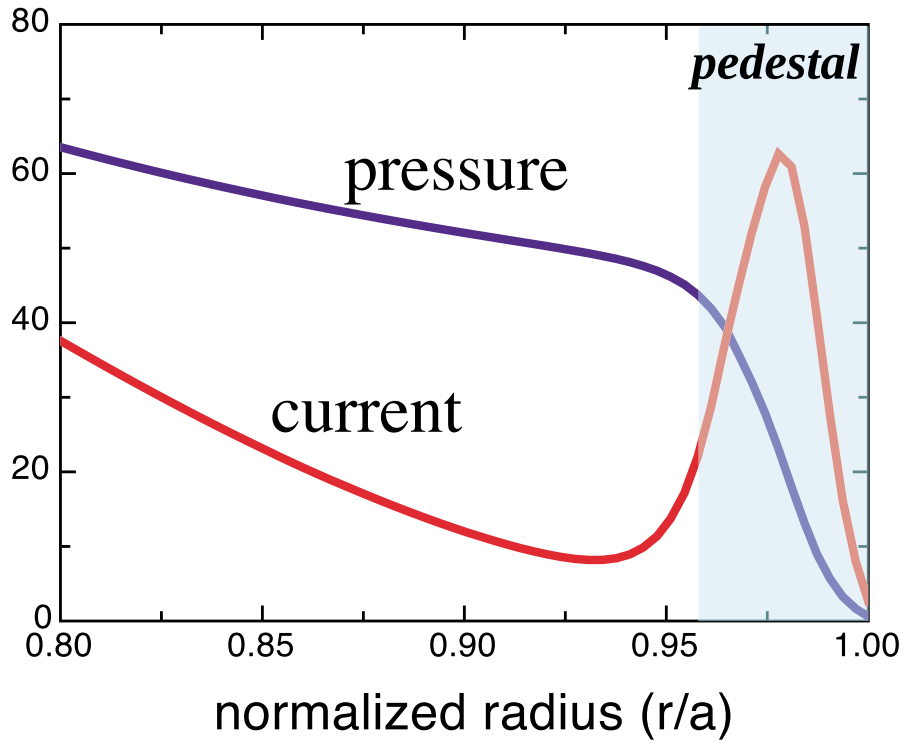
➡ Goal is predictive understanding of physics controlling pedestal height and ELM characteristics ⇒ combination of high pedestal and tolerable ELMs

UKAEA Fusion Working with Europe

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

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

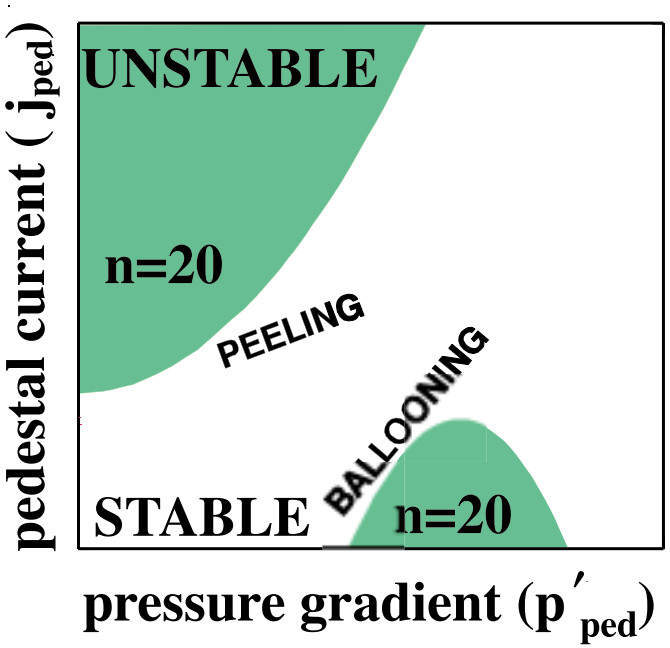
- **Model Verified Against Experiment in Two Ways**
  - Direct comparisons to experiment
  - Use of model equilibria to assess pedestal limits in current and future devices
- **Summary and Future Work**

UKAEA Fusion Working with Europe

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

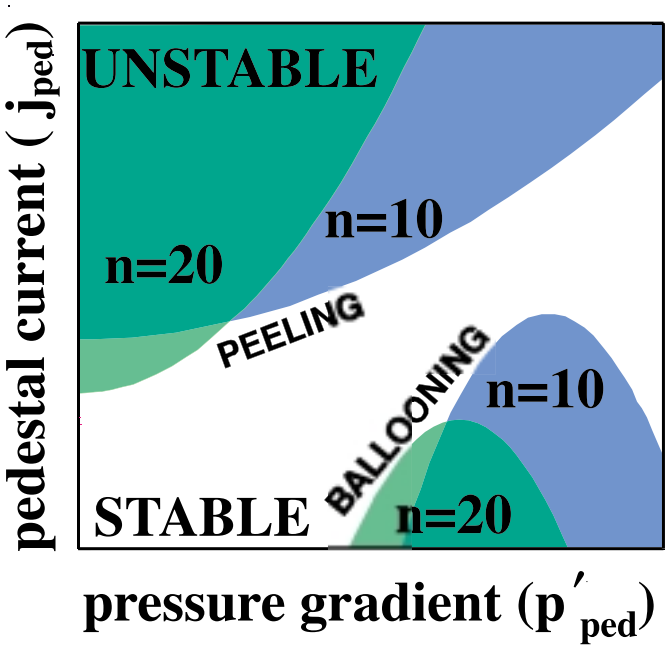
GENERAL ATOMICS

Peeling-Ballooning Stability Picture



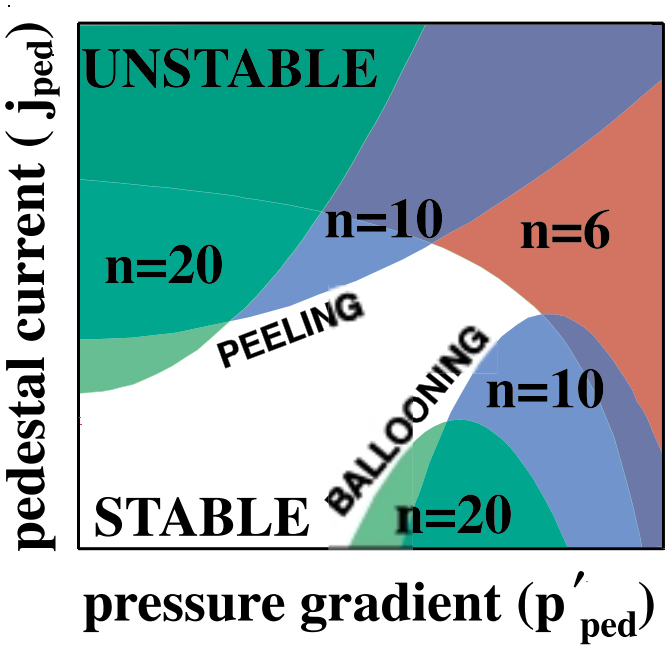
- **Two Principal MHD Instabilities in the Pedestal**
  - Ballooning Modes (pressure driven)
  - External Kink or "Peeling Modes" (current driven)
- **Bootstrap Current Plays a Complex Role**
  - Drives Peeling Modes
  - Opens 2nd stability access to ballooning modes

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 and Ballooning modes couple at finite n**

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 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

UKAEA Fusion Working with Europe

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

ELITE is a Highly Efficient 2D MHD Code for n>~5

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

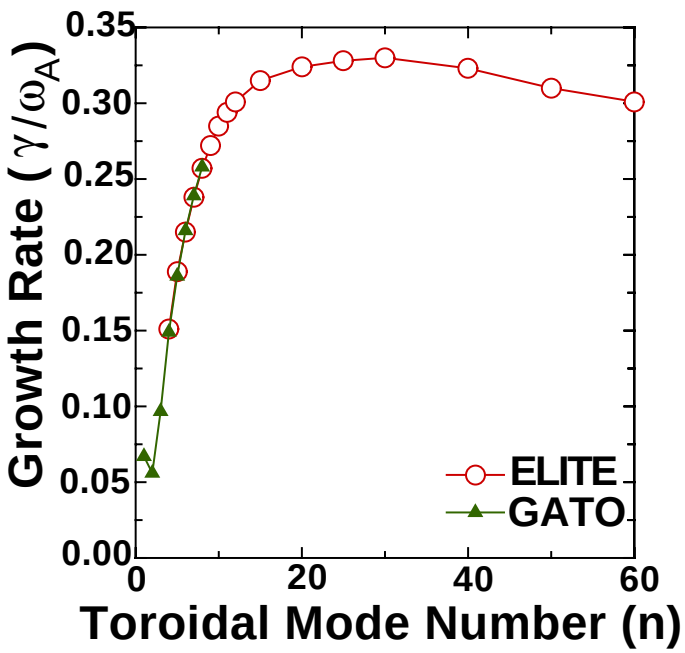
-Generalization of ballooning theory:

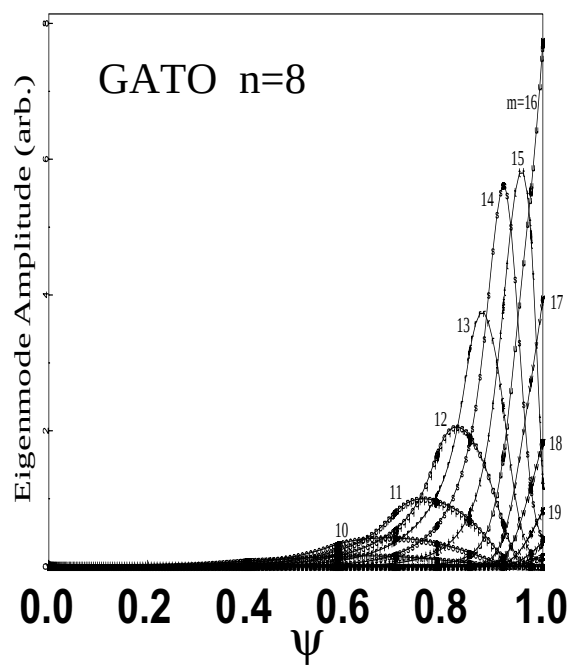
1) incorporate surface terms which drive peeling modes
2) retain first two orders in 1/*n* (treats intermediate *n*>~5)

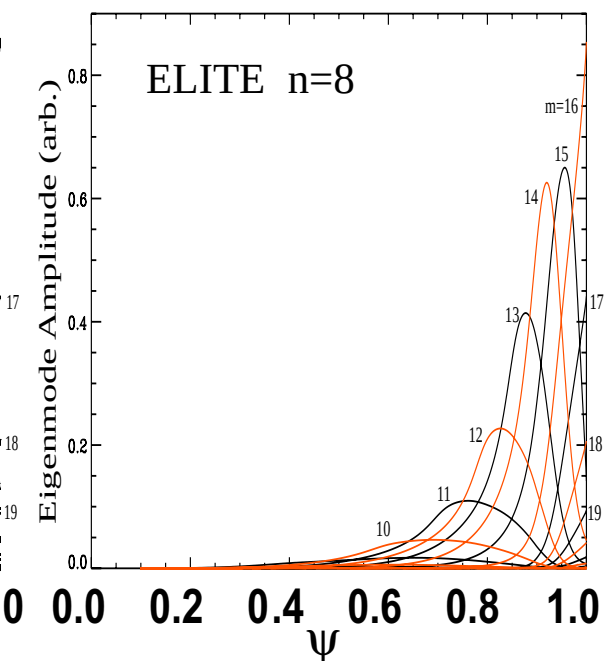
-Makes use of poloidal harmonic localization for efficiency

-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).]*



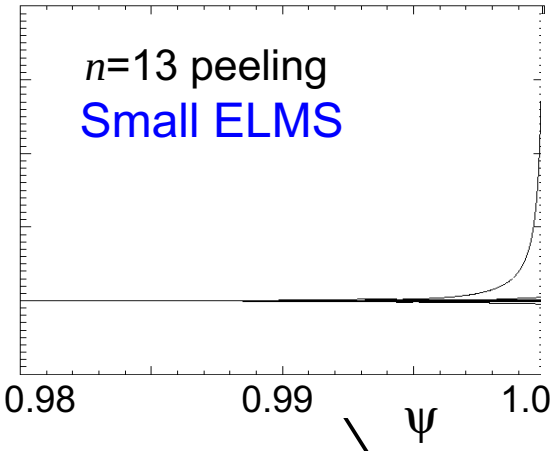


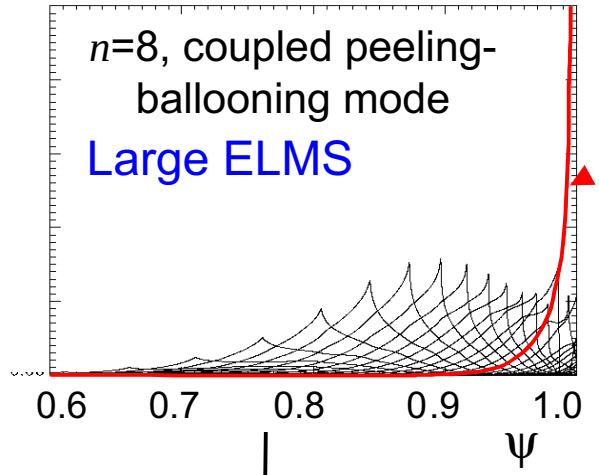


UKAEA Fusion Working with Europe

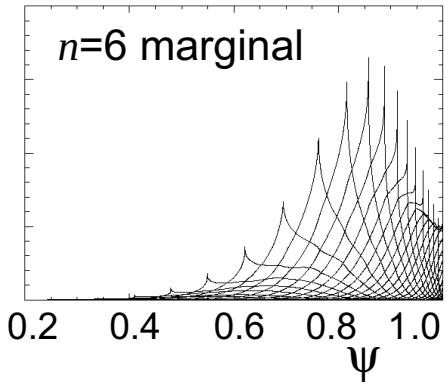
GENERAL ATOMICS

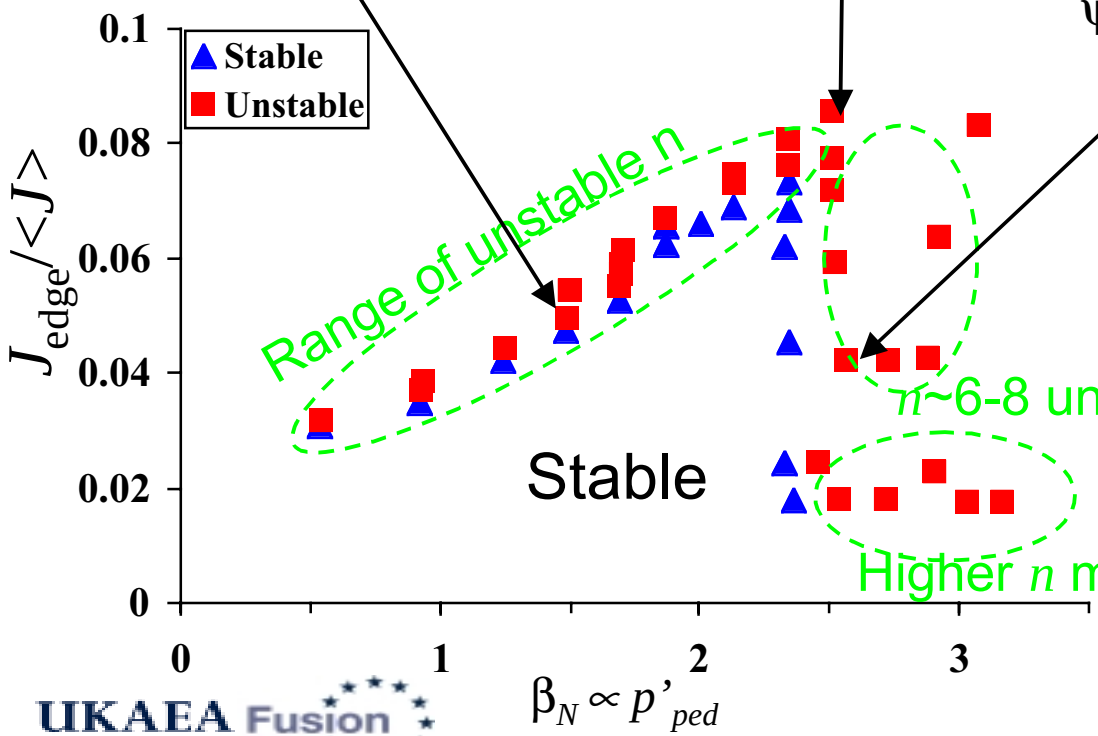
Different n's and Mode Structures Predicted in Different Regimes



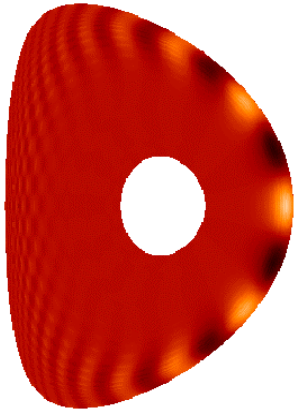


Peeling component





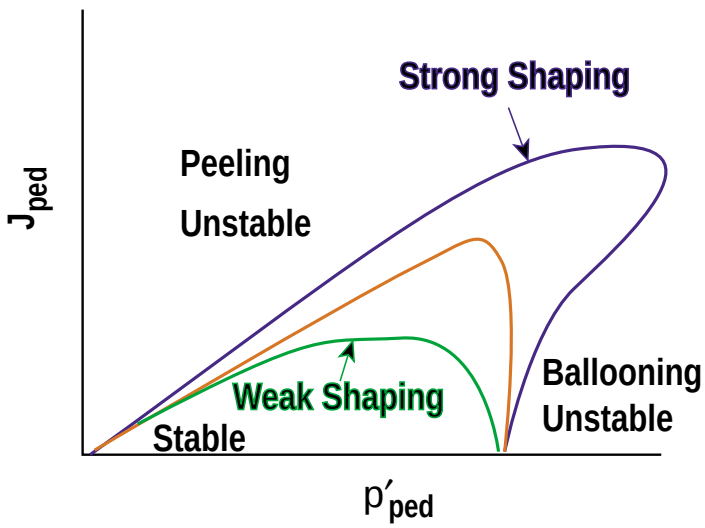
- Series of JET-like equilibria with self-consistent $J_{bs,}$ high *n* 2nd access
- Edge stability limits scanned with ELITE (6<*n*<30)

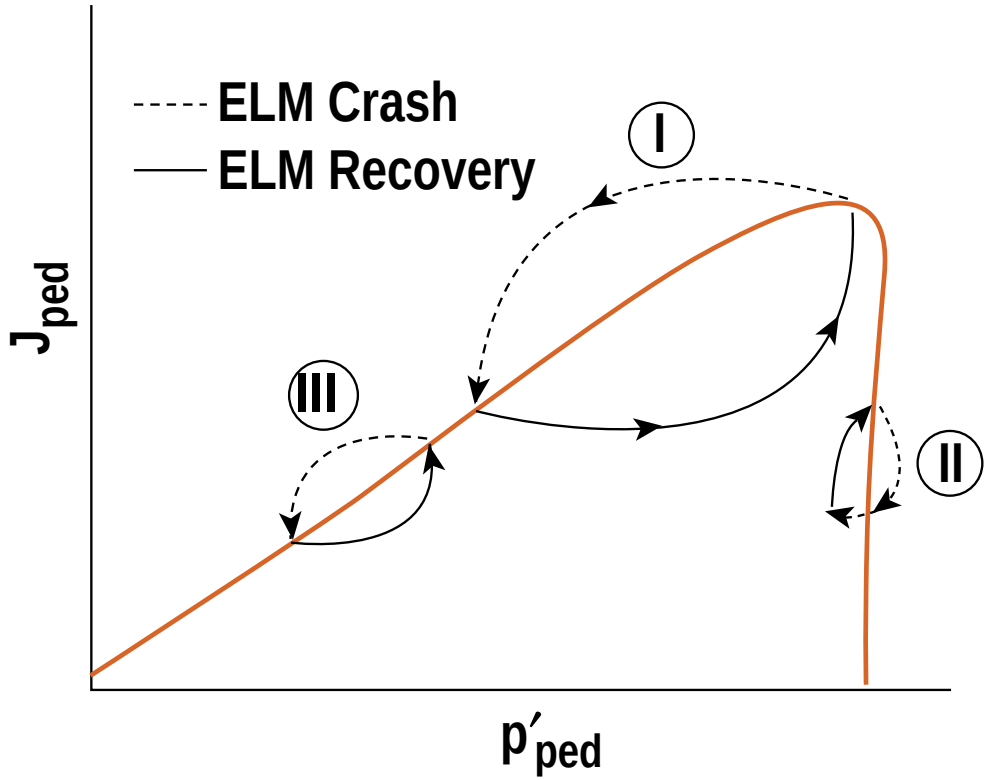


UKAEA Fusion Working with Europe

GENERAL ATOMICS

Different Types of ELM Cycles can be Envisioned



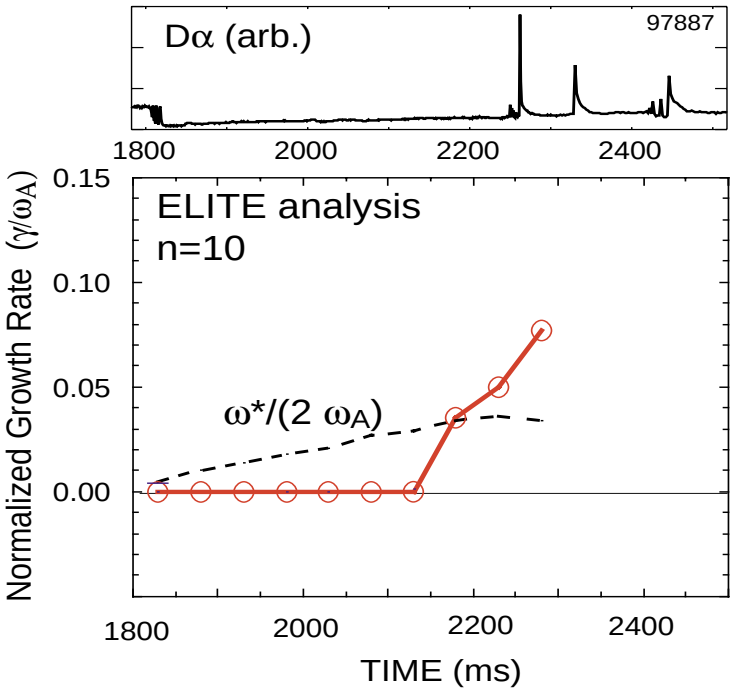


- ELMs triggered by peeling-ballooning modes, ELM size correlates to depth of most unstable mode and to location in parameter space
- Pressure rises up on transport time scale between ELMs, current rises to steady state value more slowly
- Predict changeover in ELM behavior when $J_{ped}<J_{peel} \Rightarrow$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

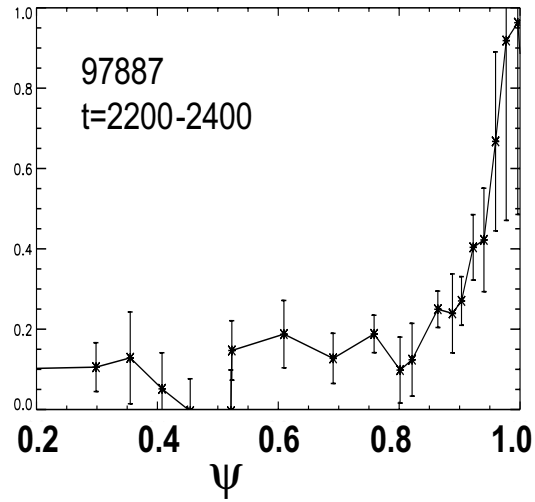
UKAEA Fusion Working with Europe

GENERAL ATOMICS

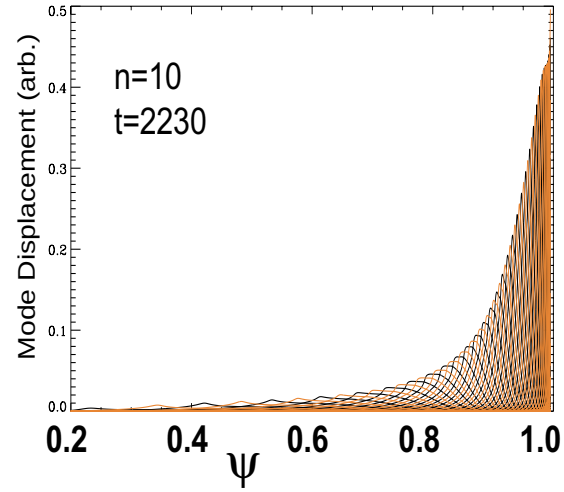
Verification of Peeling-Ballooning Mode Model for ELMs: Case Study in DIII-D

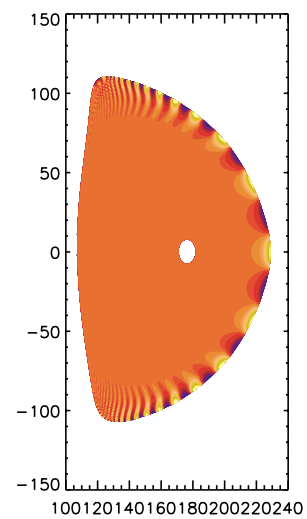


Observed $\Delta T_e/T_e$ across ELMs



Calculated eigenmode structure





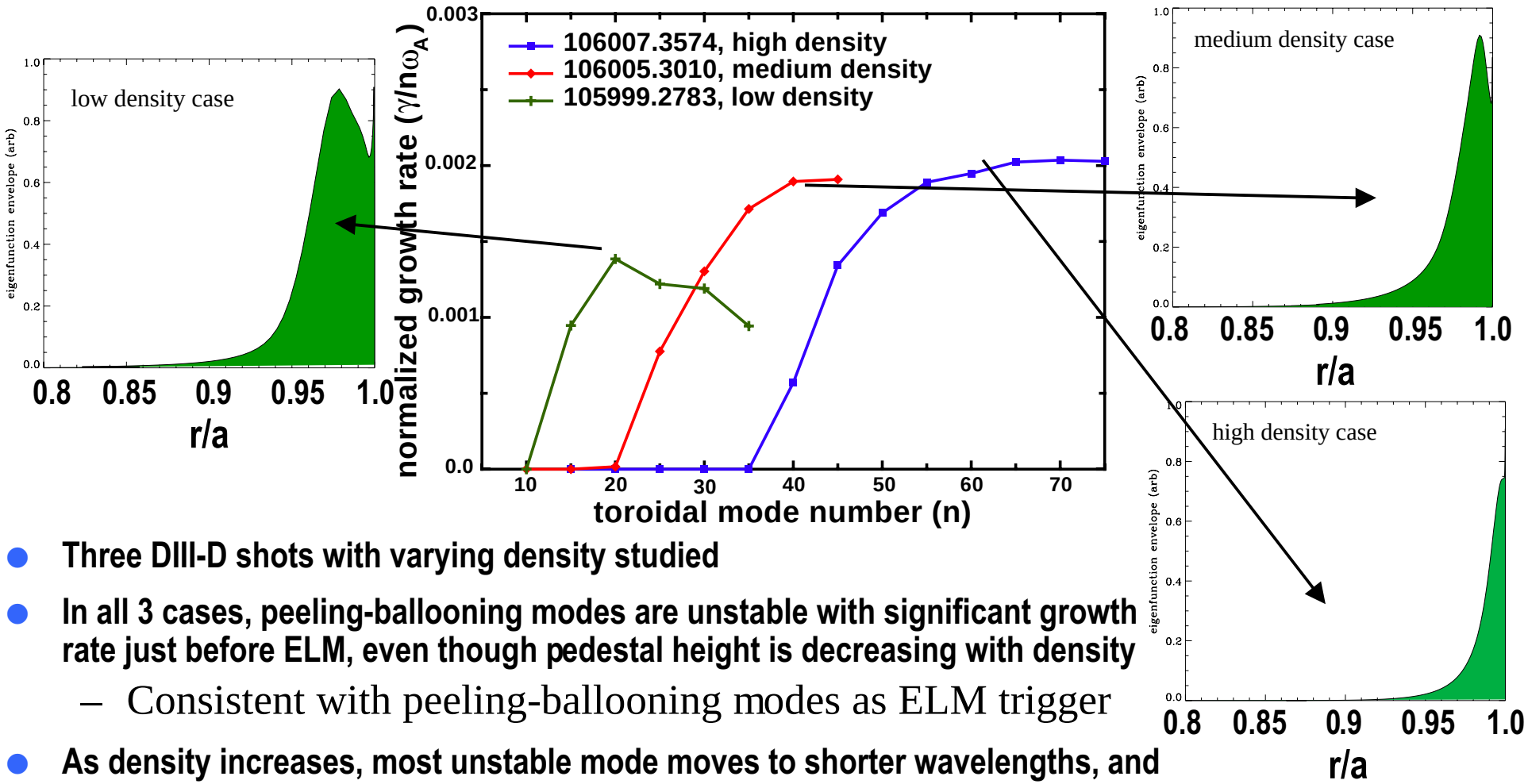
- ***n*=10 growth rate attains significant value just before ELM observed**
- **Predicted radial mode width consistent with ELM affected area**
  - Both extend beyond pedestal
- **Mode localized on outboard side, consistent with observations in divertor balance experiments**

UKAEA Fusion Working with Europe

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

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]***

UKAEA Fusion Working with Europe

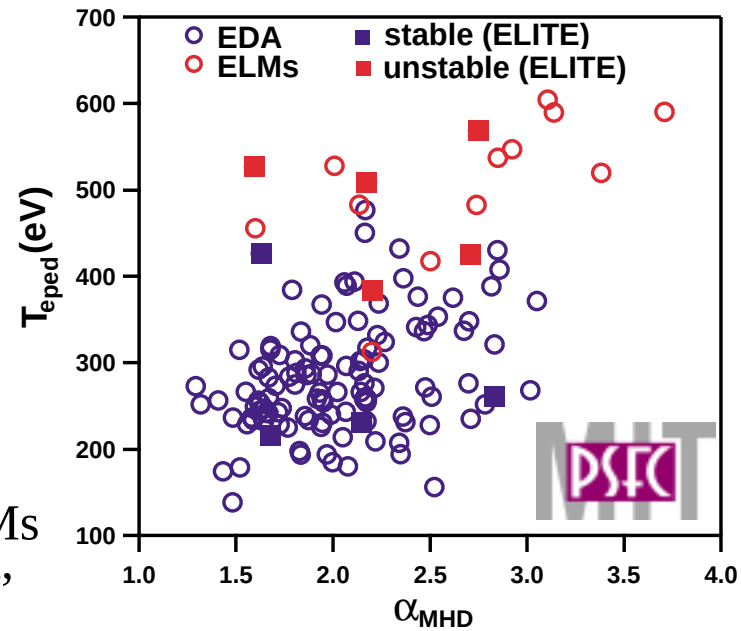
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

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]

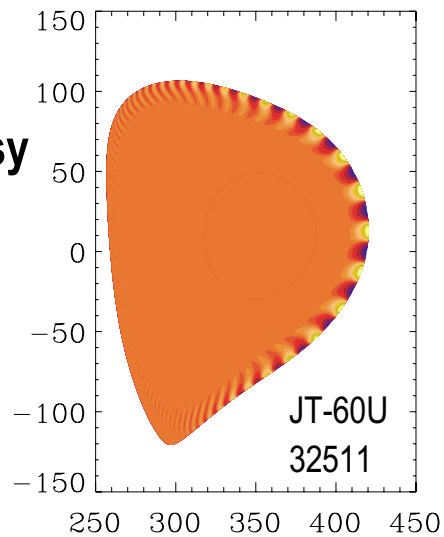


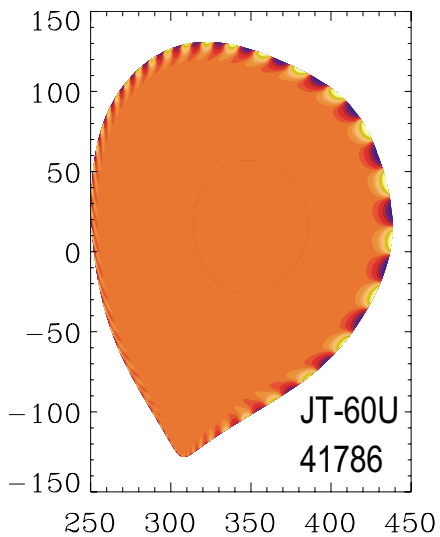
- **JT-60U**

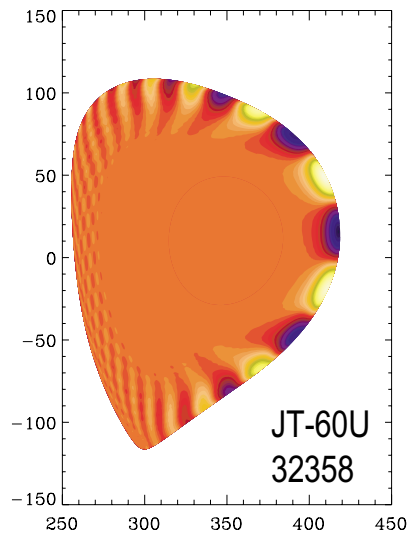
  -Peeling ballooning modes unstable before ELMs

  -Broader mode structures in "Giant ELM cases"

Grassy ELMs







Giant ELMs

JAERI

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

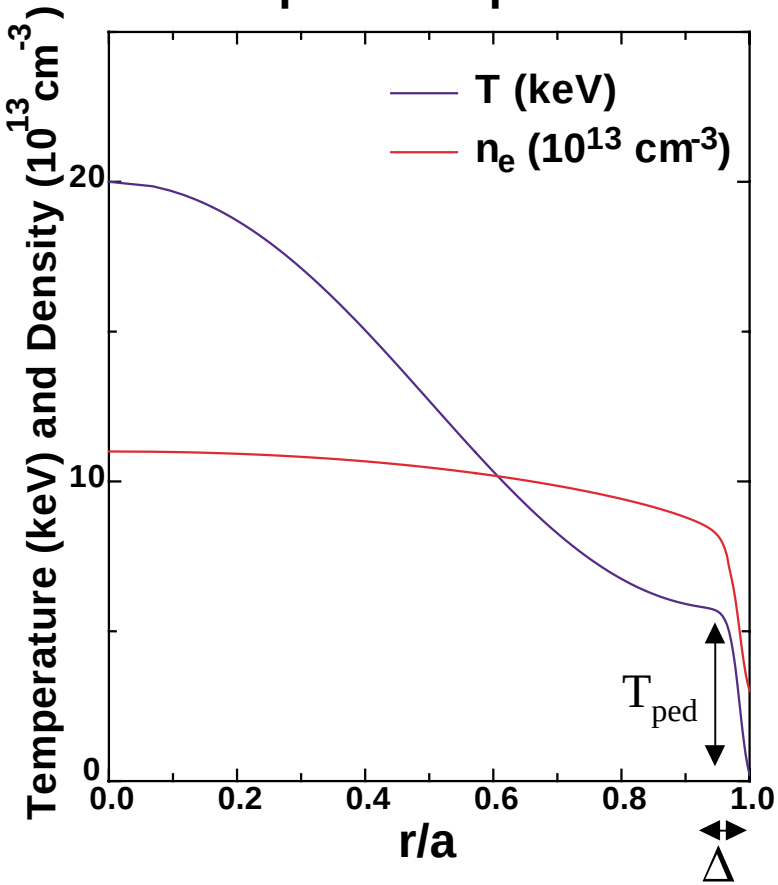
UKAEA Fusion

GENERAL ATOMICS

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

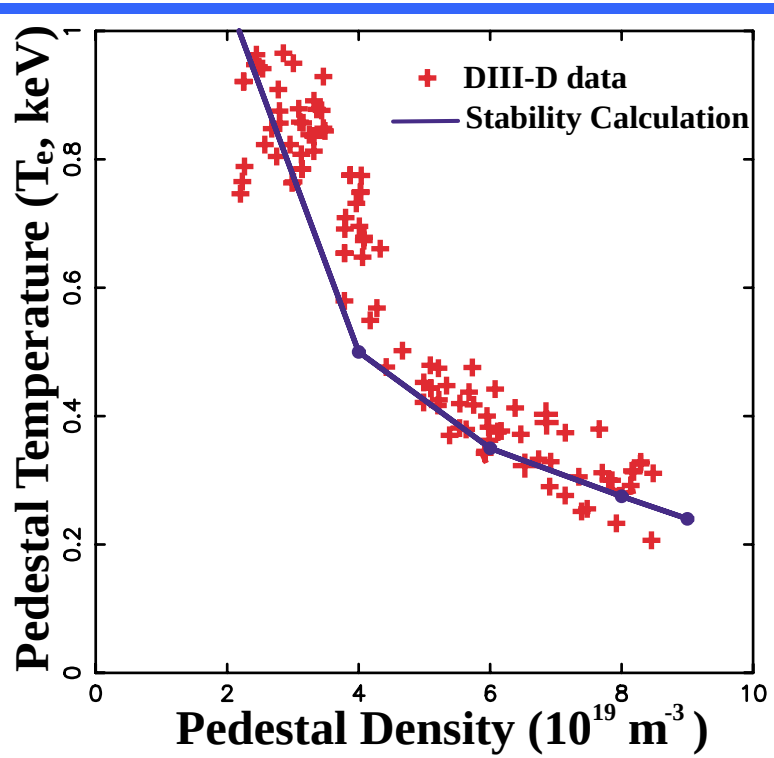


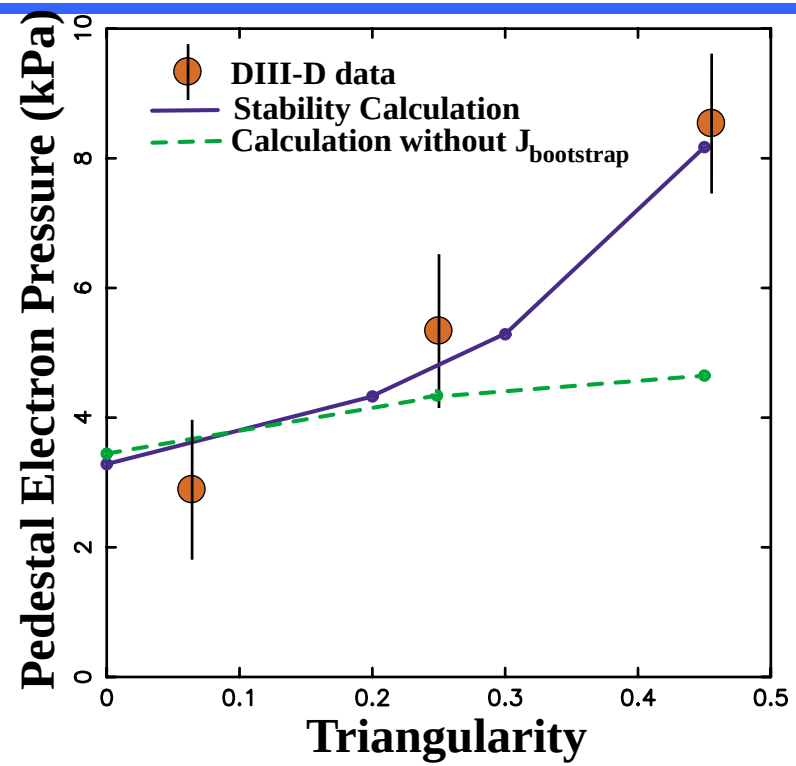
- **Model equilibria, match global parameters (B_t, I_p, R, a, κ, δ, <n_e>)**
- **Current profile aligned to Sauter collisional bootstrap model in the pedestal**
- **Width (Δ) is an input: at each Δ, T_{ped} is increased until n=8-40 stability bounds are crossed**

UKAEA Fusion Working with Europe

GENERAL ATOMICS

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

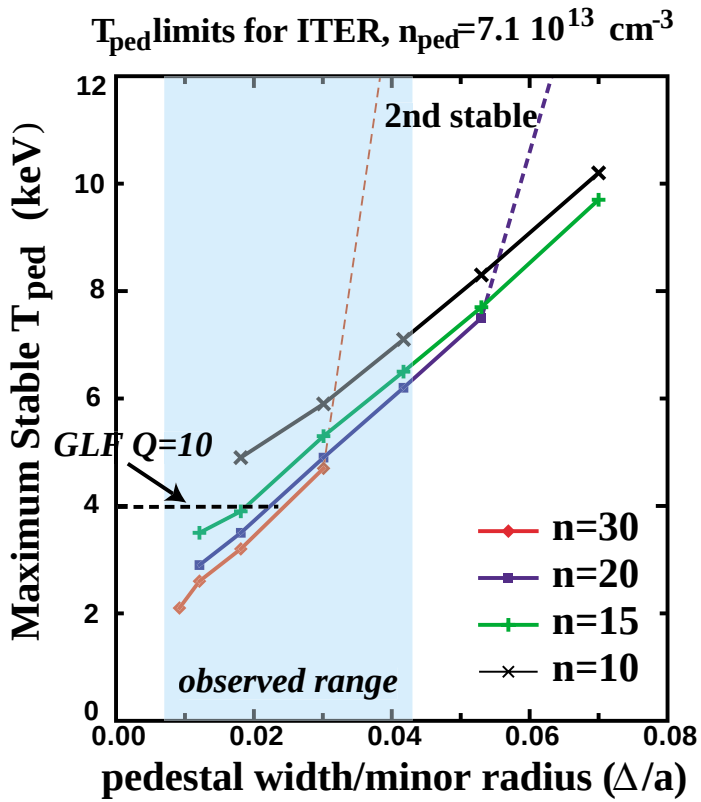




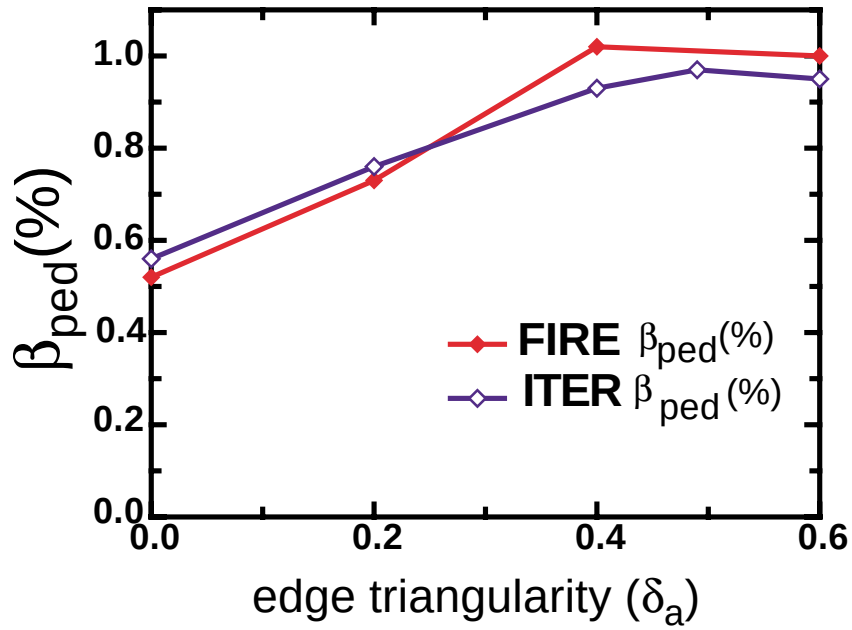
- **Trends with density and triangularity calculated using series of model equilibria, and compared to database**
  - Inputs are B_t, I_p, R, a, κ, δ, $\langle n_e \rangle$, Δ
- **Strong increase in pedestal height with triangularity is due to opening of second stability access**
  - Bootstrap current 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**
  - encourages use of this method as a predictive tool for future devices

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Prediction of ITER Pedestal Constraints



Variation in Stability Limits with Triangularity

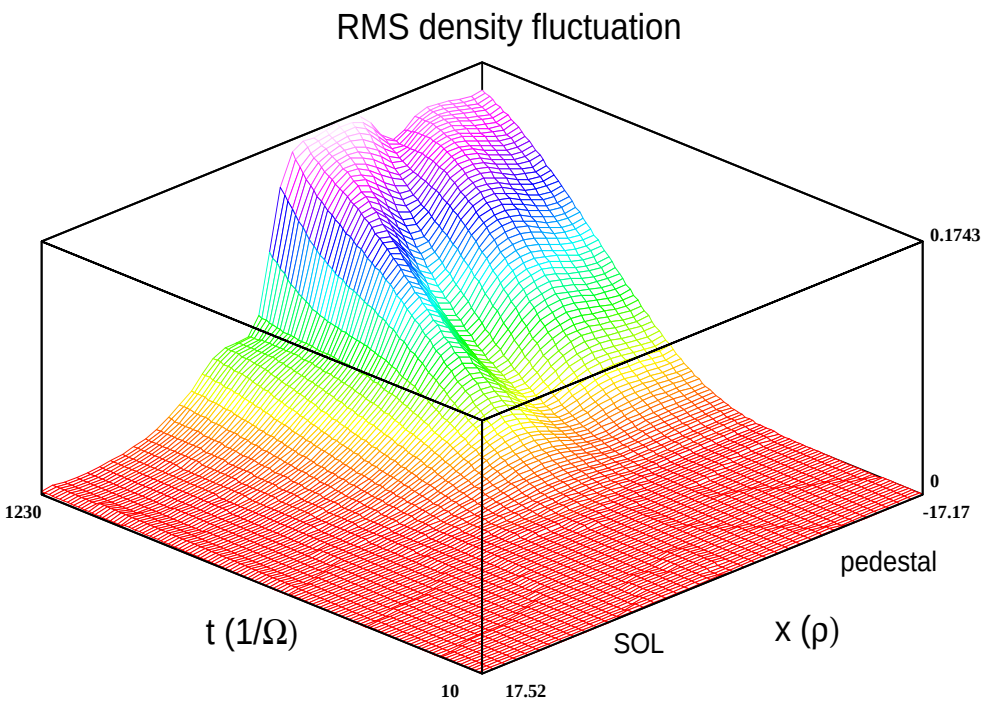


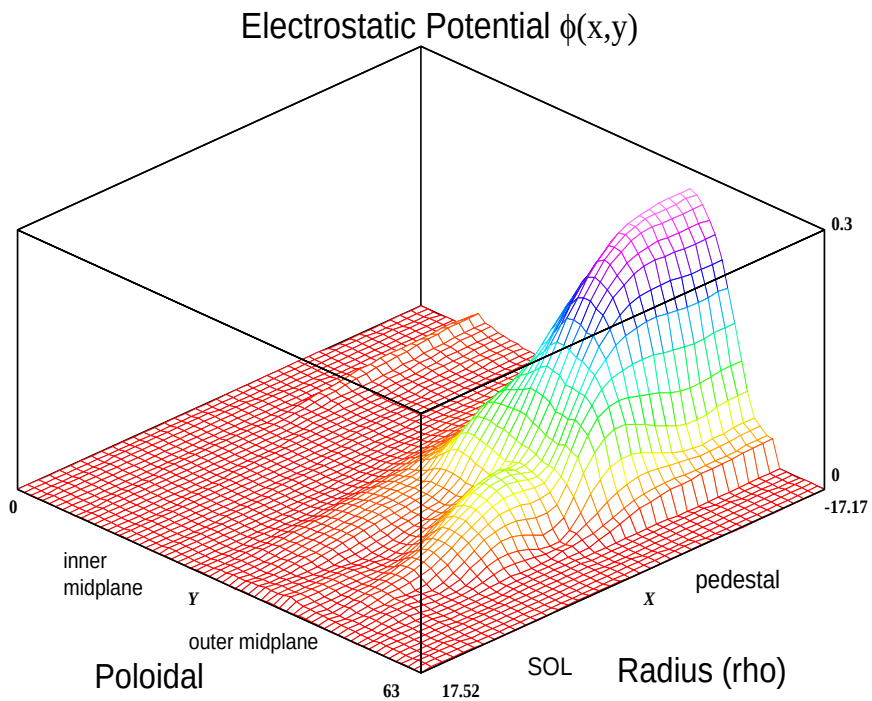
- **High *n* modes limiting at narrow widths, go second stable at wider widths**
- **Pedestal height increases with width, but not linearly (~ $\Delta^{2/3}$)**
- **Reaches adequate pedestal height for predicted high performance in observed range of Δ/a**
  - Increase height by optimizing δ, n_e, including ω_* effects
  - Scaling of pedestal width remains a key uncertainty ***[Osborne CT-3]***

UKAEA Fusion Working with Europe

GENERAL ATOMICS

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

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
  - 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

UKAEA Fusion Working with Europe

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS