Stability and dynamics of the tokamak edge region, with parallel current

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Motivation: Edge Stability

- □ Pressure Pedestal: The pressure at the top of the H-mode edge region, or "pedestal height", plays a key role in determining overall confinement in most theory-based transport models. A wide range of evidence suggests edge stability may determine the pedestal height and/or width.

- □ ELMs: Edge localized modes directly limit performance of high confinement discharges, and can couple to other modes leading to termination of some discharges. Giant ELMs may also cause heat load problems in large reactors.

$\rightarrow$ Want "optimized edge" with high pedestal and small ELMs for high performance with density and impurity control

Background

- ELM stability studies and observed ELM precursors suggest important role for intermediate toroidal mode number instablities ($3 \lesssim n \lesssim 30$)
  - An increasingly wide range of modes ($n \lesssim 10$) can be studied with low-n MHD codes [Ferron NP1.088, Chu]
  - Very high n's expected to be FLR stabilized
  - Conventional ballooning theory not strictly valid in the H-mode edge, edge bootstrap current can drive "peeling" modes, even at high n
  - Edge ballooning theory [Connor, Hastie, Wilson, Miller, Phys. Plas. **5** 2687 (1998)] developed to study coupled peeling and ballooning modes

Edge ballooning/peeling code (`ELITE`) + low-n MHD codes allows study of ideal stability over essentially the full spectrum of n

Caveats:

- `ELITE` includes only the dominant finite-n terms [$\mathcal{O}(n^{-2/3})$]
- both `ELITE` and most low-n codes do not cross the separatrix

The ELITE code

The `ELITE` *(Edge Localized Instabilities in Tokamak Experiments)* code was developed to solve *Connor et al's* Edge Ballooning equations in the edge region, to evaluate the stability of coupled peeling and ballooning modes

- expansion keeps dominant $\mathcal{O}(n^{-2/3})$ correction to the $n = \infty$ eigenvalue, but still requires moderately large $n \gtrsim 10$ for accuracy
- fixed edge surrounded by vacuum

Original local version by *[Wilson, Miller et al, Phys. Plas.* **6** *1925 (1999)]*

- free variation of s and α provides physical insight

New `ELITE` code uses nonlocal, multiple flux surface equilibria (`EFIT` and `TOQ`)

- can treat radially extended modes and strongly shaped cross-sections
- typical domain is outer ~ 45 rational surfaces ($\sim 5-40\%$ of flux)
- realistic, though full equilibrium reconstruction required for each change in parameters

Code fully rewritten in F90, running on workstation. Work in progress on finite inertia and including addition terms in $1/n$ expansion.

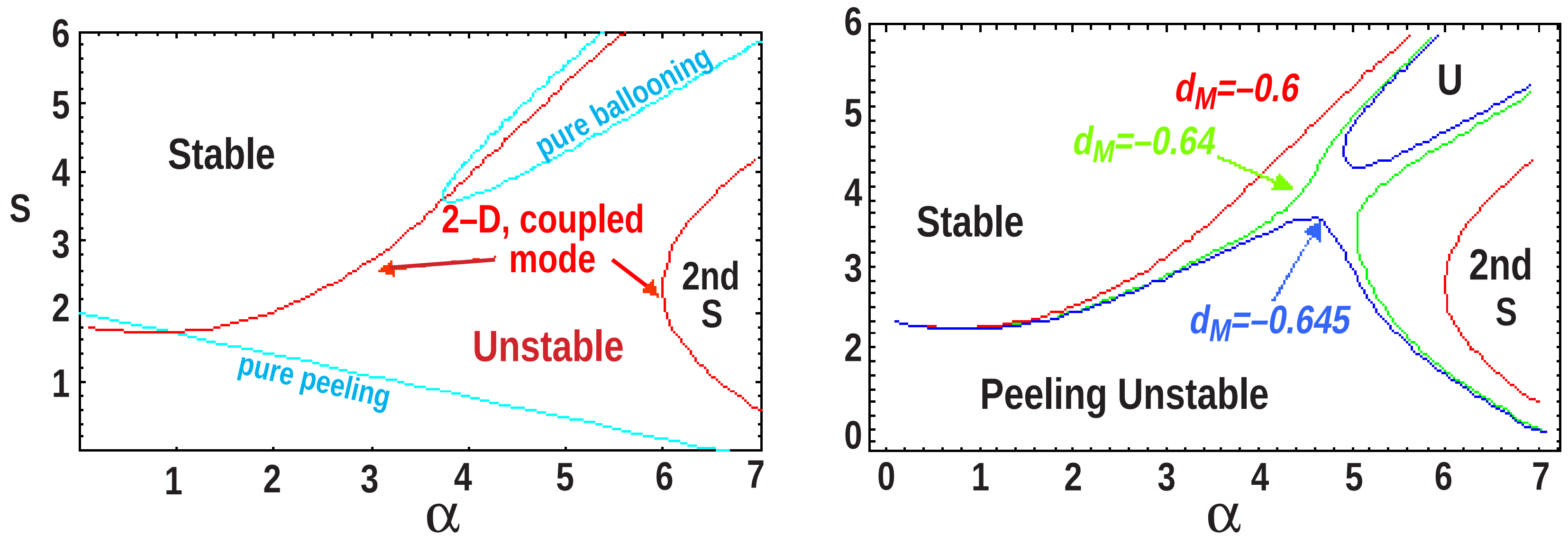
Physical Insight Provided by Analysis in $s - \alpha$ Geometry

- The $s - \alpha$ code uses a shifted circle geometry with the addition of a magnetic well parameter $d_m = D_m s^2/\alpha$ to model the effects of finite aspect ratio and shaping. [Here s is magnetic shear, α is the normalized pressure gradient, and D_m is Mercier's parameter.]

- Nearest vacuum rational surface, which plays a key role in peeling mode stability, is placed at a fixed distance from the plasma edge. Here $\Delta = n(q_{0_{vac}} - q_a) = 0.1$

- $\alpha = -8\pi \frac{Rq^2}{B^2}\frac{dp}{dr}$ is specified at the edge, and decreases inward. Here $\alpha = \alpha_a - \alpha_d(q_a - q)$ with $\alpha_d = 4$.

Peeling and Ballooning Mode Coupling

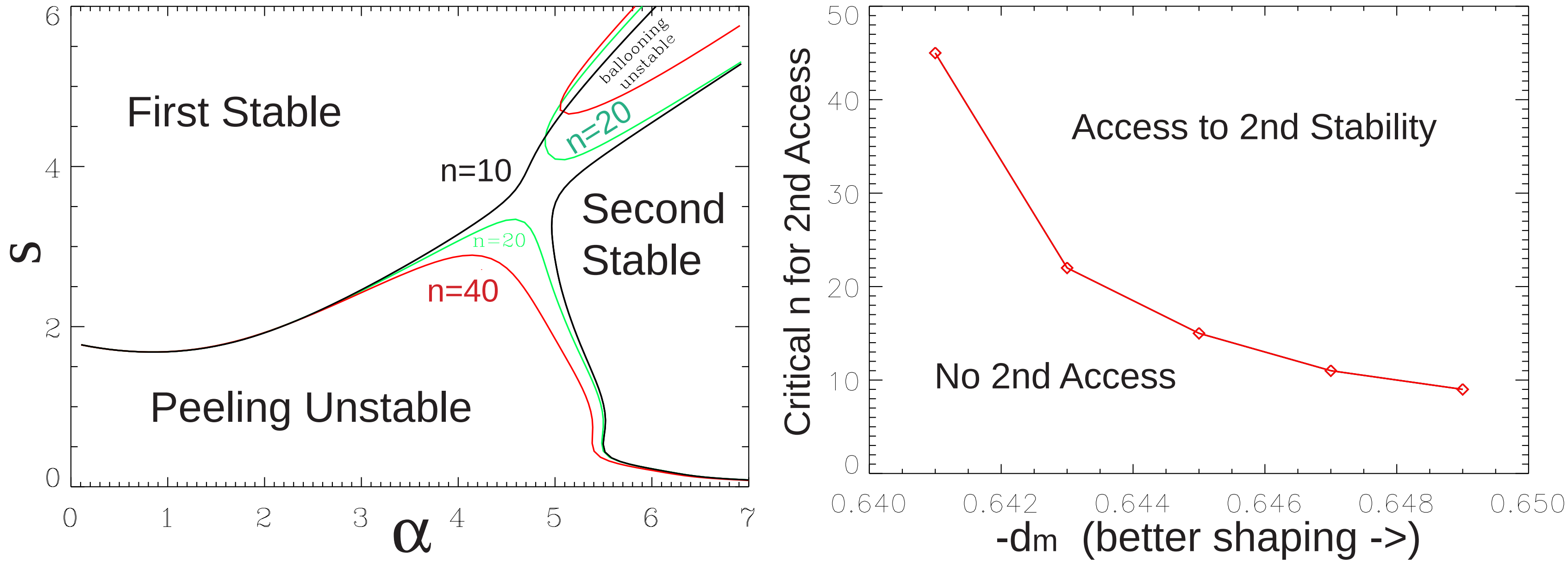


$s-\alpha$ *stability boundaries*, $n=20$, $q_0=4$, $\triangle=0.1$

- The pure ballooning and peeling modes are coupled at finite n, and can restrict access to second stability
- Increasing magnetic well (larger negative d_m) opens up a window to second stability *[Wilson, Miller, Phys. Plas.* **6** *873 (1999)]*

Dependence on Mode Number (n)

- Second stability access is easiest at high-n, while the pressure gradient limit is higher at low n.



- Suggests that discharges with "good" shaping (large negative d_m) can reach a higher edge p' value via access to second stability. However, the first mode to go unstable will have a low n and may therefore cause a large ELM.
- In contrast, discharges with poor shaping (smaller magnetic well) will go unstable at lower p', but the first unstable mode will have large n and may lead to smaller "grassy" ELMs. [Ferron et al Phys. Plasmas **7** (2000) 1976]

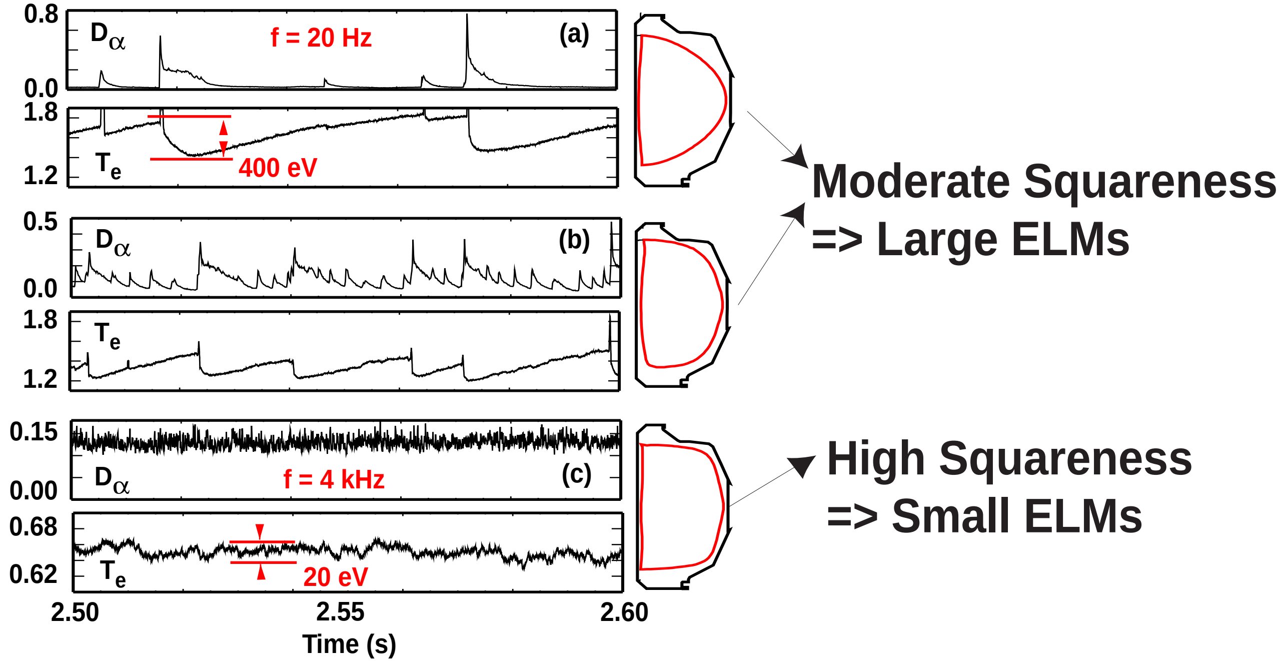
Discussion of $s - \alpha$ results

- Strong dependence on magnetic well suggests careful treatment of edge equilibrium geometry crucial for quantitative analysis

- Results support presence/absence of second stability access as explanation for change in ELM behavior with discharge shape [Ferron et al Phys. Plasmas **7** (2000) 1976, and this meeting]

- Broad mode structure of ballooning modes suggests a local equilibrium expansion about the outer flux surface is inadequate in some cases. Prompted code enhancement to treat nonlocal equilibria.

Case Study: ELM behavior vs. squareness in DIII-D

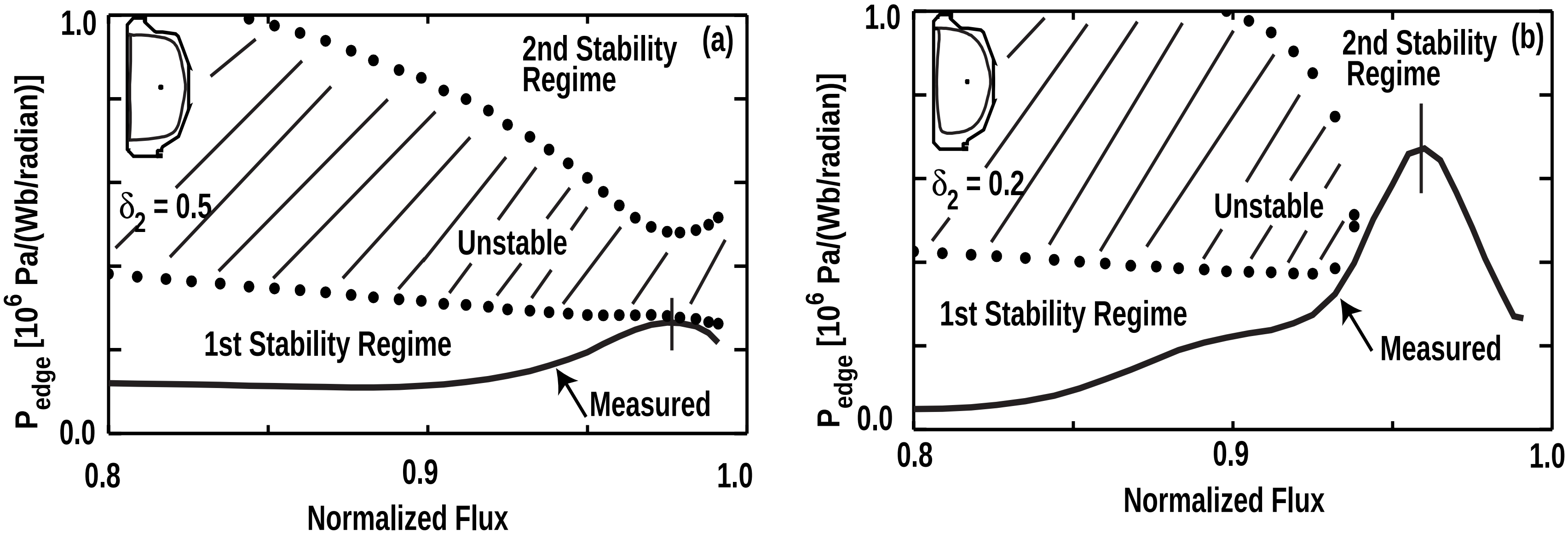


Edge D_α emission, indicating ELM frequency, and edge electron temperature T_e, indicating ELM amplitude, in shots with varying squareness (δ_2), (a) $\delta_2 = 0.05$ (b) $\delta_2 = 0.2$ (c) $\delta_2 = 0.5$.

- Moderate squareness ($0.05 \lesssim \delta_2 \lesssim 0.2$) shots reach high p' with large, infrequent ELMs [Cross section characterized by triangularity (δ) and squareness (δ_2), where $R(\theta) = R_0 + a\cos(\theta + \sin^{-1}\delta\sin\theta)$, $Z(\theta) = \kappa a \sin(\theta + \delta_2 \sin 2\theta)$. Here squareness is varied while other quantities are approximately fixed.]

- High squareness ($\delta_2 \sim 0.5$) shots have small, high frequency ELMs, and low edge p'

Infinite-n Ballooning Analysis



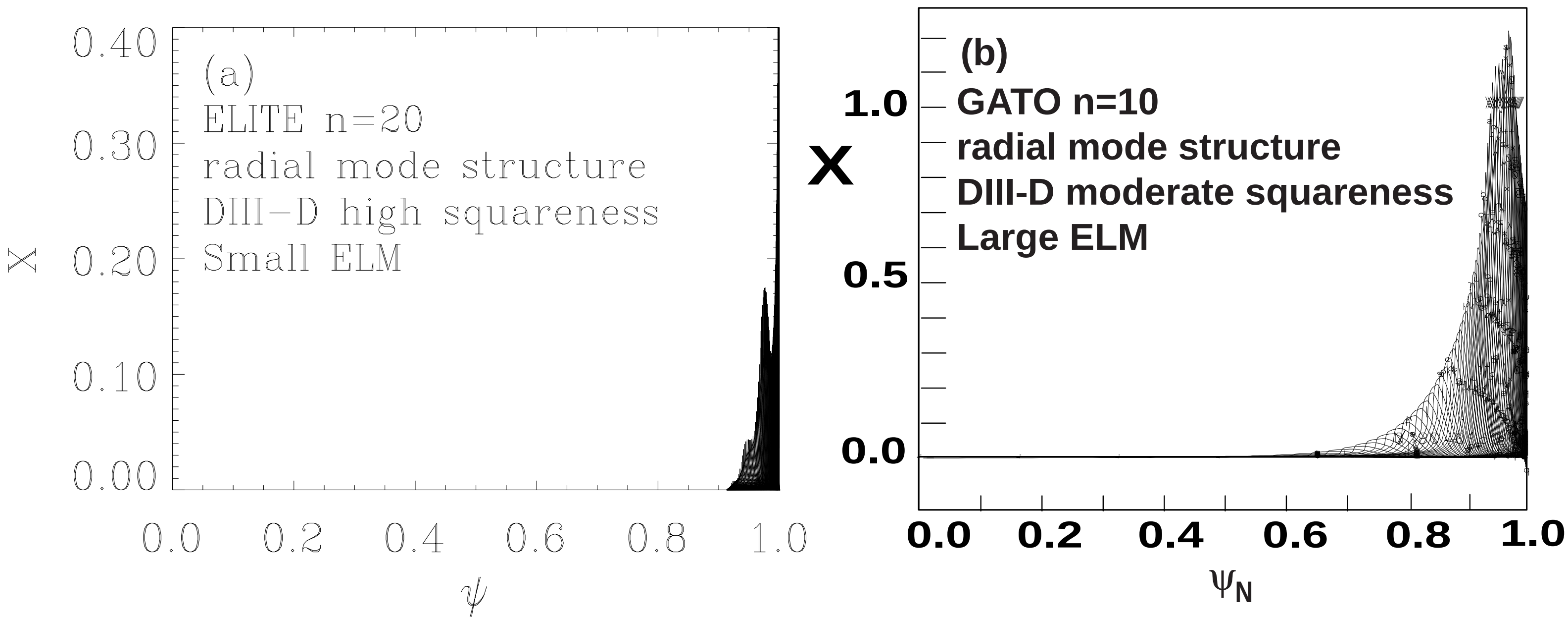
Measured edge pressure gradient, and infinite-n conventional ballooning stability boundaries (a) during high frequency ELMs in a high squareness ($\delta_2 = 0.5$) discharge and (b) during low frequency ELMs in a moderate squareness case ($\delta_2 = 0.2$)

- Infinite-n analysis suggests that moderate squareness shots have second stability access in the edge while high squareness shots do not
- Result must be carefully checked with finite-n analysis, including coupled peeling and ballooning modes

Low to Intermediate n Stability Analysis

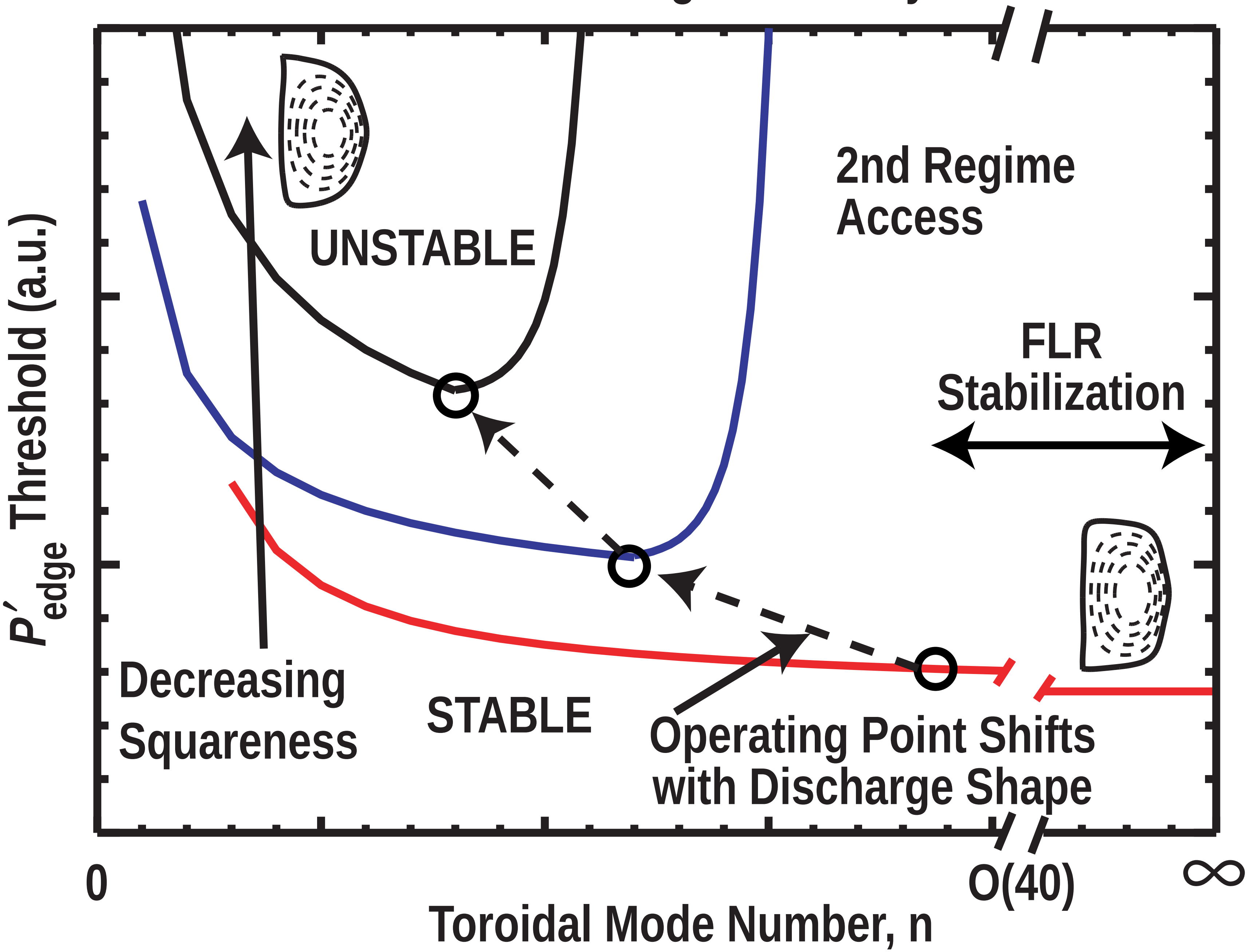
MHD stability analysis using model equilibria with hyperbolic tangent pressure profiles and bootstrap current finds:

- High-squareness shots are stable to low $n \lesssim 10$ modes for the observed p' values, but unstable to higher $n \gtrsim 20$ peeling/ballooning modes
- Moderate squareness shots are (second) stable at high n, but approach the threshold for low $5 \lesssim n \lesssim 10$ instability. Critical p' decreases with n.



Radial mode structure of the (a) n=20 instability in the high squareness case (b) n=10 instability in the moderate squareness case

Schematic of Ideal MHD Edge Instability Thresholds



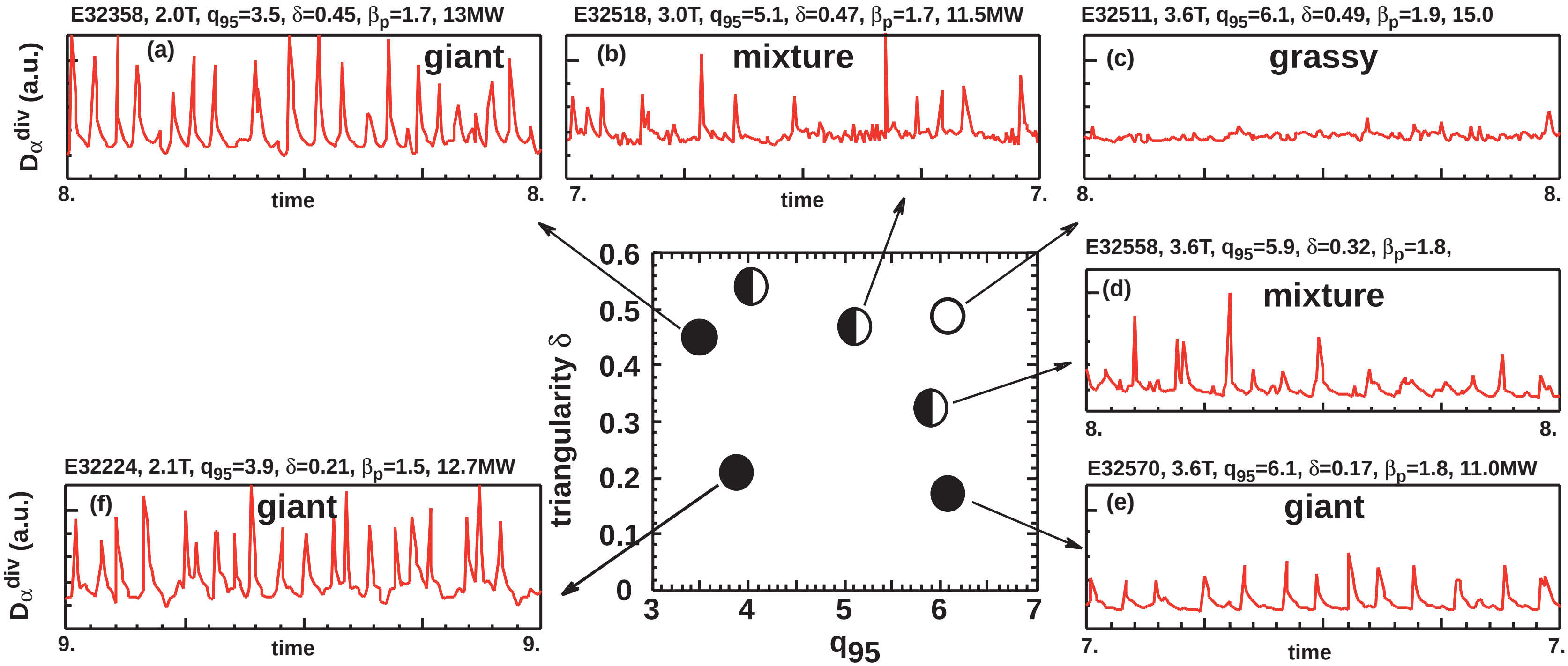
ELM model developed from MHD stability calculations on DIII-D

MHD Stability analysis on DIII-D using several codes (GATO, ELITE, BAL-MSC, DCON) leads to a model of edge stability and ELMs

- First mode to go unstable is approximately the lowest n without second stability access
- Size of ELM correlated to radial mode width of first unstable n
  - In DIII-D, low-n modes tend to be broader
  - get large ELMs for “good” shapes (eg moderate squareness) which allow second stability access to high n modes
  - small ELMs when there is little or no second access (eg high squareness)

[Ferron et al Phys. Plasmas **7** (2000) 1976, and this meeting]

JT-60U ELM Behavior Seems Different

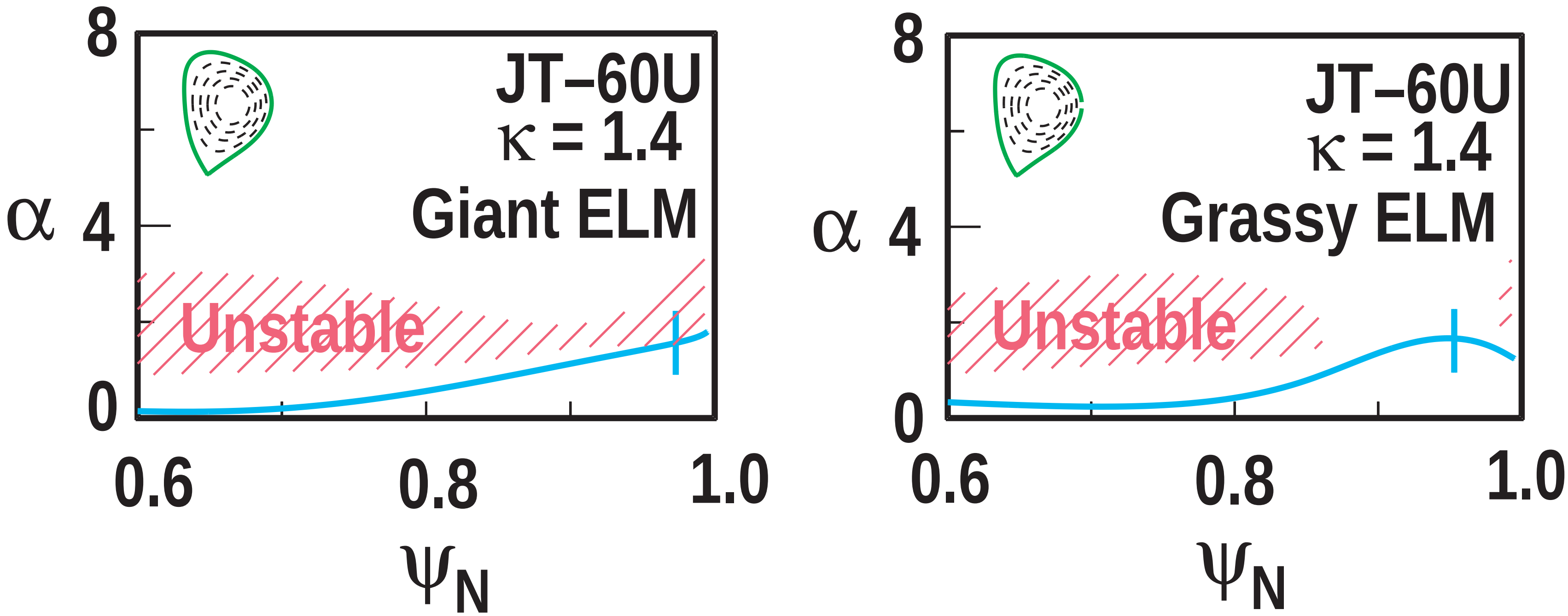


Change in ELM character with q_{95}, triangularity, and β_p on JT-60U

[Y. Kamada et al PPCF **42** *A247 (2000)]*

- Giant ELMs observed in regions where ballooning instability is expected. Small ("grassy") ELMs seen where second stability access is expected.
- Choose a giant ELM shot (32358) and a grassy ELM shot (32511) for closer analysis

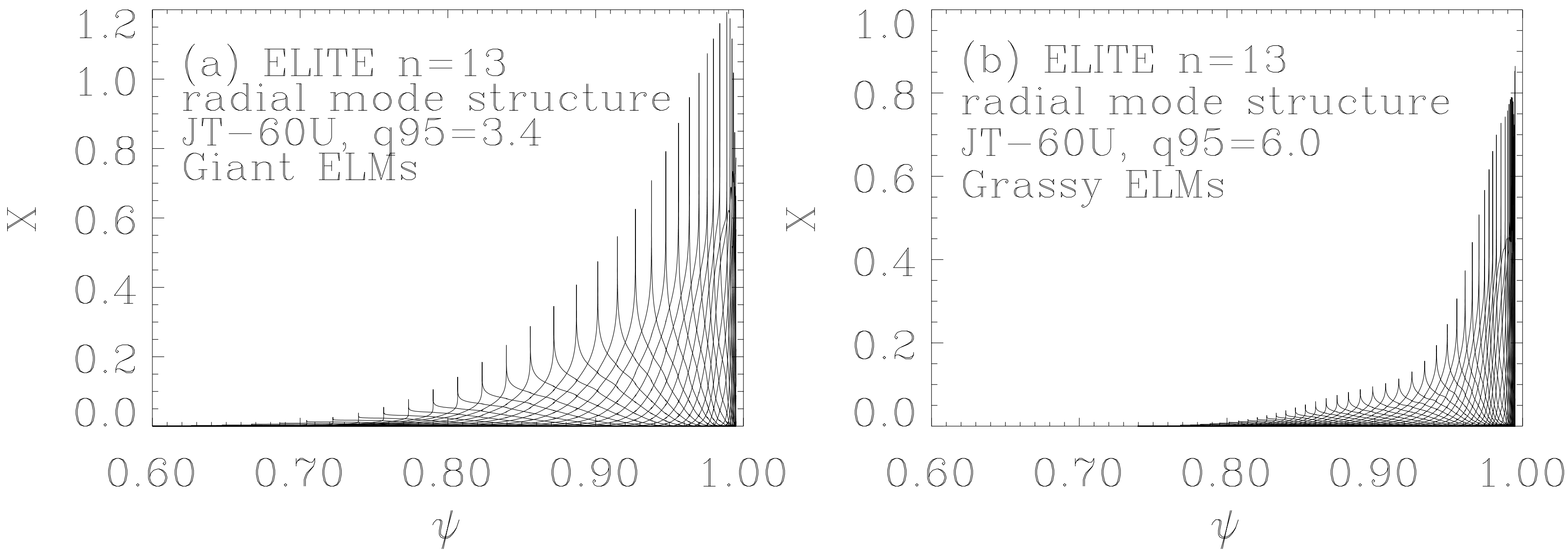
JT-60U Edge Ballooning Analysis



Comparison of edge ballooning stability for JT-60U shots with (a) giant ELMs, $q_{95} \sim 3.4$ (b) small "grassy" ELMs, $q_{95} \sim 6.0$
[L. Lao et al IAEA-CN-77/EXP3/06 (2000)]

- JT-60U sees large ELMs when shots have no second stability access
- small ELMs with second access (though p' hardly exceeds nominal first ballooning limit)

Intermediate n analysis shows JT-60U Edge also Consistent with Model



Radial mode structure of marginally stable modes for JT-60U cases with (a) giant ELMs, $q_{95} \sim 3.4$ (b) small "grassy" ELMs, $q_{95} \sim 6.0$

- Radial width of most unstable mode corresponds to ELM size, as in DIII-D
- Grassy ELM case has 2nd stability at infinite n, but not for intermediate n modes, leading to a pressure gradient near the nominal ballooning limit

Speculative Implications for Pedestal Scaling

Much unknown about dynamics of p', $J_{bootstrap}$, $\gamma_{E\times B}$

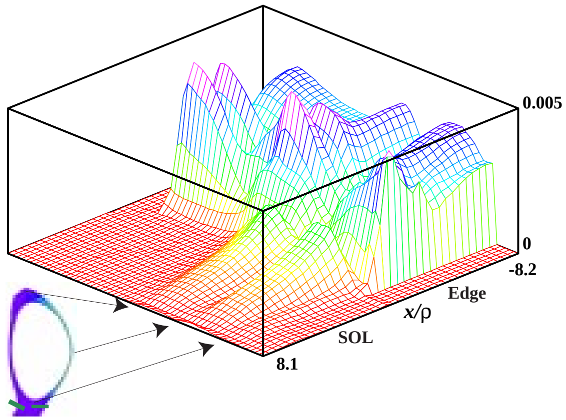
Speculations on scaling of edge barrier gradient (p') and width (Δ)

- Commonly assumed that p' set by ideal ballooning limit
  - Good fit in shots without "deep" second stability access (where intermediate $n \gtrsim 15$ are second stable)
  - Many DIII-D shots have "deep" access, and exceed nominal ballooning limit by factors of 2-5 [Osborne, Ferron, Groebner]
    - What limits p' with "deep" access? Transport? Low-n stability?
  - "Deep" access not seen so far on JT-60U, p' close to ballooning limit
  - May need to divide database into shots with and without access to get consistent scaling
- Pedestal width often assumed to be related to $\gamma_{E\times B} > \gamma_{micro} \rightarrow \Delta \sim \rho_\theta$
  - Possible that finite-n, finite width MHD rather than tranport physics sets width, particularly with 2nd stability ($\Delta \sim \beta_p^{0.4}$ on DIII-D)
  - Perhaps width is set by minimum of a) region where $E \times B$ strong enough to stabilize microturbulence b) maximum finite-n MHD stable width given above p' - but dynamics are a real issue here

On DIII-D, high pedestals usually have giant ELMs which need to be avoided in a reactor (QDB on DIII-D, EDA on C-Mod, Grassy ELMs on JT-60U etc)

Nonlinear Simulations with BOUT

- Ultimately need nonlinear simulations including non-ideal effects and X-point geometry to study ELM dynamics and test models
- BOUT code [X. Q. Xu et al Nucl. Fusion **40** 731] evolves the nonlinear Braginskii equations on both sides of the separatrix - parallel current terms are being added



Contour plot of the electrostatic potential (ϕ) vs. the normalized radial (x) and poloidal coordinates, in the linear phase of a BOUT *simulation with parallel current. Equilibrium is ideal ballooning unstable. Peaks in ϕ near the top and bottom of the machine highlight the impact of X-point geometry on ballooning-type modes.*

Summary and Future Work

ELITE code, together with low-n MHD codes, can study the ideal edge stability of nonlocal tokamak equilibria over essentially the entire toroidal spectrum

The behavior of intermediate to high-n instabilities is significantly altered by $J_{bootstrap}$, peeling/ballooning coupling and finite-n effects

A case study of different shaped equilibria in DIII-D finds that changes in cross section shape can open or close access to the second stability regime for ballooning-like modes.

- Suggests an explanation for the different p' and ELM types seen in different shaped discharges

ELM model based on ideal MHD stability of detailed equilibria, including edge current and second stability access, appears consistent with DIII-D and JT-60U results

- ELM size correlates with radial width of most unstable mode

X-point geometry and non-ideal effects need to be considered. Nonlinear simulations using the BOUT code with parallel current terms are being undertaken to assess the importance of these effects and to further elaborate ELM dynamics.