Optimized beta limits in DIII-D advanced tokamak discharges: global and edge

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General Atomics

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STEADY-STATE ADVANCED TOKAMAK OPERATION AT HIGH BETA IN DIII–D IS BEST ACHIEVED IN A STRONGLY-SHAPED DISCHARGE WITH A BROAD PRESSURE PROFILE

- Focus is on modification of the present successful scenario with 100% noninductively driven current
- Goal of a high fraction of bootstrap current leads to exploration of methods to maximize $q_{min}\ \beta_N$
- Without modification of the pressure profile, the maximum achieved β_N decreases with increasing q_{min}
- With a broadened pressure profile, $q_{min}\ \beta_N$ is maximized at the highest q_{min} tested
  - Modeling indicates that $\beta_N = 5$ should be possible
- Increases in beta limits with elongation and triangularity motivate double-null divertor operation

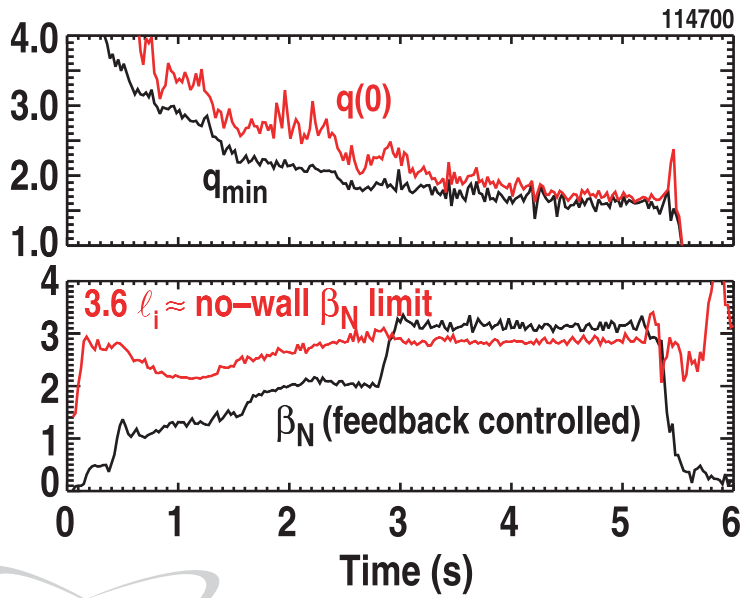
BALANCING THE REQUIREMENTS FOR STEADY-STATE OPERATION AND HIGH FUSION GAIN LEADS TO A SCENARIO WITH HIGH q_{min} β_N

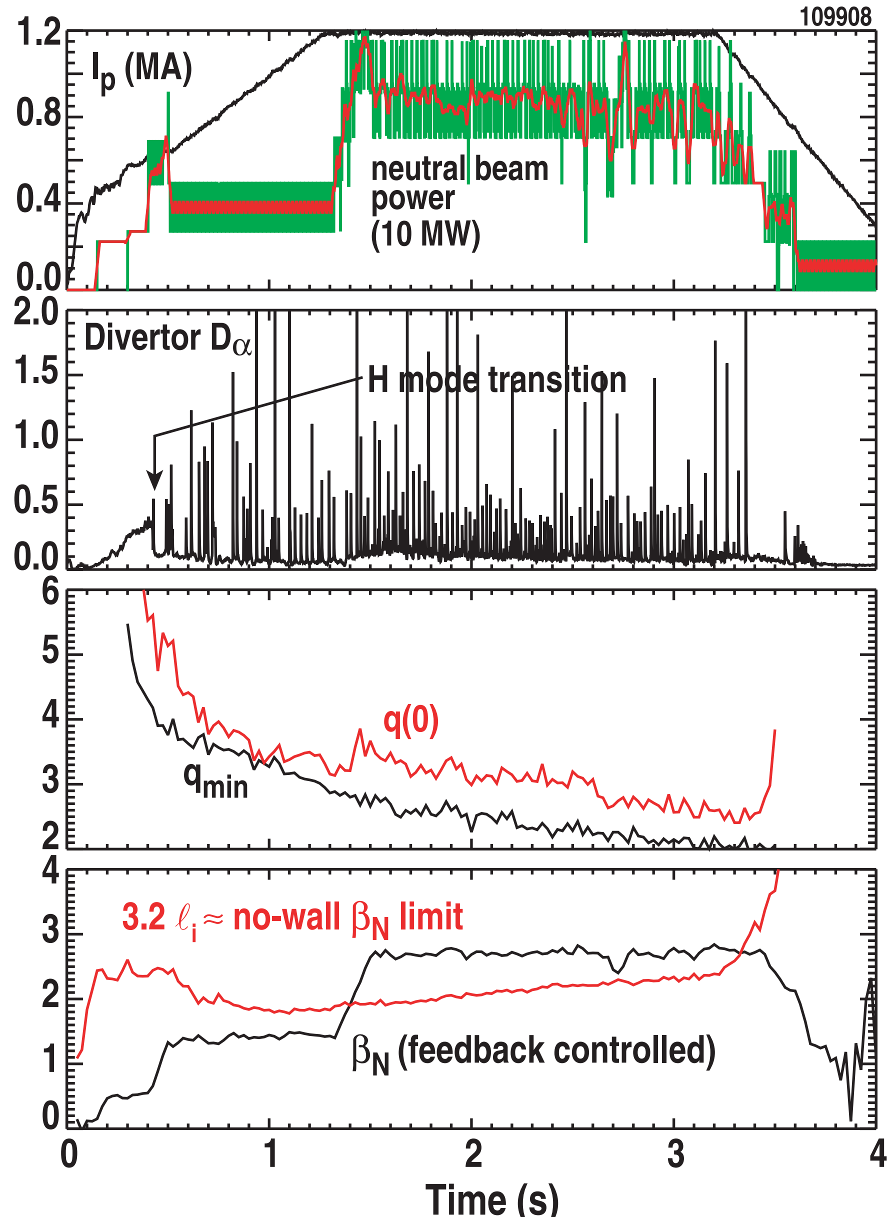
- **Steady state:** requires a large bootstrap current fraction
  $f_{BS} \propto \beta_p \propto q\beta_N$
- Motivates operation with elevated q across the entire profile
- For high fusion gain $\propto \beta\tau_E \propto \beta_N H_{89}/q_{95}^2$, increase q_{min} rather than q_{95}
- Highest possible β_N to maximize fusion gain and f_{BS}
- Off-axis electron cyclotron current drive (ECCD) used to regulate current profile
  - Efficiency increases with β_e
- Divertor exhaust pumping to control H–mode density
  - For relevant collisionality and efficient ECCD
  - Presently in DIII–D, this requires an upper single-null divertor shape

SCALING WITH q_{min}

THE q PROFILE IS VARIED BY MODIFYING THE DISCHARGE FORMATION OR DELAYING THE HIGH BETA PHASE

- Increased T_e in H-mode slows rate of current penetration
- $1.5 < q_{min} < 3$, $q_{95} \approx 5$
- Two examples, $q_{min} \approx 2.5$, $\beta_N = 2.7$ and $q_{min} \approx 1.7$, $\beta_N = 3.2$ run without significant MHD for discharge duration





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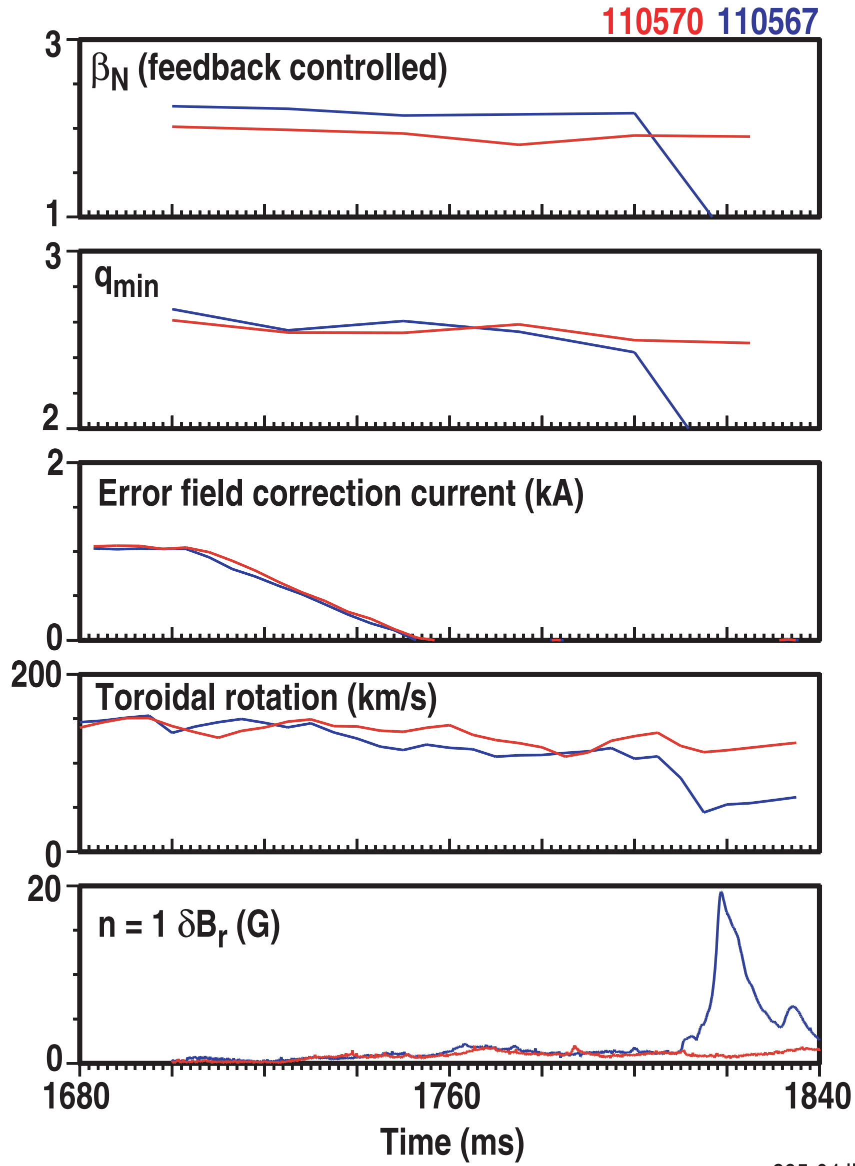
THE NO-WALL β_N LIMIT IS MEASURED BY MONITORING STABILITY AS THE CORRECTING CURRENT FOR NONAXISYMMETRIC FIELDS IS REMOVED

- For β_N above the no-wall limit, the drag on toroidal rotation is enhanced because of the plasma response to the nonaxisymmetric fields

- Rotation decreases significantly to below the critical level for n = 1 resistive wall mode stabilization



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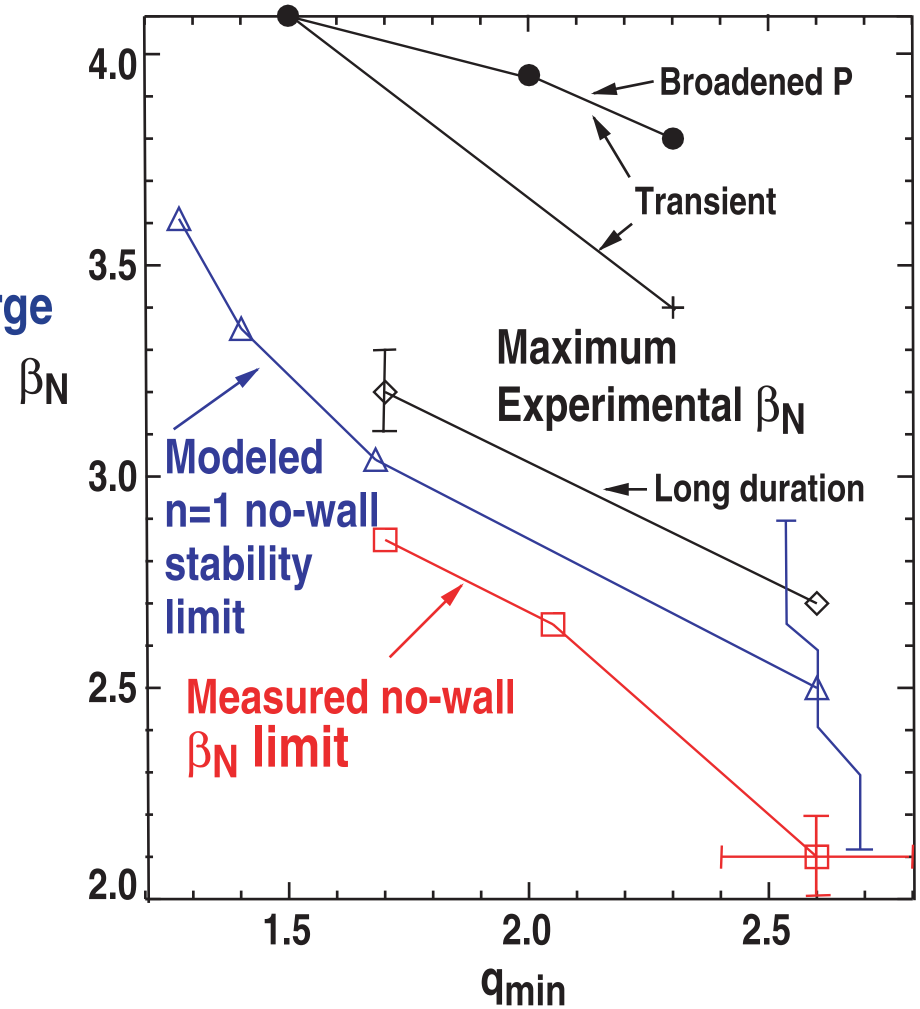
MEASURED NO-WALL β_N LIMIT AND MAXIMUM EXPERIMENTAL β_N DECREASE AS q_{min} INCREASES

- Trend is the same for the n = 1 no-wall stability limit calculated for model equilibria
- High β_N for the full DIII–D discharge duration without MHD is limited to 10% – 30% above measured no-wall limit
- Dependence of maximum achievable β_N on q_{min} reduced by broadening pressure profile



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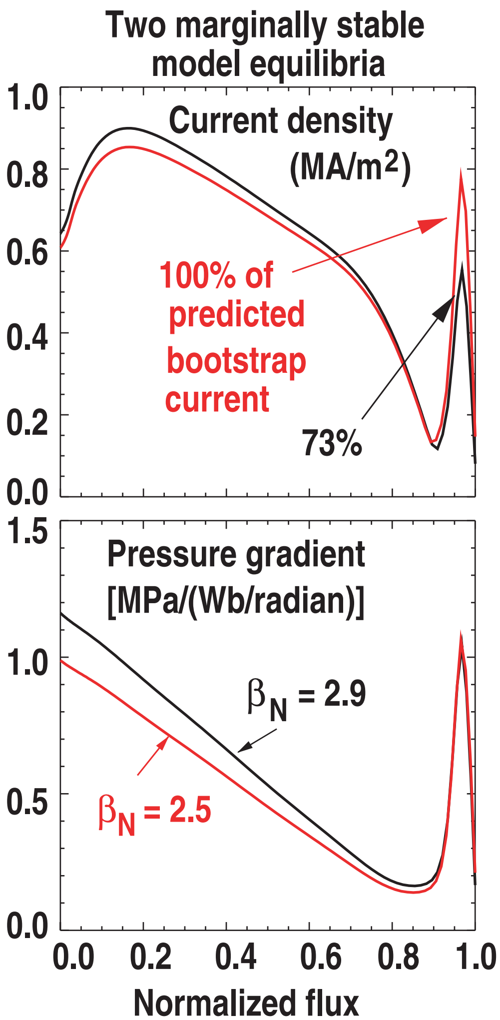
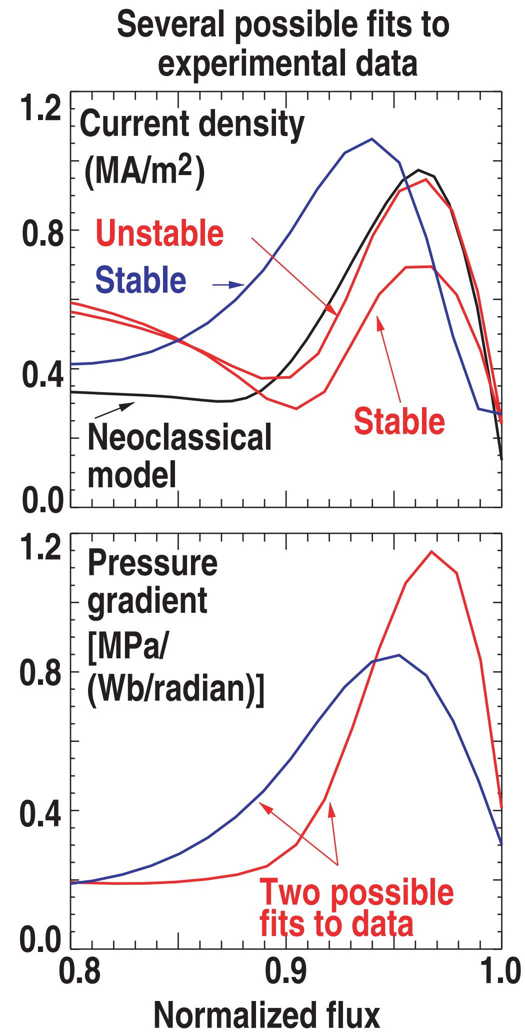
QUANTITATIVE AGREEMENT BETWEEN THE MEASURED NO-WALL β_N LIMIT AND THEORY DEPENDS ON VALUES OF H-MODE PEDESTAL J AND P′



- Increased $J_{pedestal}$ is destabilizing
- Stability is sensitive to the position of P′ and J peaks
- Peak J matching neoclassical bootstrap plus ohmic best matches experimental observation of an instability



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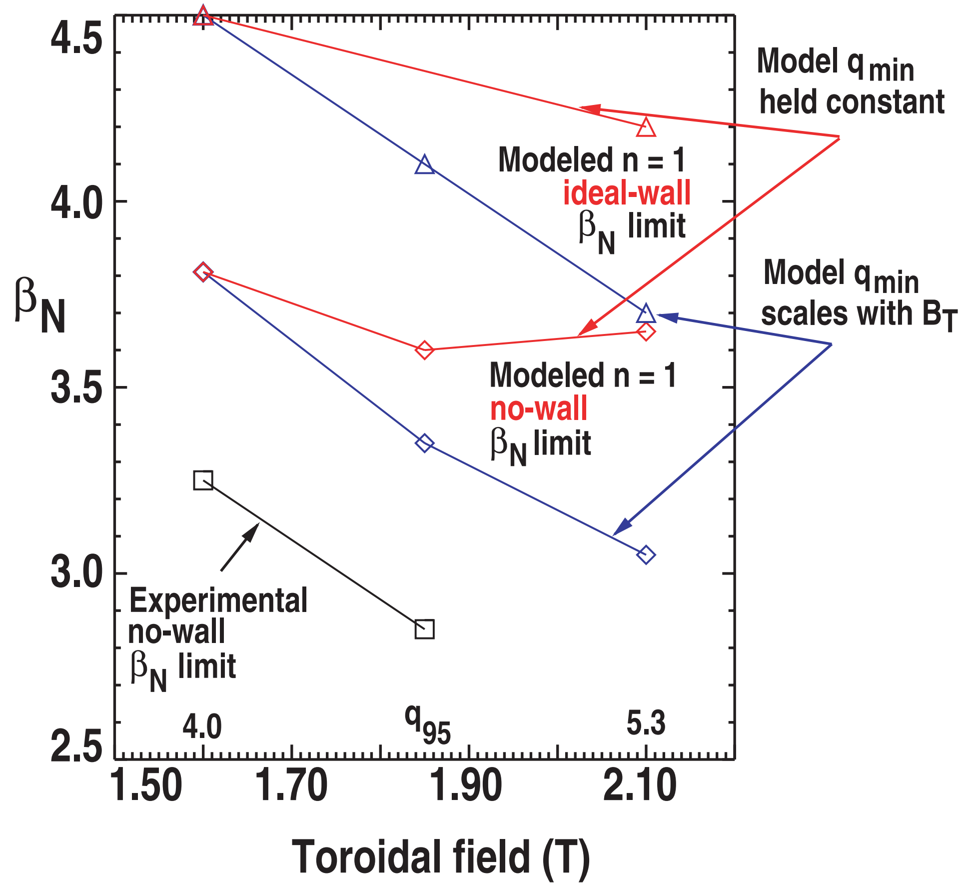
q_{95} FOR STEADY-STATE EXPERIMENTS IS CHOSEN TO MAXIMIZE THE EXPERIMENTALLY ACHIEVABLE β_N

- Modeled n = 1 stability limits show a decrease with increasing B_T (q_{95})
- Trend with q_{95} of measured no-wall limit agrees with the modeling
  - Quantitative difference results from different q_{min} values



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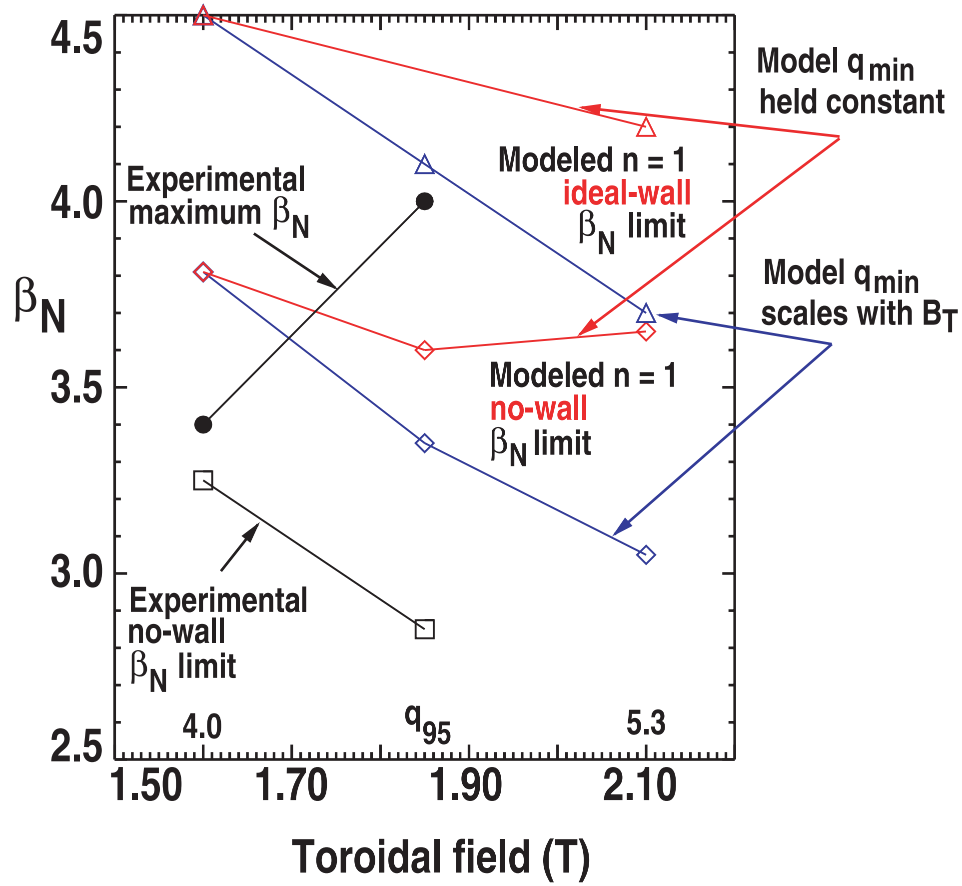
- Modeled n = 1 stability limits show a decrease with increasing B_T (q_{95})
- Trend with q_{95} of measured no-wall limit agrees with the modeling
  - Quantitative difference results from different q_{min} values
- Operation closer to the ideal-wall limit at increased B_T is responsible for the increase in achievable β_N



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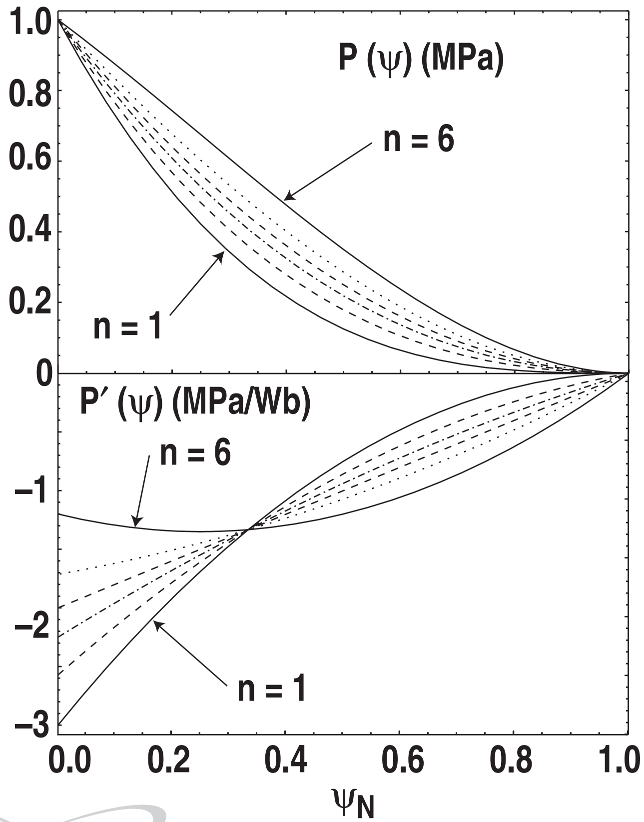
EFFECT OF BROADENED PRESSURE PROFILE

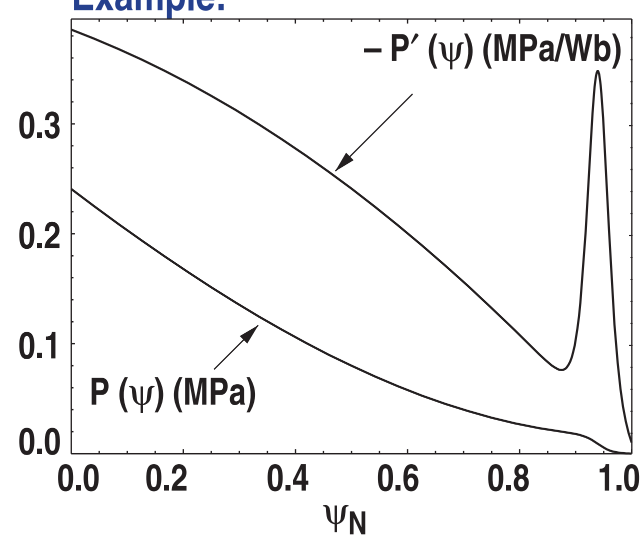
A MODELING STUDY INVESTIGATED THE DEPENDENCE OF β_N LIMITS ON THE PRESSURE GRADIENT PROFILE SHAPE IN f_{BS} > 70% EQUILIBRIA

- Core P′ specified by a family of polynomials:
  - $P'(\psi) = 1 + b_n\psi - (1 + b_n)\psi^2$



- Hyperbolic tangent form used for H-mode edge pressure pedestal:
  - Based on experiment scaling
  - $P_{ped} \propto I_p^2 (1+\beta_p)^{0.9}(1+\delta)^{2.11}(1+\kappa^2)^{-1.15}$
- Total pressure = core + pedestal
  - $P(0)/\langle P \rangle$ ranges from 2 to 4.5

Example:



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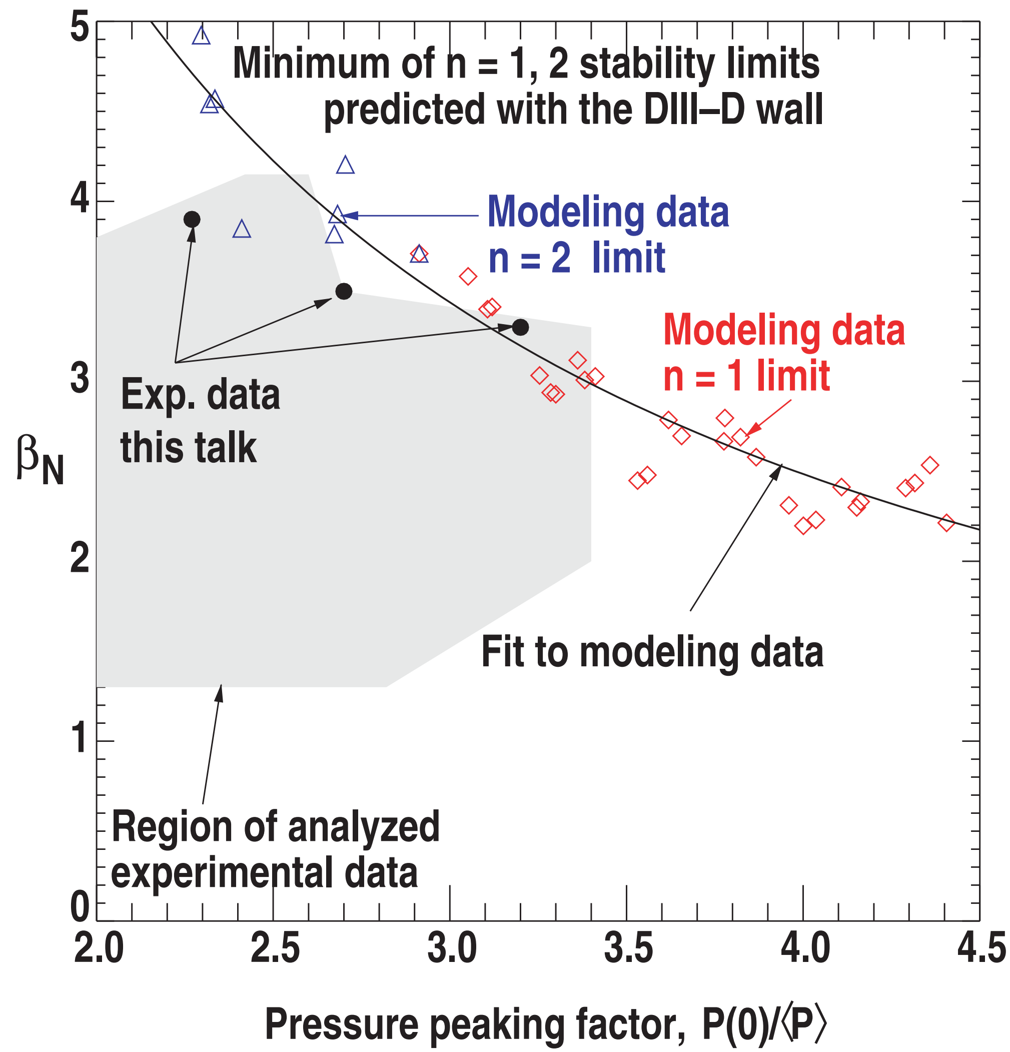
PREDICTED β_N LIMITS DECREASE STRONGLY AS THE PRESSURE PROFILE BECOMES MORE PEAKED

- n = 2 is the limit for P(0)/⟨P⟩ < 3
- Scatter results from the range of discharge shapes included
- Model equilibria have $q_{min} \approx 2$
- Predicted values agree roughly with the experimental data
- Fit:
  $\beta_N = 11.9[P(0)/\langle P\rangle]^{-1.13}$



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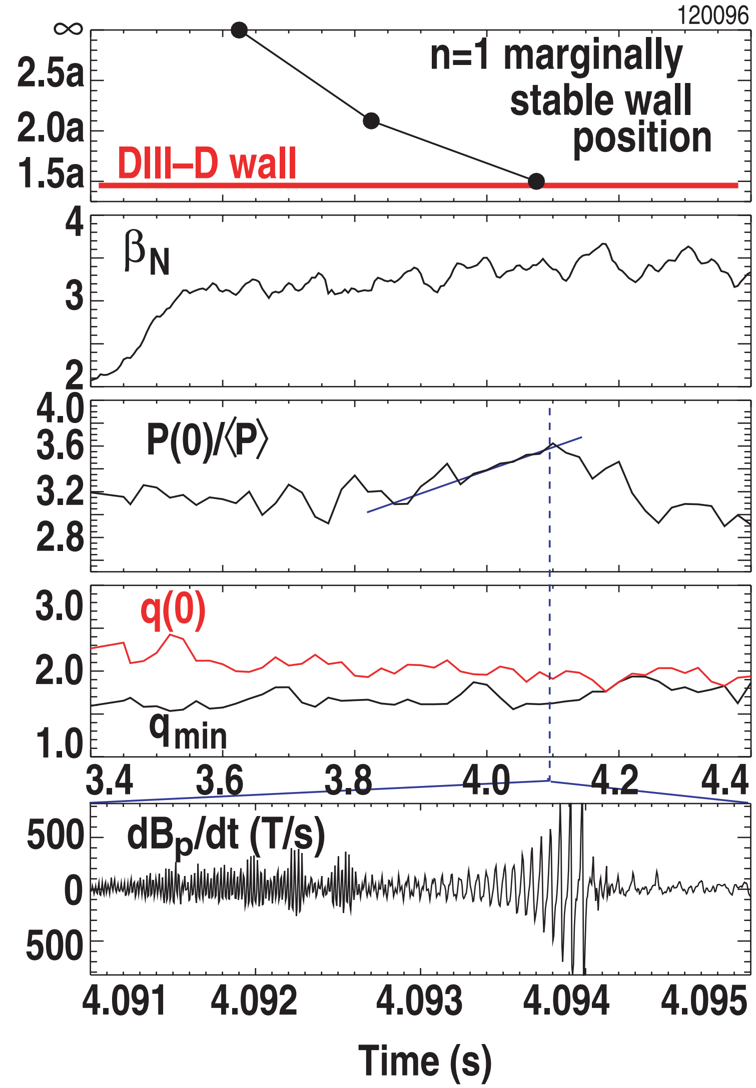
WITH EFFICIENT PARTICLE EXHAUST PUMPING $P(0)/\langle P\rangle$ IS HIGH AND β_N LIMIT IS REDUCED

- Pumping reduces $n_e^{pedestal}$, core neutral beam fueling increases $n_e(0)$
- There is weak negative central shear that leads to a weak internal transport barrier, further peaking n_e, T_i
- Internal mode grows on a rapid time scale
  - Kink mode phasing similar to pressure gradient driven resistive interchange
  - Initiates reduction in P peaking and change in bootstrap profile
  - In some discharges, a disruption immediately follows the mode



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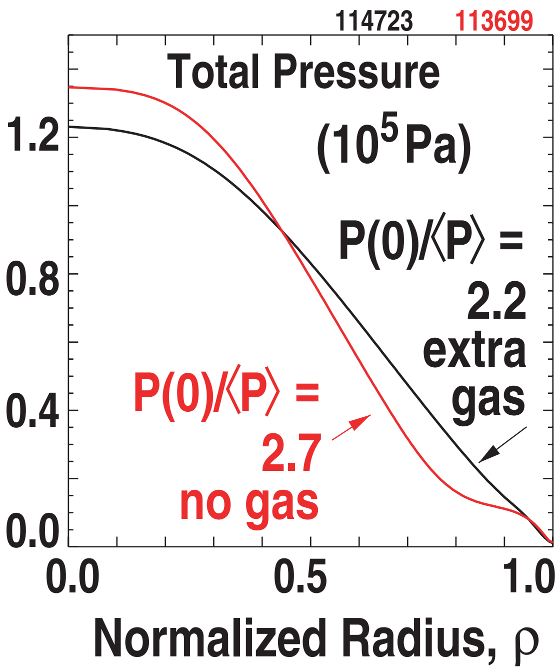
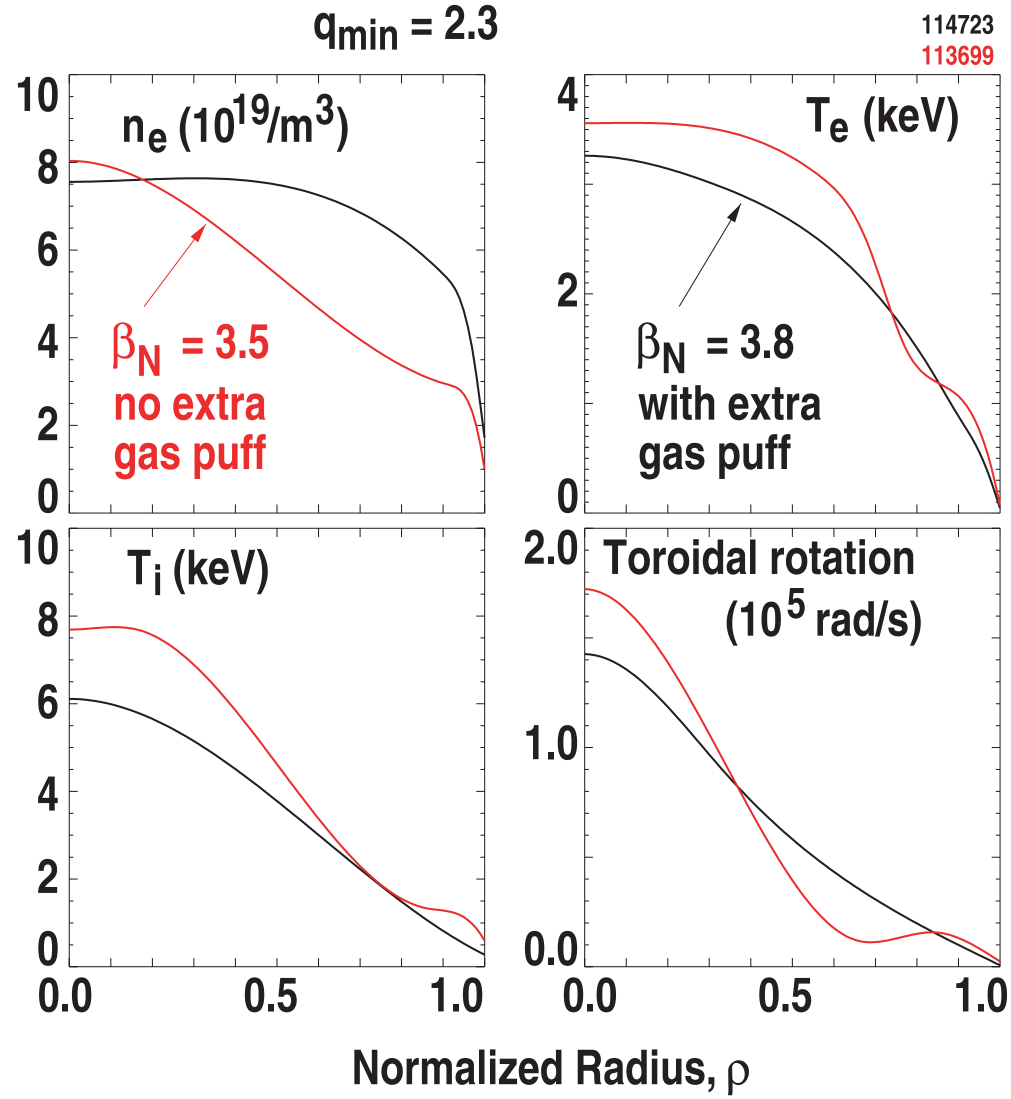
IN THE EXPERIMENT, A BROADER PRESSURE PROFILE AND HIGHER β_N WERE OBTAINED BY BROADENING THE DENSITY PROFILE WITH EXTRA GAS PUFFING





- P(0)/⟨P⟩ = 2.2 versus 2.7
- In the case without the gas puff, P(0)/⟨P⟩ is enhanced because core rotational shear increases

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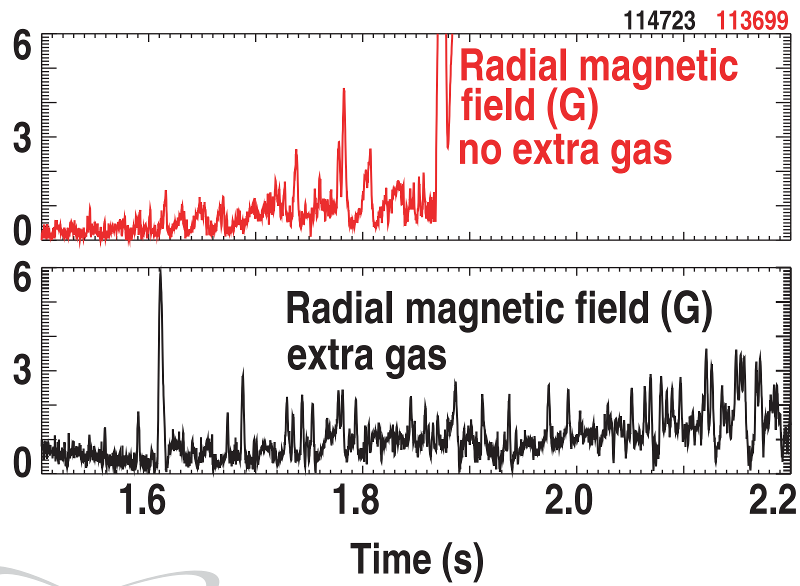
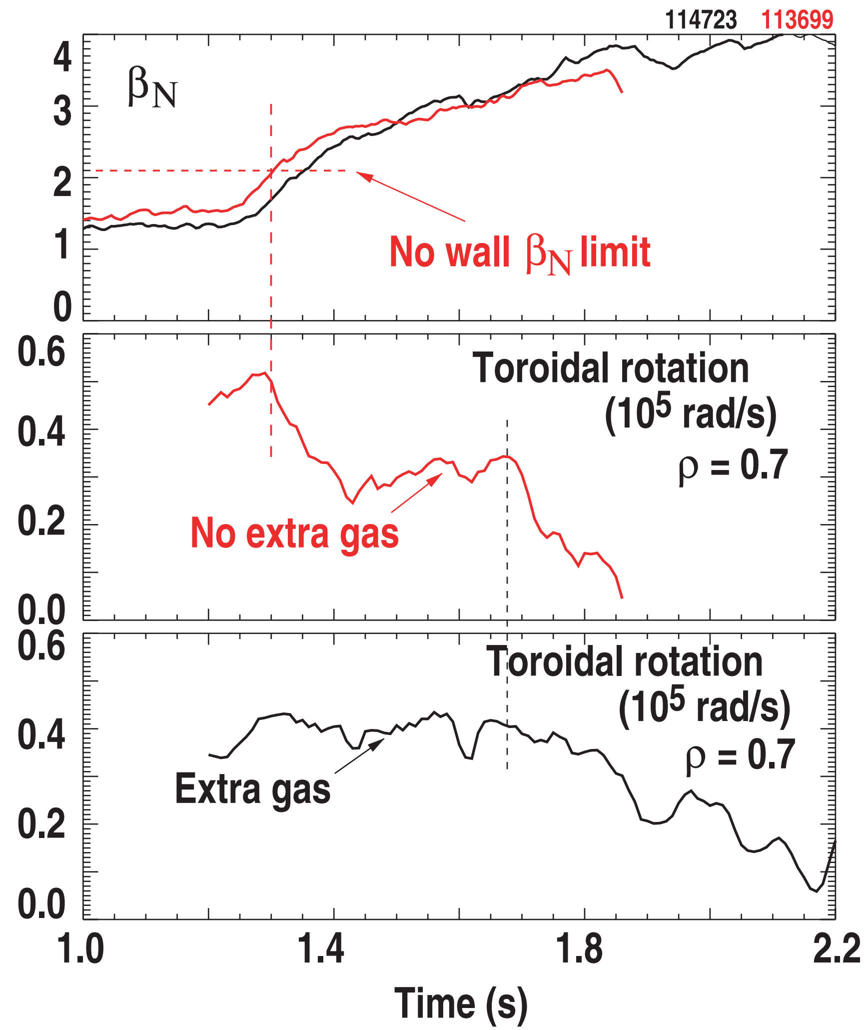
BROADER PRESSURE PROFILE ALLOWS BETA TO CONTINUE RISING TO $\beta_N = 4$ at $q_{min} = 2$

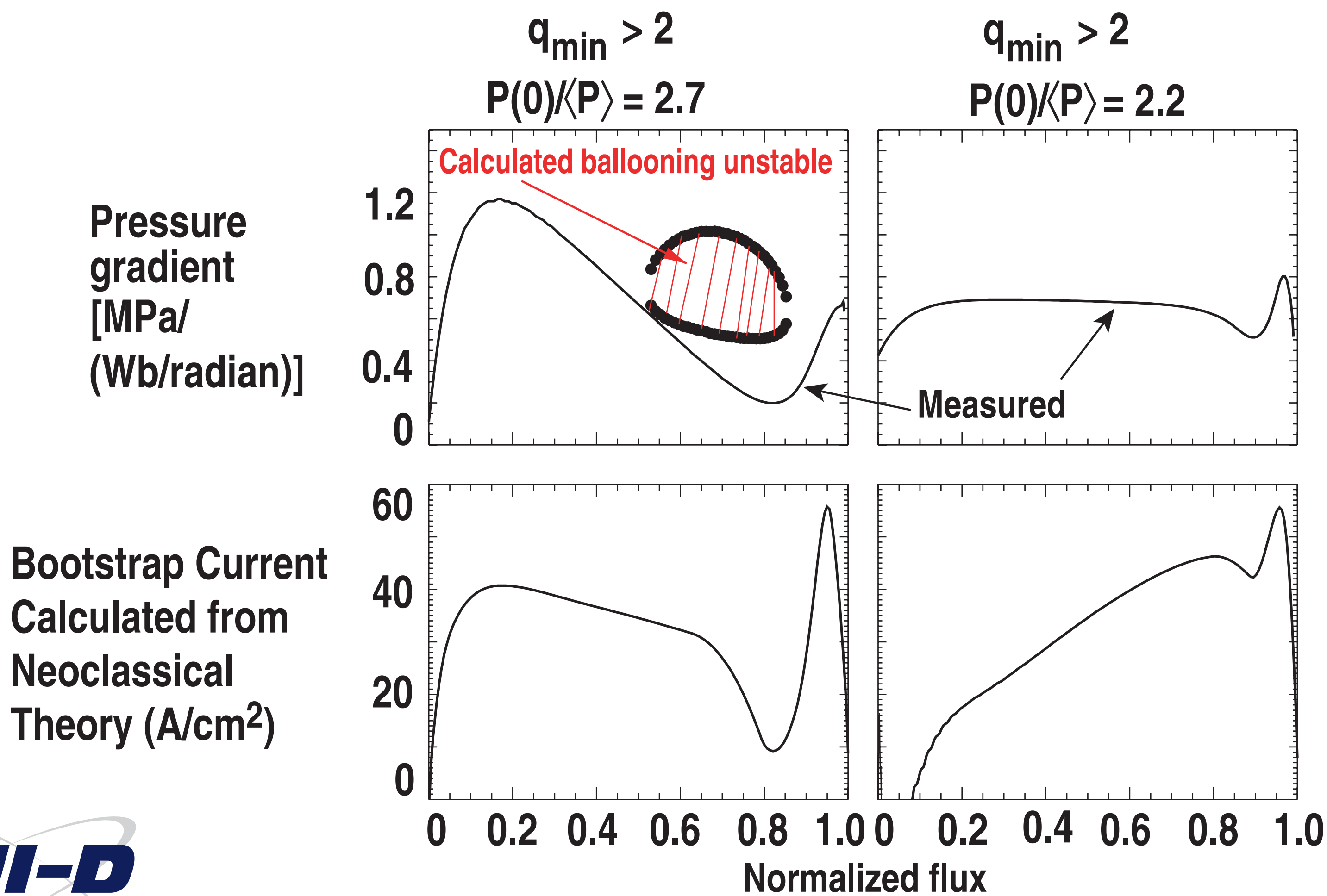
- Rotation decreases as β_N passes above the ideal no-wall limit as a result of the enhanced plasma response to external, nonaxisymmetric fields
- Drop in rotation to near 0 as β_N approaches the maximum value results from low level n = 1 resistive wall mode activity





BROAD PRESSURE IS POSSIBLE BECAUSE OF ACCESS TO THE INFINITE-n BALLOONING MODE SECOND STABLE REGIME ACROSS THE FULL PROFILE

- Normally there is a region where $dP/d\psi$ is limited by ballooning stability
- Magnetic shear profile modified by broadening bootstrap current



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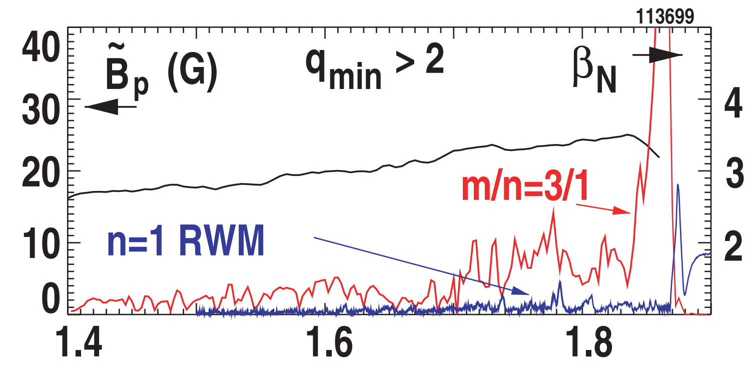
EVEN WITH β_N NEAR THE IDEAL-WALL LIMIT, THE HIGH BETA PHASE ALMOST ALWAYS ENDS AS A RESULT OF A TEARING MODE, NOT A KINK MODE

- $q_{min} > 2$, more peaked pressure:
  n = 1 tearing mode locks to low level
  n = 1 RWM



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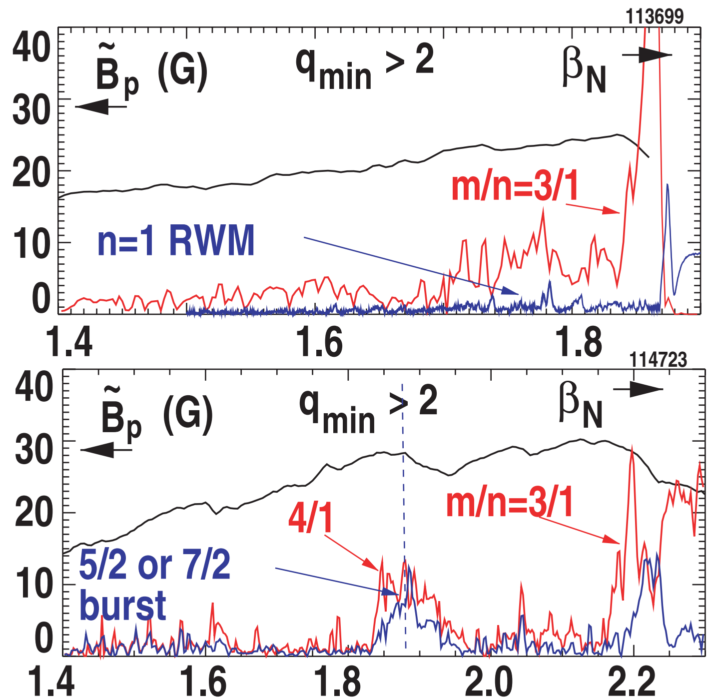
- **q_{min} > 2, more peaked pressure:**
  n = 1 tearing mode locks to low level
  n = 1 RWM
- **q_{min} > 2, broad pressure:**
  3/1 mode grows to large amplitude.
  Earlier n = 5/2 or 7/2 burst briefly reduces beta



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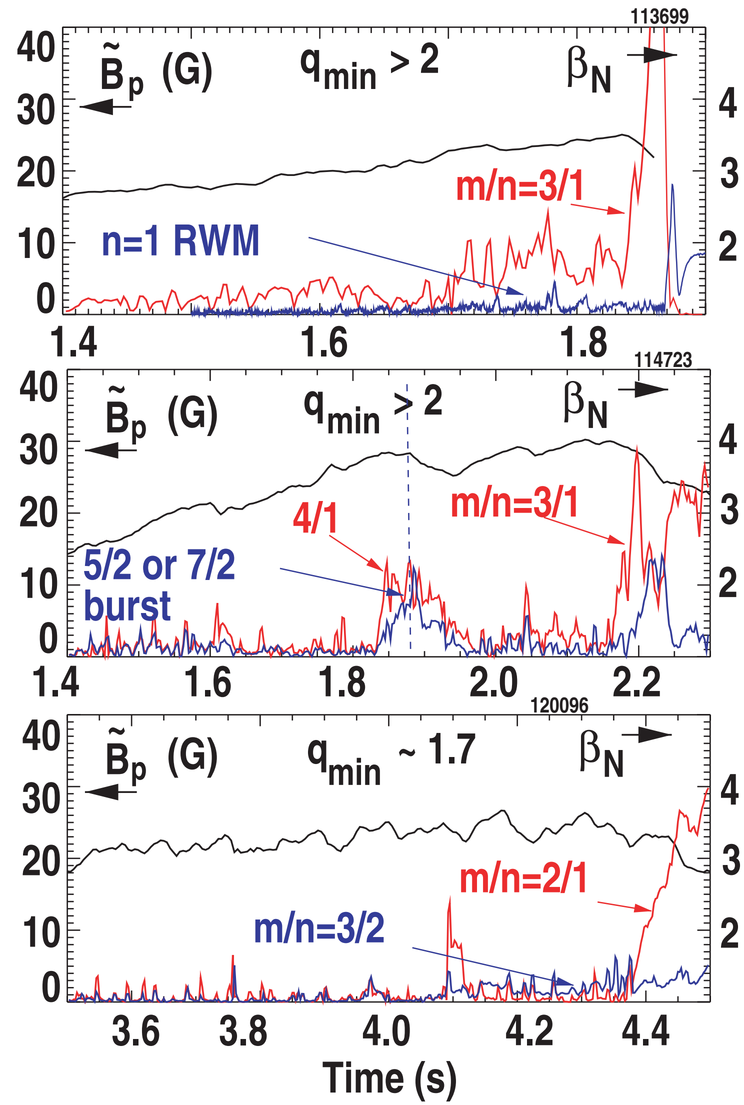
  n = 1 tearing mode locks to low level
  n = 1 RWM
- **$q_{min} > 2$, broad pressure:**
  3/1 mode grows to large amplitude. Earlier n = 5/2 or 7/2 burst briefly reduces beta
- **$q_{min} \approx 1.7$:** 2/1 mode grows to large amplitude. Earlier fast growing n = 1 kink-type mode triggers 3/2 tearing
- **Even if q_{min} is maintained above 2 to avoid the 2/1 tearing mode, other modes with larger m/n can still have significant effects on confinement**



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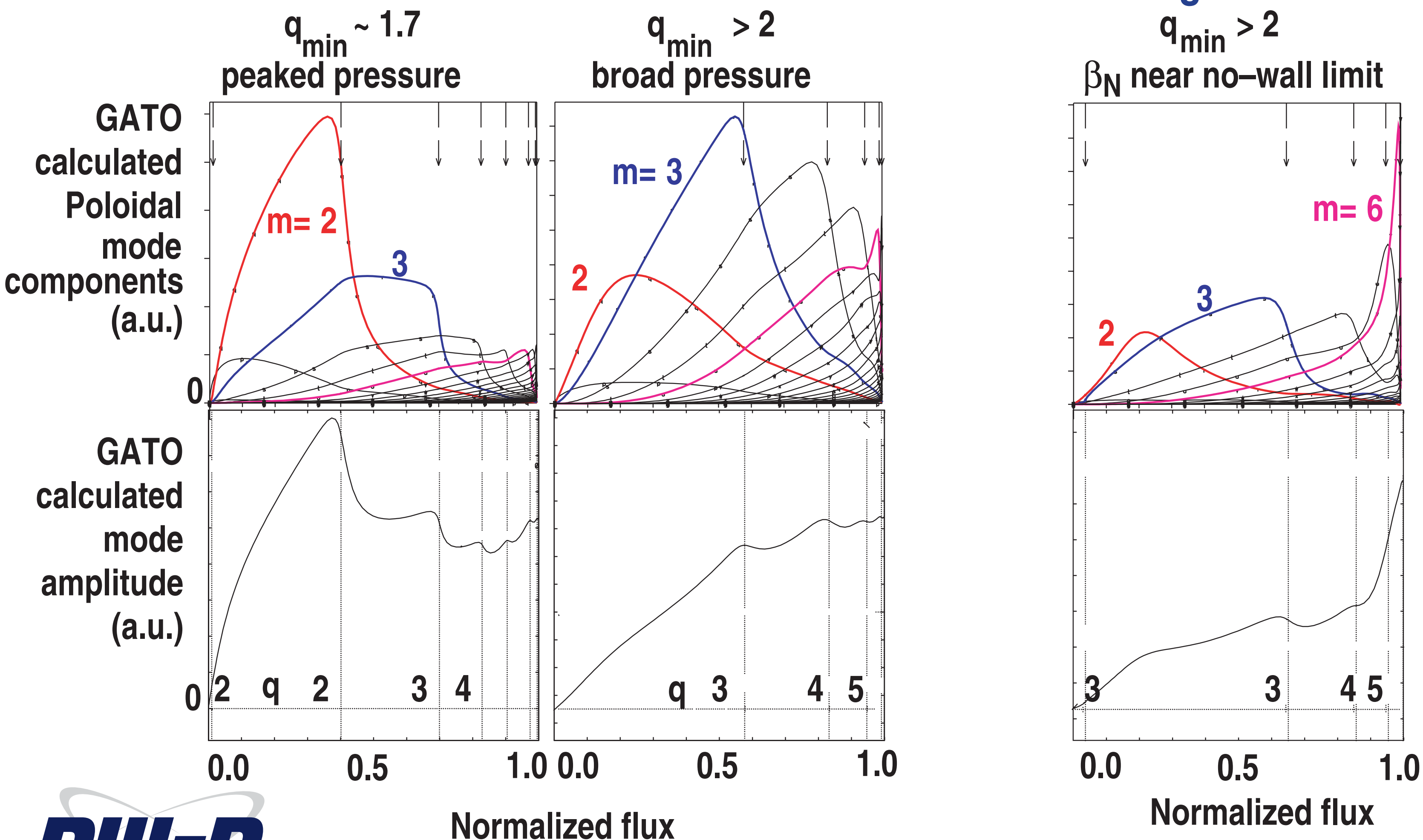
THE CALCULATED STRUCTURE OF THE UNSTABLE n=1 MODE ILLUSTRATES THE REGIONS OF THE DISCHARGE MOST STRONGLY AFFECTING STABILITY

- Peaked pressure, $q_{min} \approx 1.7$: m = 2, mode peaks in the core
- Beta near no-wall limit: m = 6,7, mode peaks at the edge



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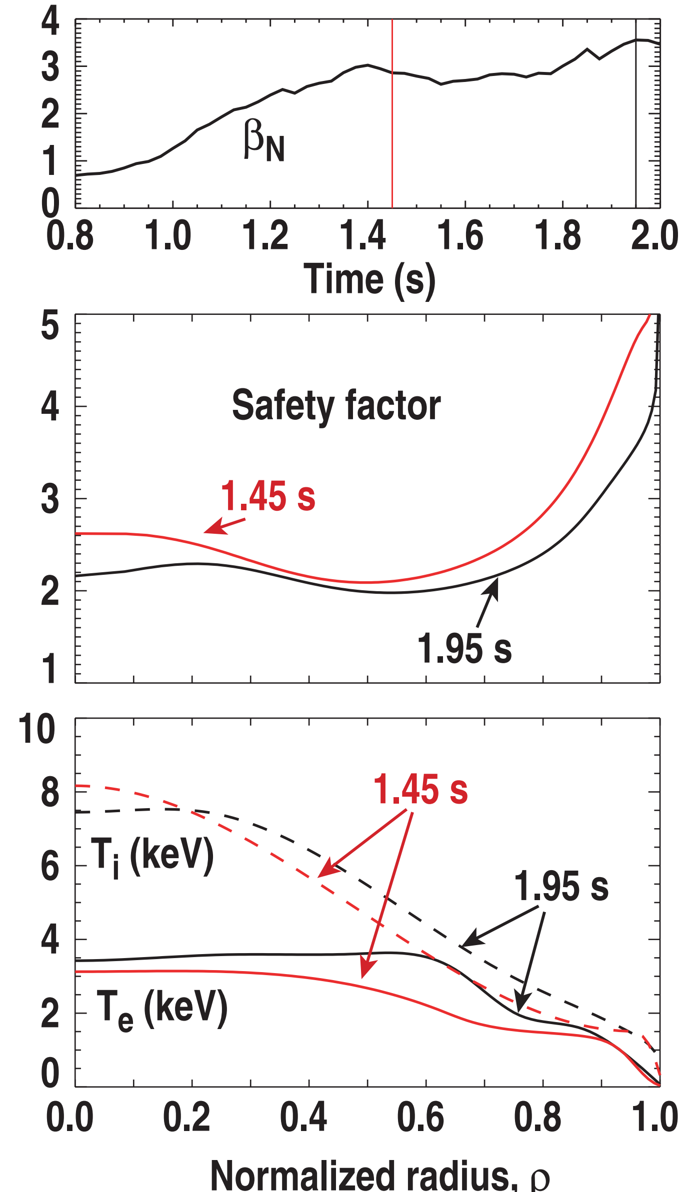
A RELATIVELY FLAT q PROFILE WITH LARGE $\rho(q_{min})$ IS UNDER STUDY AS A WAY TO BROADEN THE PRESSURE PROFILE

- Preliminary results show broadening of temperature profiles as q_{95} decreases and $\rho(q_{min})$ increases

- A safety factor profile with qmin > n (n integer) and q95 < n + 1 could be a way to avoid tearing modes



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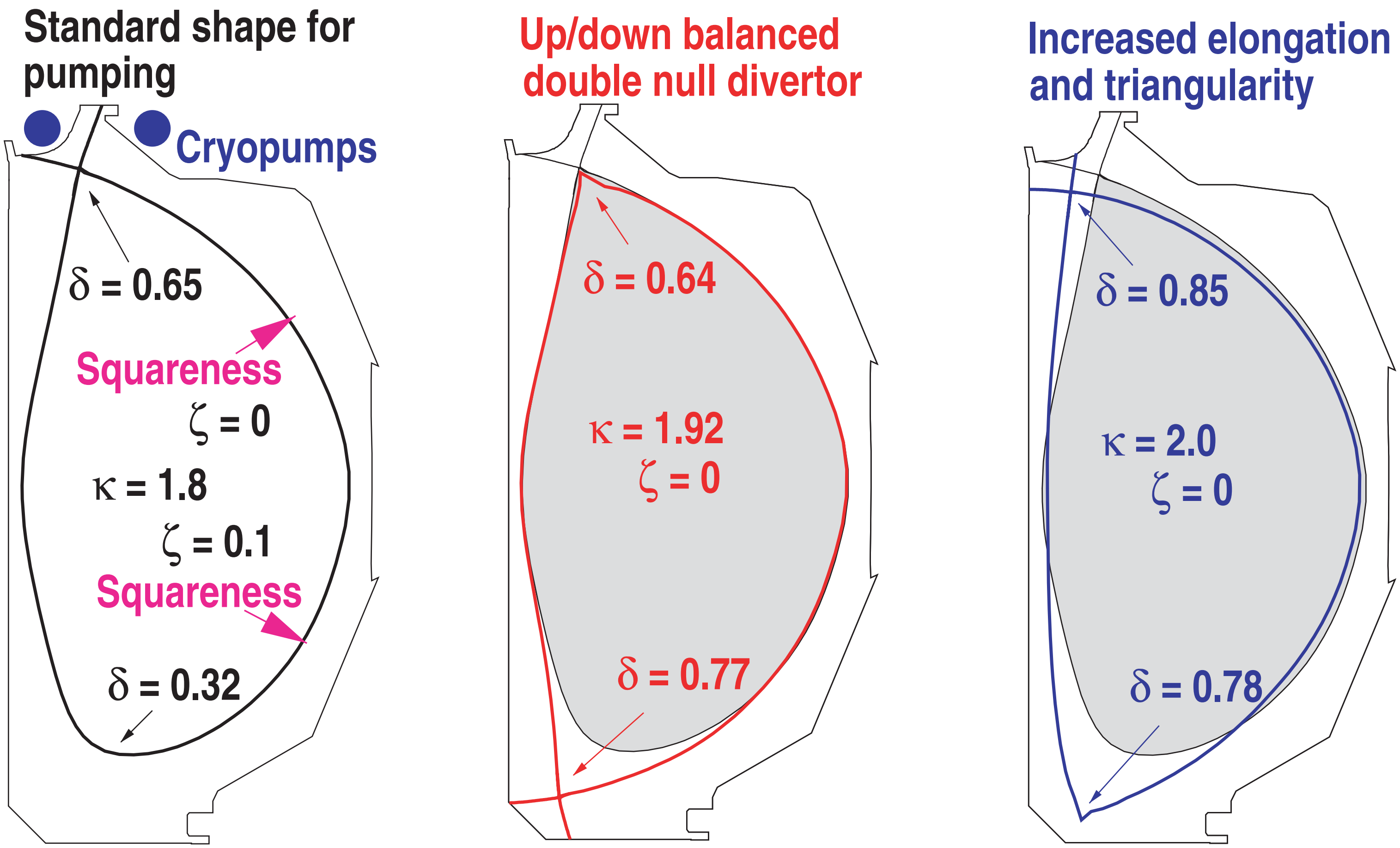
DISCHARGE SHAPE CHANGES

IN THE EXPERIMENT, THE ACHIEVABLE β_N WAS COMPARED IN THE STANDARD PUMPING SHAPE AND DISCHARGES WITH STRONGER SHAPING

- Cryopumps were not used so no change in particle pumping with shape



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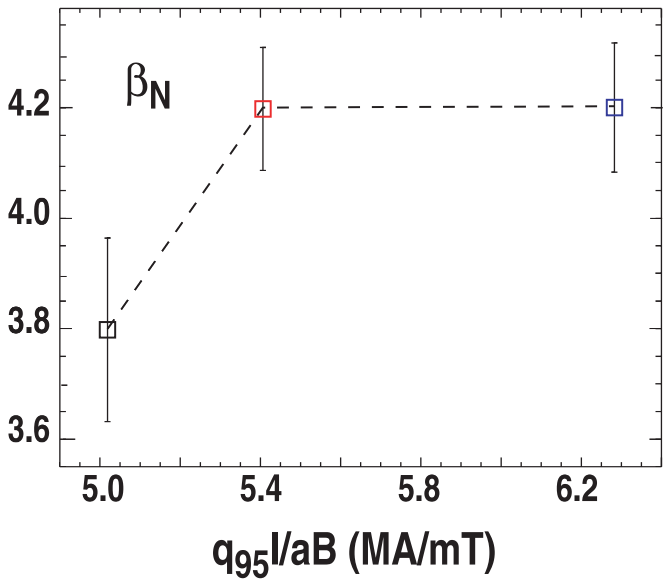
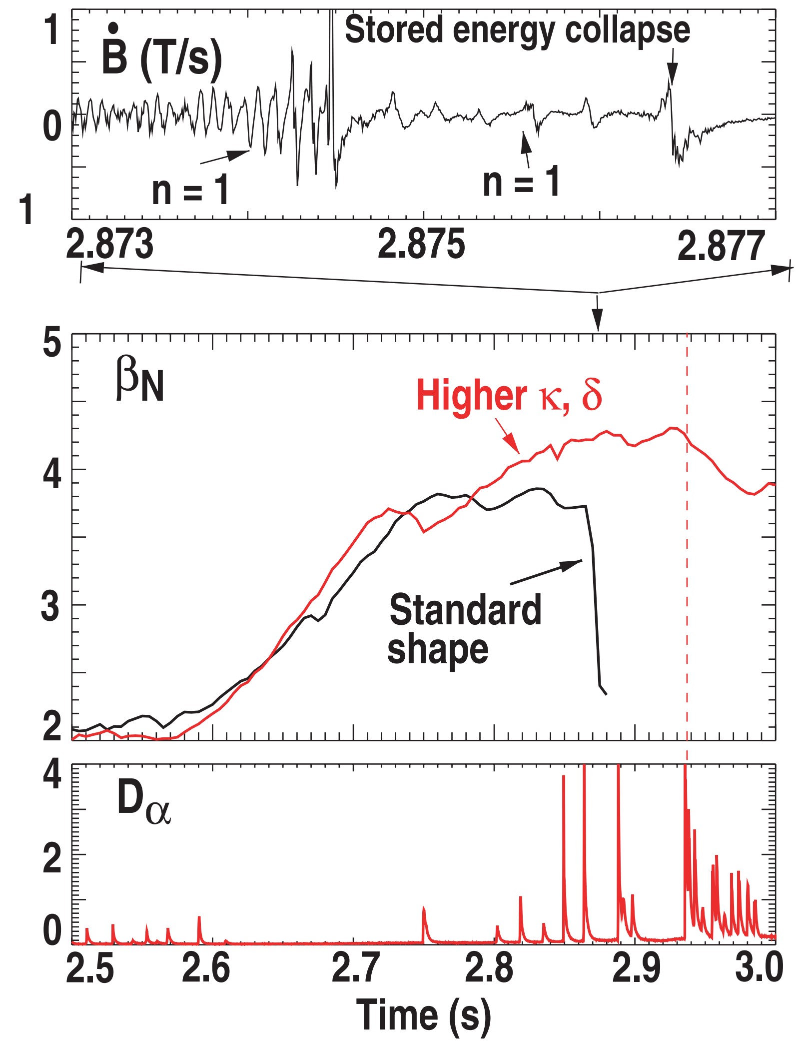
THE MAXIMUM β_N WAS OBTAINED IN THE UP/DOWN SYMMETRIC DOUBLE-NULL DIVERTOR SHAPES

- Changes in profiles could also be important: ℓ_i, $P(0)/\langle P \rangle$, H–mode pedestal



- β_N not limited by an ideal kink
  - Standard shape: fast growing core n = 1 leads to a disruption
  - Higher κ, δ shapes: large ELMs lead to a soft collapse



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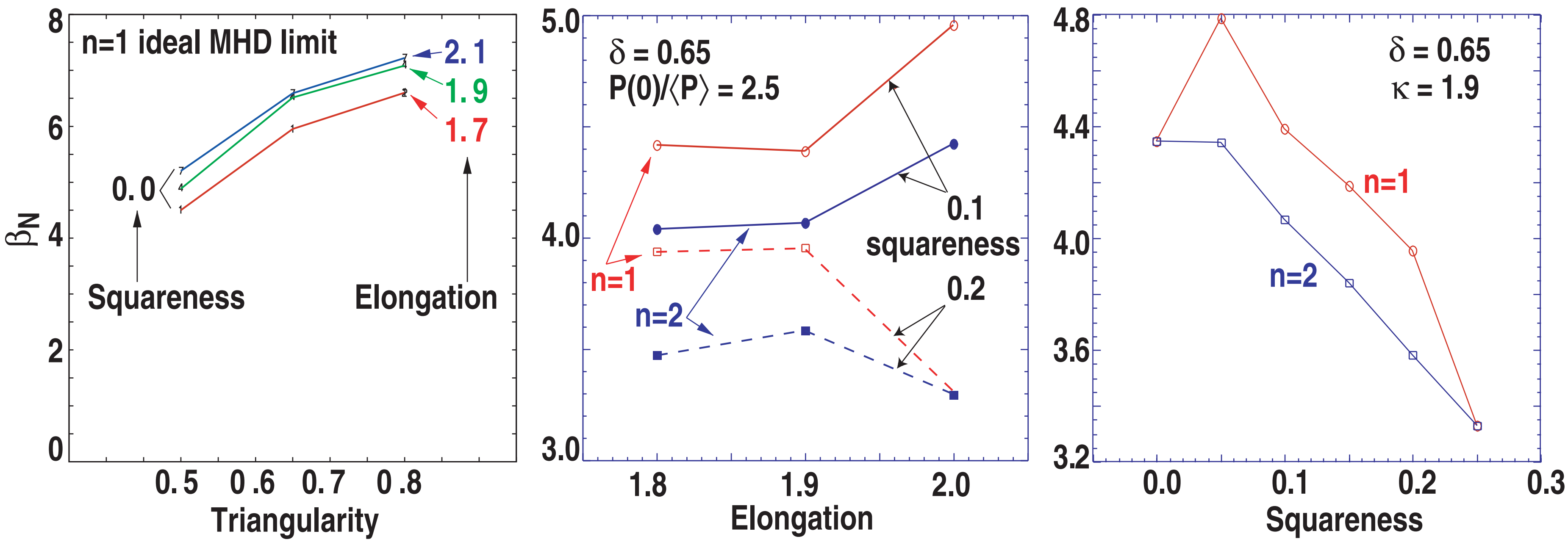
MODELING STUDIES PREDICT THAT INCREASES IN κ, δ INCREASE THE IDEAL, LOW-n β_N LIMITS

Examples of results from a broad range of parameter scans with double-null



- Indicates increase in experimental β_N likely results from increase in κ, δ in transition from single-null to double-null shape
- n = 2, n = 3 limits are lower than for n = 1 (here pressure is broad)

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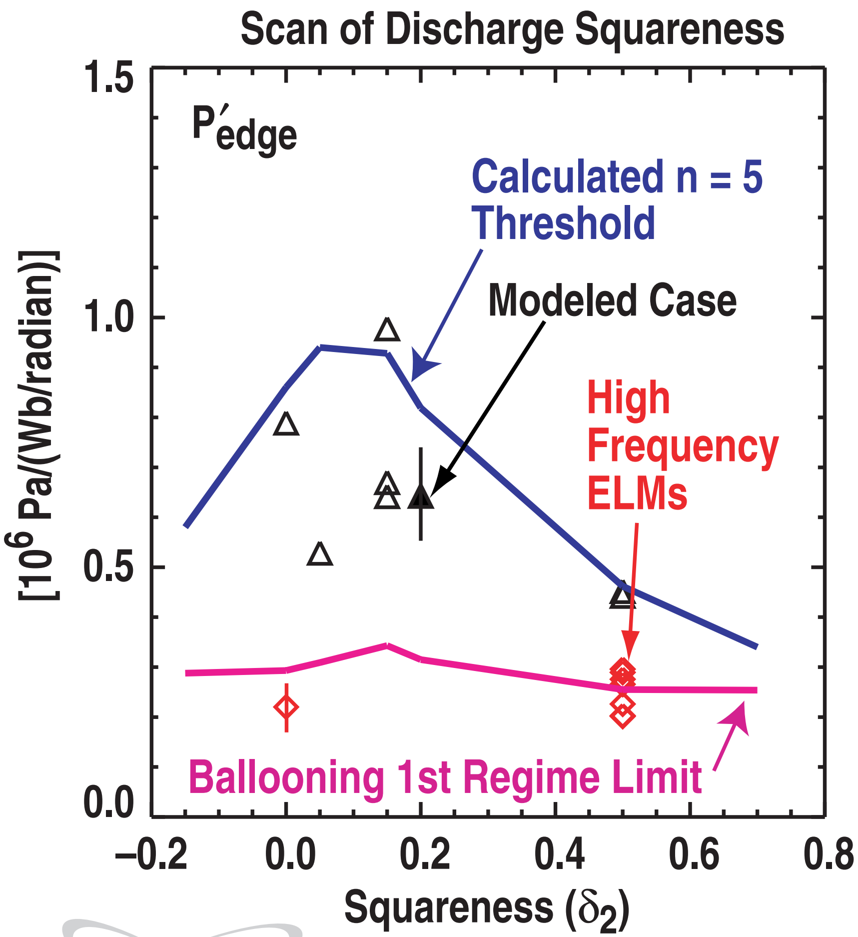
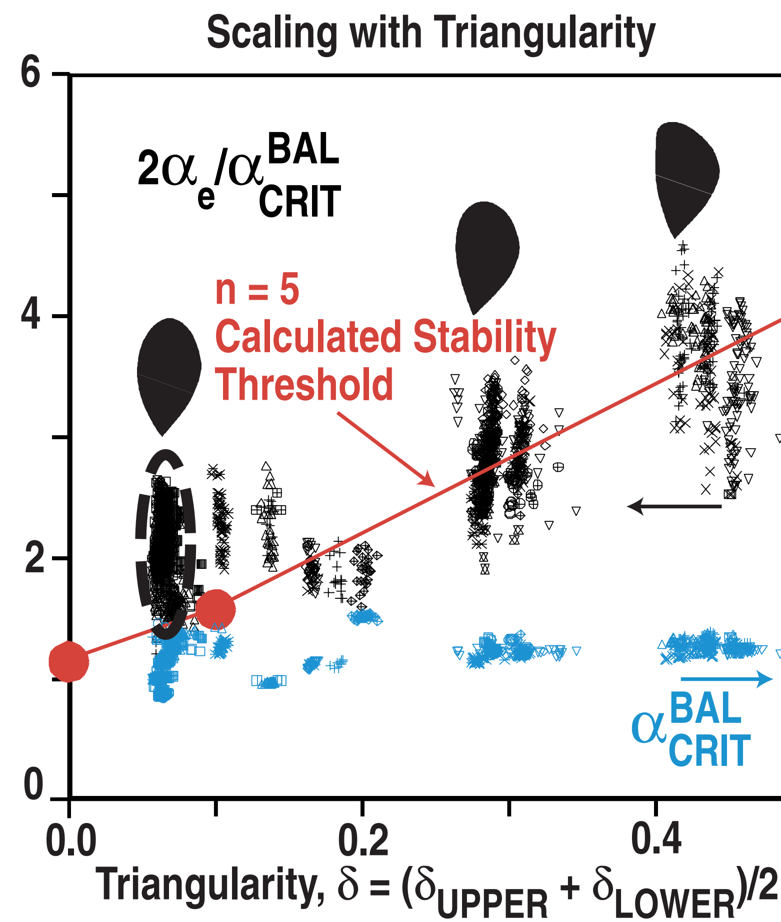
Increasing the H-mode edge pedestal height can help to broaden the pressure profile

- The pressure pedestal height is a function of the discharge shape.
- The pedestal height is limited by ELMs.
  - Type I ELM stability has been successfully compared to stability of medium-n ballooning/peeling modes.
- For fixed pedestal width, increasing the height increases the edge-region pressure gradient and bootstrap current.
  - These changes are destabilizing for low-n and medium-n edge-driven modes.
- Additional modeling is probably necessary in order to understand the net effect on global, low-n stability of changes in the pedestal height and width.

MEASURED P'_{edge} SCALES WITH DISCHARGE SHAPE LIKE THE PREDICTED THRESHOLD FOR n = 5 IDEAL, KINK/BALLOONING MODES

- Squareness scan shows quantitative agreement within 40% for similar pedestal width
- Pedestal pressure also increases with triangularity





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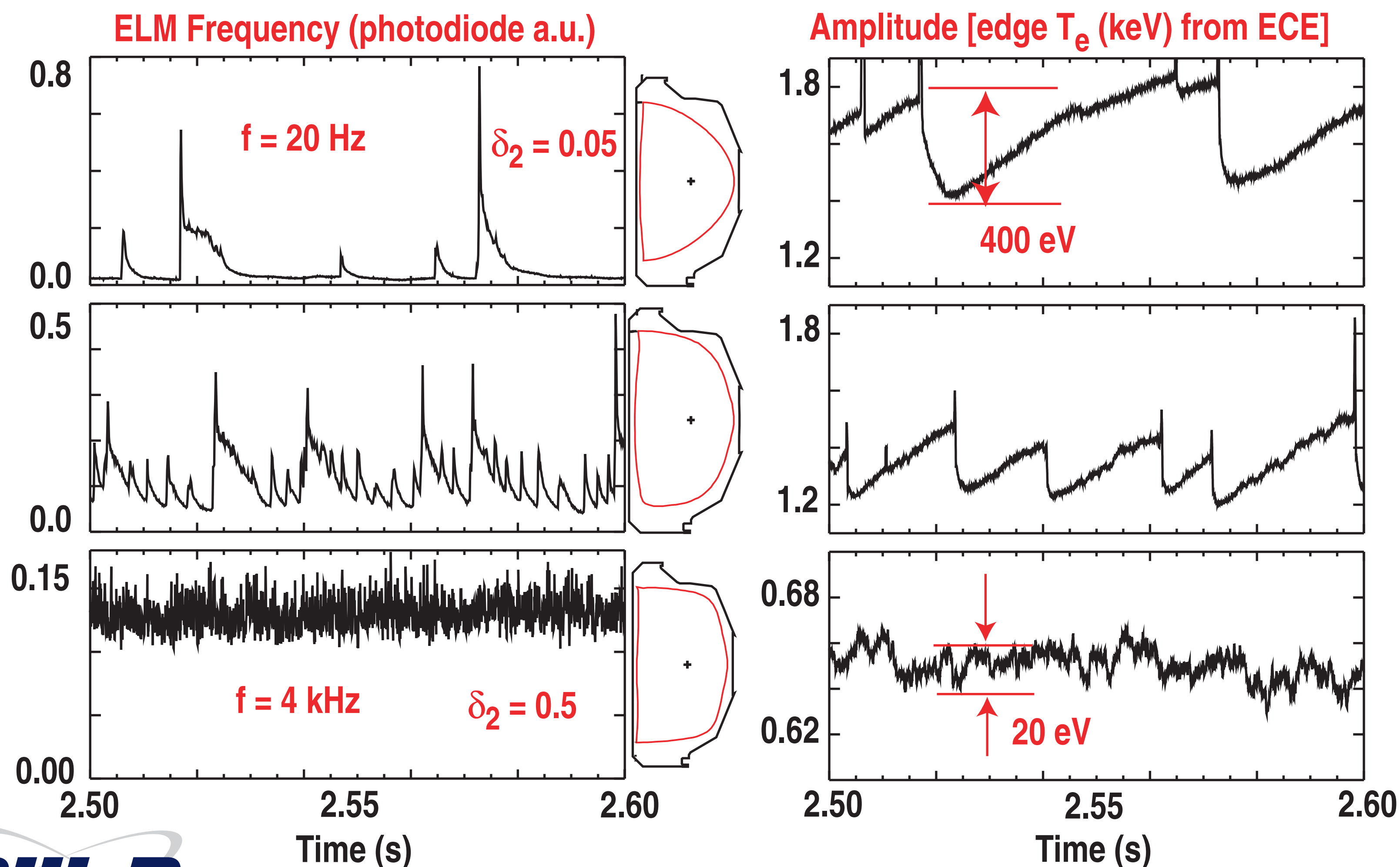
CHANGE IN BALLOONING 2nd REGIME ACCESSIBILITY IS INDICATED BY CHANGES IN ELM FREQUENCY AND AMPLITUDE

- At sufficiently high squareness:
  - ELM frequency increases a factor of 10
  - T_e perturbations are not measurable
- Abrupt: only a small shape change required



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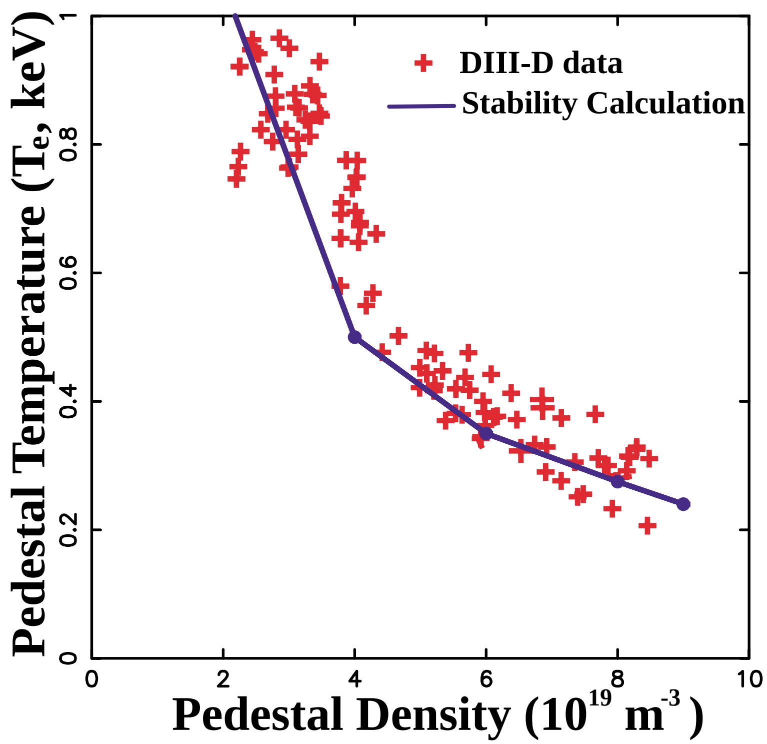
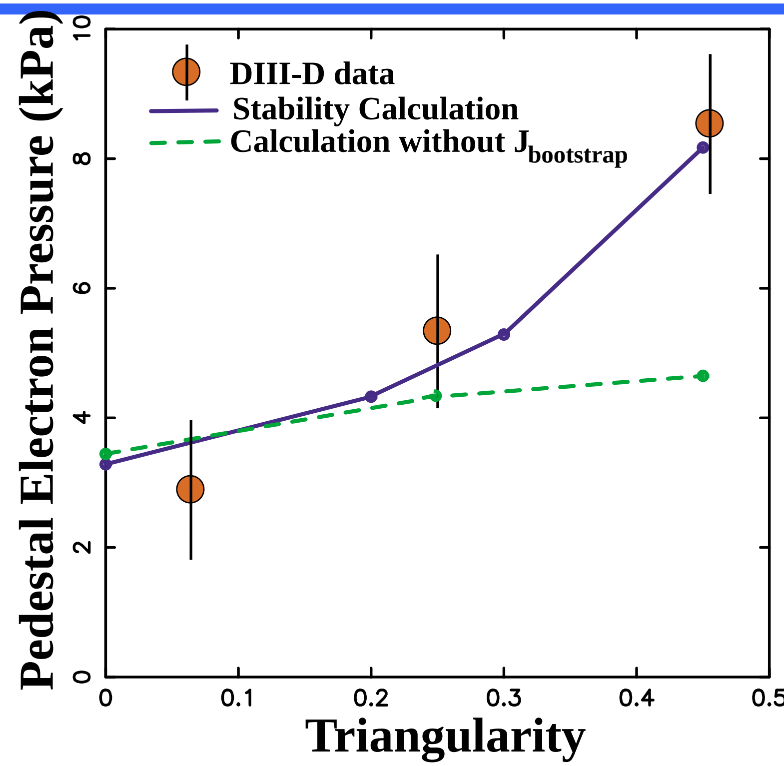
Trends in Existing Pedestal Database Can Be Understood Using Stability of Model Equilibria





- **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, $<n_e>$, 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

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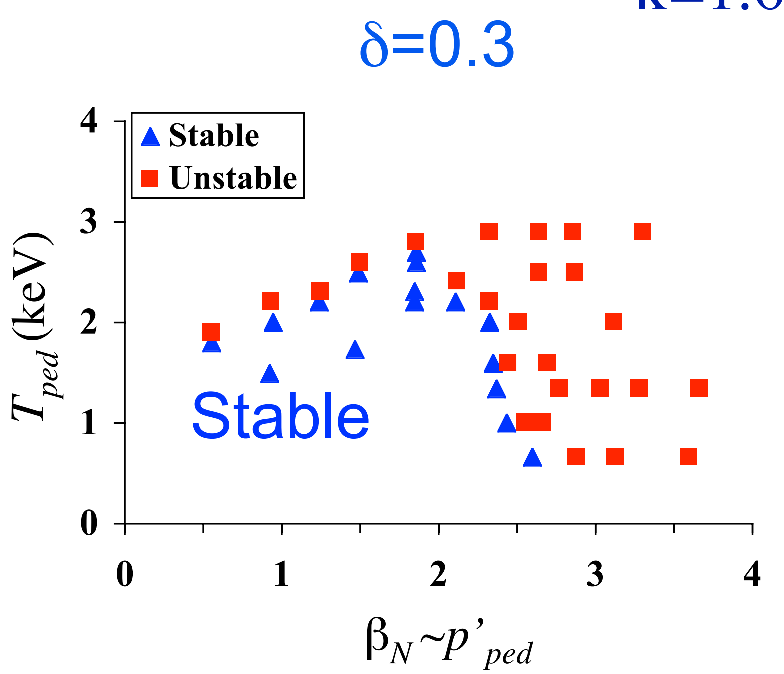
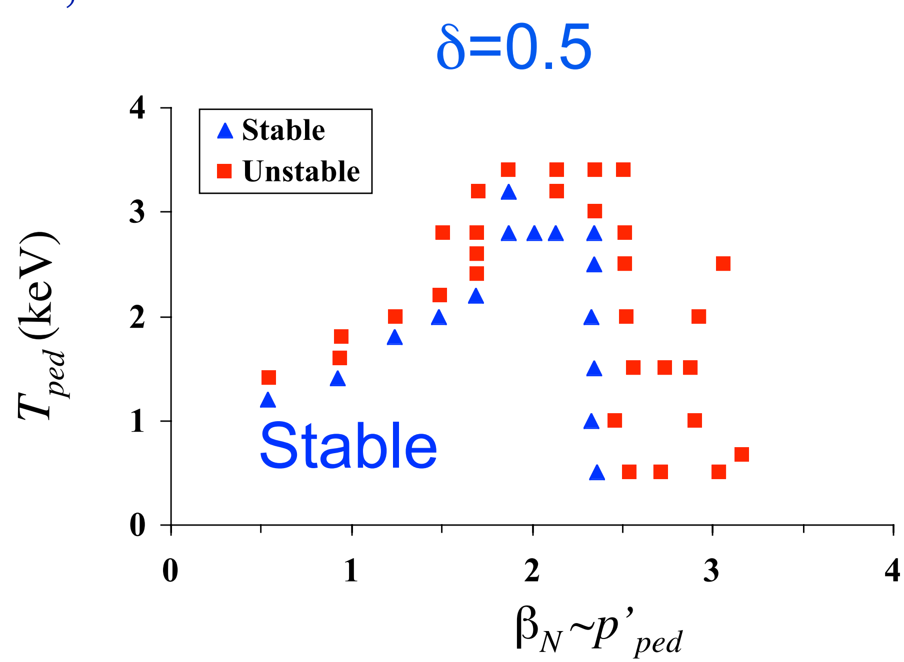
Peeling-ballooning modes provide a constraint on the edge temperature pedestal, as well as β

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





UKAEA Fusion Working with Europe

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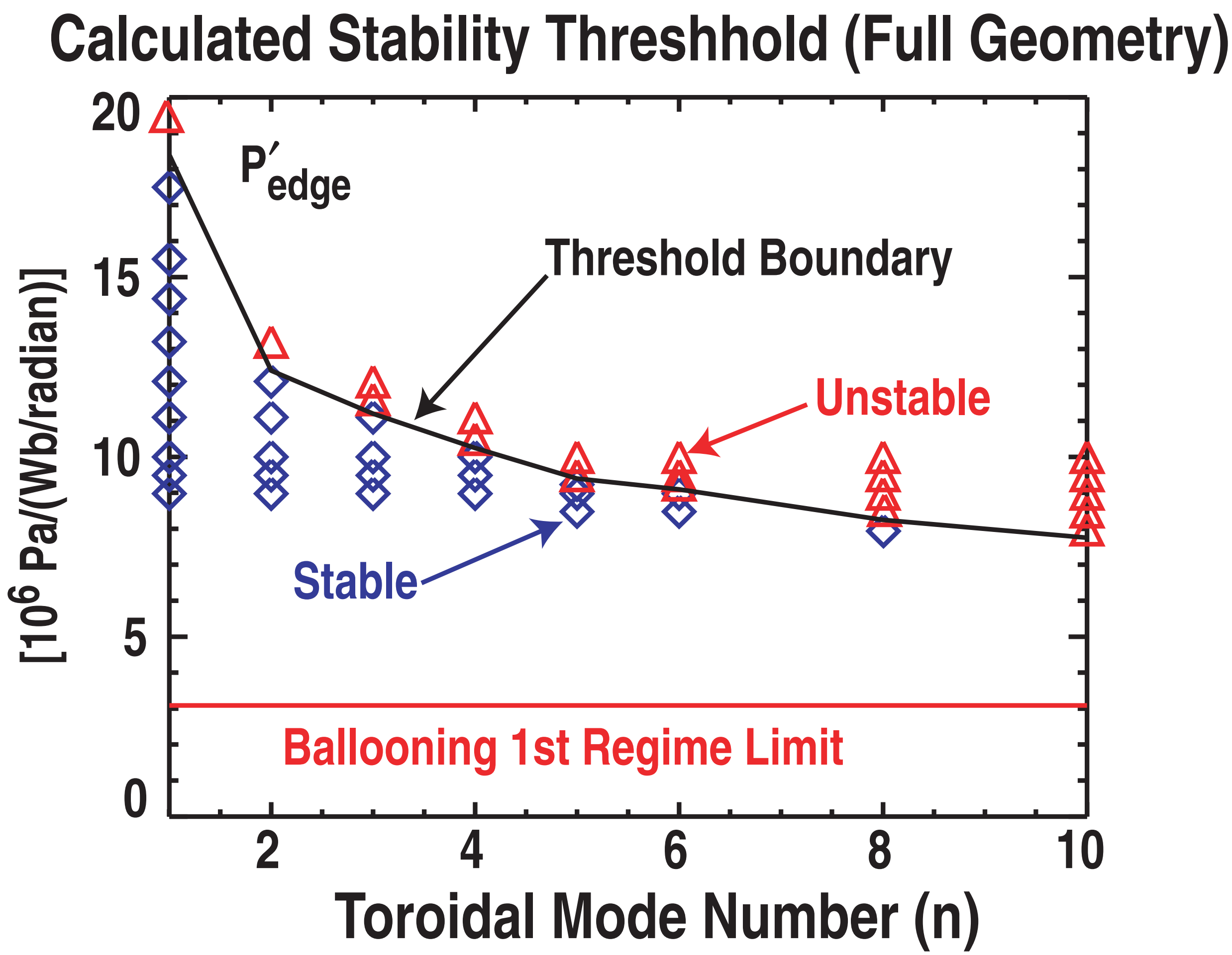
MODE WITH THE LARGEST n WITHOUT 2nd STABLE REGIME ACCESS WILL HAVE THE LOWEST P'_{edge} STABILTY THRESHOLD

- Calculated P'_{edge} threshhold decreases with toroidal mode number
- Fixed, medium squareness (δ_2 = 0.05) shape, wall radius = 1.5α, GATO code



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OPTIMIZATION OF ADVANCED TOKAMAK DISCHARGES WITH RESPECT TO THE BETA LIMIT IS POSSIBLE THROUGH TUNING OF THE q PROFILE, PRESSURE PROFILE AND DISCHARGE SHAPE

- Goal: find the best way to operate at high β_N and q in order to maximize f_{BS} for steady-state and β_T for fusion gain

- A test of the effect of a broader pressure profile resulted in increased β_N
  - From modeling, pressure profile broadening could allow large increases in achievable beta

- q_{min} β_N increased from 6 at q_{min} = 1.5 to 9 at $q_{min} \approx 2.3$, the highest value tested
  - Increasing f_{BS} by increasing q_{min} is feasible with broad pressure

- Operation is routinely above the no-wall stability limit
  - Optimized correction of nonaxisymmetric fields and active feedback stabilization of the RWM are essential

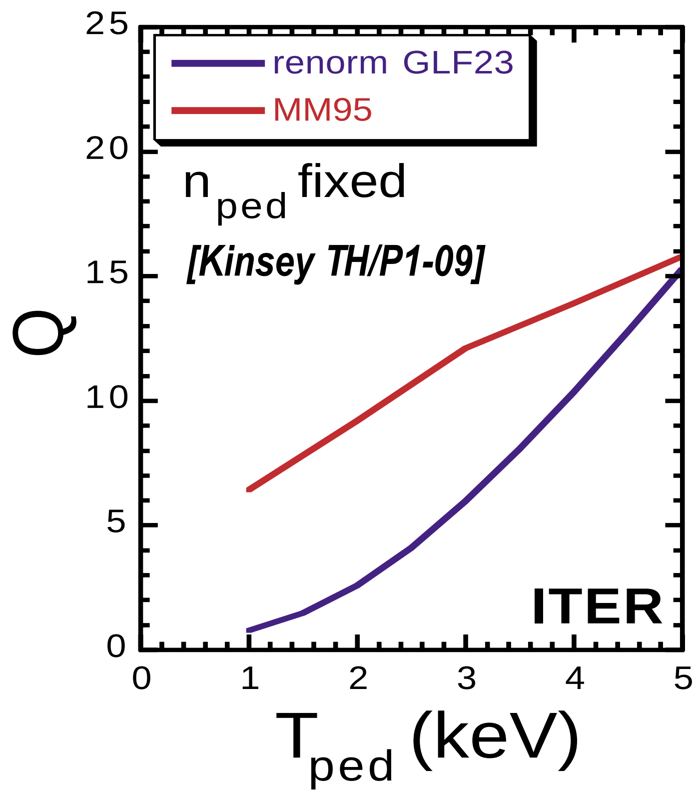
- Highest experimental β_N values were obtained in balanced double-null discharge shapes with the largest κ, δ

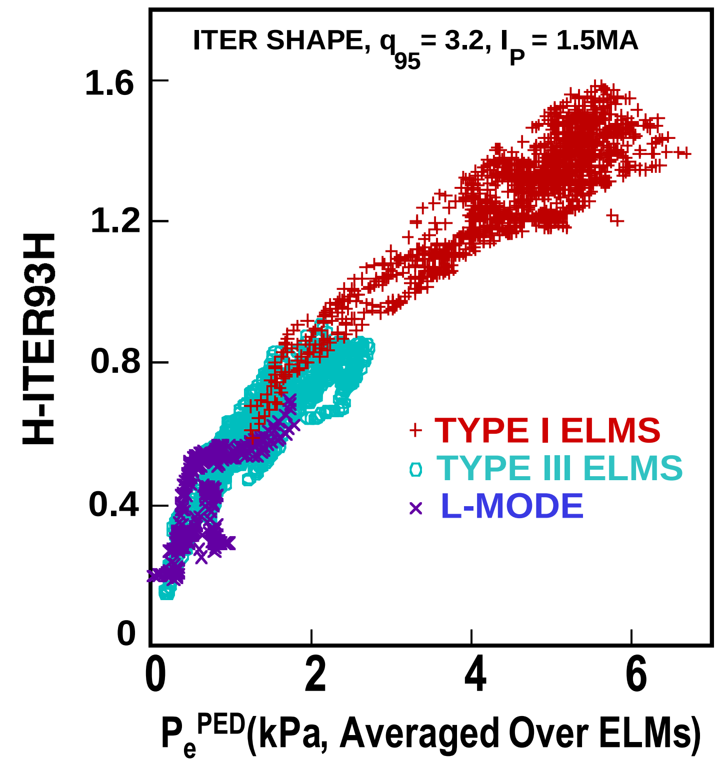
UPCOMING WORK IN DIII–D IS WELL POSITIONED TO FOLLOW THE PATH TO HIGH β_N AT INCREASED q_{min} INDICATED BY THESE RESULTS

- Additional power for electron cyclotron and fast wave current drive will be available to control q_{min} and q(0)
- Conversion of 1/4 of the neutral beams to counter-injection will allow additional rotation profile control
  - Together with current profile control, provides a possible mechanism for pressure profile broadening through energy transport modification
- Lower divertor pump to be converted to pump higher triangularity double-null divertor discharges
- Recently installed internal nonaxisymmetric coils will be used for improved error field correction and improved active RWM feedback control to allow steady-state operation close to the ideal-wall beta limit

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

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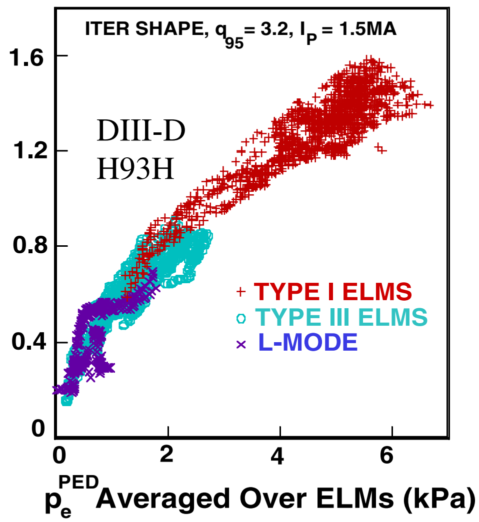
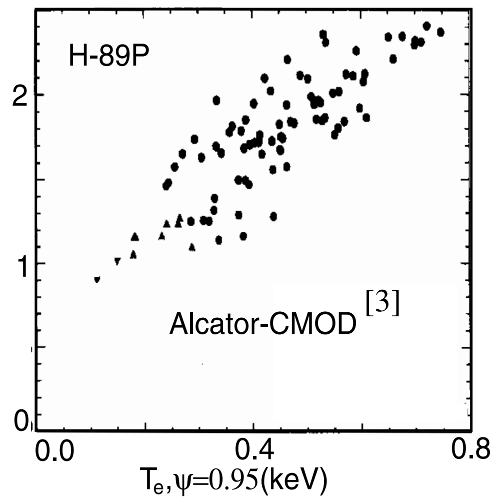
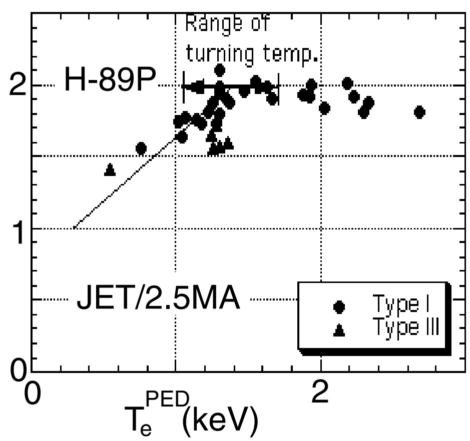
H-mode pedestal may impact H-mode based tokamak reactor performance through temperature profile stiffness.

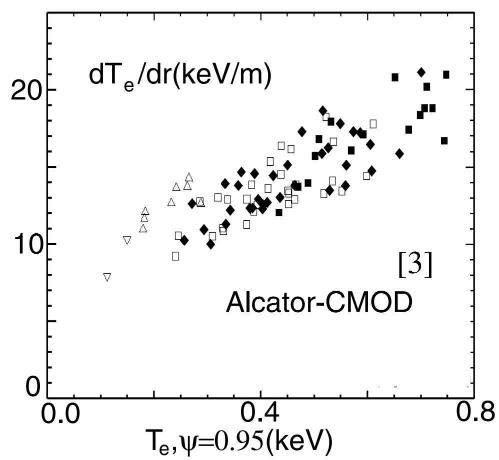
- Maximum P_F and Q are obtained at min <T> for stable operation => $P_F/P_{LOSS} \sim H^2$

Effect of H-mode pedestal on H factor varies with tokamak possibly due to changes in turbulent transport process[2]

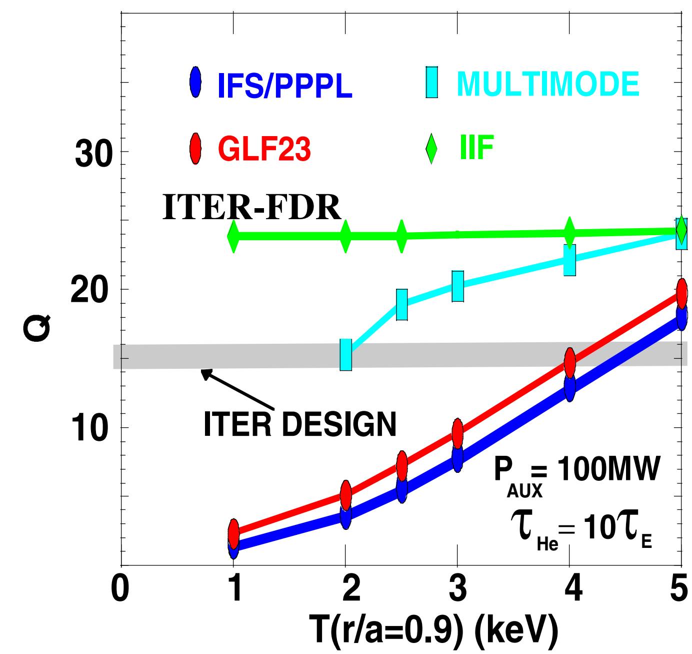








Turbulent transport simulations that predict stiff temperature profiles (ITG) show strong dependence of core on edge [1]



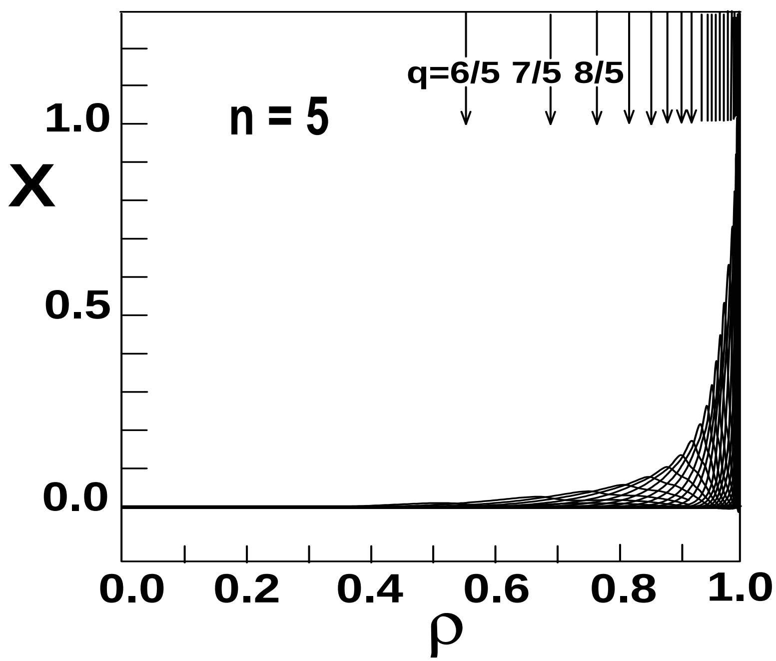
[1] J.E. Kinsey, et al., *Berchtesgarten EPS*, **III** 1081 (1997)

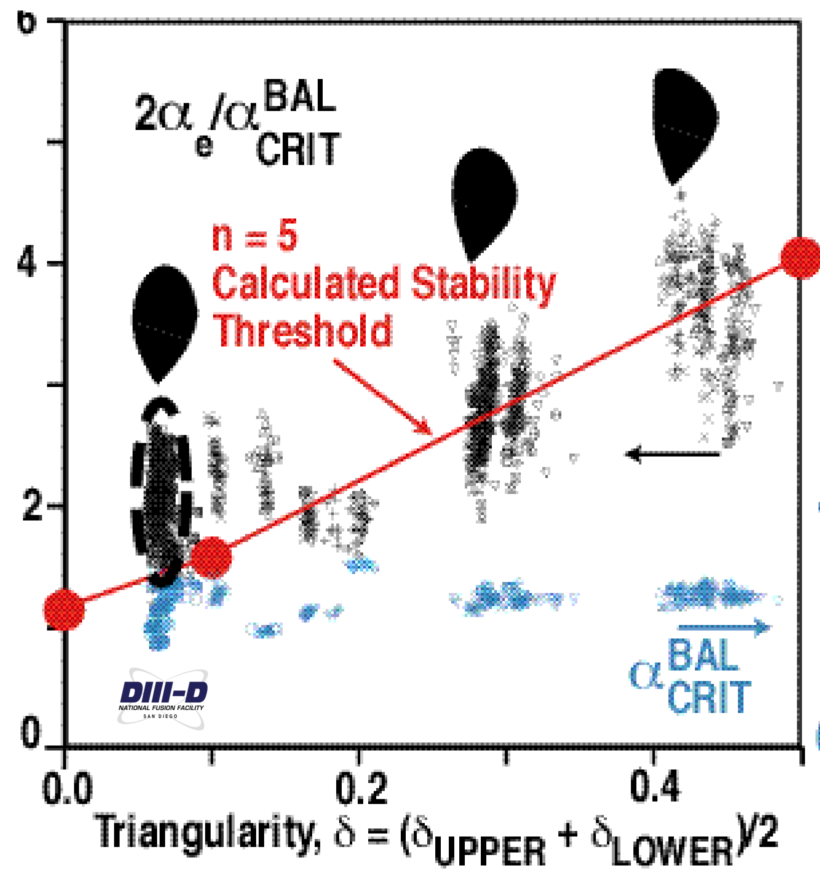
[3] M. Greenwald, et. al Nucl. Fus. **37** (1997) 793.

[2] G.Janeschitz, et.al Maastricht EPS, **23J** (1999) 1445.

Intermediate *n* Peeling-Ballooning Mode Model of the Type I ELM Instability is Consistent With Observations

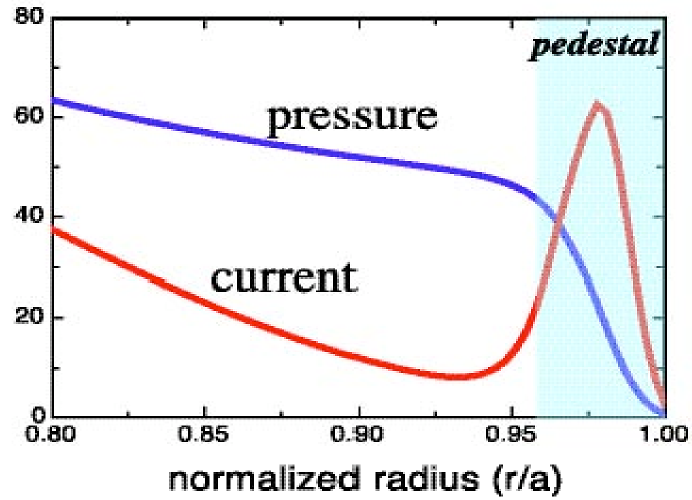
- **P′ variation with shape in DIII-D, JT-60U, and AUG consistent with edge peeling-ballooning stability**
- **ELM onset time consistent with predicted instability onset**
- **Fast growing low 1 < *n* < 30 modes are observed as Type I ELM precursors**



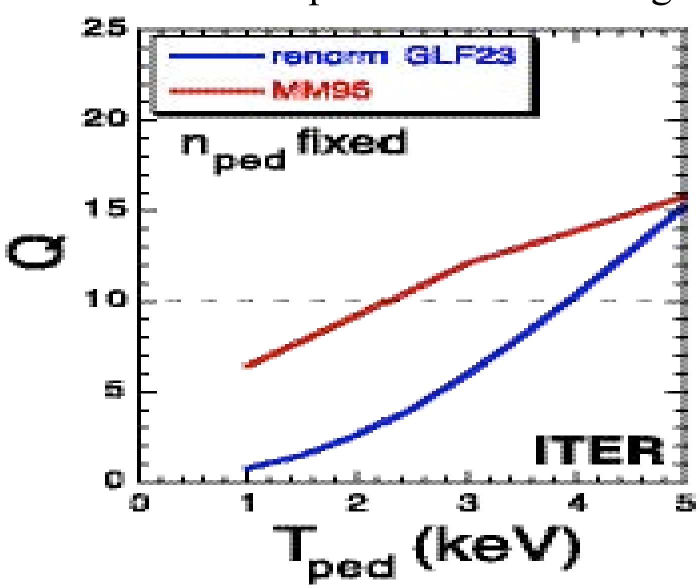


Motivation and Background

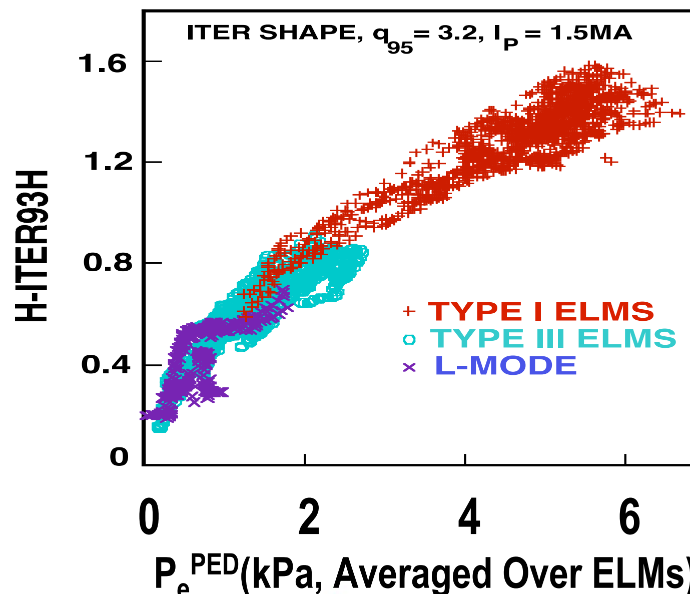
- ELMs and the edge pedestal are key fusion plasma issues
  - “Pedestal Height” controls core confinement and therefore fusion performance (Q)
  - ELM heat pulses impact plasma facing materials



Predicted Impact of Pedestal Height



Observed Impact of Pedestal Height (DIII-D)



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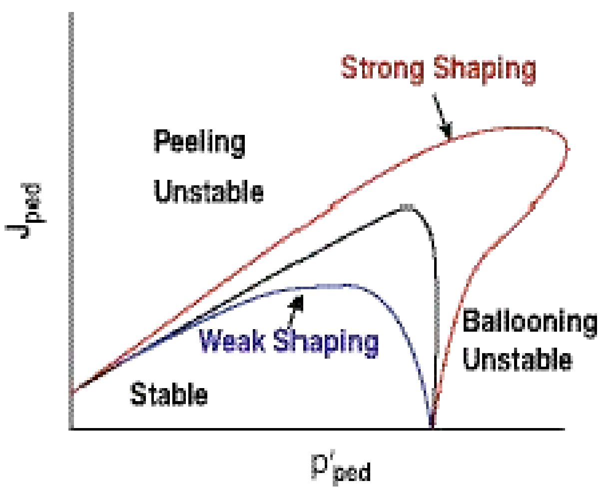
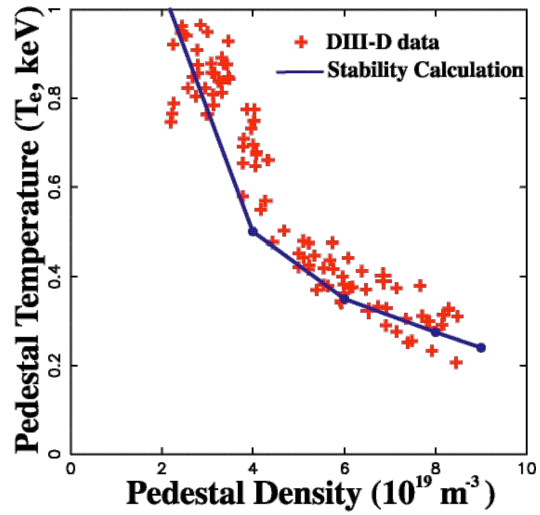
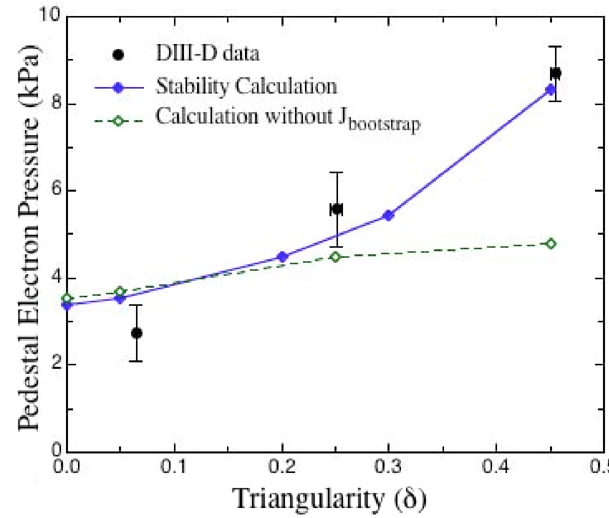
Background: Extending the Peeling-Ballooning Model







- Peeling-Ballooning Model of ELMs - significant successes
  - ELMs caused by intermediate wavelength (n~3-30) MHD instabilities
    - Both current and pressure gradient driven
    - Complex dependencies on ν_*, shape etc due to bootstrap current and “2nd stability”
  - Successful comparisons to experiment both directly and in database studies
- Need to understand sources and transport to get profile shapes (“pedestal width”)
- Rotation and non-ideal effects to precisely characterize P-B limits, nonlinear dynamics for ELM size

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