Dependence of Edge Stability on Plasma Shape and Local Pressure Gradients in the DIII-D and JT-60U Tokamaks

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MOTIVATION

- Predictability of the edge pedestal height and control of divertor heat load are two of the major issues in the design of future tokamak devices. Both are strongly influenced by edge stability
- Predicted performance of future tokamak devices is sensitive to the magnitude of the edge pressure pedestal assumed in transport simulations
- An improved understanding of edge instabilities (ELMs) provides a more accurate prediction of future device performance
- Discharge shaping provide a powerful tool to test and validate ELM models by varying the stability properties of the plasma edge
- Test and validate DIII-D working ELM model against JT-60U edge stability observations

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OUTLINE / KEY RESULTS

- Stability analyses and DIII-D edge stability experimental results suggest an ideal stability based working model of type I ("giant") ELMs as low to intermediate *n* kink/ballooning modes
- At large $\delta \geq 0.45$, low $q_{95} \sim 3.4$ JT-60U discharges have type I ELMs and are near the 1^{st} ballooning stability limit, whereas high $q_{95} \sim 6.0$ JT-60U discharges have small "grassy" ELMs and access to the 2^{nd} ballooning stability regime in the edge
- Strong plasma shaping in DIII-D allows the edge region of DIII-D type I ELM discharges to have 2^{nd} ballooning stability access and larger P'_{edge} than JT-60U type I ELM discharges
- Results of stability analysis of JT-60U type I and "grassy" ELM discharges indicate that predictions from this ELM model are consistent with JT-60U edge stability observations

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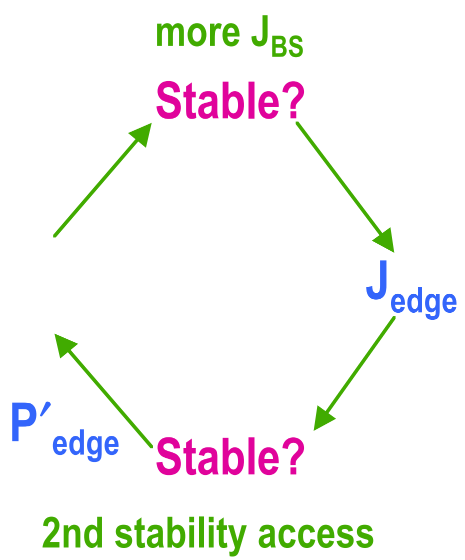
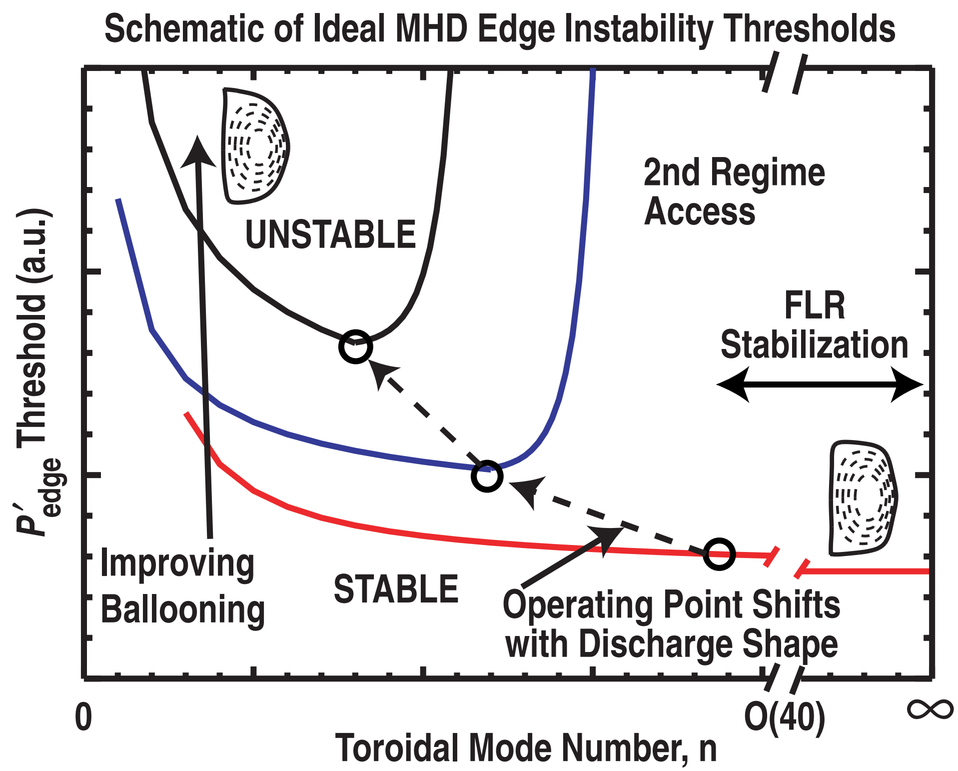
DIII-D THEORY AND EXPERIMENT SUGGEST A MODEL OF TYPE I ELM AS LOW TO INTERMEDIATE *n* KINK / BALLOONING MODES

- Main driving forces are P'_{edge} and J_{edge}, interact through J_{BS} and 2nd ballooning access
- ELM amplitudes are assumed to be determined by the radial width of the unstable modes
- Critical P'_{edge} is set by modes with the highest *n* without 2nd ballooning stability access

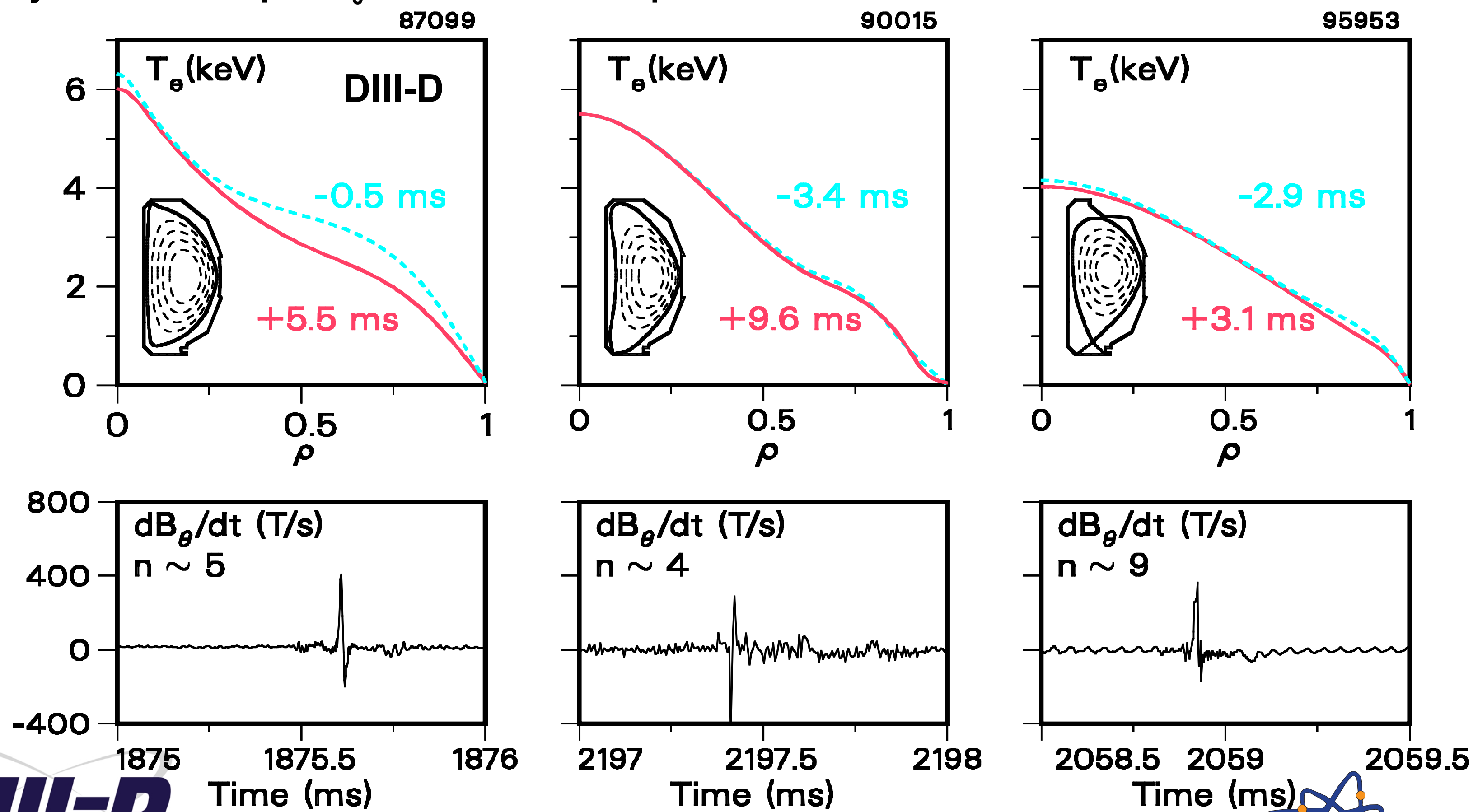




Ferron, et al, Phys. Plasmas 7, 1976 (2000)

MAGNETIC OSCILLATIONS WITH $n \approx$ 2-9 ARE OFTEN OBSERVED PRIOR TO THE 1st GIANT ELM IN MODERATE SQUARENESS DISCHARGES

- Localized poloidally in the outboard bad curvature region
- Usually rotate in the electron diamagnetic drift direction with a fast growth time γ^{-1} = 20-150 μs
- May lead to a drop of T_e across the entire plasma



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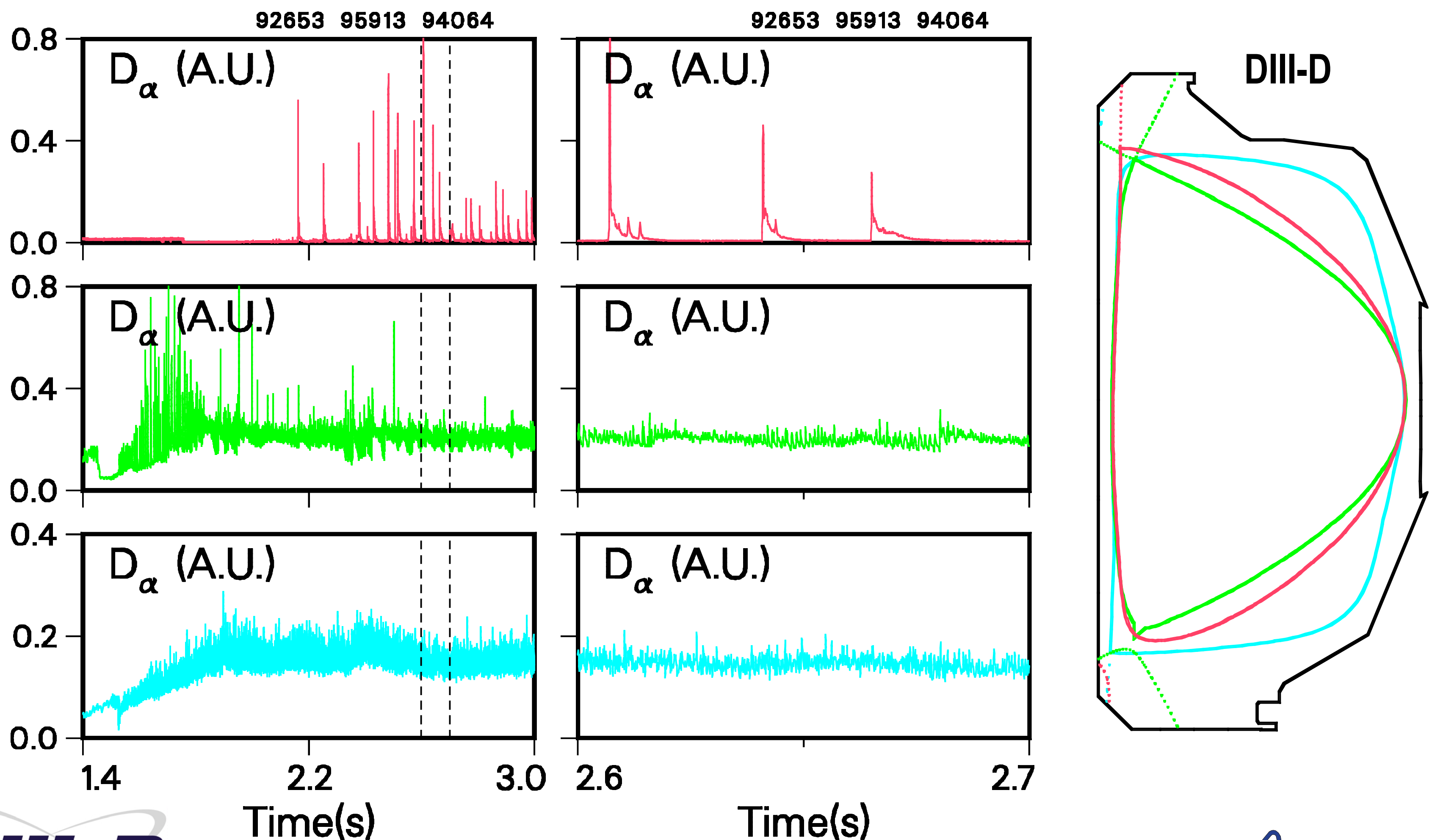
ELM FREQUENCY AND AMPLITUDE CAN BE VARIED BY CHANGING THE SQUARENESS OF THE DISCHARGE SHAPE

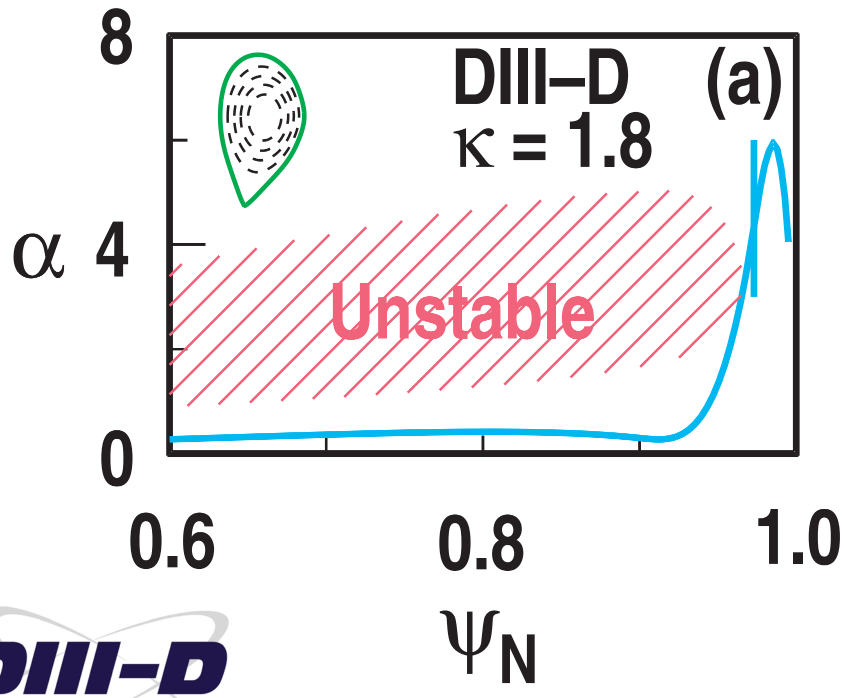
- **ELM amplitudes are strongly reduced in DIII-D discharges at low or high squareness**

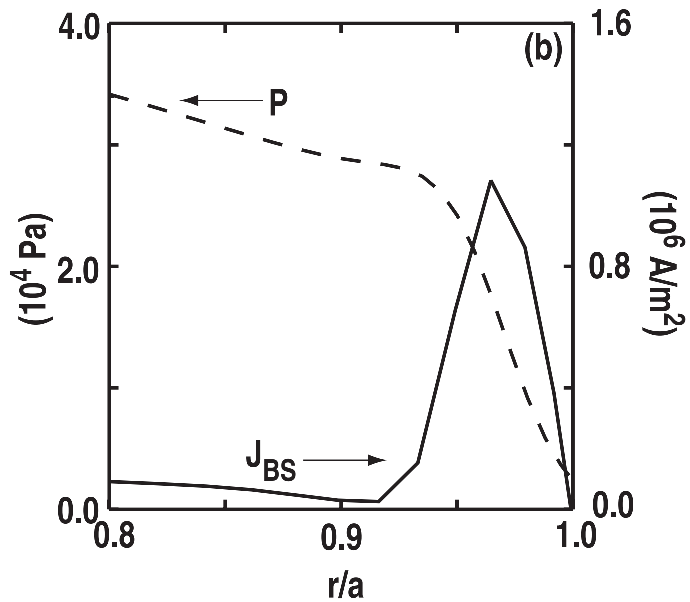


Ferron, et al, Nucl. Fusion 40, 1411 (2000)

EDGE ACCESS TO THE 2ND BALLOONING STABILITY REGIME IS A DISTINGUISHING FEATURE OF THIS ELM MODEL

- 2nd ballooning stability access plays a supporting role by facilitating the buildup of edge P' and J_{BS} which then drives lower *n* MHD modes
- Not a necessary element of the ELM model. With low q_{95}, weak shaping, and large pedestal width, low to intermediate *n* modes can become unstable at low edge P'
- Giant ELM: 1.5 MA, 1.9 T, q_{95} = 3.5, β_P = 0.6, β_N = 1.6, l_i = 1.1, κ = 1.8, δ = 0.26





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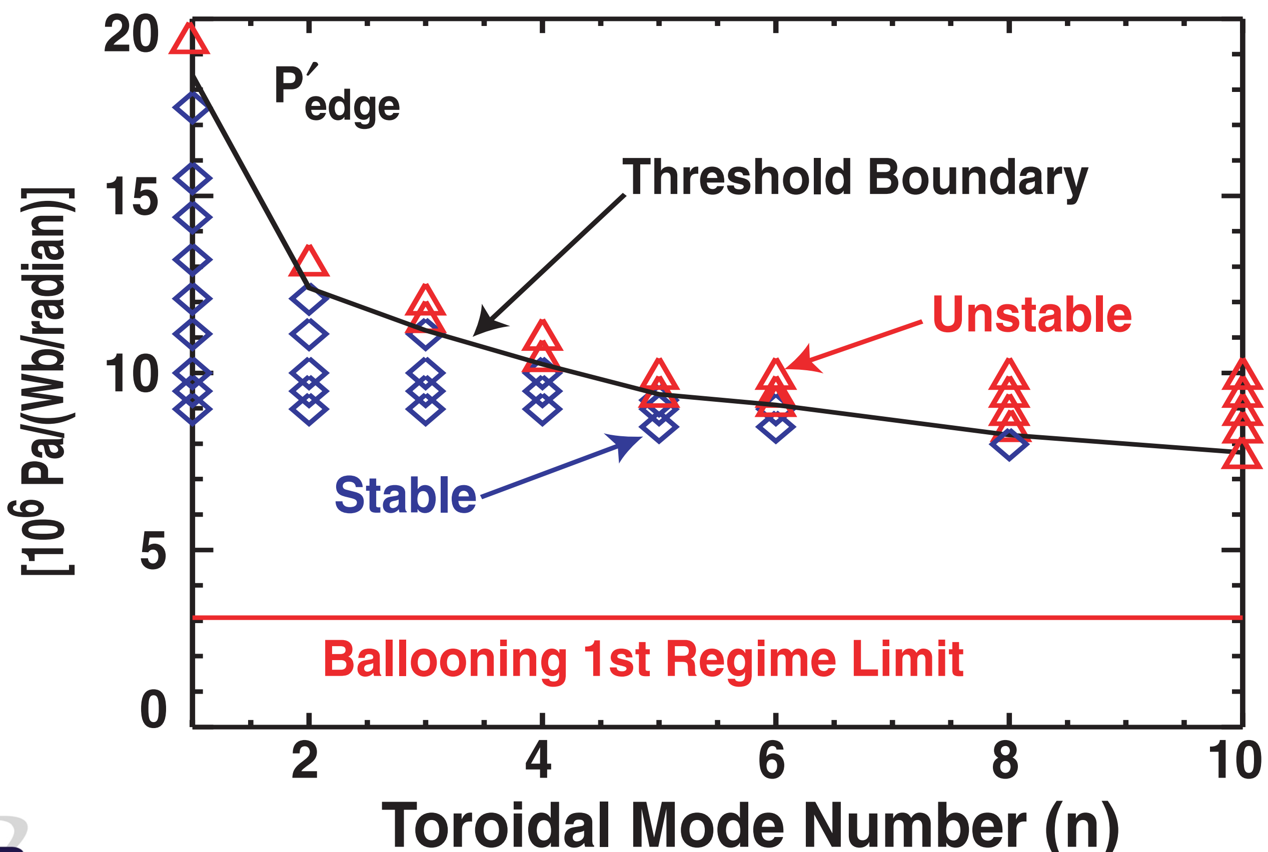
THE LOW / INTERMEDIATE $n \leq 10$ BRANCH CAN BE EVALUATED USING THE IDEAL STABILITY CODE GATO

- Critical P'_{edge} computed using model equilibria based on an experimental DIII-D discharge
- Critical P'_{edge} is set by modes with the highest *n* without 2nd ballooning stability access



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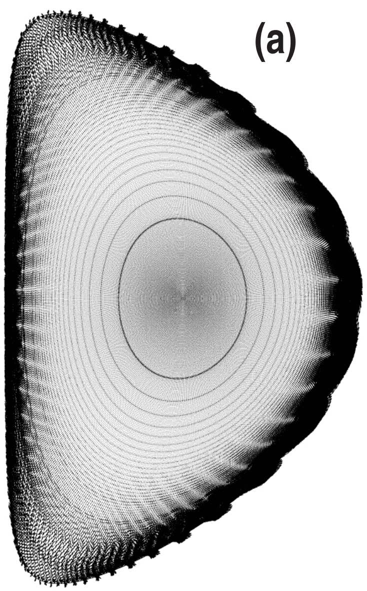
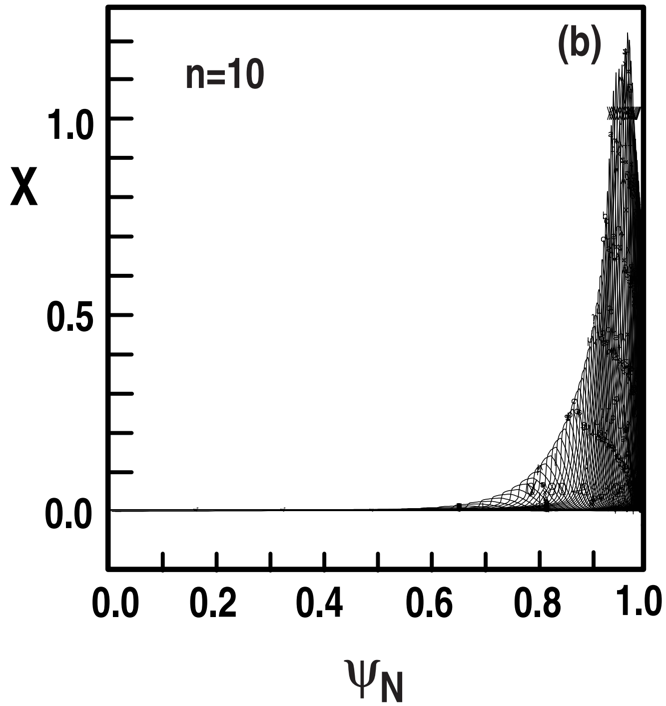
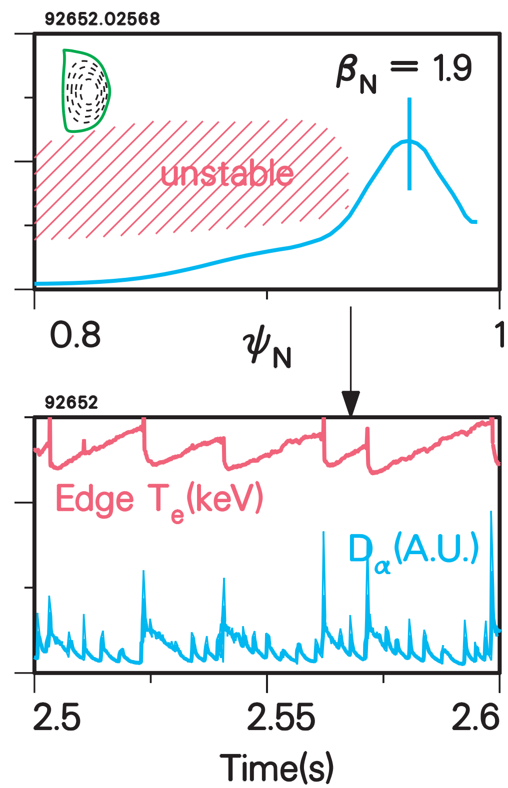
UNSTABLE *n* = 10 MODE HAS A LARGE PEELING COMPONENT LOCALIZED IN THE EDGE REGION

- ELM amplitude is assumed to be determined by the radial width of the unstable mode
- Computed using GATO

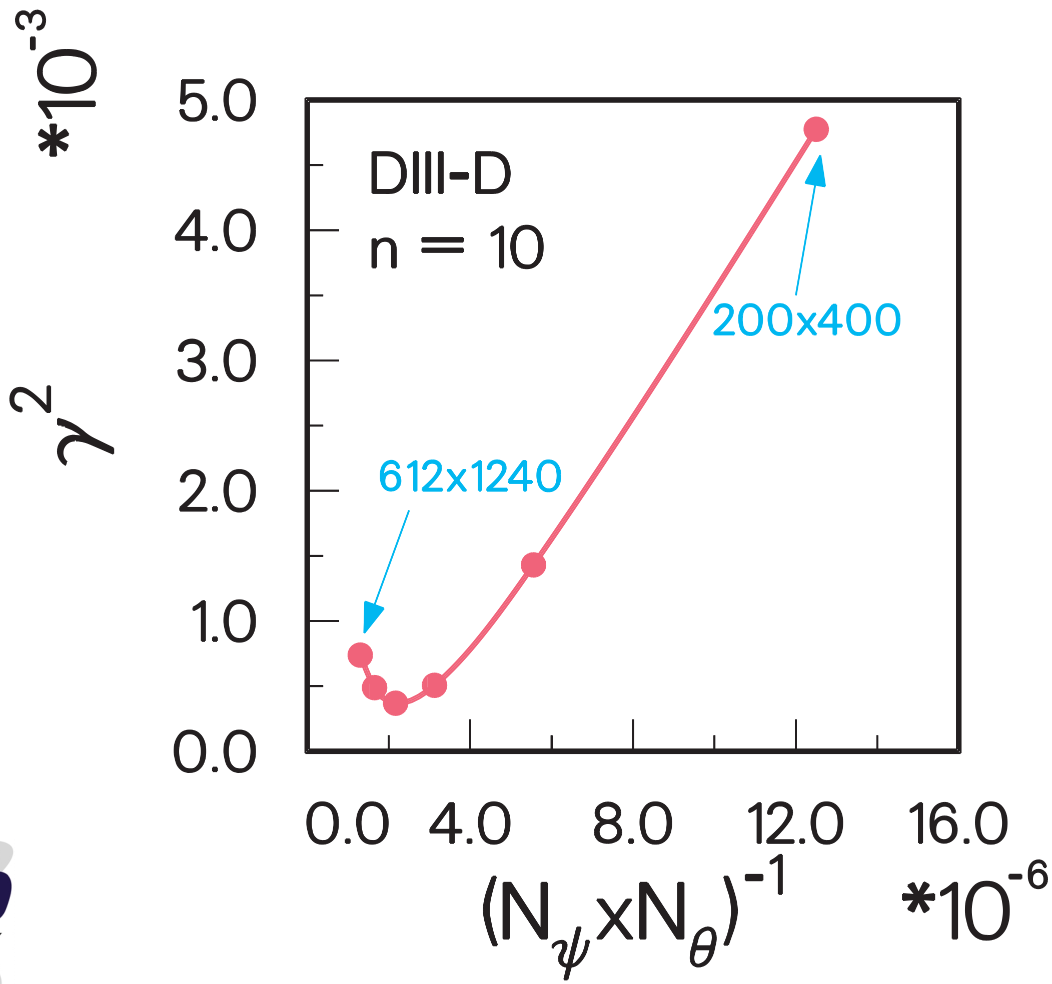






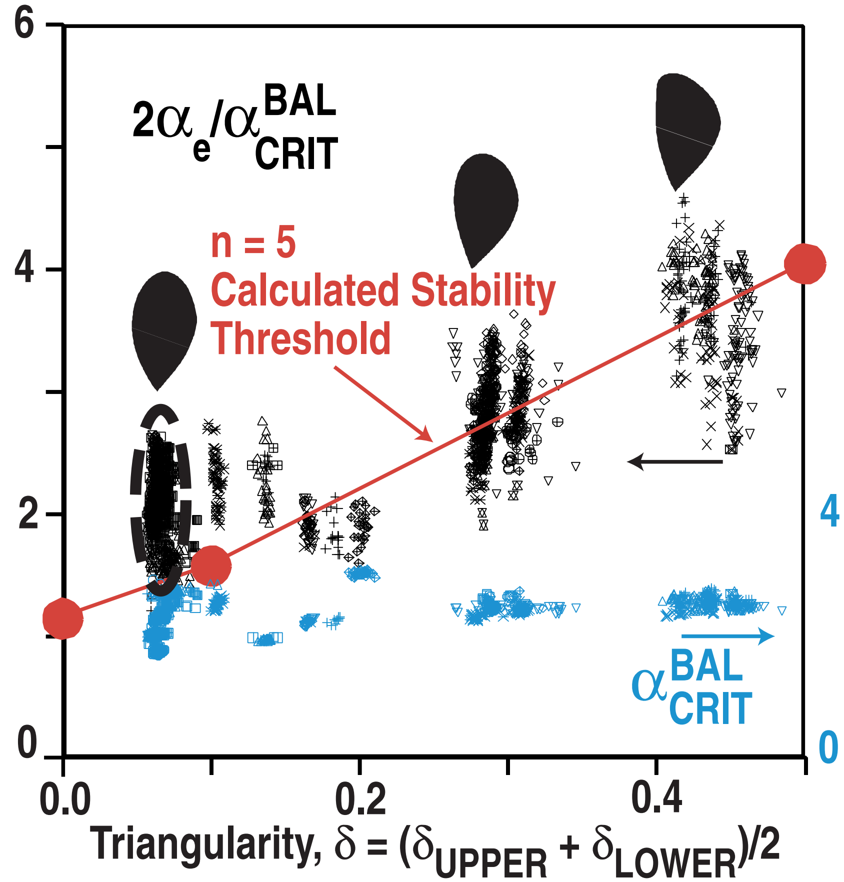
HIGH RESOLUTION GRID IS NEEDED TO PROPERLY INDENTIFY THE UNSTABLE *n* = 10 KINK / BALLOONING MODE

- Computed using the ideal stability code GATO
- Stability analysis using high resolution grid is computationally very expensive



OBSERVED INCREASE OF P'_{edge} WITH TRIANGULARITY IS CONSISTENT WITH PREDICTIONS FROM THIS ELM MODEL

- Increase of P'_{edge} with δ also observed in JT-60U and ASDEX-U
- Predicted critical P'_{edge} due to the unstable modes is indicated using the critical P'_{edge} for a $n = 5$ mode



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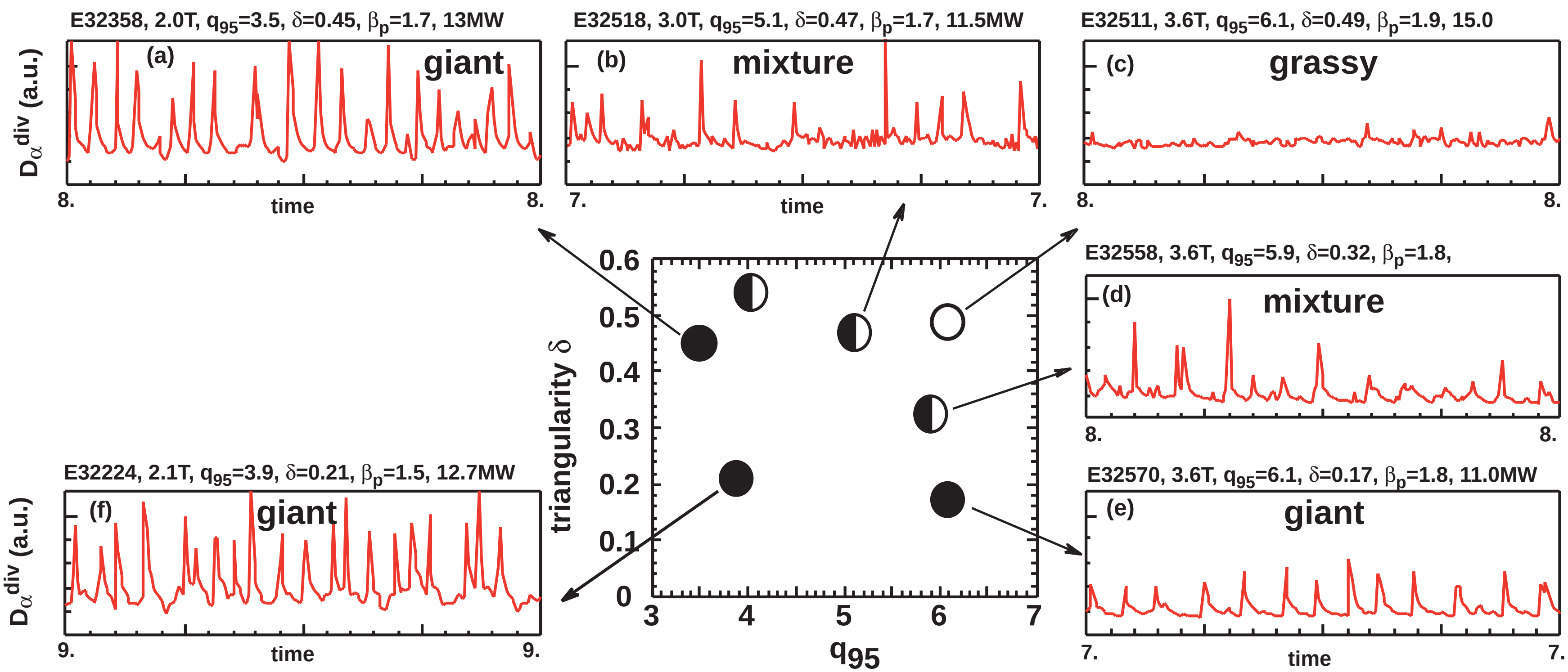
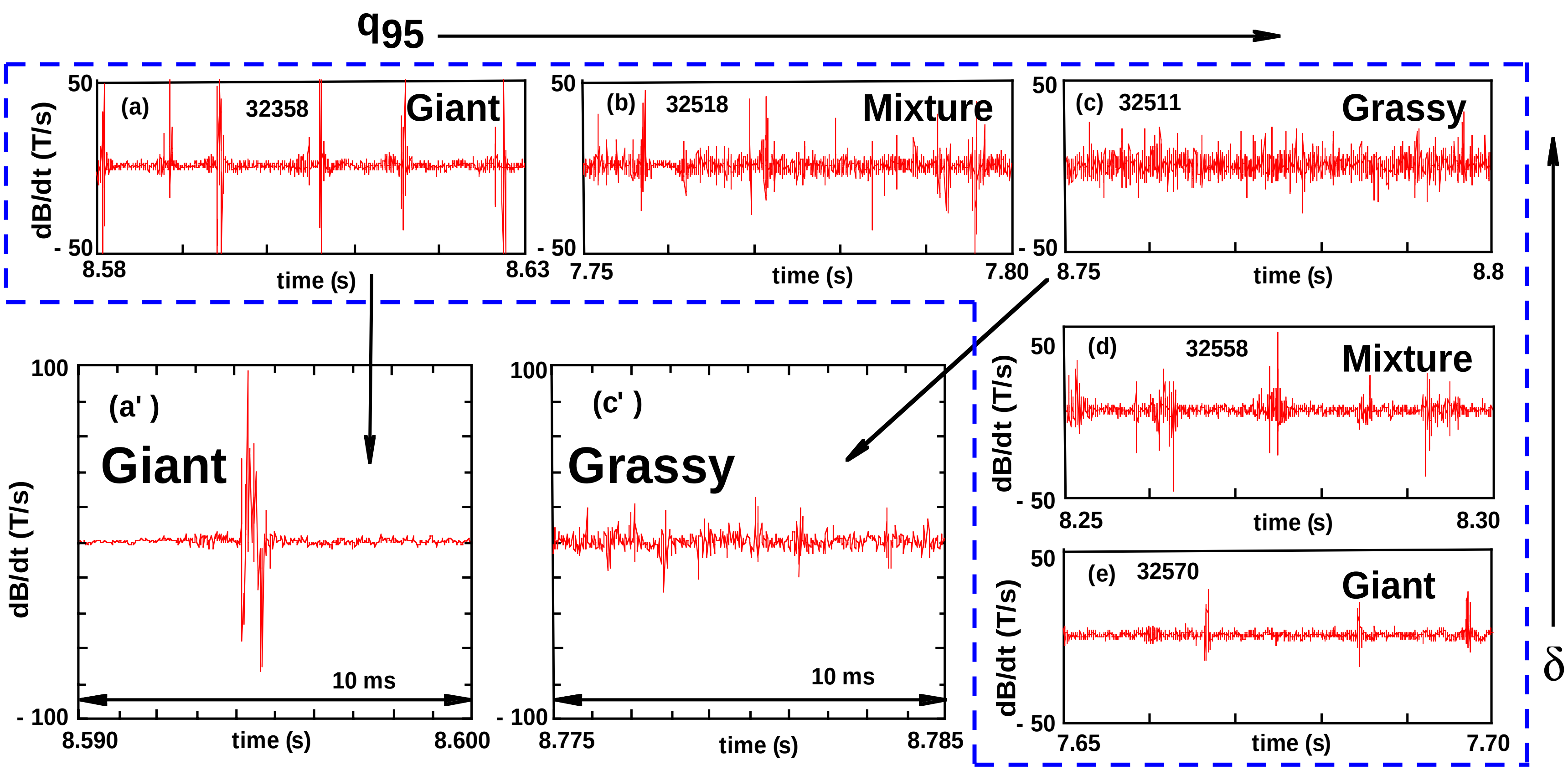
LARGE AMPLITUDE ELMS DISAPPEAR AND SMALL ELMS APPEAR IN JT-60U DISCHARGES AT LARGE $\delta \geq 0.45$ AND $q_{95} \geq 5$

- Giant ELMs ~ 100 Hz, small amplitude “grassy” ELMs ~ 500-1000 Hz
- At intermediate δ and q_{95} discharges consist of mixtures of giant and grassy ELMs
- 1 MA discharges, q_{95} increased by raising toroidal magnetic field from 2.0T to 3.6T



MAGNETIC BURSTS FROM GRASSY ELMS ARE MORE FREQUENT AND HAVE SMALLER AMPLITUDES

- ~ 100 Hz for giant ELMs
- ~ 500-1000 Hz for grassy ELMs



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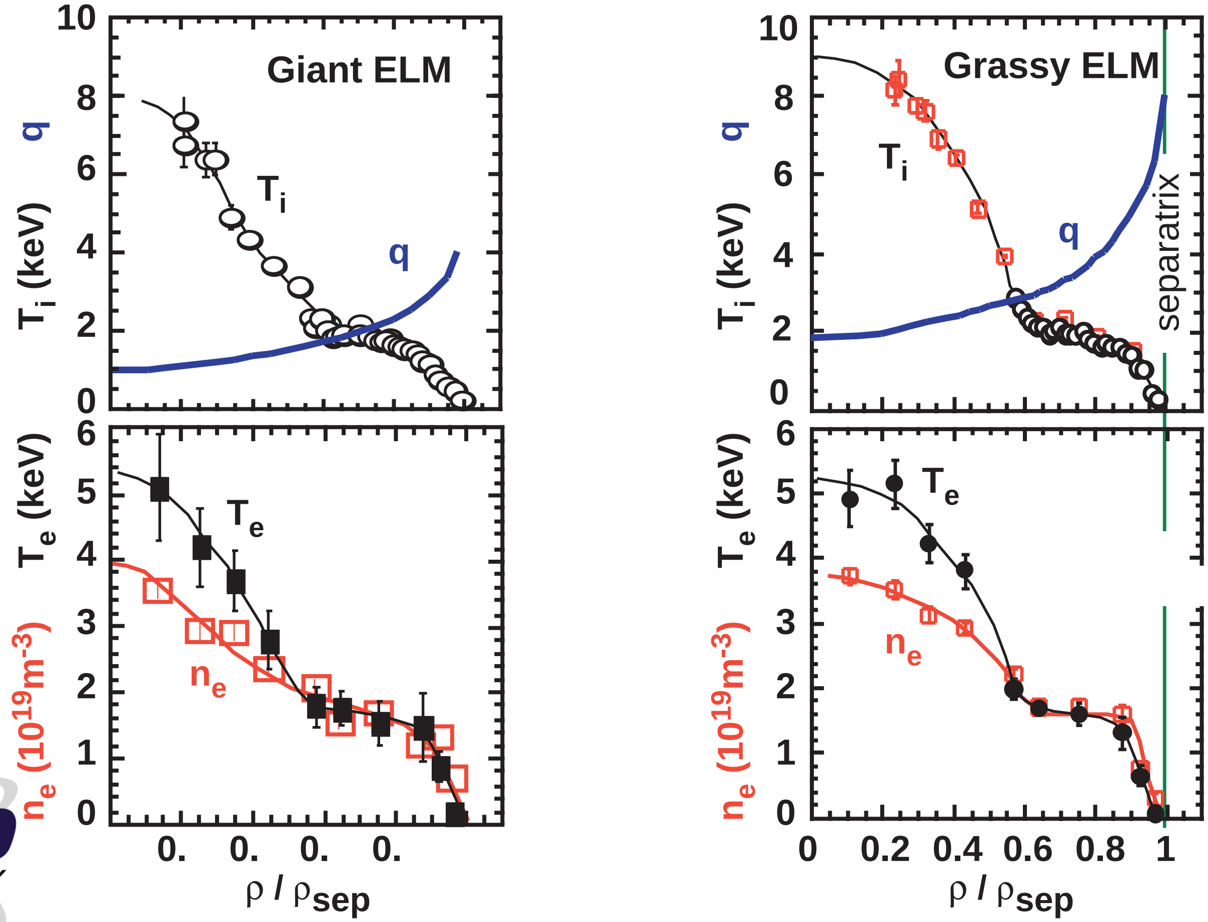
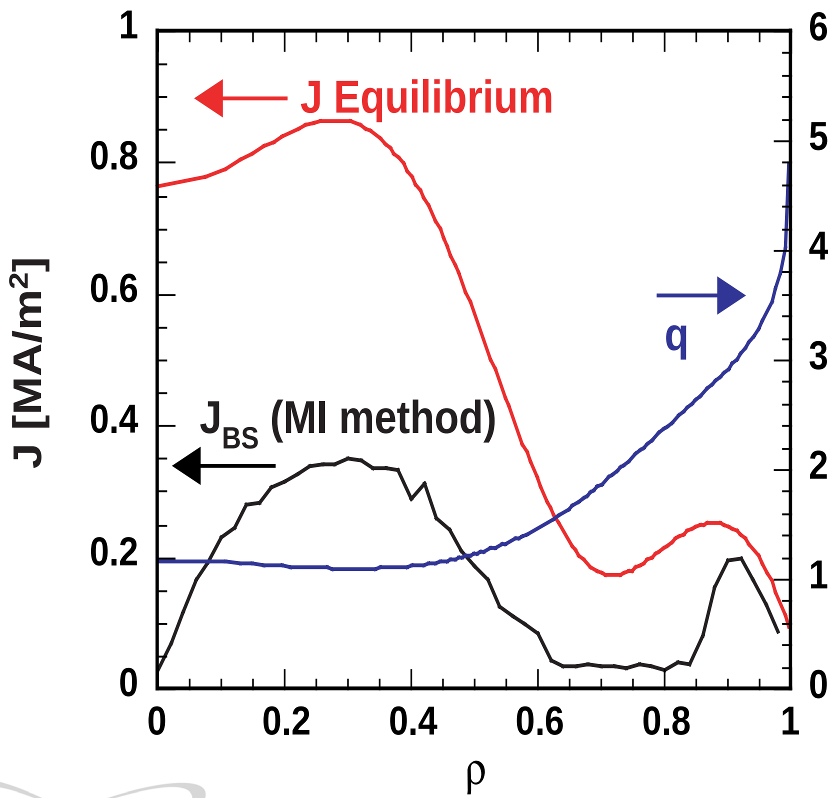
PEDESTAL P′ IN JT-60U "GRASSY" ELM DISCHARGES IS AS HIGH AS THAT IN JT-60U GIANT ELM DISCHARGES

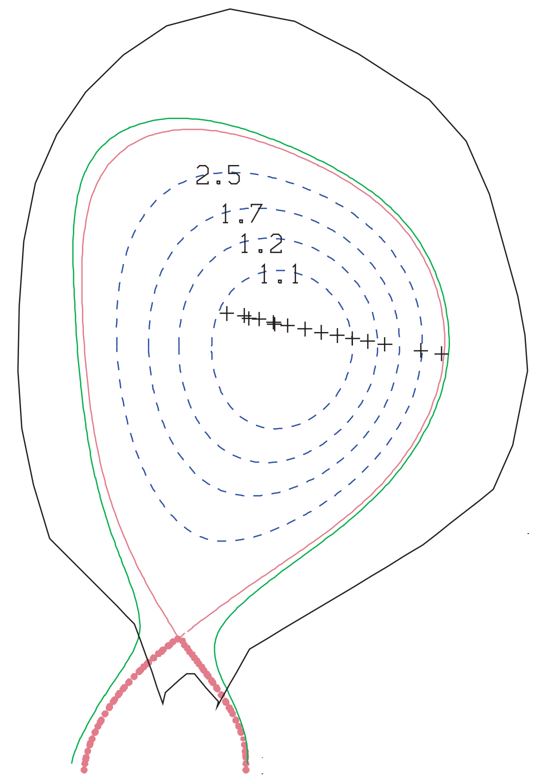
- Both are high β_P ELMy H-mode discharges
- Giant ELM: 1 MA, 2.0 T, $q_{95} = 3.4$, $\beta_P = 1.4$, $\beta_N = 2.4$, $l_i = 1.0$, $\kappa = 1.4$, $\delta = 0.43$
- Grassy ELM: 1 MA, 3.6 T, $q_{95} = 6.0$, $\beta_P = 1.6$, $\beta_N = 1.6$, $l_i = 1.0$, $\kappa = 1.4$, $\delta = 0.47$



MHD EQUILIBRIA ARE RECONSTRUCTED USING THE EFIT CODE WITH KINETIC PROFILES AND MSE MEASUREMENTS

- MSE (15 channels) + magnetics + kinetic profiles
- Reconstructed J_{edge} is consistent with J_{BS} computed using matrix inversion method [1]

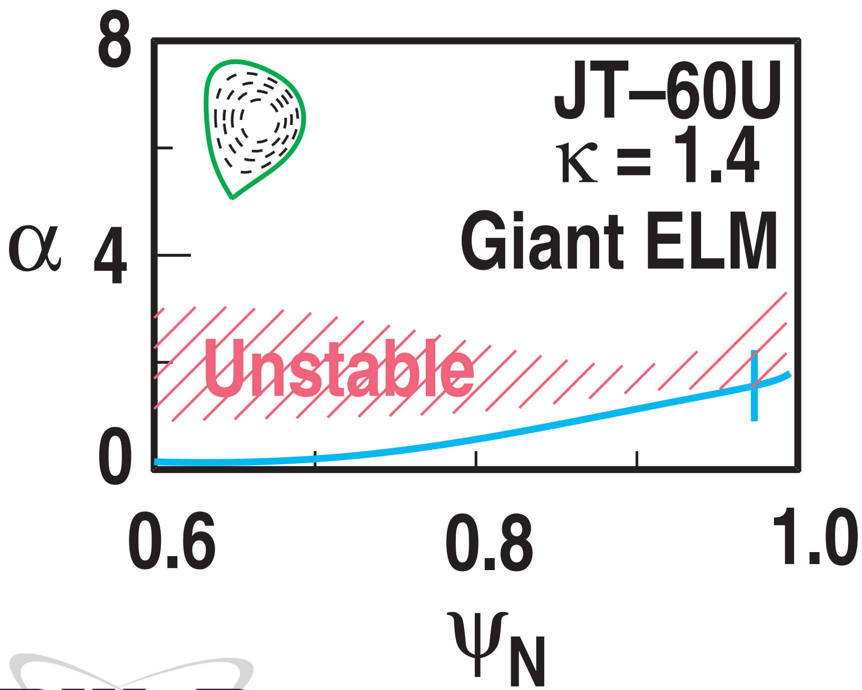


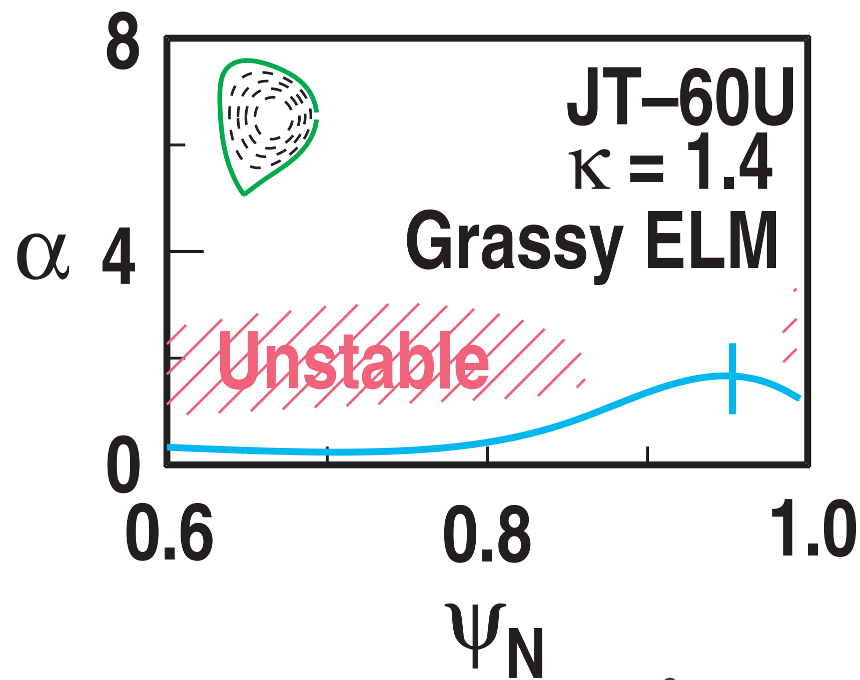


[1]Kikuchi, et al, Nucl. Fusion 30, 343 (1990)

EDGE REGION OF JT-60U GIANT ELM DISCHARGES IS NEAR THE BALLOONING MODE 1ST REGIME STABILITY LIMIT

- Edge region of JT-60U grassy ELM discharges has 2nd ballooning stability access, however edge P′ remain similar to that of giant ELM discharges
- DIII-D giant ELM discharges typically have higher $\kappa \geq 1.8$ and 2nd ballooning stability access in the edge region and larger edge P′ than JT-60U discharges





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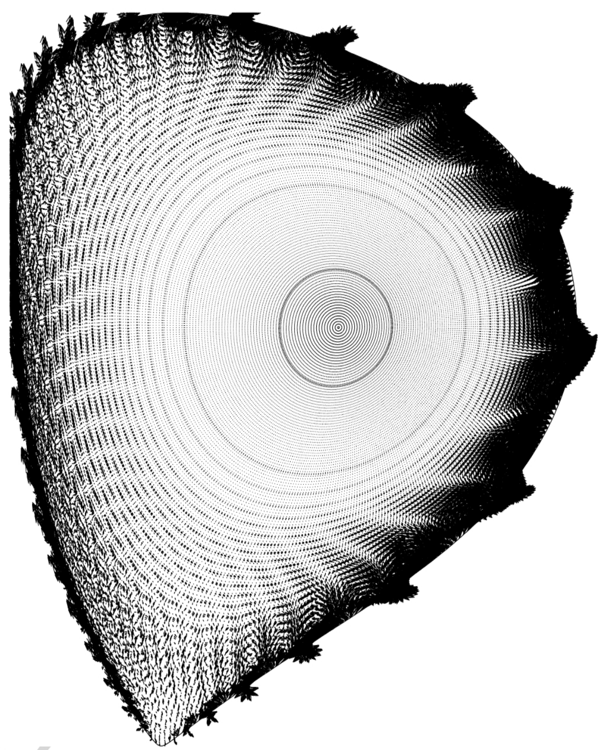
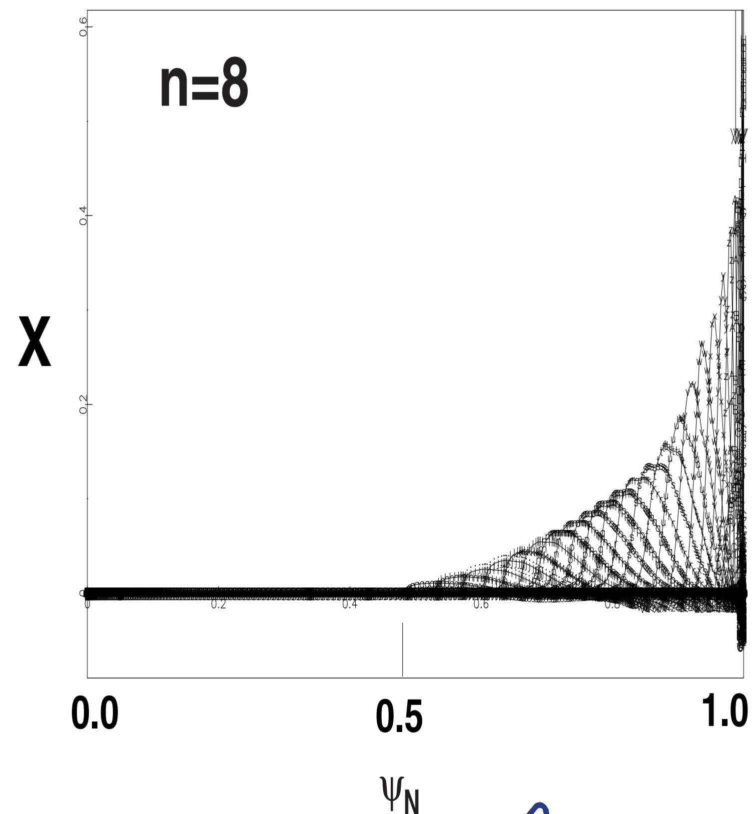
JT-60U LOW q_{95} ~ 3.4 GIANT ELM DISCHARGES ARE MARGINALLY STABLE TO THE *n* ~ 5-10 MODES

- Experimental and simulated equilibria with increasing P are used to guide the analysis
- A small increase in P' can strongly destabilize these MHD modes
- When P is increased by 20%, an *n* = 8 unstable mode can be clearly identified





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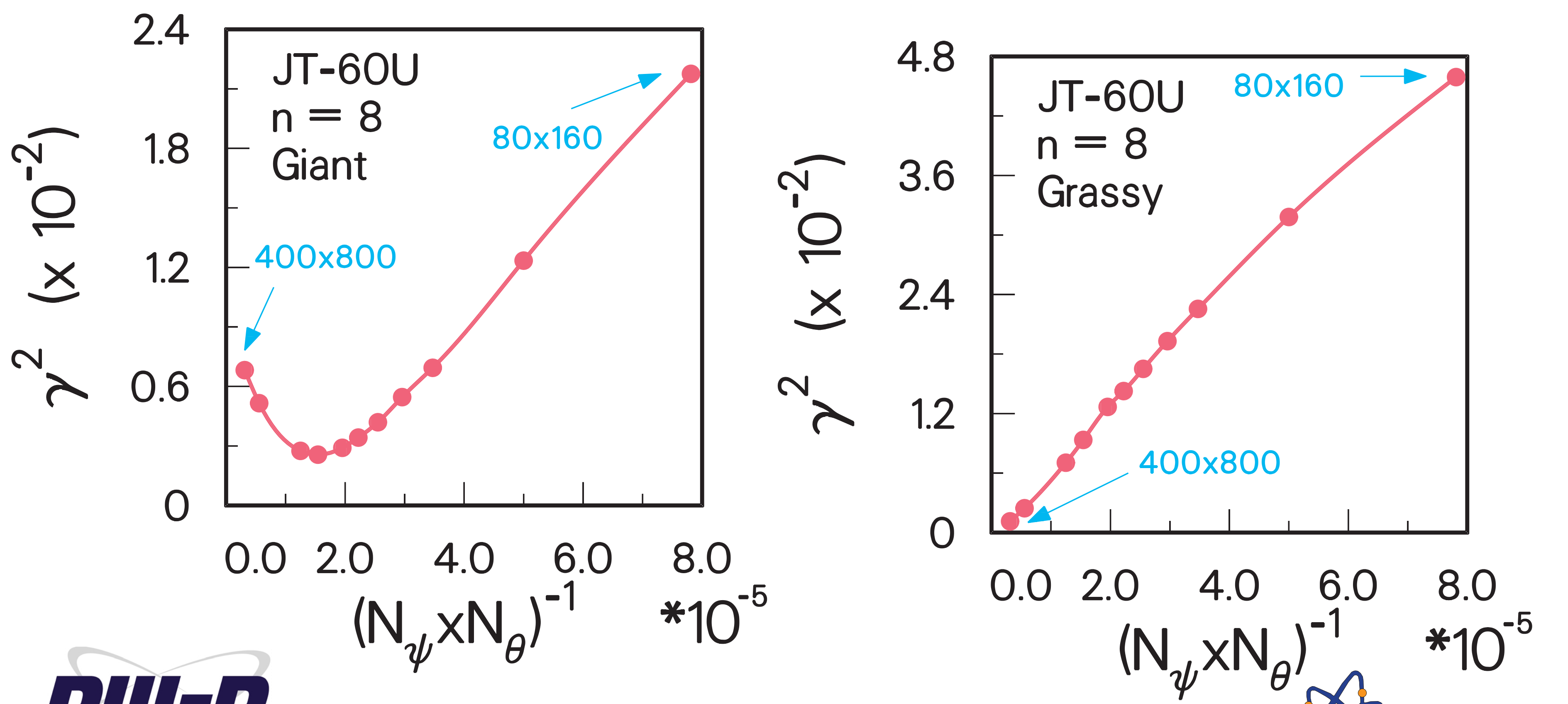
JT-60U HIGH q_{95} ~ 6.0 SMALL AMPLITUDE "GRASSY" ELM DISCHARGES ARE STABLE TO THE *n* ~ 5-10 MODES

- Unstable modes may have *n* > 10
- Higher *n* modes are expected to be more localized due to shorter wave length and perturb a smaller edge region



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SUMMARY

- DIII-D edge stability results support an ideal stability based working model of type I ("giant") ELMs as low to intermediate *n* kink/ballooning modes
- Although more works need to be done to further test and validate this ELM model, initial results from stability analysis of JT-60U type I and "grassy" ELM discharges are in support of this ELM model
  - Reduction of ELM amplitudes from giant to "grassy" in JT-60U discharges likely due to the shift of the toroidal mode number of the unstable modes to a higher one