IDEAL AND NON IDEAL MHD STABILITY IN HIGH PERFORMANCE DIII–D DISCHARGES

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*Work supported by U.S. Department of Energy under Contracts DE-AC03-99ER54463 and DE-AC05-96OR22462.

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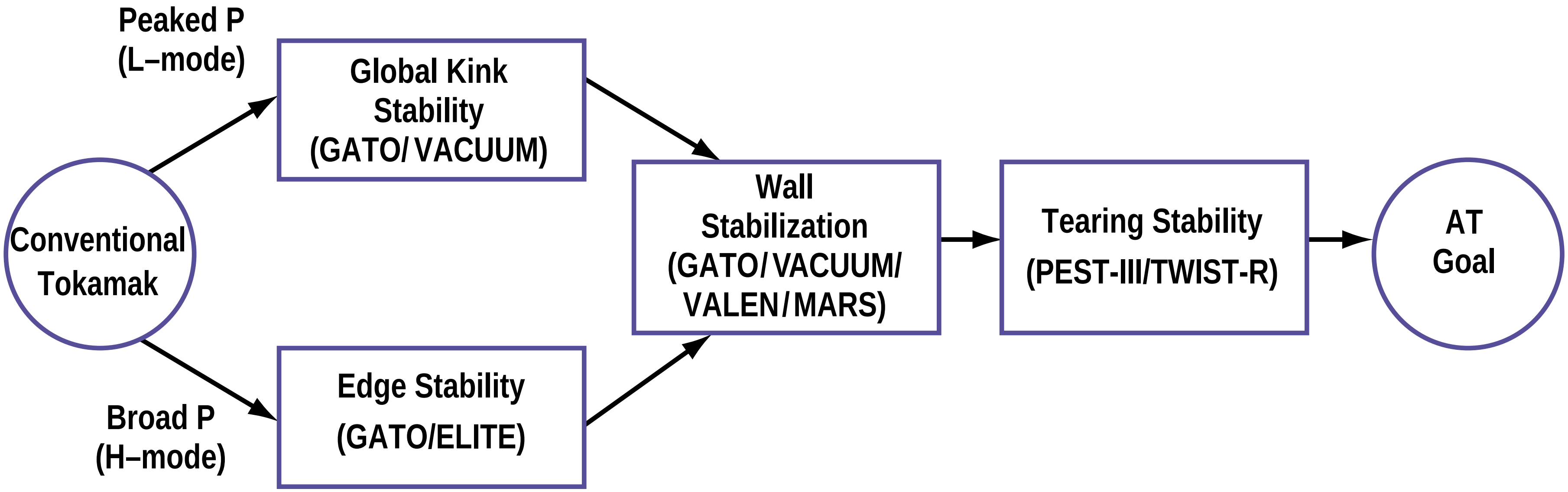
HIGH PERFORMANCE OF TOKAMAK DISCHARGES IS LIMITED BY MHD INSTABILITY

- Basic challenge: high confinement, and high β with steady-state
  ⇒ Large pressure gradients and bootstrap currents ⇒ MHD instability
- Route to high performance AT scenarios requires several stability issues to be resolved
  ⇒ Require accurate and realistic numerical tools



Peaked P
(L–mode)

Conventional Tokamak

Global Kink Stability (GATO/ VACUUM)

Broad P
(H–mode)

Edge Stability (GATO/ELITE)

Wall Stabilization (GATO/ VACUUM/ VALEN/ MARS)

Tearing Stability (PEST-III/TWIST-R)

AT Goal

- In all cases accurate equilibrium reconstructions (using EFIT) are crucial

PEAKED PRESSURE DISRUPTIONS DESCRIBED BY MODEL OF DISCHARGE DRIVEN THROUGH INSTABILITY BOUNDARY

- Discharges with highly peaked pressure invariably disrupt near β_N ~2 from n = 1 mode
- Time scale ~(200 μs) slower than characteristic ideal time (τ ~10 μs) but faster than resistive time ($\tau \gtrsim$10 ms)
- Time scales can be explained by new model for instability driven through ideal limit

$$\xi \sim \exp\left((t/\tau)^{3/2}\right)$$

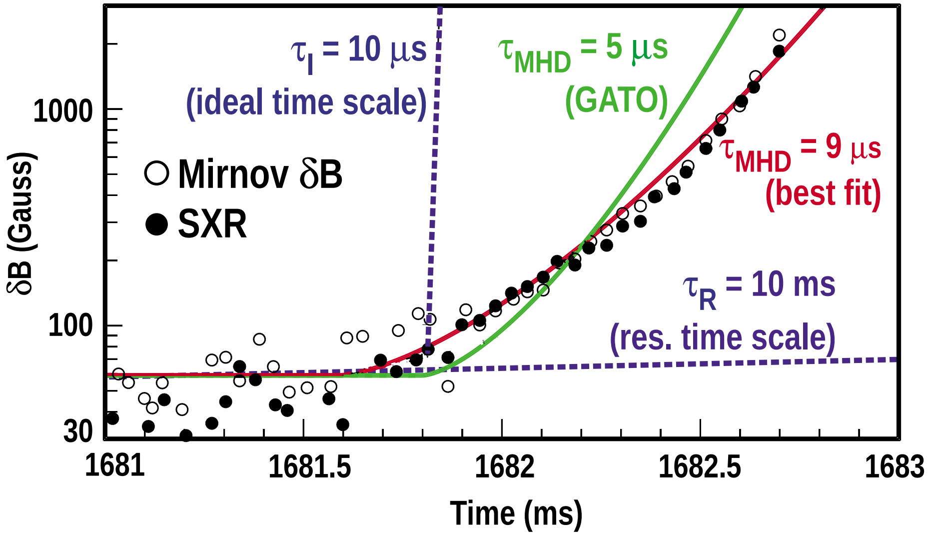
$$\tau = \left(3/2\right)^{2/3} \tau_D^{1/3} \left(\tau_{MHD}\right)^{-2/3}$$

τ_D = Heating time scale

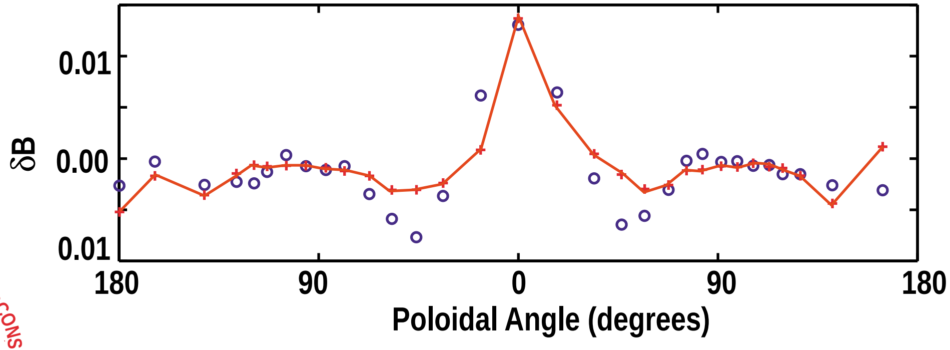
$$\tau_{MHD} \propto \frac{d}{d\beta}\gamma_{MHD}$$

[Callen et al Phys. Plasmas 6 2963 (1999)]

- Mode growth fits exp $((t/\tau)^{3/2})$



- Measured and predicted poloidal Mirnov also agree



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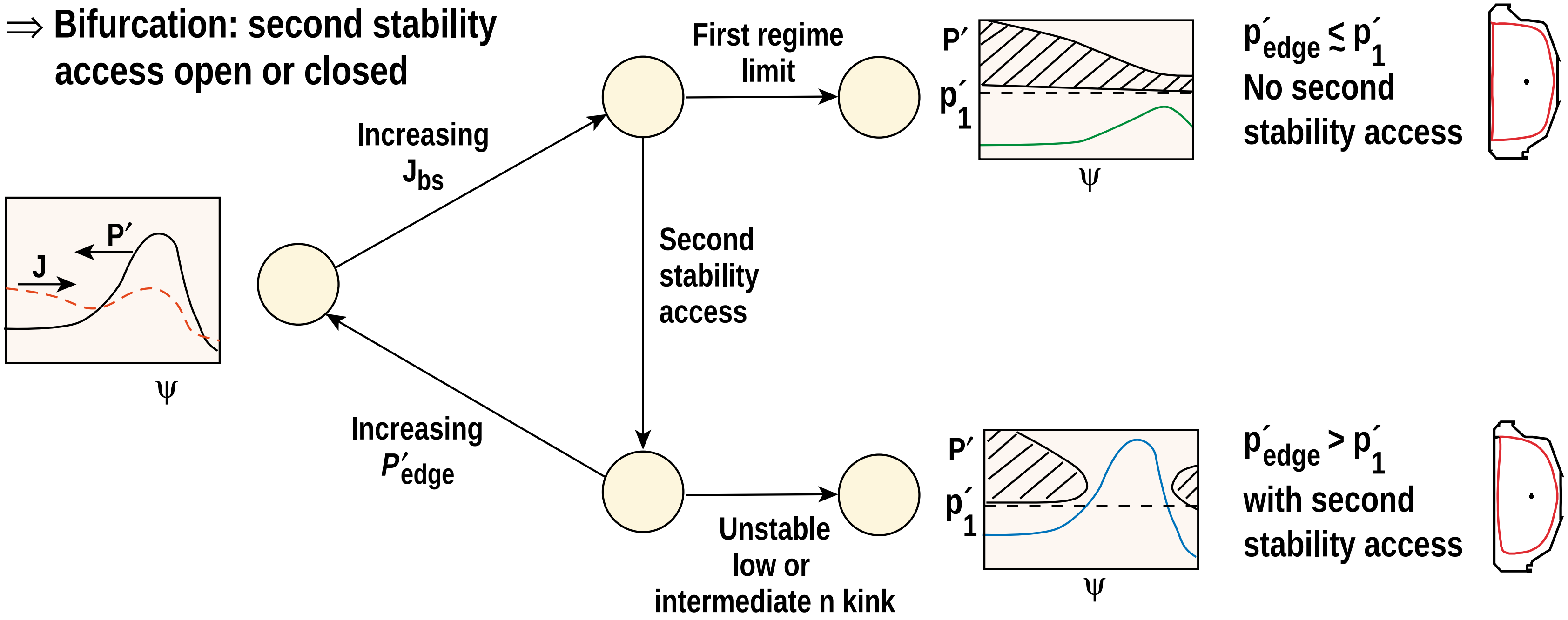
NEW MODEL FOR EDGE INSTABILITY AS IDEAL EDGE INSTABILITIES DRIVEN BY EDGE PRESSURE GRADIENT AND BOOTSTRAP CURRENT

- ELMs in DIII–D range from small frequent benign through larger less frequent Type I ELMs to large X events that terminate high performance
- Key to new model: Increasing p'_{edge} drives increasing j_{BS} which facilitates second stability across

  ⇒ Bifurcation: second stability access open or closed



Increasing J_{bs}

First regime limit

Second stability access

Increasing P'_{edge}

Unstable low or intermediate n kink

$p'_{edge} \lesssim p'_1$
No second stability access

$p'_{edge} > p'_1$
with second stability access

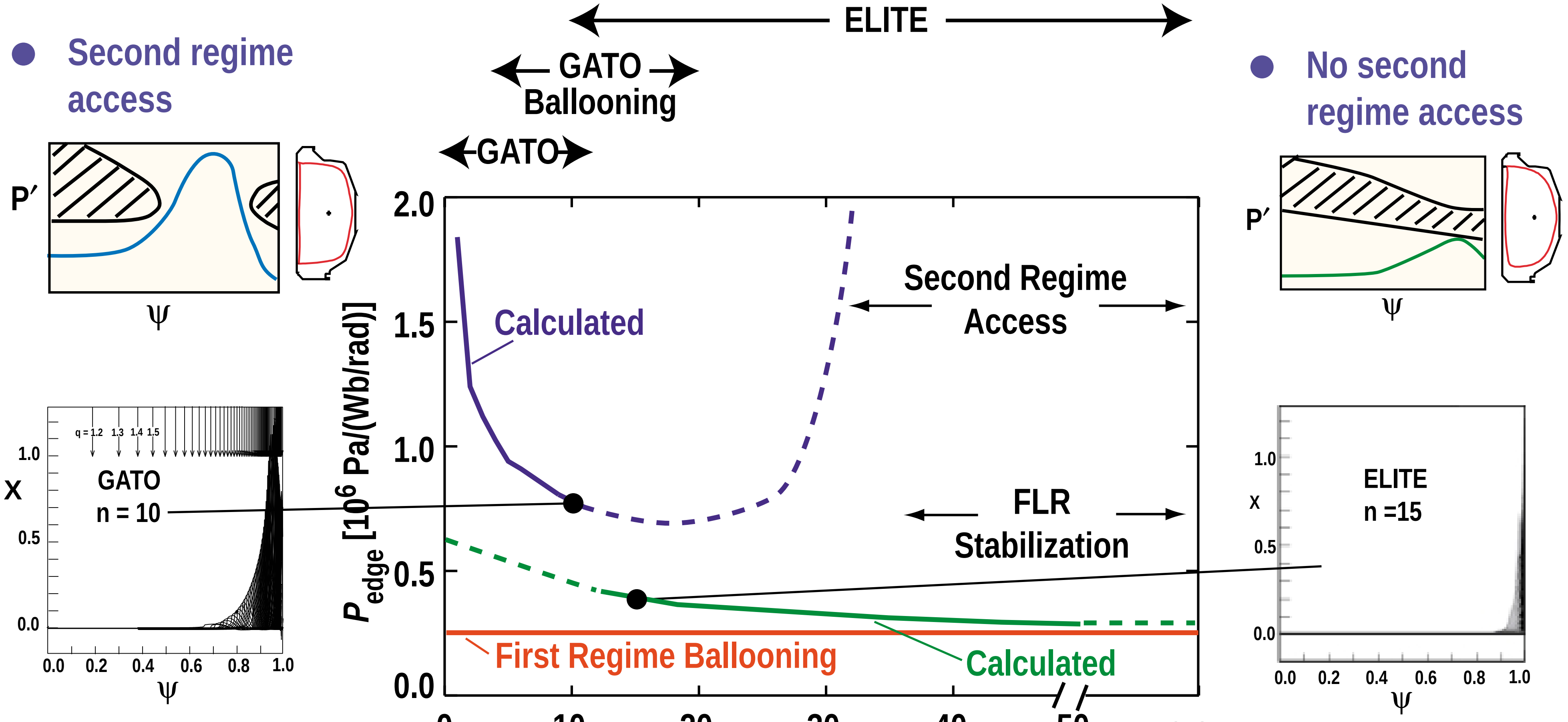
- Model predicts observed n as that which has lowest p'_{edge} limit with aligned j_{BS}
  - Verification requires quantitative stability calculations for full n range
- ELM size is determined by radial width of unstable mode

THEORY AND EXPERIMENTS SUPPORT A NEW MODEL FOR ELMS AS LOW TO INTERMEDIATE n IDEAL MODES

- Quantitative verification of model is obtained using stability calculations for full range of n

- Second regime access

- No second regime access



⇒ Large ELM

⇒ Small ELM

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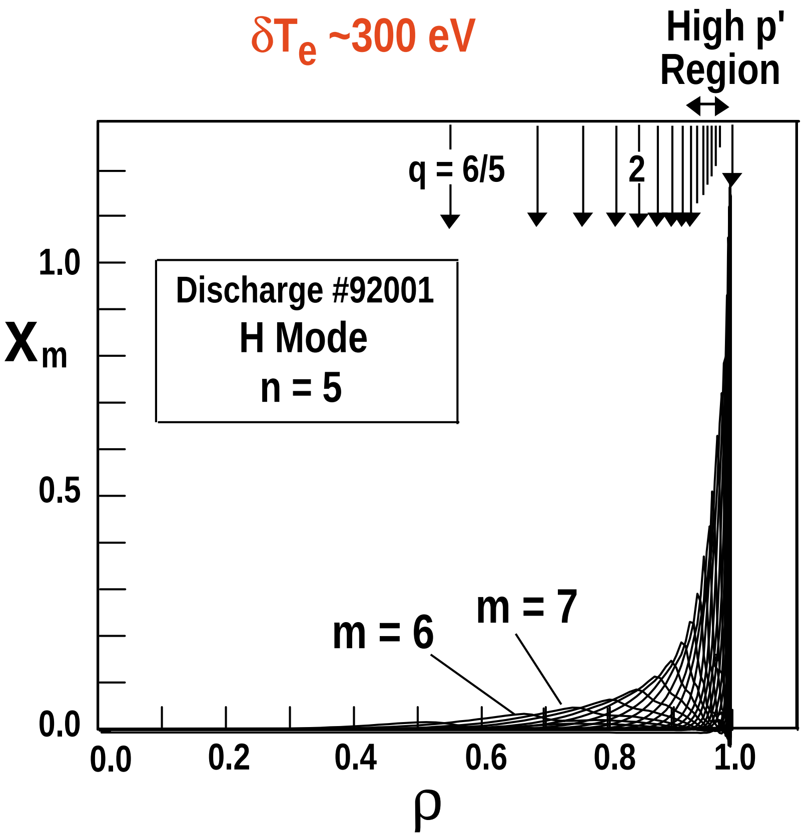
ELM SIZE CORRELATES WITH RADIAL WIDTH OF PREDICTED UNSTABLE INTERMEDIATE n KINK MODE

- Highly localized instability computed from GATO

  ⇒ Type I ELM has little effect

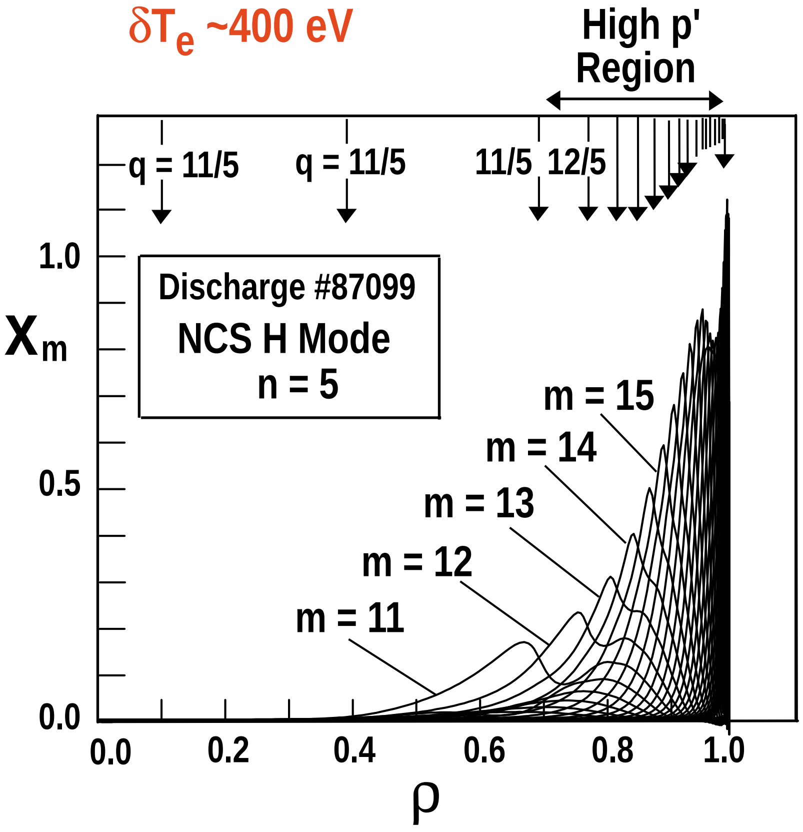
  δT_e ~300 eV



- Predicted instability computed from GATO code penetrates into core

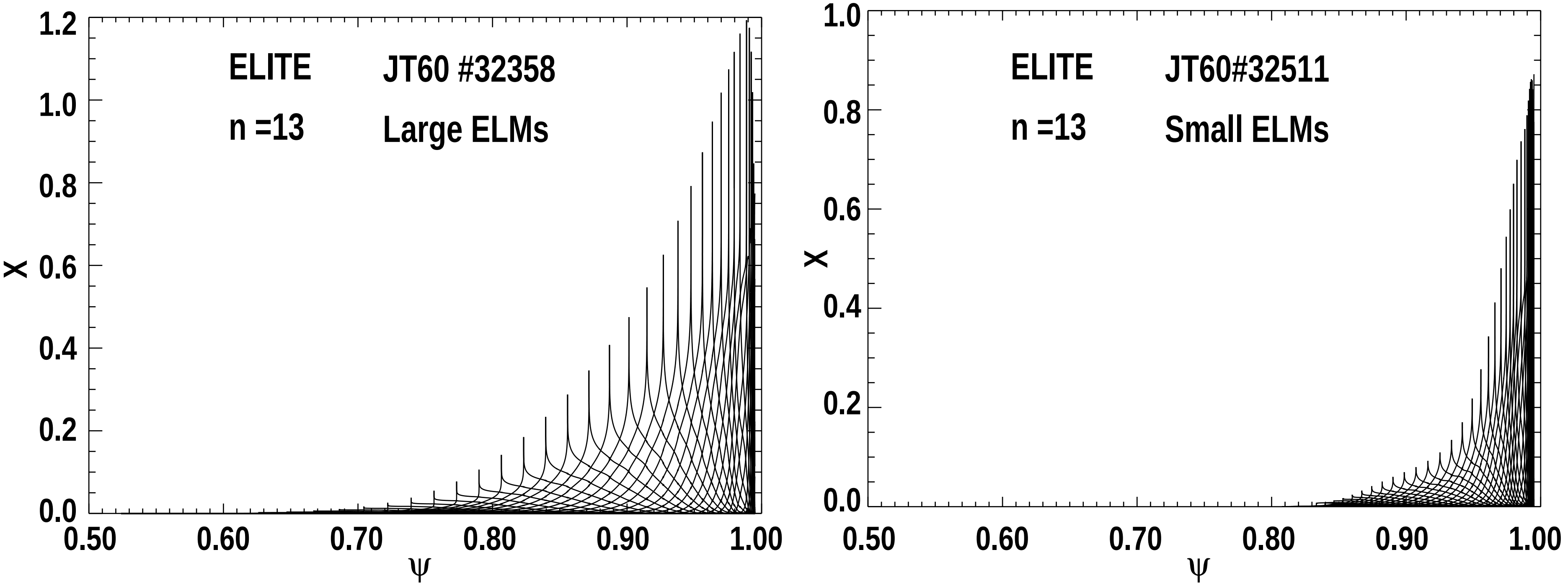
  ⇒ High performance is lost

  δT_e ~400 eV



CALCULATIONS ALSO SHOW JT60 ELM BEHAVIOR FITS MODEL

- In JT–60 small “grassy” and Type I ELMs both have P'_{edge} at nominal first regime limit
- Calculated mode penetration (ELITE) is significantly larger in case with larger Type I ELMs



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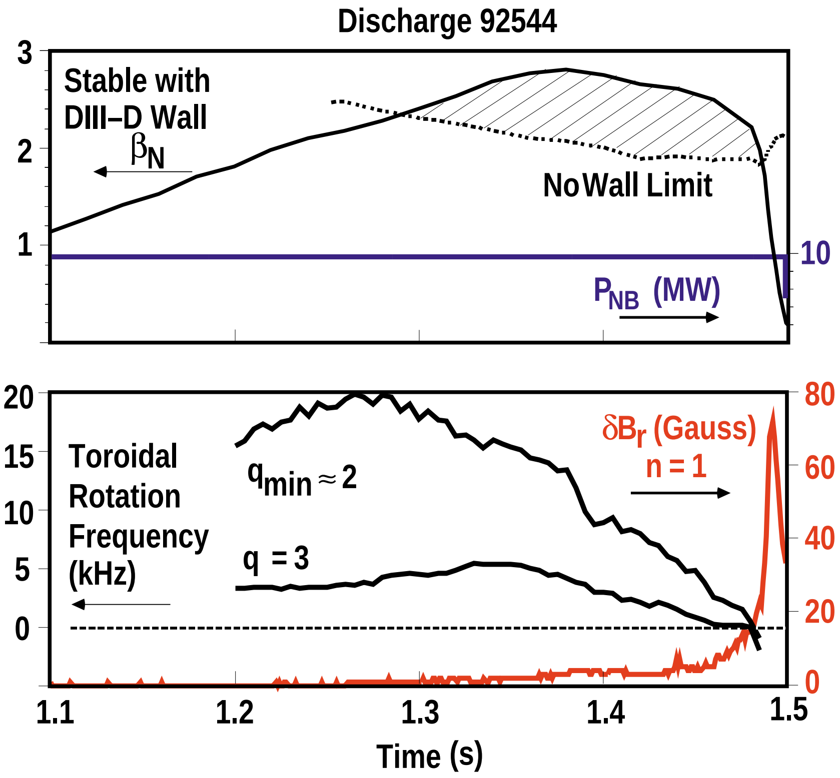
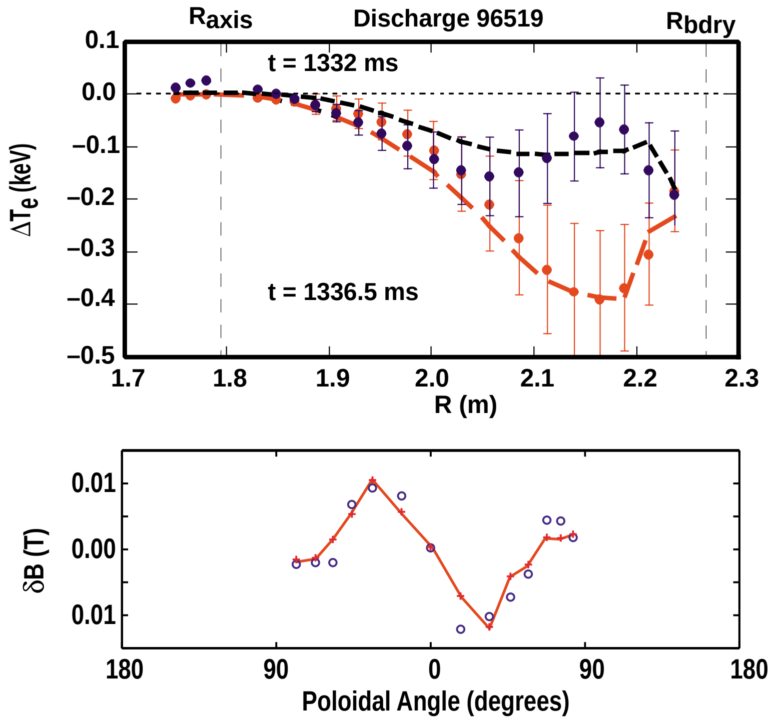
IDEAL STABILITY CALCULATIONS PROVIDE DEMONSTRATION OF RESISTIVE WALL MODE SUPPRESSION BY PLASMA ROTATION AND IDENTIFICATION OF RESISTIVE WALL MODE

- DIII–D discharges exceed predicted no-wall β limit by ~40% for ~70 wall times while plasma is rotating



- Predicted resistive wall mode radial and poloidal structive matches measured ECE and Mirnov fluctuations



⇒ Ideal no wall eigenfunction from GATO is a good representation of the RWM

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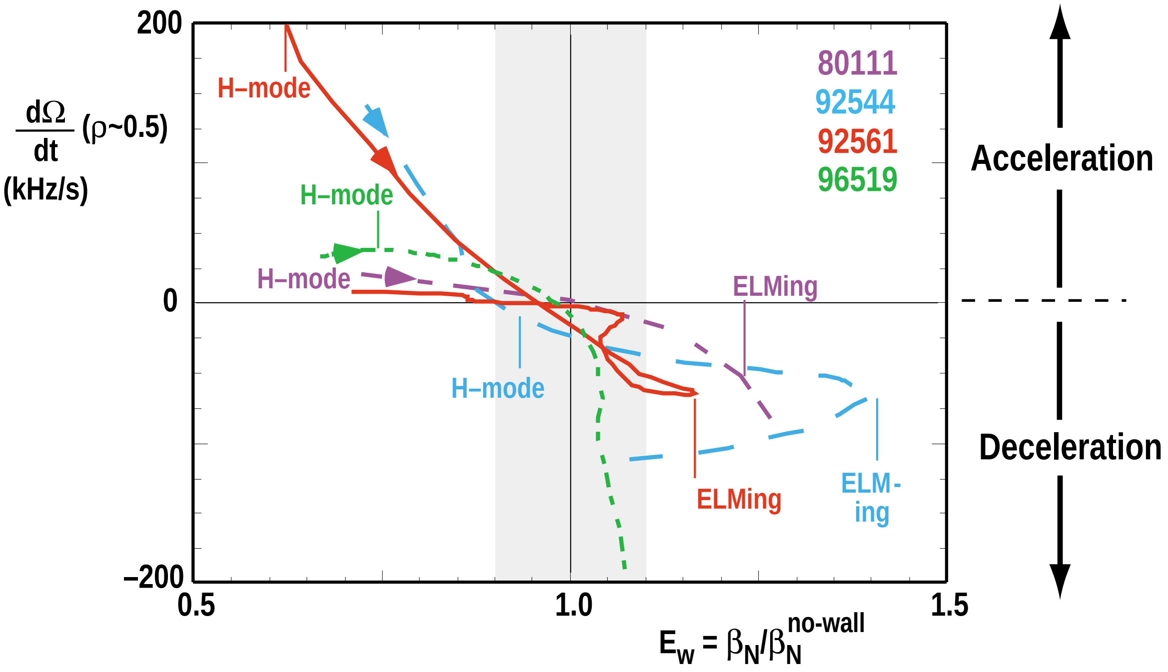
STABILITY CALCULATIONS SHOW CLEAR CORRELATION OF PLASMA SLOWDOWN WITH CROSSING NO WALL β LIMIT SUGGESTING NEW PHYSICS



- Correlation points to new physics and led to improved diagnostic detection
  - — Small very slowly growing ($\tau^{-1} << \tau_W^{-1}$) mode observed in early phase
- Two competing models are being investigated
  - — Gimblett and Hastie predict qualitative behavior but quantitatively is incorrect
  - — New data is consistent with resonant amplification of static error fields by marginal RWM

(see Garofalo et al Exp 301/Navratil et al Ex 3/4)

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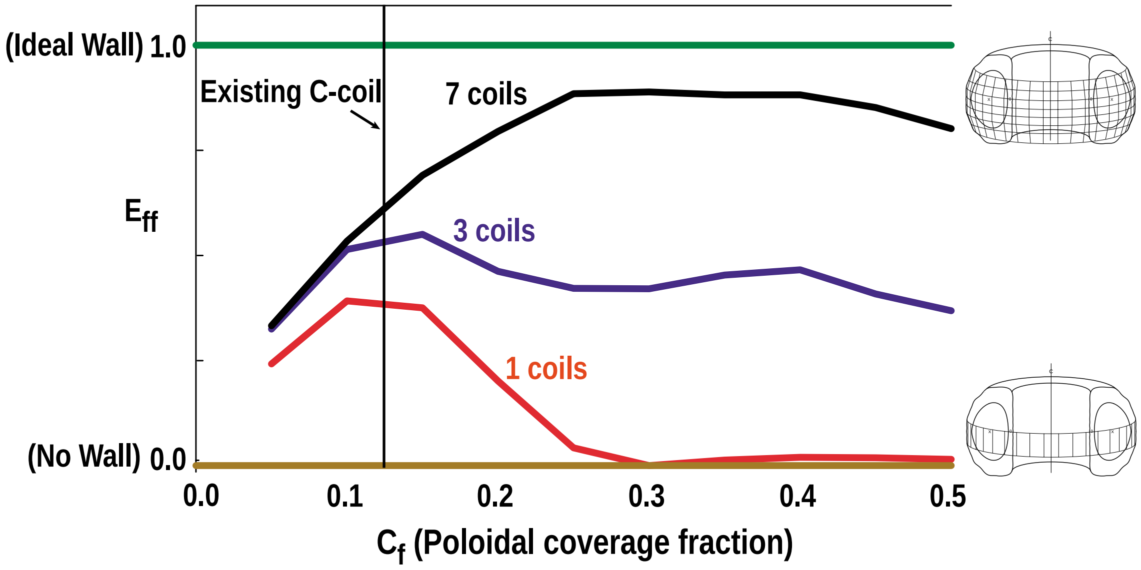
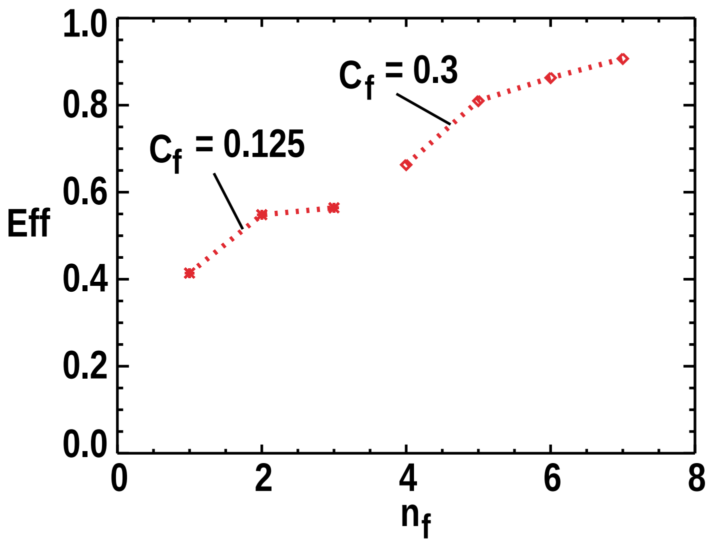
ACTIVE STABILIZATION MODELED USING GATO CODE COUPLED TO VACUUM CODE PREDICTS FEEDBACK EFFECTIVENESS

- Includes self consistent effect of feedback coils on instability
- Optimum effectiveness depends on poloidal coverage

$$E_{ff} = \frac{\partial W_F - \partial W_{\eta=\infty}}{\partial W_{\eta=0} - \partial W_{\eta=\infty}}$$



- Optimum effectiveness increases with number of individual coils



- Mode deformation found to be insignificant in present experimental situation

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(see Chance et al THP2/01)

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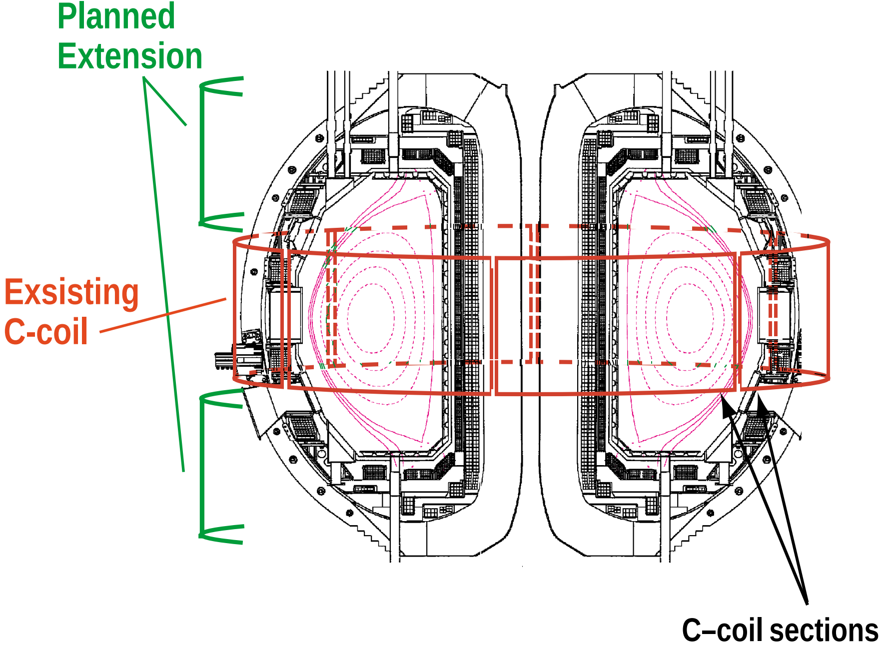
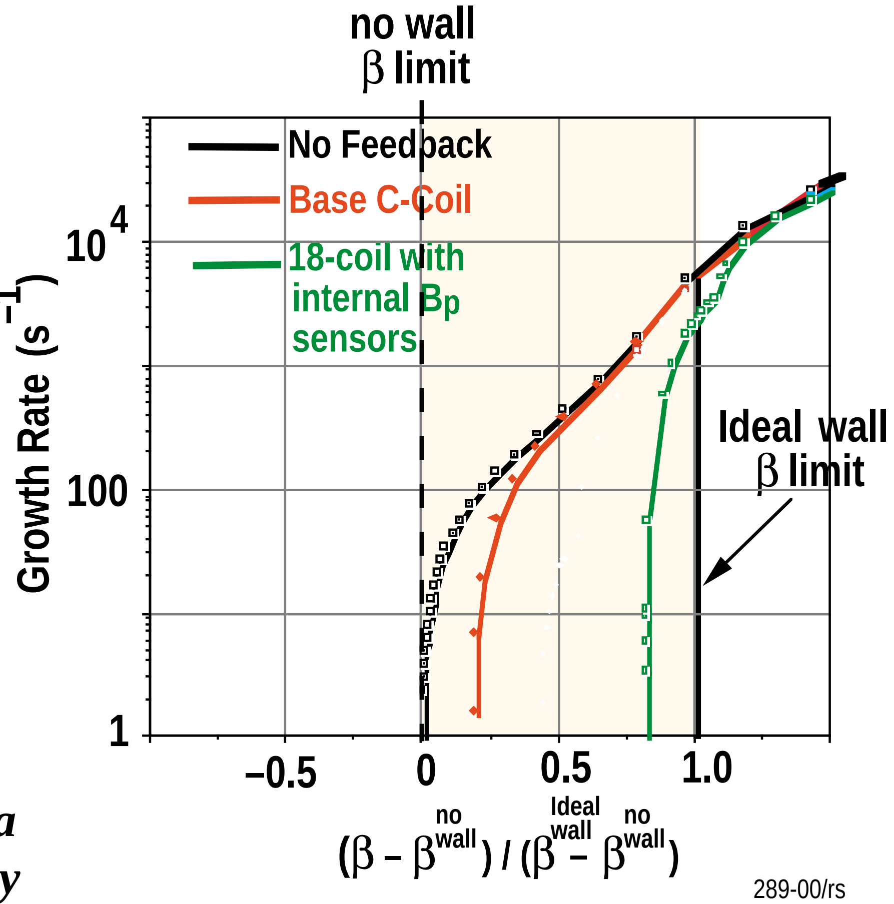
COUPLED GATO-VALEN CALCULATIONS PREDICT SIGNIFICANT GAIN IN DIII–D β LIMIT FOR EXTENDED C–COIL FEEDBACK SYSTEM

- DIII–D error field correction coils used in initial feedback experiments
  - — 6 coil set at midplane



- Fixed ideal mode (GATO) input to VALEN used to optimize 3D coil and sensor loops

⇒ Increasing present C coil set to 18 coils and using internal B_{pol} sensors can recover 80% of effectiveness of an ideal wall



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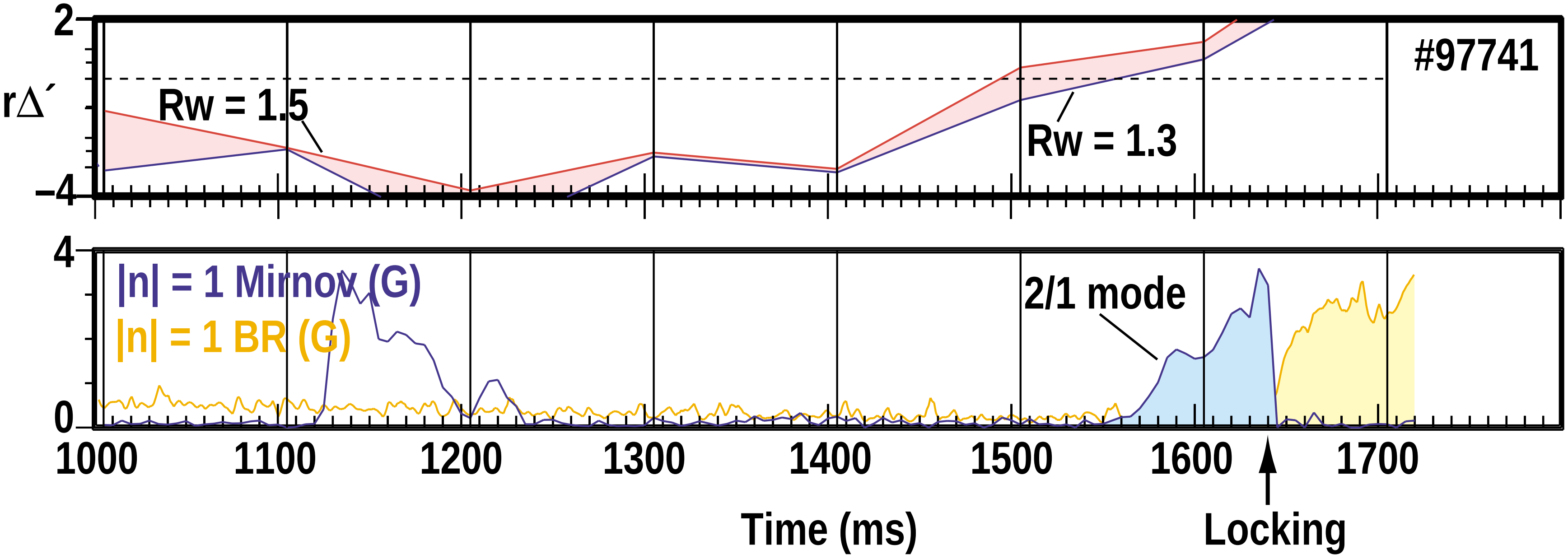
EQUILIBRIUM RECONSTRUCTIONS AND PEST-III CALCULATIONS PREDICT LINEARLY UNSTABLE TEARING MODE ONSET AT LOW β

- Calculations predict $\Delta' > 0$ at 1500–1550 ms for m/n = 2/1 mode
- Unstable 2/1 mode observed at 1550 ms in agreement with predicted onset



- Correlation with observed stability obtained only with realistic 2D finite β stability calculation and using best fit equilibrium reconstruction

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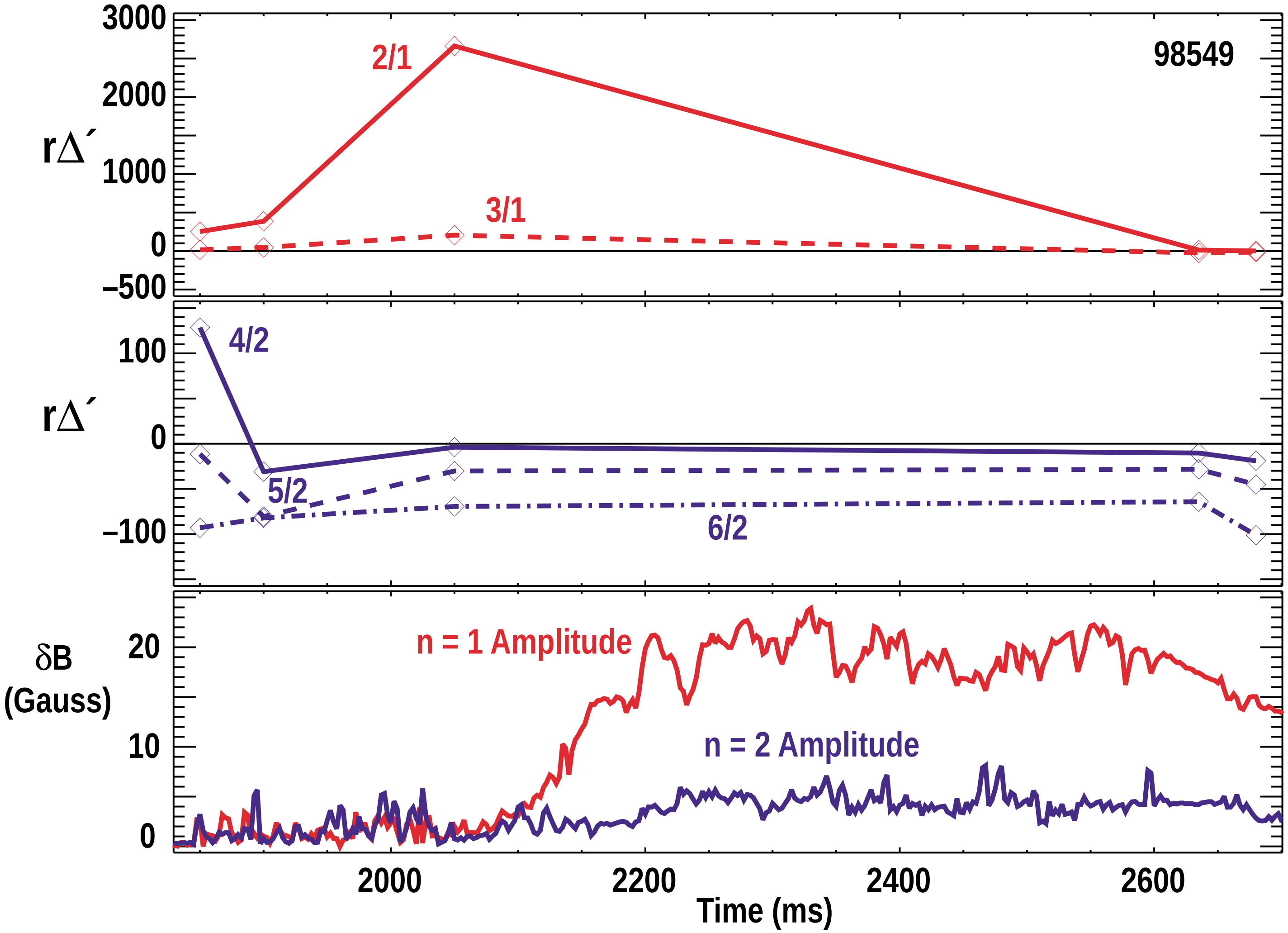
STABILITY OF HIGH PERFORMANCE LONG PULSE DISCHARGE IS CONSISTENT WITH PREDICTED LINEAR TEARING CALCULATION



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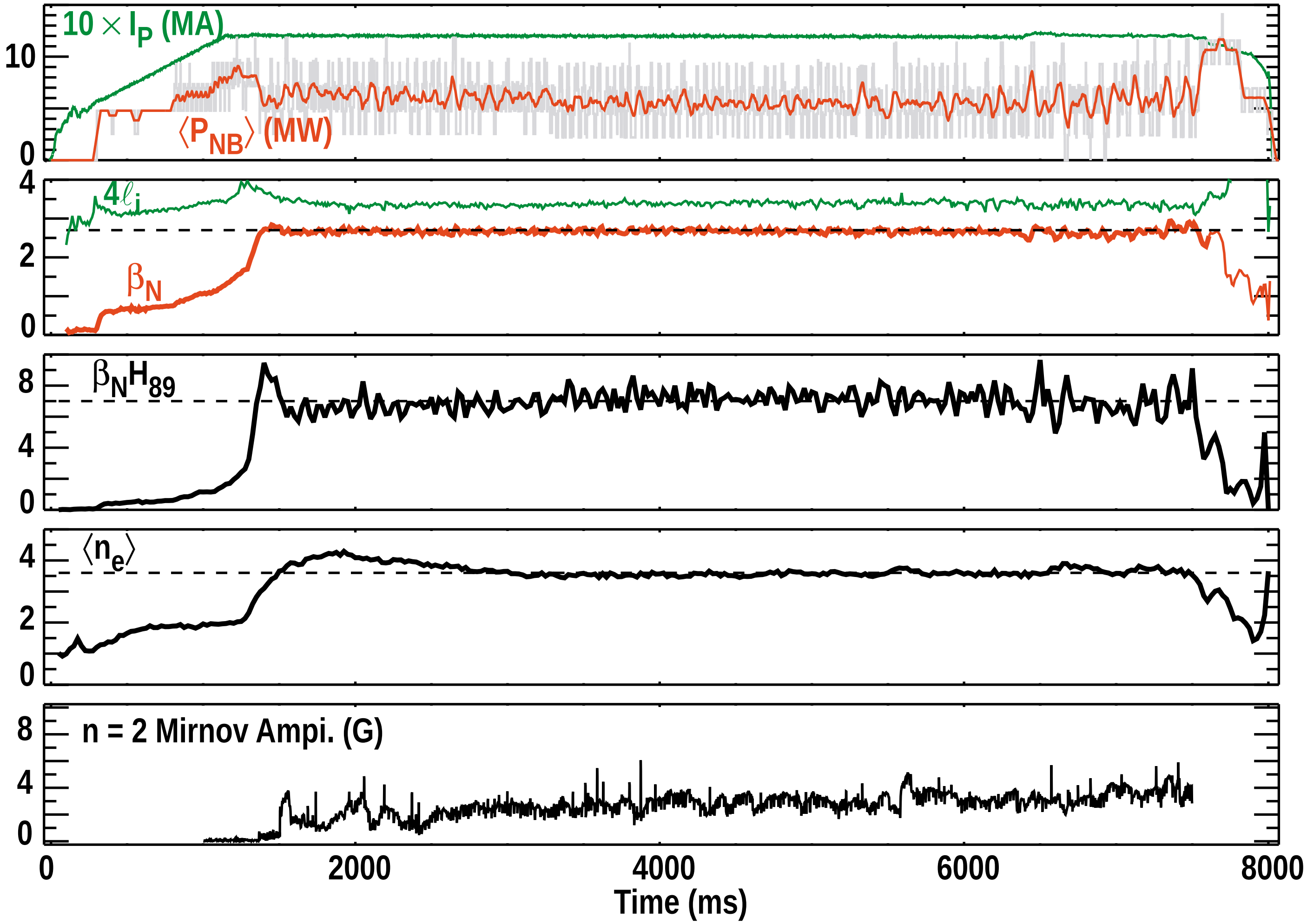
SUMMARY

- MHD theory and calculations can make quantitative predictions of AT stability
  - Attention to details of profiles shape, walls etc. is crucial
  - Development of accurate and realistic computational tools is also essential
- Quantitative comparisons with observations are important for:
  - Identifying observed instabilities
  - Further progress

Peaked pressure global stability:	Correct time dependence and mode structure	→	Avoidance by broadening pressure
Edge stability:	ELMs as intermediate n ideal modes	→	Optimum edge pedestal and ELM control
Wall stabilization:	RWM identified and slowdown correlated with $\beta > \beta^{\text{no wall}}$	→	Feedback stabilization
Tearing stability:	Linearly unstable and possible NTMs identified	→	Tearing mode avoidance and Active stabilization with ECCD

STEADY STATE HIGH PERFORMANCE DISCHARGES CAN BE ACHEIVED USING UNDERSTANDING OF STABILITY LIMITS AND DISCHARGE CONTROL

- β controlled to remain ~20% below predicted RWM limit
  - — β also kept 5% below experimental 2/1 NTM β limit
- Discharge continued in steady state until beam termination



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