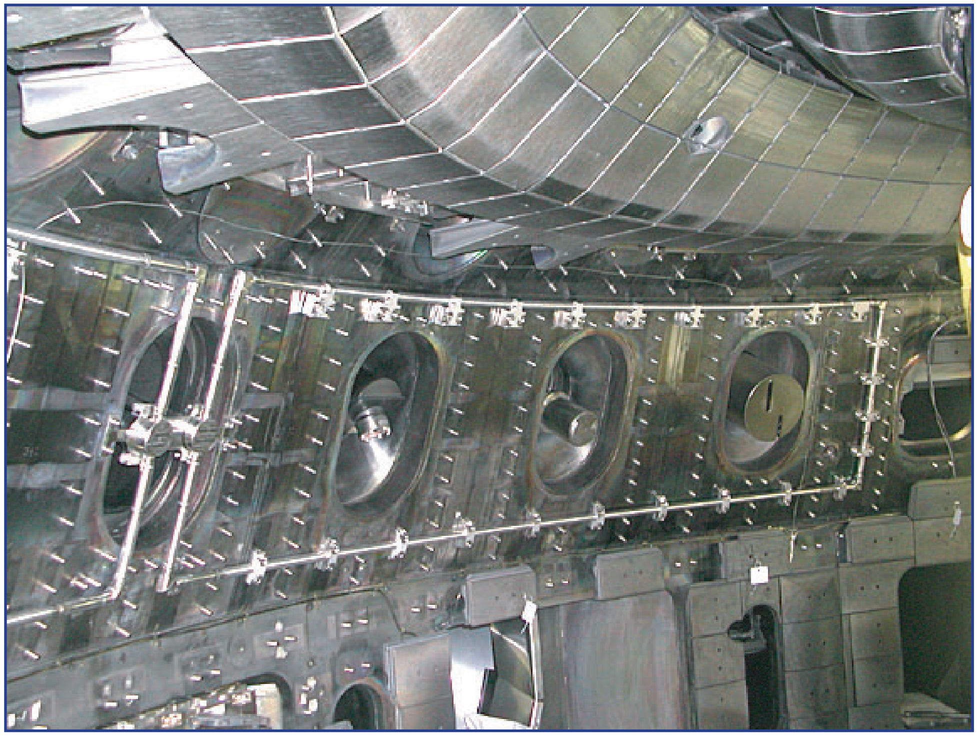
Resistive Wall Mode Stabilization with Internal Feedback Coils in DIII–D



by
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GENERAL ATOMICS

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INTERNAL CONTROL COILS IMPROVE WALL STABILIZATION

- Advanced tokamak scenarios (and other magnetic fusion concepts) require wall stabilization of external kink modes for operation at high beta

- A finite-conductivity wall does not completely stabilize the ideal kink mode, but converts it to a slowly-growing Resistive Wall Mode (RWM)

OUTLINE

- There are two approaches to stabilization of the resistive wall mode:
  - — Passive: rapid plasma rotation
  - — Active: feedback control

- Internal coils are predicted to be effective for both passive and active control of RWMs

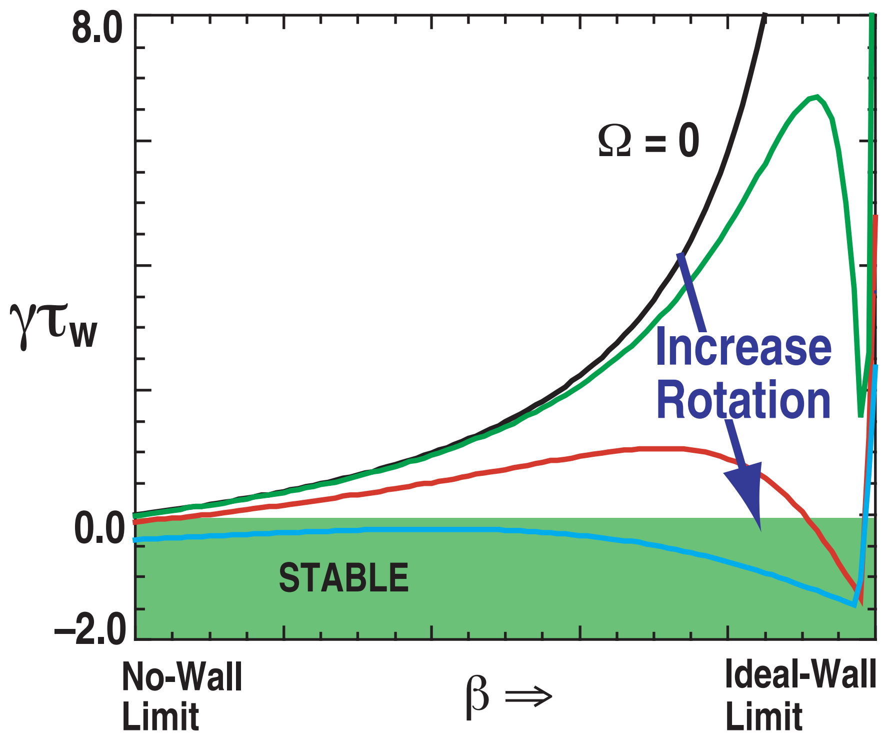
- DIII–D internal coils support RWM stabilization by plasma rotation
  - — Feedback-controlled error field correction

- DIII–D internal coils improve RWM stabilization by direct feedback control
  - — Stabilization at higher beta, lower rotation than external coils

TWO DISTINCT APPROACHES FOR RWM CONTROL HAVE BEEN PROPOSED

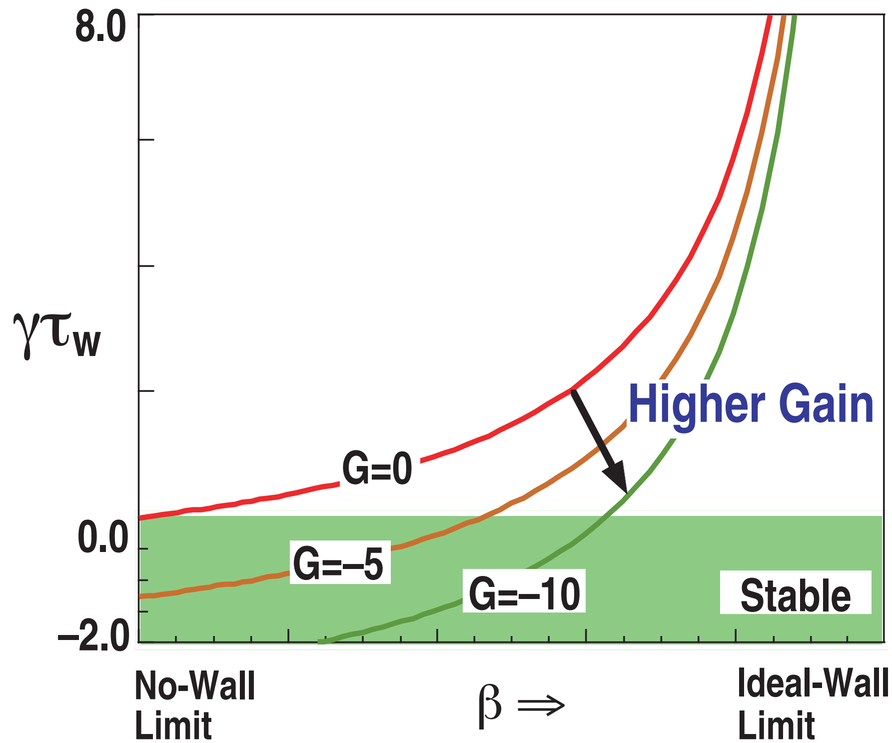
Passive: Plasma Rotation with Dissipation

- Required rotation for stability ~ a few % of Alfvén velocity



Active: Magnetic Feedback

- Required power level is modest



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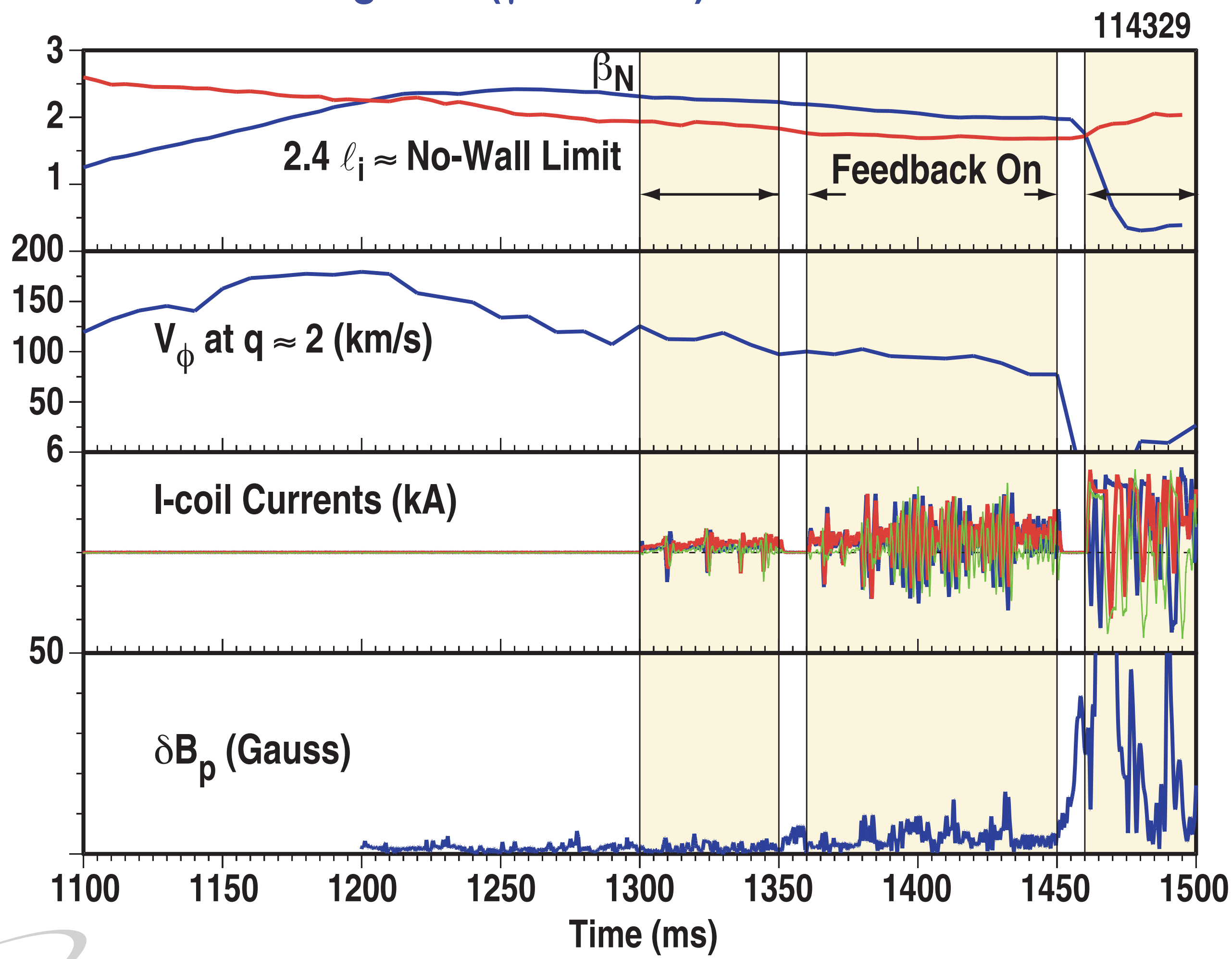
PLASMA ROTATION AND DIRECT FEEDBACK CONTROL PROVIDE STABILITY WITH A RESISTIVE WALL

- Rotation stabilizes RWM before feedback is turned on
- Feedback becomes important as rotation decreases
- Resistive wall mode grows (γ^{-1} ~4 ms) when feedback is turned off



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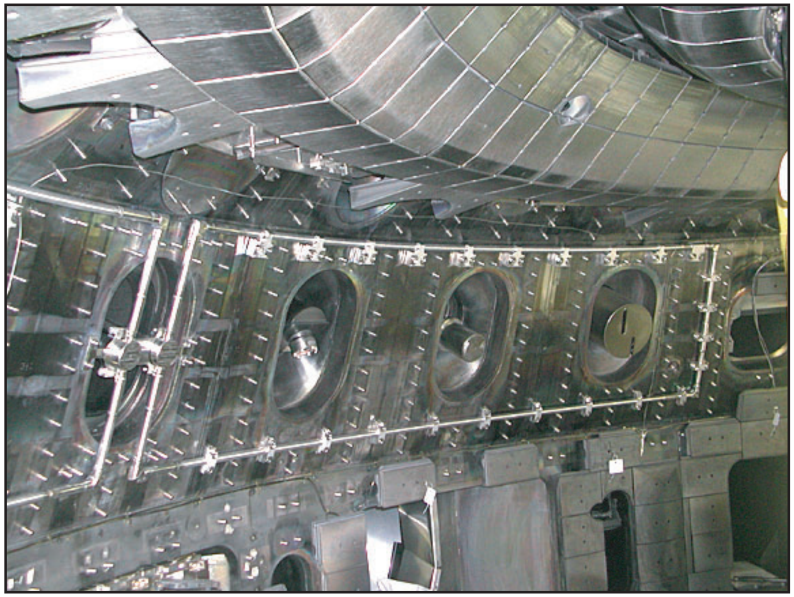
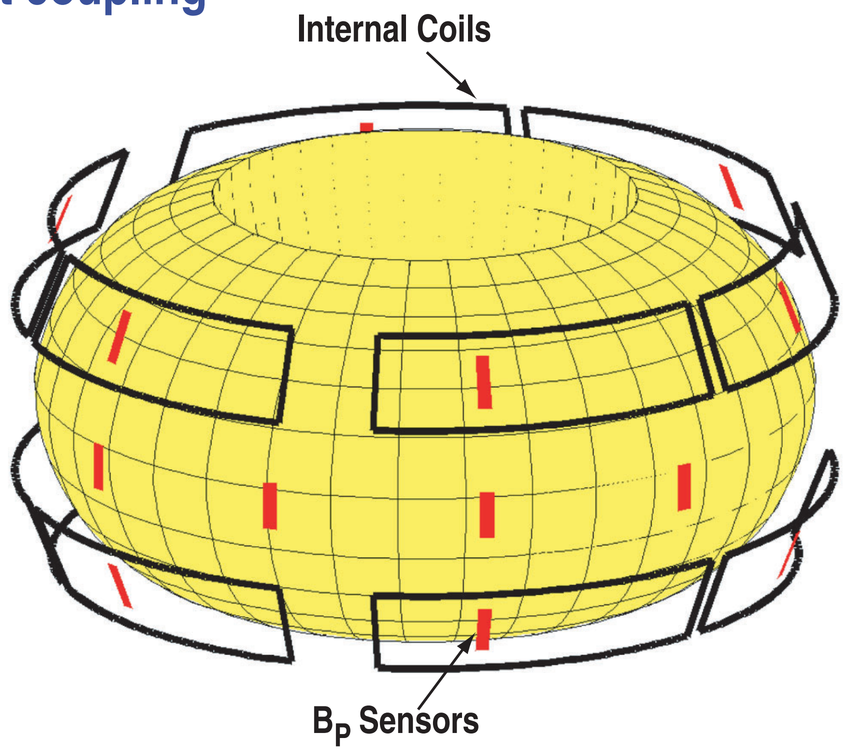
NEW INTERNAL CONTROL COILS ARE AN EFFECTIVE TOOL FOR PURSUING ACTIVE AND PASSIVE STABILIZATION OF THE RWM

- Inside vacuum vessel: Faster time response for feedback control
- Closer to plasma: more efficient coupling





- 12 “picture-frame” coils
- Single-turn, water-cooled
- 7 kA max. rated current
- Protected by graphite tiles

G.L. Jackson, G01.003

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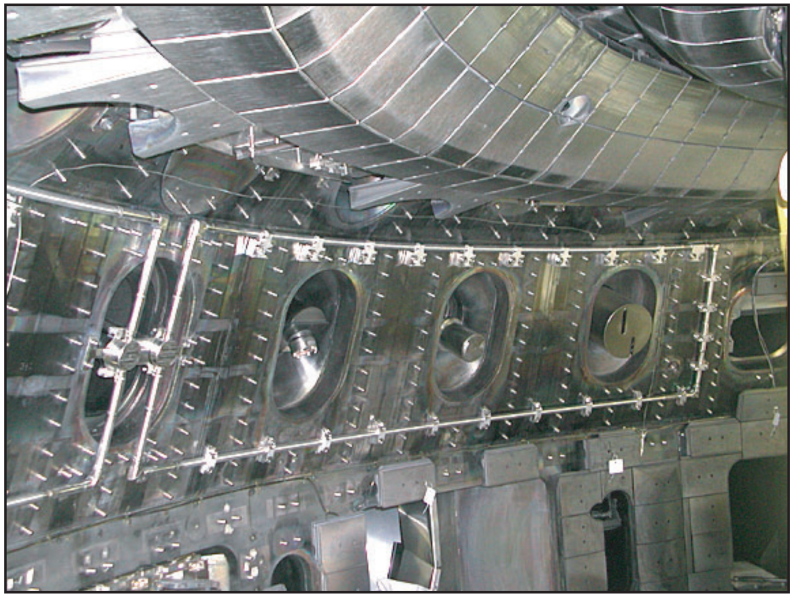

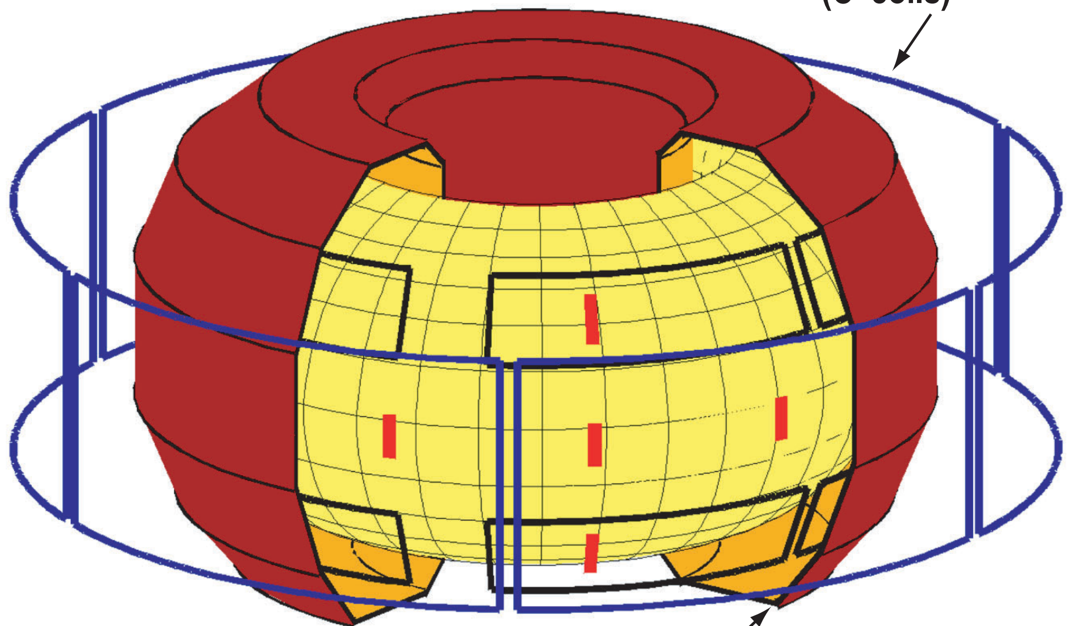

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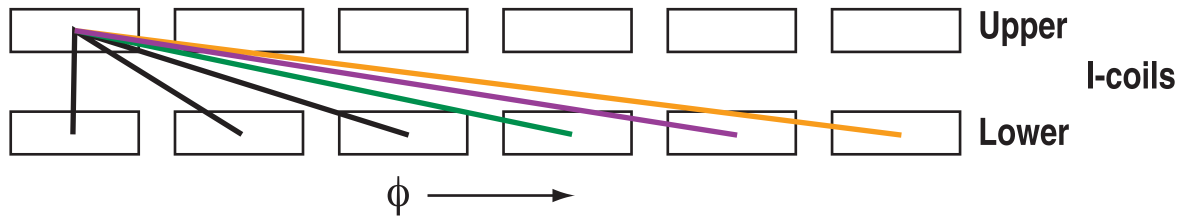
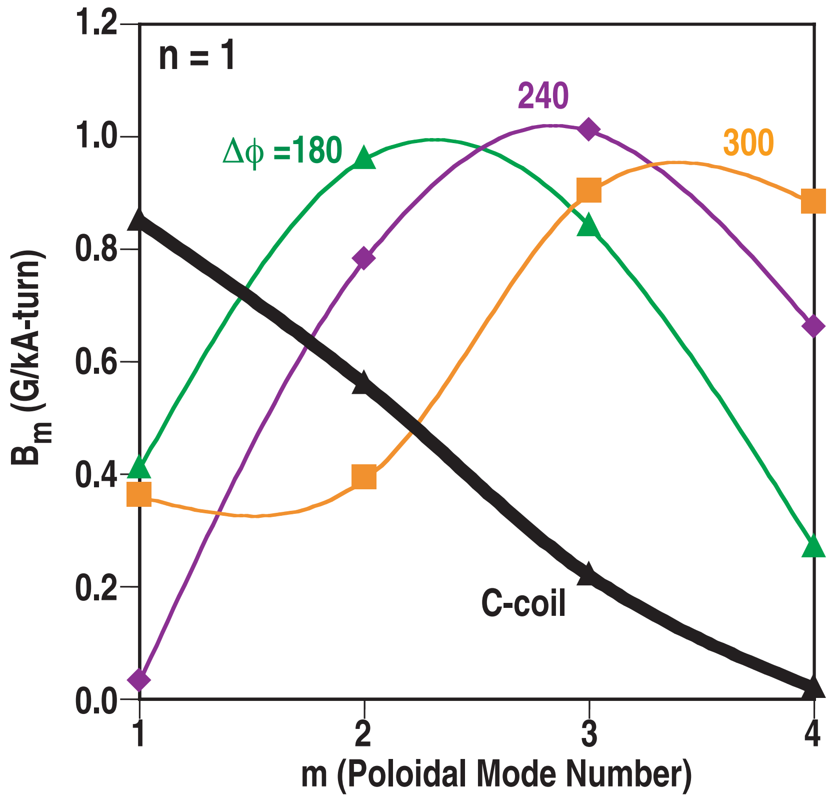
I–COIL CONNECTIONS ALLOW A WIDE RANGE OF (m,n) SPECTRA

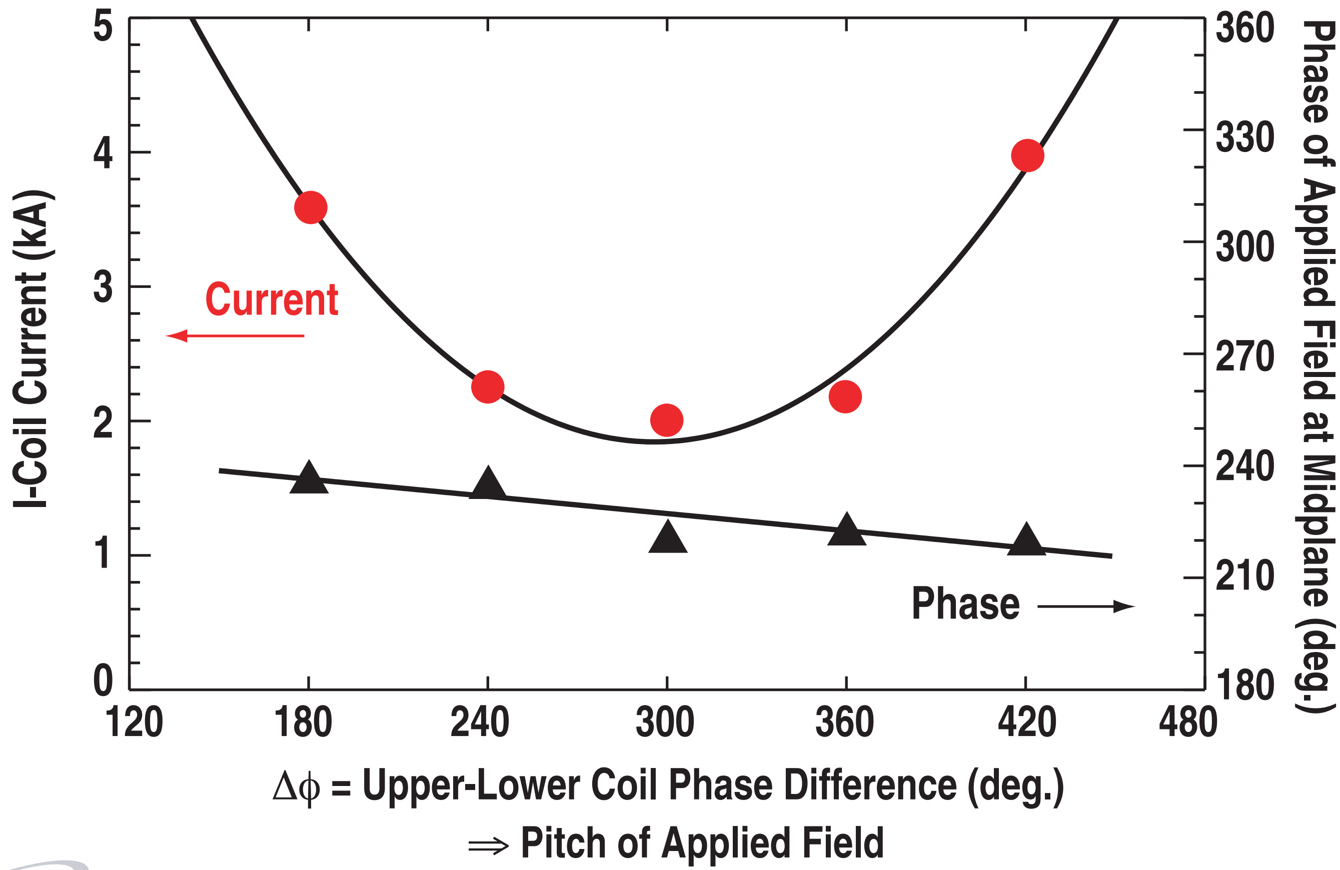




- **Toroidal mode number: $0 \le n \le 3$**
  - Antisymmetric pairs (n = odd) used for most experiments
- **Poloidal mode number: $0 \le m \lesssim 4$**
  - 240 degree upper-lower phase difference used for most experiments

ERROR FIELD COMPENSATION IS MOST EFFICIENT WHEN I–COIL FIELD MATCHES RWM STRUCTURE

- Correction field pitch scanned by varying upper/lower coil connections
- Correction field amplitude and phase determined by feedback control
- Constant phase is consistent with correcting a fixed error field



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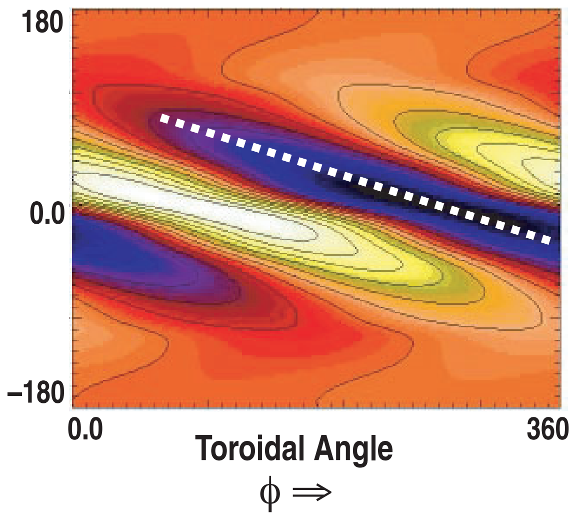
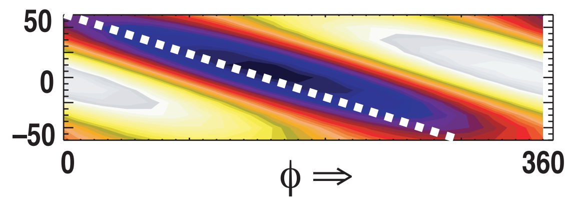
I–COIL FLEXIBILITY ALLOWS A GOOD MATCH TO THE HELICAL STRUCTURE OF THE n = 1 RWM

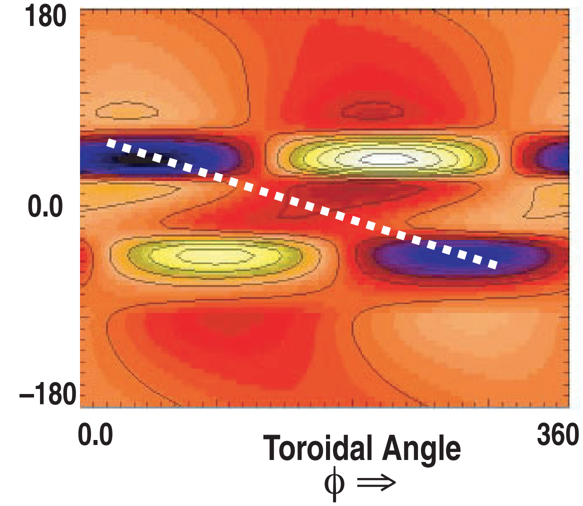
- Calculated and measured RWM structure agree well



Calculated Mode Structure at Plasma Surface



Measured Mode Structure at Vessel Wall



Calculated I–coil Field at Plasma Surface ($\Delta\phi$ = 240˚ Connection)

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MODELING PREDICTS THAT INTERNAL COILS IMPROVE RWM STABILIZATION BY FEEDBACK CONTROL

- Improved feedback performance is predicted for internal coils
  - — Faster time response
  - — Improved coupling to plasma
- Feedback stabilization up to the ideal-wall limit requires that coil-wall coupling is not too large, compared to direct coil-plasma coupling:

$$C = \frac{M_{pw}\,M_{wc}}{L_w\,M_{pc}} \leq 1$$

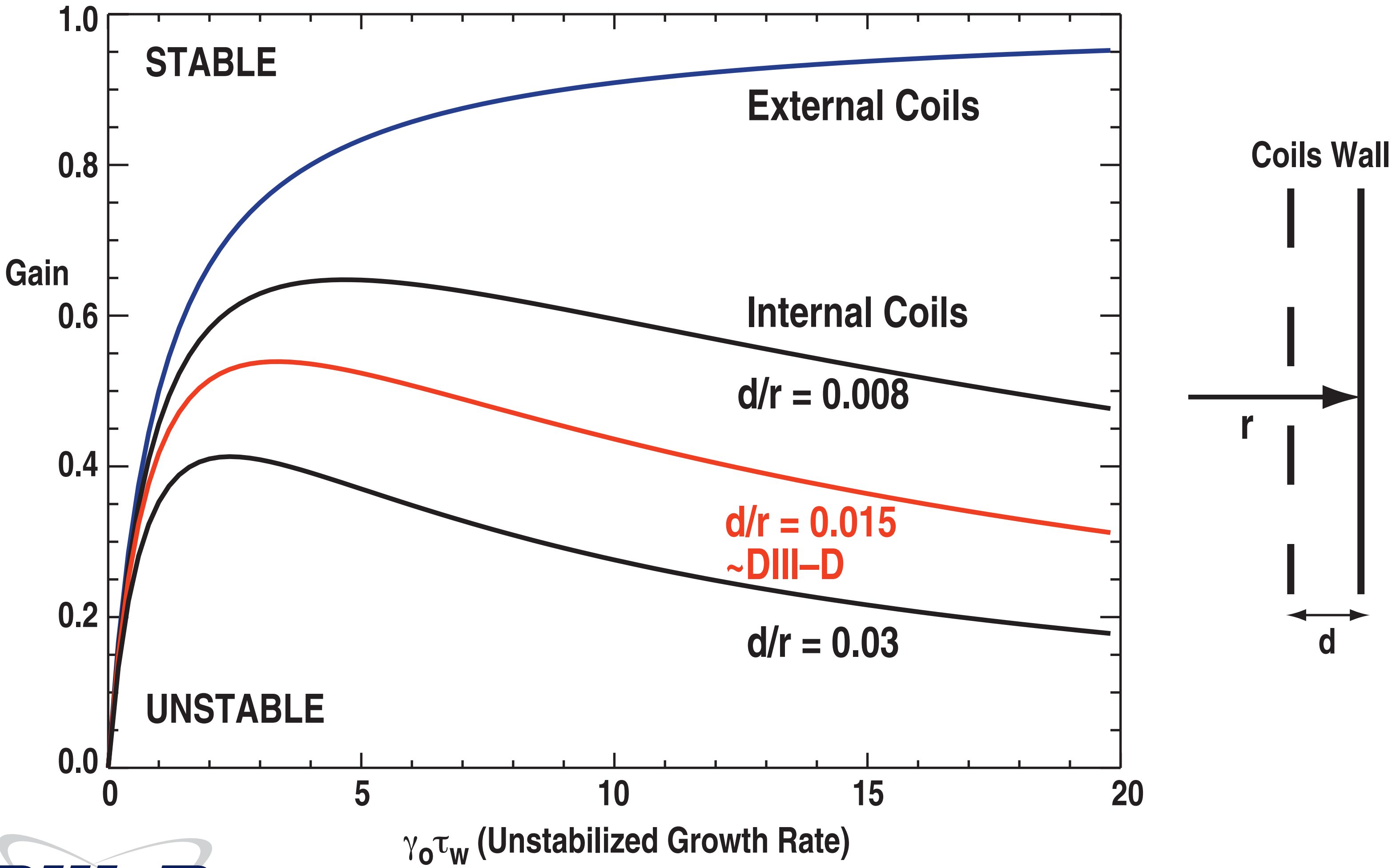
  - — In cylindrical model: C = 1 for external coils;

$$C = \left(\frac{r_c}{r_w}\right)^{2m} \text{ for internal coils}$$

- Feedback performance is improved with internal poloidal field sensors
  - — Faster time response
  - — Decoupled from radial field of control coils

SIMPLE ANALYTIC MODEL OF RWM FEEDBACK SHOWS BENEFITS OF INTERNAL COILS

- Slab model with decoupled poloidal field sensors
- Strong reduction in gain, even for small coil-wall spacing



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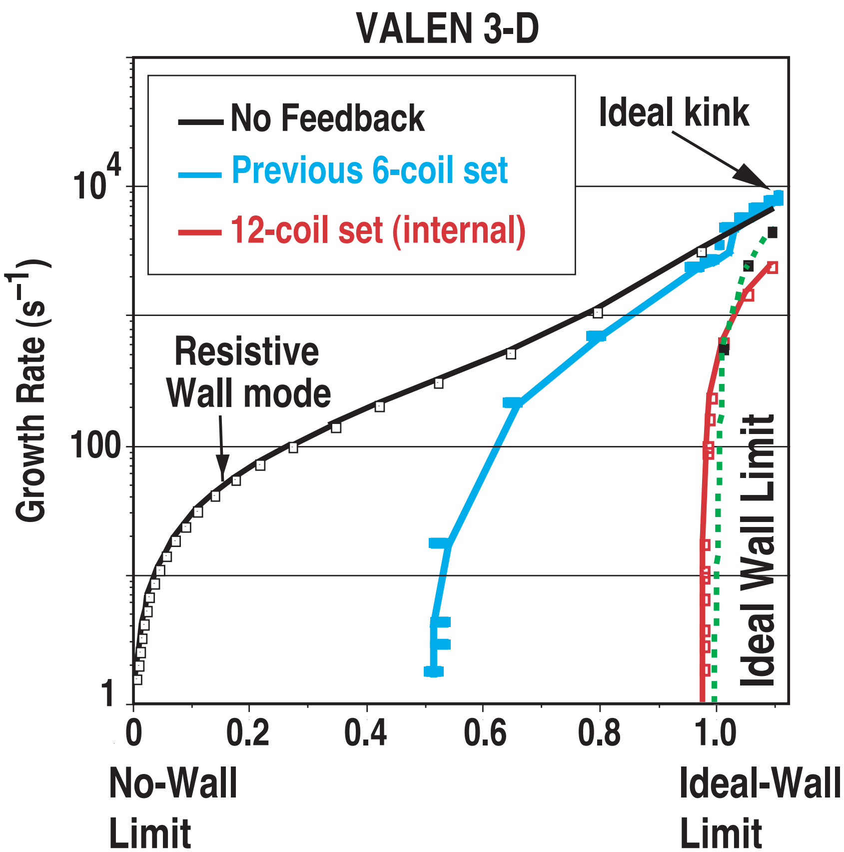
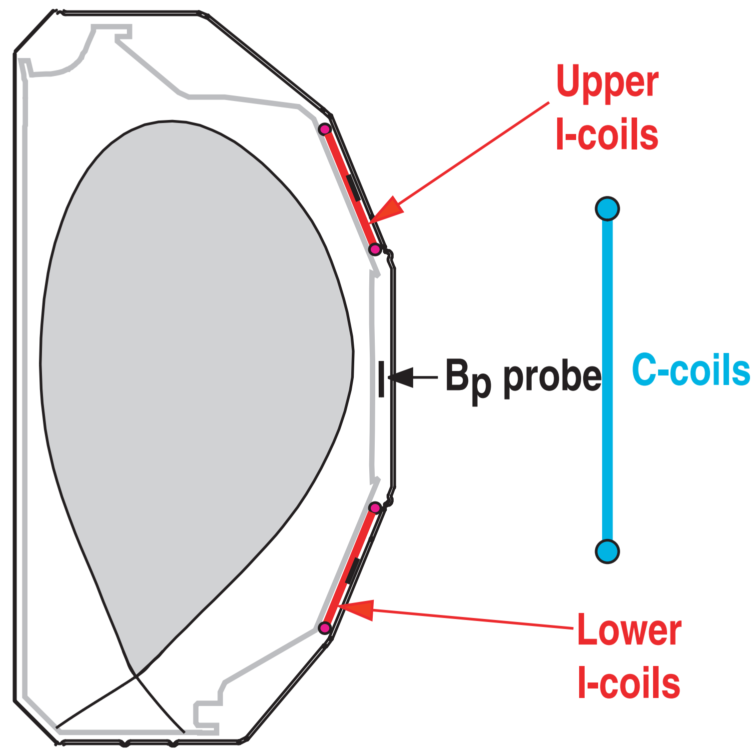
I-COIL SHOULD PROVIDE RWM STABILIZATION COMPARABLE TO AN IDEAL WALL

- Modeling with VALEN (3D electromagnetics code) using realistic geometry
  - Idealized amplifiers (optimistic)





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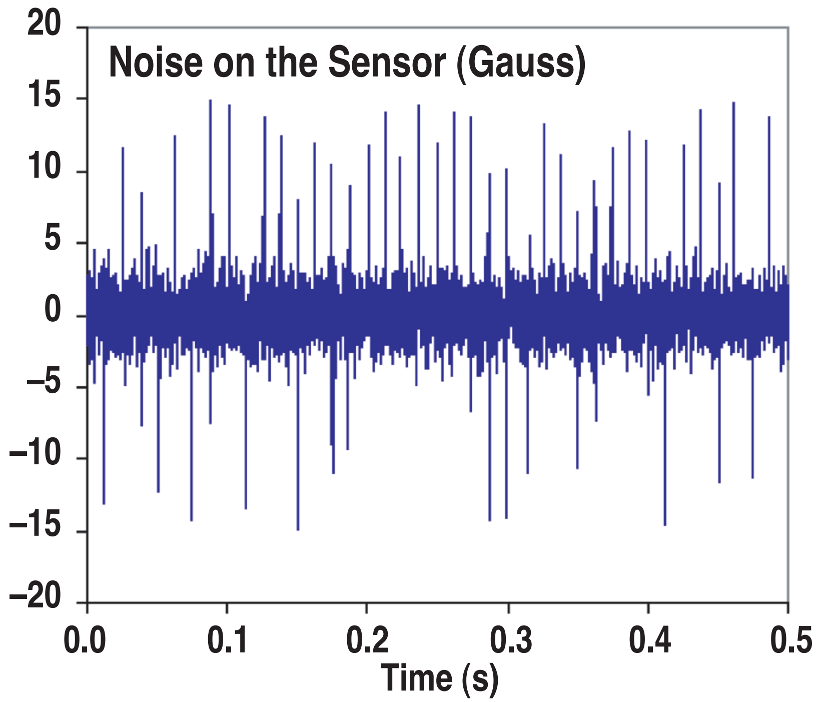
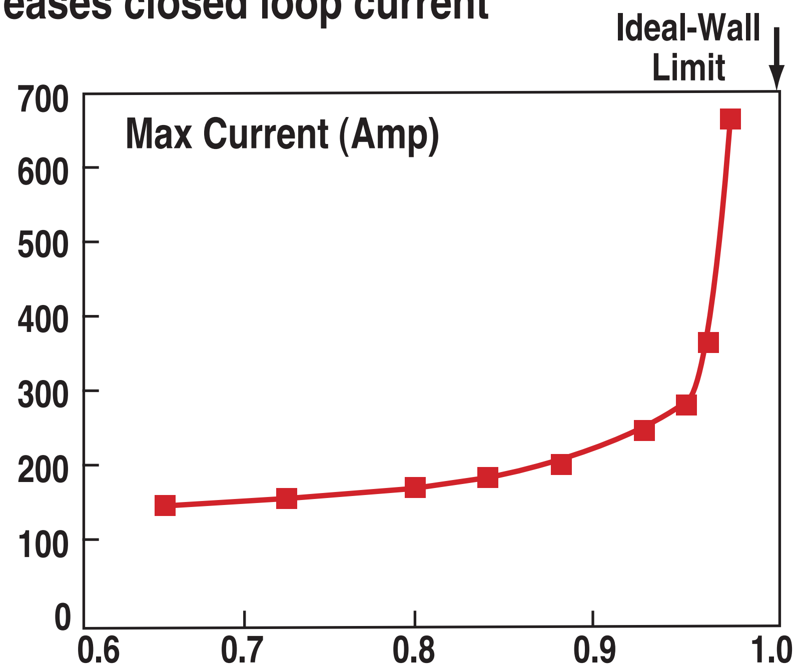
NOISE AND TIME DELAY LIMIT FEEDBACK CONTROL

- Time-dependent modeling with VALEN
- With noise, system can approach (but not reach) ideal wall limit
  - Broadband noise (1.5 Gauss) and ELMs (6 to 16 Gauss)
  - Resonant RWM response to noise increases closed loop current





$$C_\beta = \frac{\beta - \beta^{no\text{-}wall}}{\beta^{ideal\text{-}wall} - \beta^{no\text{-}wall}}$$

- Feedback loop delay time τ_d also limits beta
  - Stabilization limited to $\gamma_{RWM} \lesssim 0.25\ \tau_d^{-1}$

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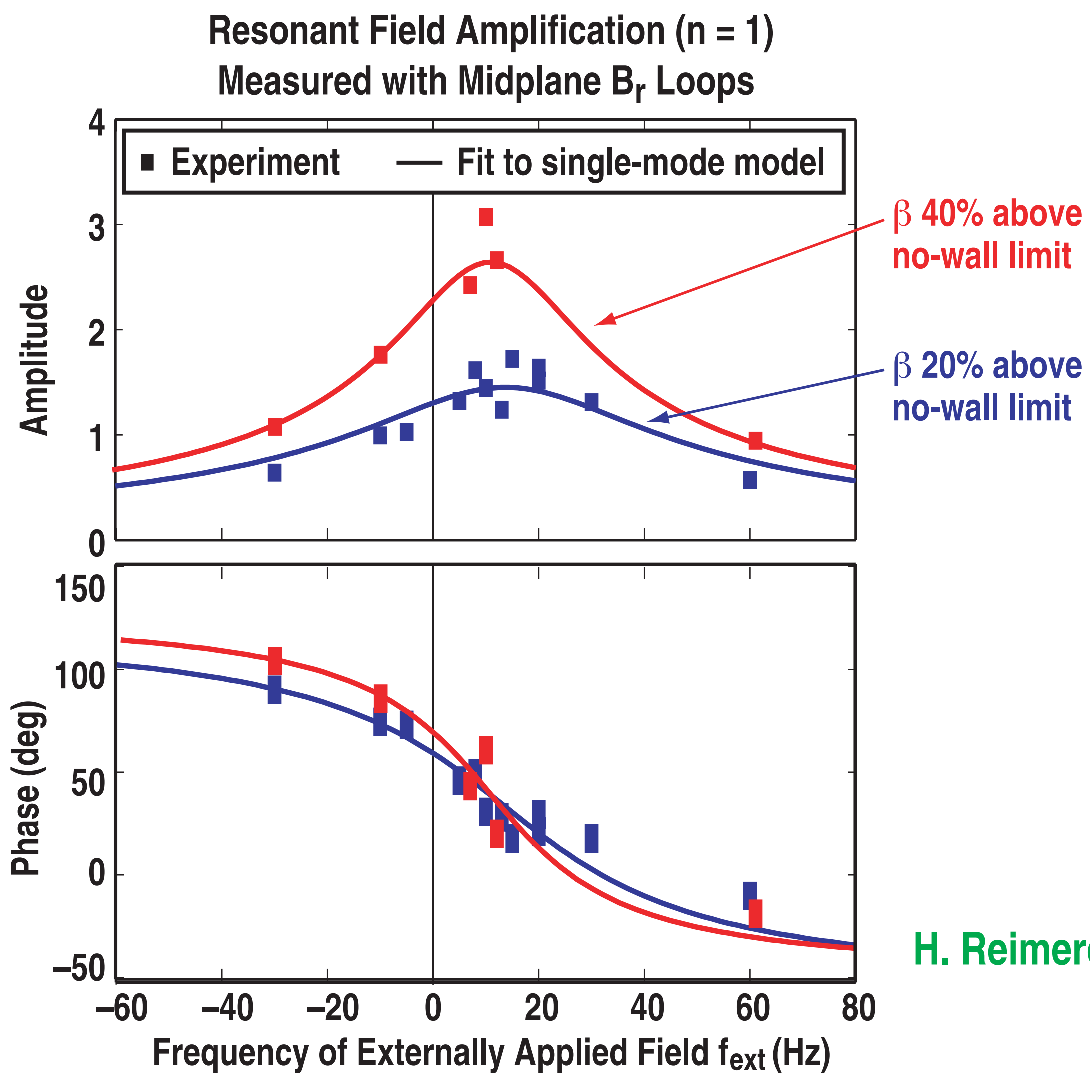
DIII–D INTERNAL COILS ASSIST RWM STABILIZATION BY PLASMA ROTATION

- I–coil selectively and efficiently corrects the resonant component of the error field
- Previous experiments have confirmed theoretical predictions that RWM is stabilized by plasma rotation frequency ~few % of Alfvén frequency
  - f_{rot} ~ 5–10 kHz for typical DIII–D plasmas
- Minimization of magnetic field errors is crucial to rotational stabilization
  - A weakly stabilized RWM has a resonant response to an external magnetic perturbation (field error, for example)
  - Resonant enhancement of the magnetic perturbation slows the plasma rotation, leading to loss of stability
- Feedback-controlled error field correction with the I-coil maintains plasma rotation
  - Resonant response of stable RWM enhances detection of small error fields
  - Feedback system corrects the error field by minimizing the plasma response

A.M. Garofalo, QP1.031
J.T. Scoville, QP1.036

"MHD SPECTROSPCOPY" PROBES RWM RESONANCE

- Frequency scan of rotating n = 1 field applied with I–coil
- Plasma response has resonant peak at f_{RWM} ~15 Hz
- Plasma response increases as β rises above the no-wall limit



H. Reimerdes, G01.003

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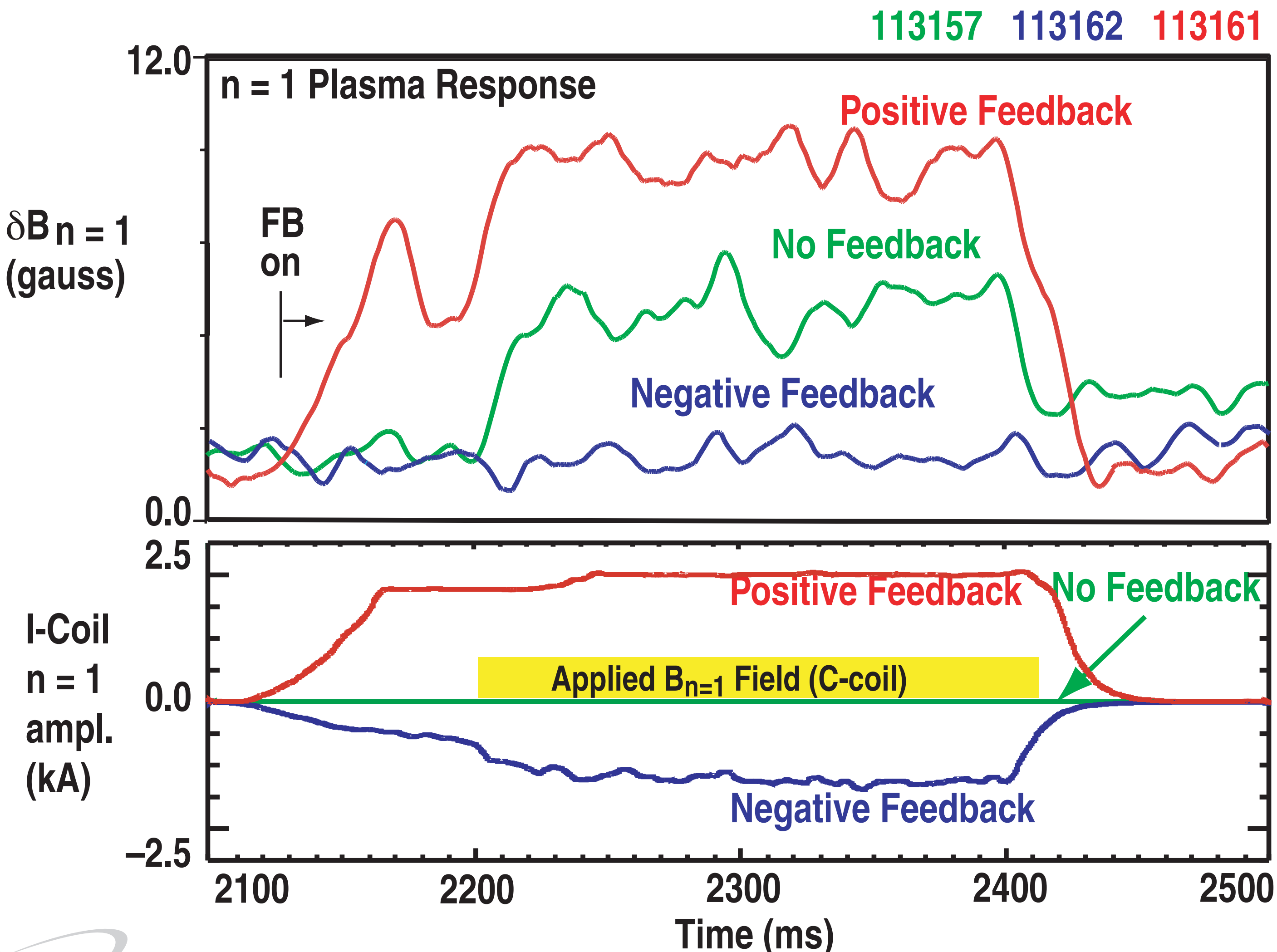
I-COIL WITH FEEDBACK CONTROL CAN NULL OUT RESONANT FIELD AMPLICATION FROM AN EXTERNALLY APPLIED FIELD

- n = 1 error field pulse applied with external C-coil



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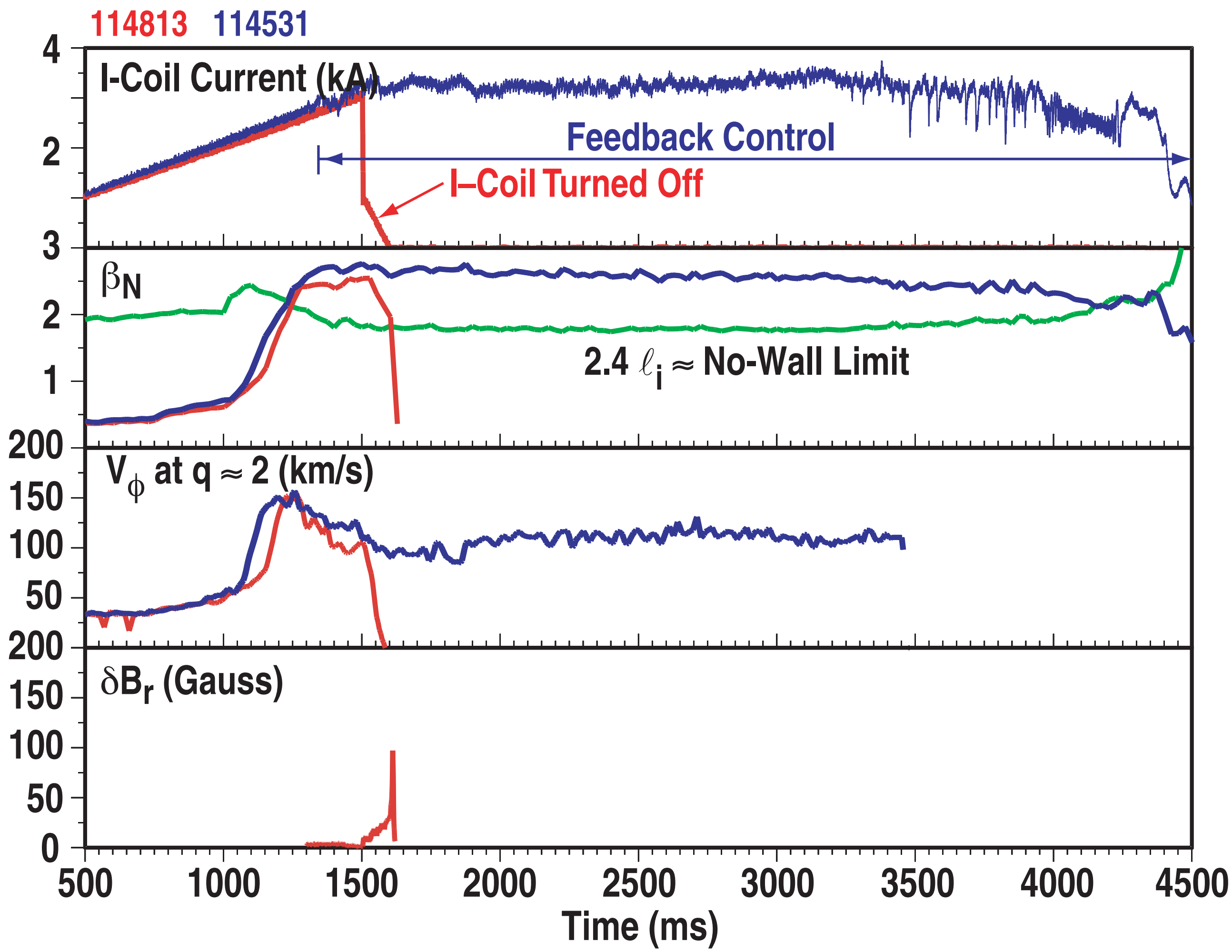
FEEDBACK–CONTROLLED ERROR FIELD CORRECTION ALLOWS SUSTAINED OPERATION ABOVE THE NO-WALL BETA LIMIT

- Rotation and stability are lost if error correction is turned off



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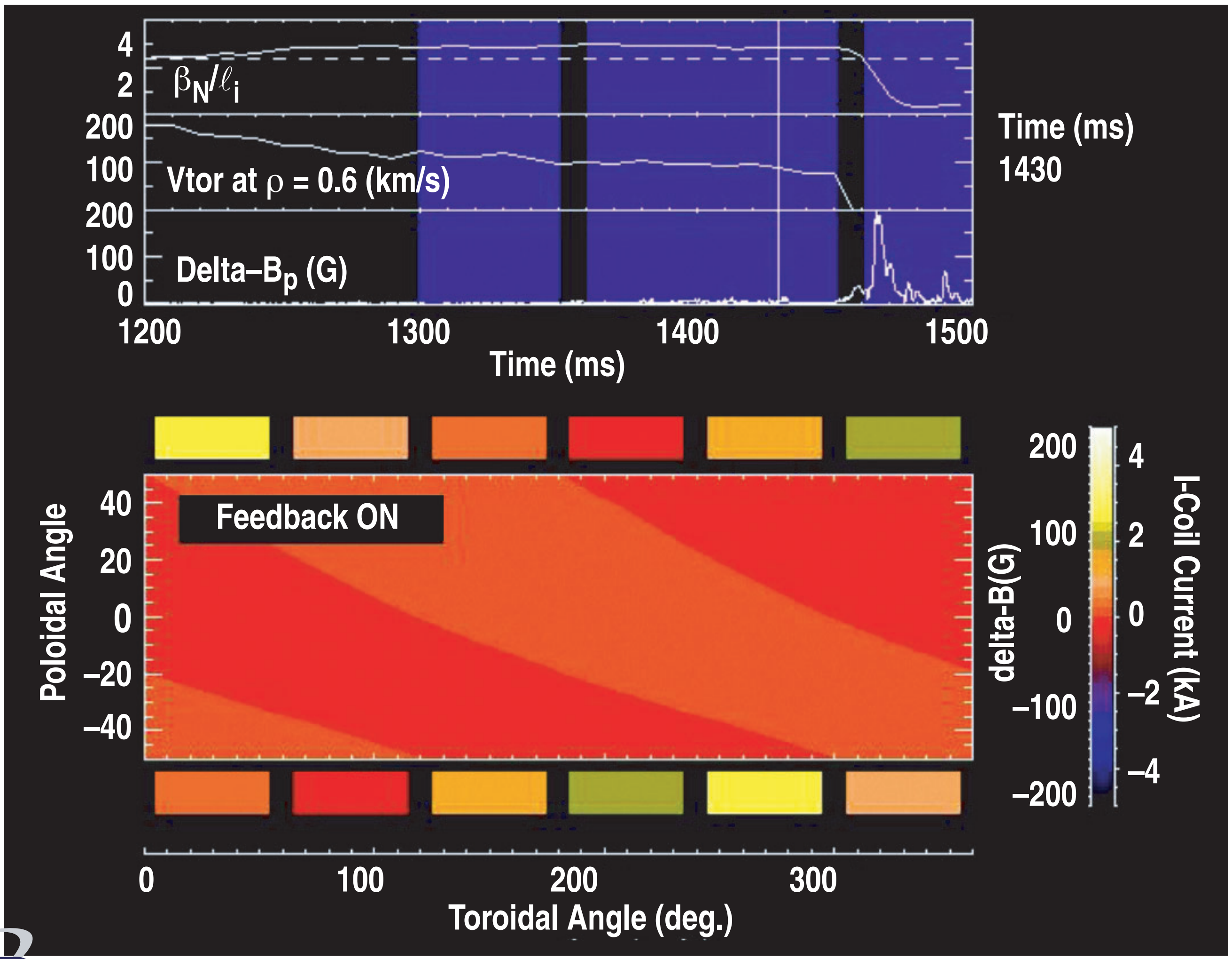
DIII–D INTERNAL COILS IMPROVE RWM FEEDBACK STABILIZATION

- Stability at higher beta
  - Closer to ideal-wall limit
- Stability at lower rotation
  - Farther below critical rotation frequency
- Consistent with modeling

M. Okabayashi, QP1.032 (Experiment)
D. Edgell, QP1.030 } (Control Modeling)
C. Fransson, QP1.027 }
N. Bogatu, QP1.029 (Detection)

FEEDBACK CONTROL WITH THE I-COIL SUCCESSFULLY STABILIZES THE RESISTIVE WALL MODE

- Rotational stabilization is slowly decreasing
- RWM becomes unstable during 10 ms when feedback is off



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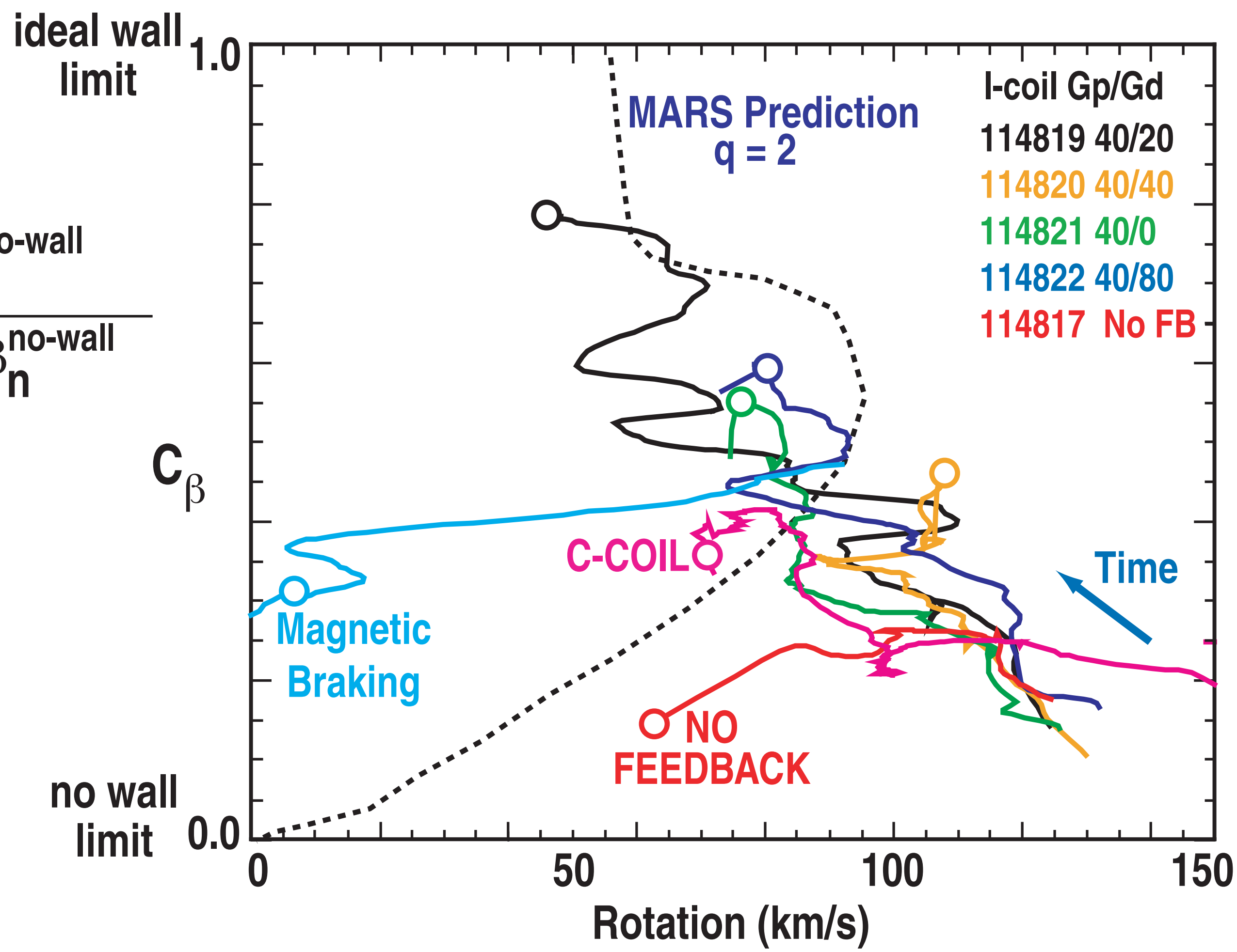
FEEDBACK CONTROL WITH I–COILS STABILIZES RWM AT HIGHER BETA AND LOWER ROTATION

- Good qualitative agreement with MARS modeling of rotational stabilization
  - Feedback allows discharges to go beyond rotation-only stability limit

$$C_\beta = \frac{\beta_n - \beta_n^{\text{no-wall}}}{\beta_n^{\text{ideal-wall}} - \beta_n^{\text{no-wall}}}$$



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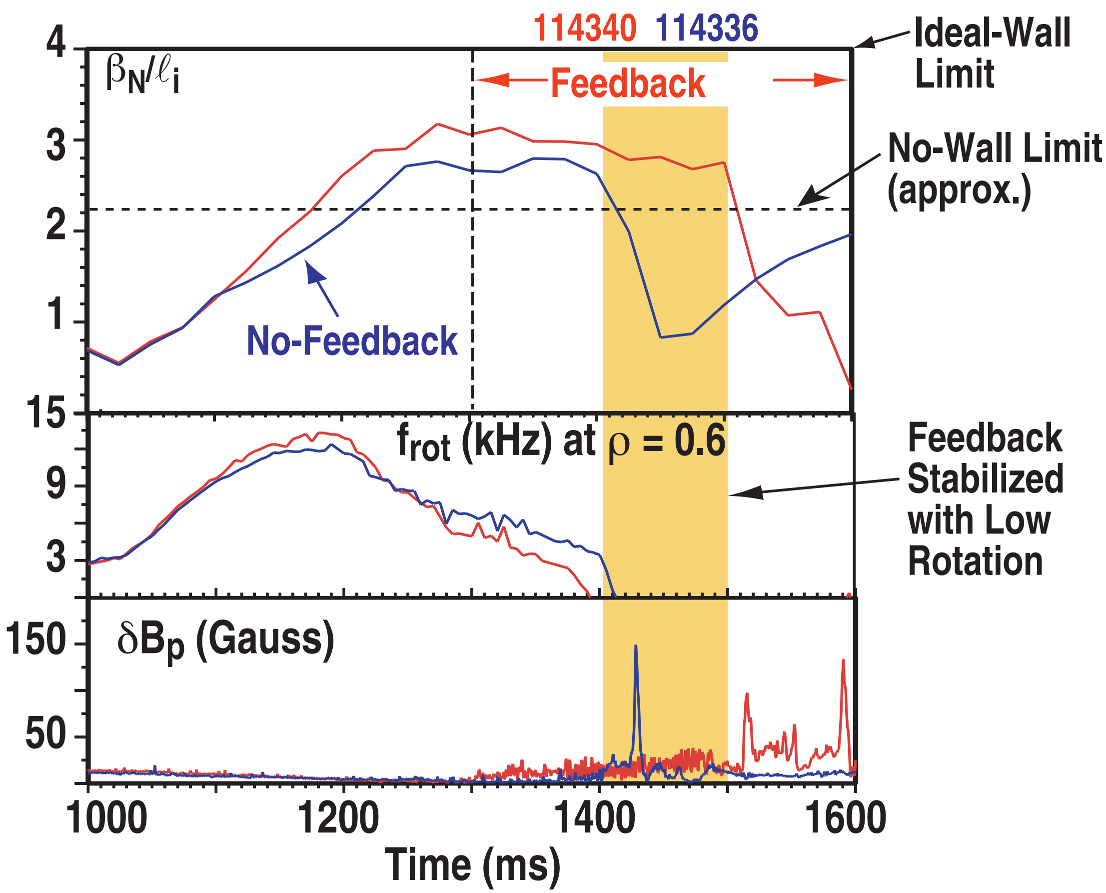
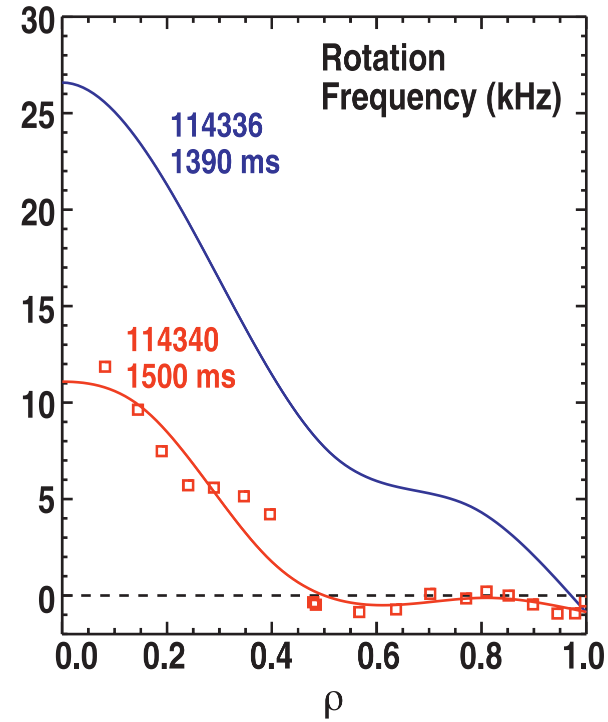
FEEDBACK CONTROL WITH INTERNAL COILS STABILIZES RWM WITH LOW ROTATION

- Magnetic braking reduces rotation to zero in the outer half of the plasma
- Feedback with internal coils maintains stability for >100 ms
- Case without feedback becomes unstable at lower beta, even with rotation





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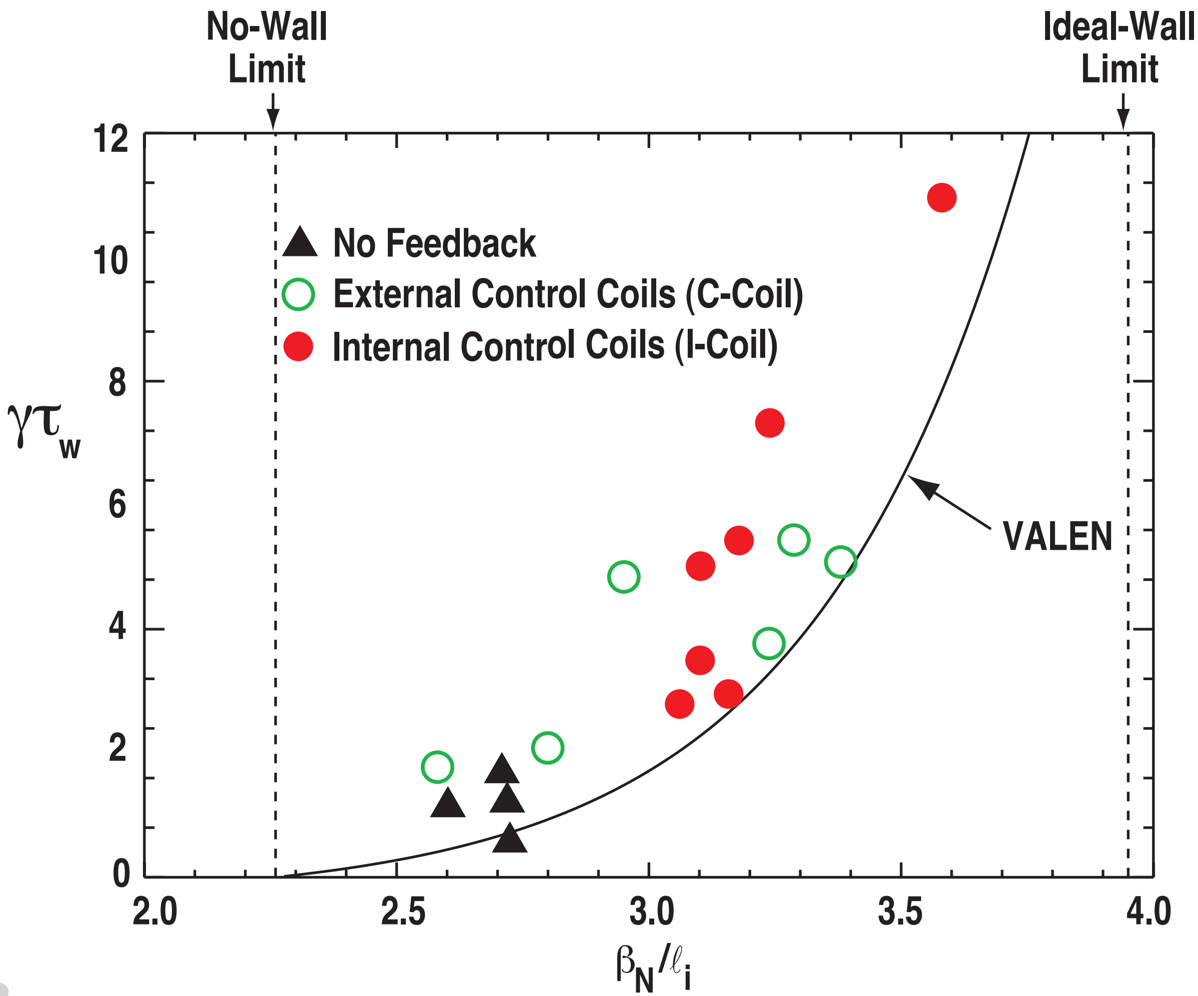
FEEDBACK WITH I-COIL CAN CONTROL RWM GROWTH CLOSER TO THE IDEAL WALL LIMIT

- Observed growth rate of unstable RWM is consistent with VALEN calculation



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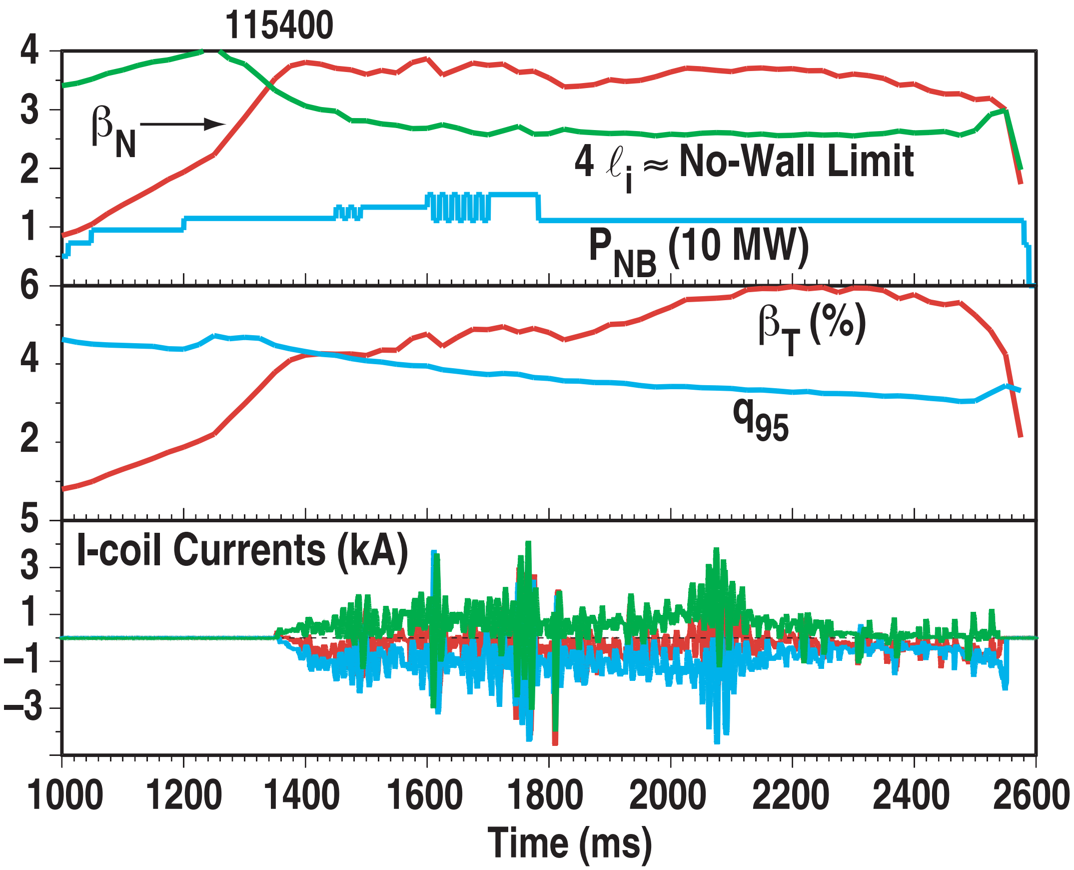
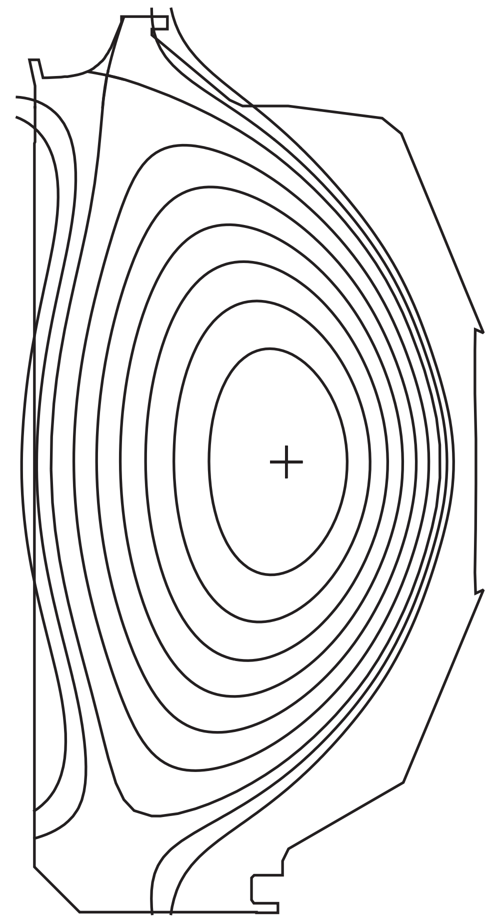
I-COIL PROVIDES SUSTAINED WALL STABILIZATION AT HIGH BETA

- Beta exceeds estimated no-wall limit for >1 s
  - $\beta_N \sim 6\ \ell_i$
  - β_T ~6%





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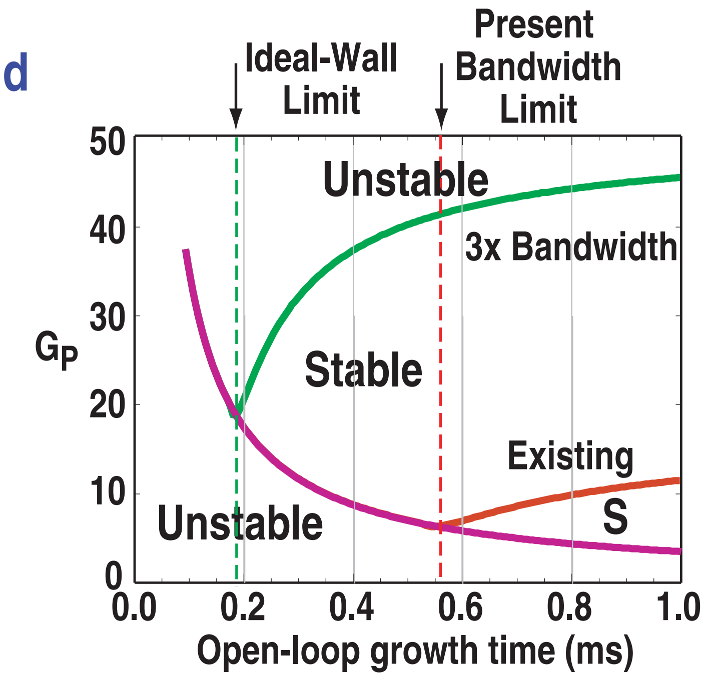
FUTURE WORK

- Continue to develop basic physics of RWM stabilization
  - In cooperation with JET, JT-60U, ASDEX-Upgrade, MAST, NSTX, HBT-EP, . . .
  - High priority of International Tokamak Physics Activity (ITPA)

- Validate models of feedback control – with and without rotation
  - Develop means of controlling rotation
    - ★ Magnetic braking
    - ★ RF heating
    - ★ Counter-NBI (planned)



- Increase bandwidth of feedback system
  - Modeling indicates bandwidth increase ~factor of 3 is needed to reach the ideal-wall limit
  - Improve existing system
  - Audio amplifiers

- Routine application to stabilization of advanced tokamak plasmas in DIII–D

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SUMMARY

- DIII–D's new internal coils have improved passive and active control of resistive wall modes

- Feedback-controlled correction of resonant error field allows RWM stabilization by plasma rotation
  - Good agreement with calculated mode structure
  - Rotational stabilization sustained for >2.5 s (>500 τ_W)

- Initial results confirm direct feedback contributes to stabilization of the RWM
  - Stability with plasma rotation well below the threshold for RWM stabilization
  - Better performance than external coils

- Flexible, high-bandwidth control coils have many other applications in measurement and control of MHD stability
  - MHD "spectroscopy"
  - Stochastic boundary for pedestal control

RWM orals: GO1.002–3 (Tuesday PM)

RWM posters: QP1.027–37 (Thursday AM)

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