Active Control of MHD Modes in DIII-D

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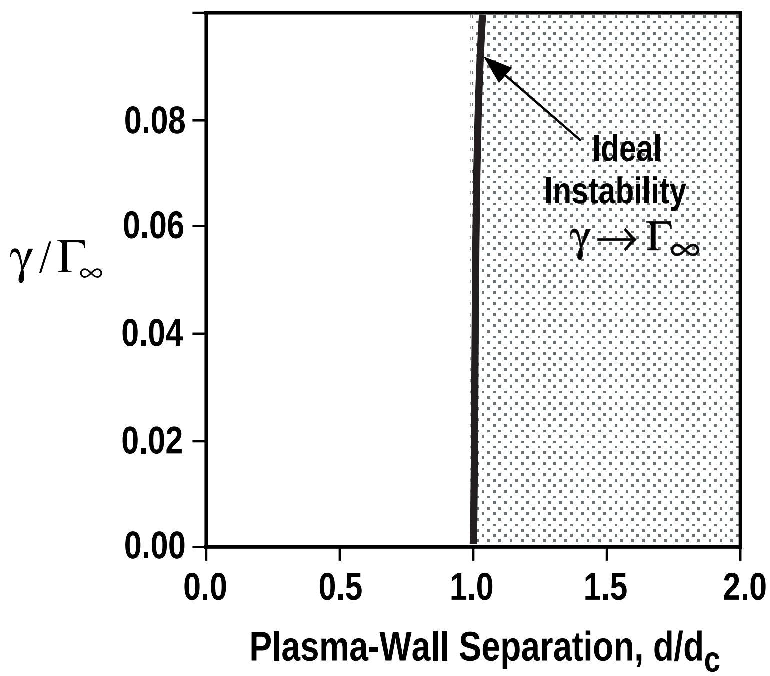
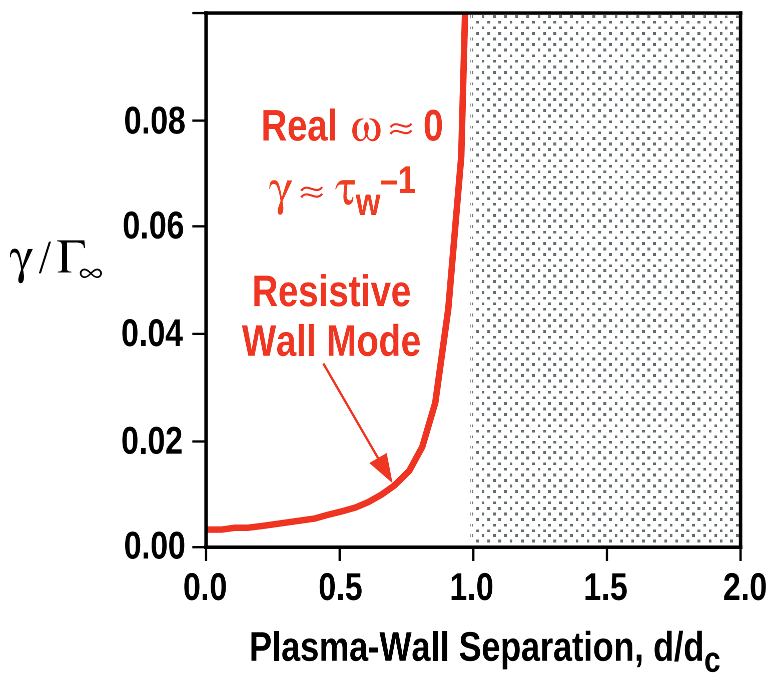
KINK MODE IS STABILIZED BY IDEAL WALL

$\beta_N > \beta_N^{\text{no-wall}}$ -> $0 = \underbrace{(\gamma + in\Omega)^2 - \Gamma_\infty^2}_{\text{Ideal Stability}}$



KINK MODE GROWTH IS ONLY SLOWED BY RESISTIVE WALL

$\beta_N > \beta_N^{\text{no wall}}$ -> $0 = \underbrace{(\gamma + in\Omega)^2 - \Gamma_\infty^2}_{\text{Ideal Stability}} + \underbrace{\frac{\Gamma_\infty^2 (d_c/d)\gamma\,\tau_w}{\gamma\,\tau_w + 1}}_{\text{Resistive Wall}}$



- Resistive wall mode (RWM) is unstable
  - Mode structure similar to ideal external kink
  - Mode grows slowly: $\gamma \sim \tau_w^{-1}$

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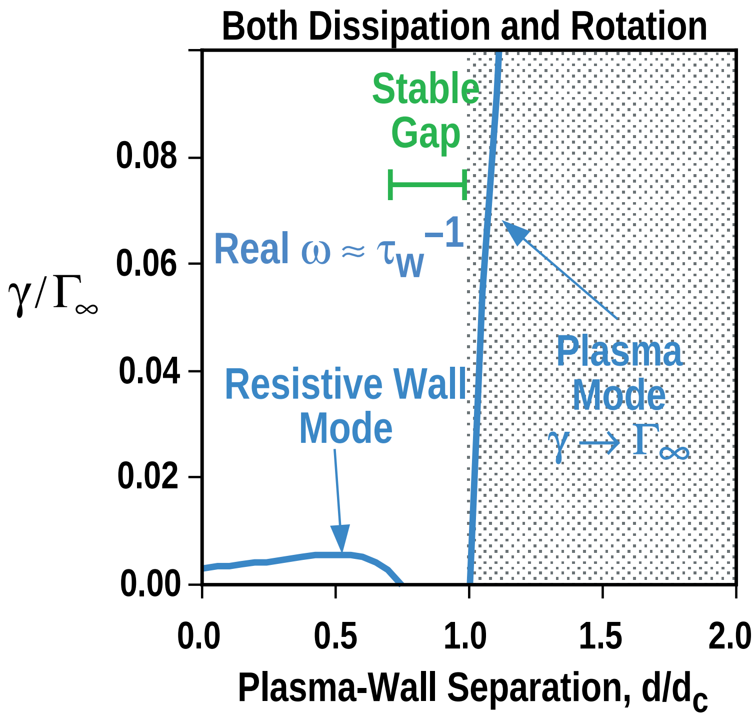
KINK MODE GROWTH IS SLOWED BY RESISTIVE WALL AND STABILIZED BY PLASMA ROTATION

$$\beta_N > \beta_N^{\text{no wall}} \rightarrow \quad 0 = \underbrace{(\gamma + in\Omega)^2 - \Gamma_\infty^2}_{\text{Ideal Stability}} + \underbrace{\frac{\Gamma_\infty^2 (d_c/d)\gamma\tau_w}{\gamma\tau_w + 1}}_{\text{Resistive Wall}} + \underbrace{(\gamma + in\Omega)\,\Gamma_{DIS}}_{\text{Plasma Dissipation}}$$



Control of rotation can open the stability window

- Resistive wall mode (RWM) is unstable
  - Mode structure similar to ideal external kink
  - Mode grows slowly: $\gamma \sim \tau_w^{-1}$
- Dissipation + rotation stabilizes RWM
  - Mode nearly stationary while plasma rotates $\omega \sim \tau_w^{-1} << \Omega_{plasma}$

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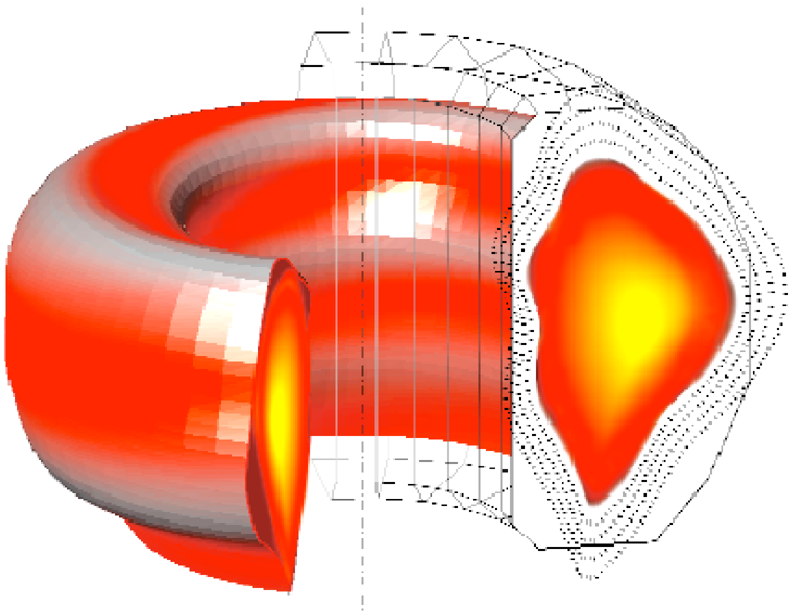
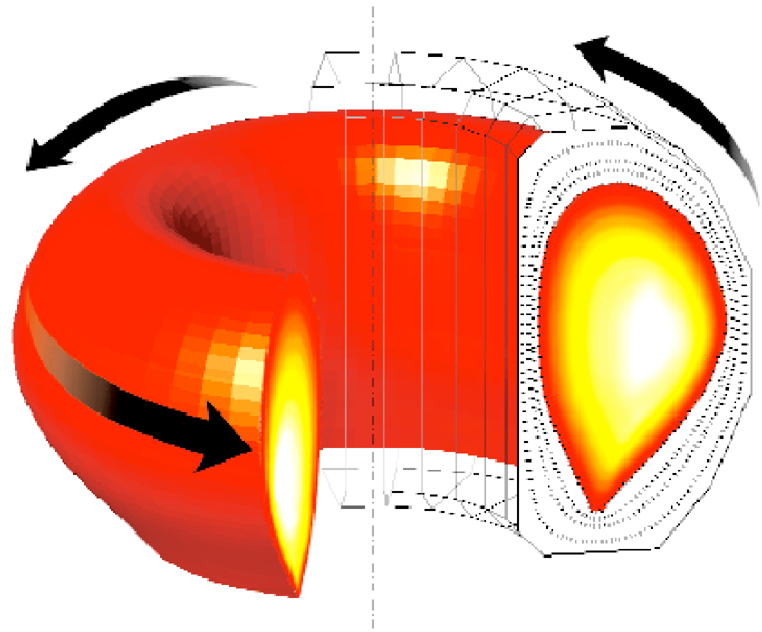
Plasma Rotation Stabilizes the RWM

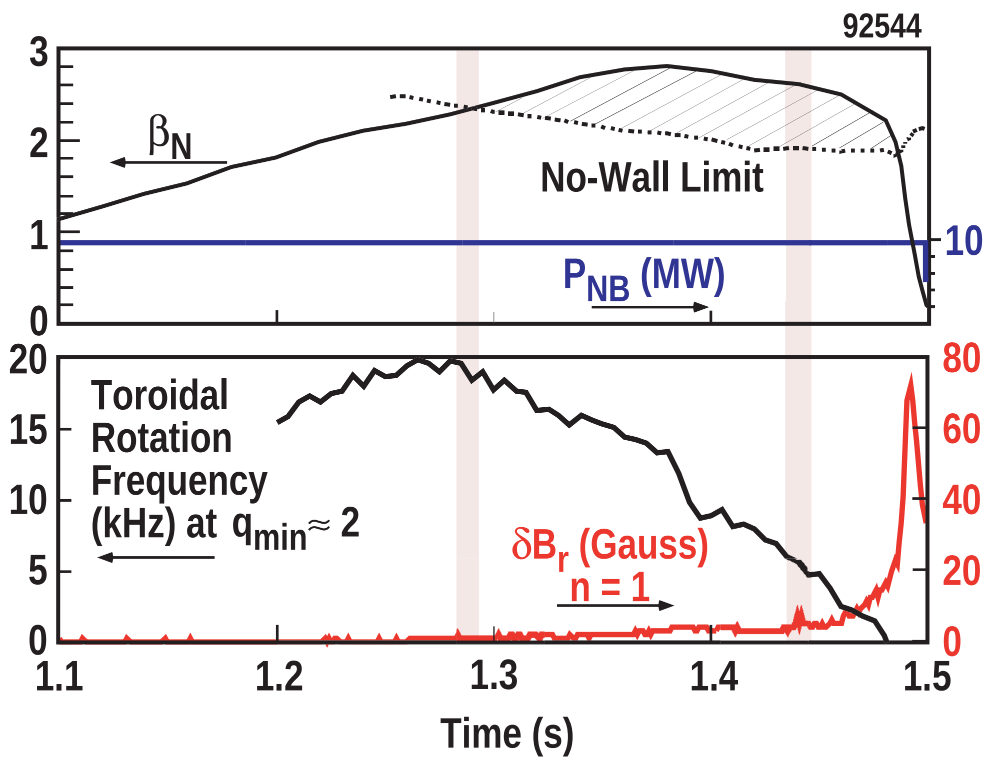


Low Rotation Plasma
UNSTABLE



High Rotation Plasma
STABLE

STABILIZATION OF THE RWM BY PLASMA ROTATION CONFIRMED EXPERIMENTALLY
— DURATION LIMITED BY ROTATION SLOWDOWN —



- The RWM becomes unstable when the plasma rotation decreases below a critical value
  - Consistent with predictions of ideal MHD with dissipation

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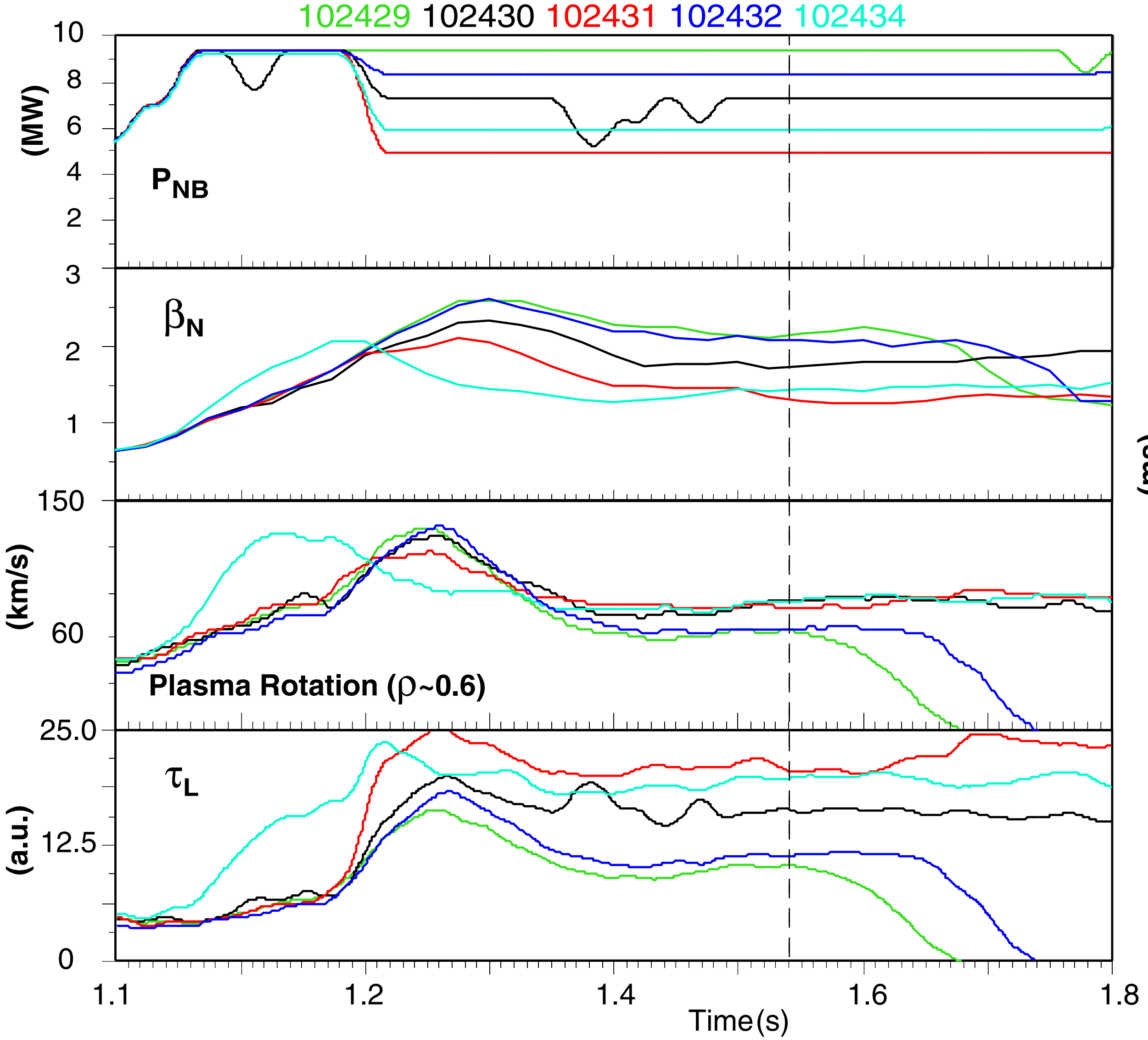
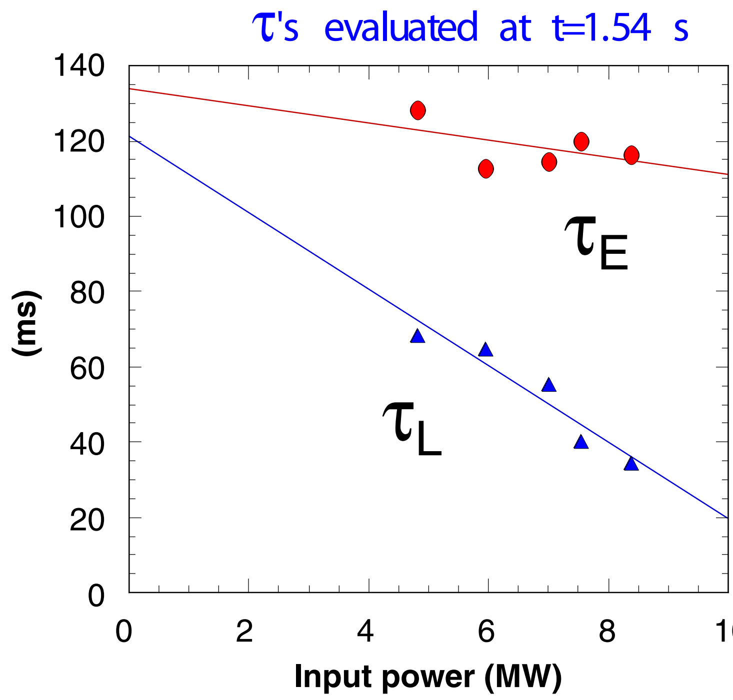
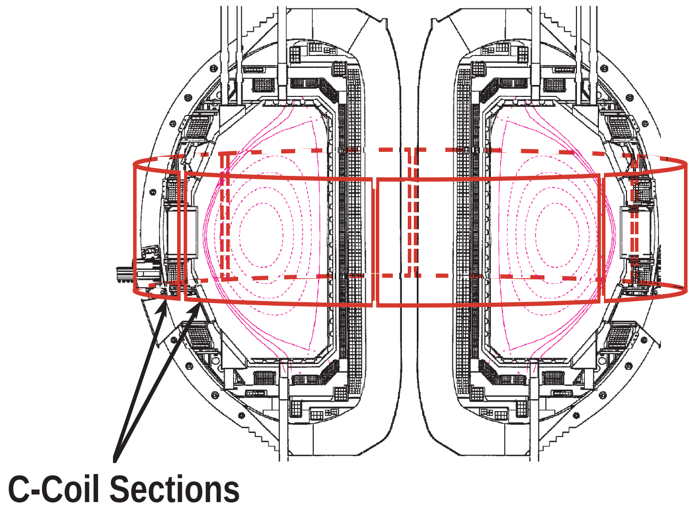
ANGULAR MOMENTUM SINK INCREASES ANOMALOUSLY WITH β_N

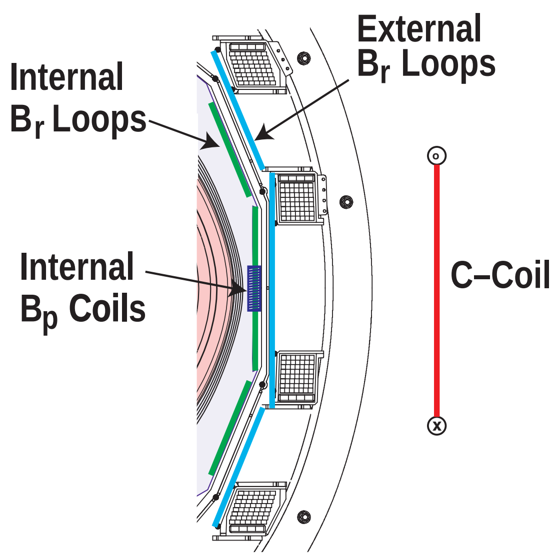
- Higher neutral beam power gives higher beta but lower rotation
- Angular momentum confinement time, τ_L, decreases rapidly with increasing neutral beam power





ACTIVE FEEDBACK AND RESONANT FIELD CORRECTION ON DIII–D USES SIX-ELEMENT COIL SET AT THE MIDPLANE





- n = 1 resonant fields arise from inevitable small irregularities in poloidal and toroidal field coils

- Uncorrected, resonant fields may exert drag on the plasma rotation

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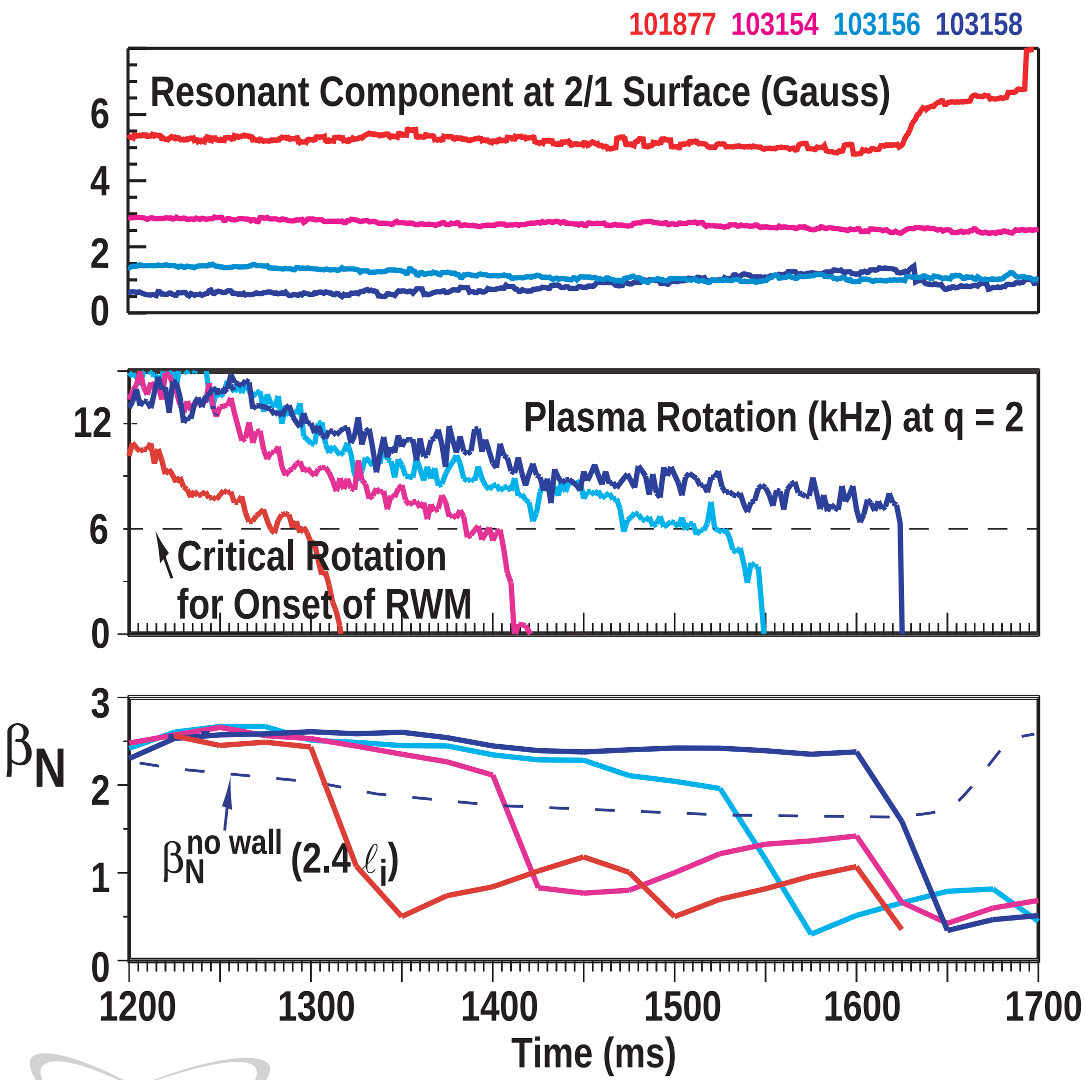
PLASMA ROTATION DECREASES MORE SLOWLY WITH DECREASING RESONANT FIELD AMPLITUDE



- Below a critical rotation value, the RWM becomes unstable

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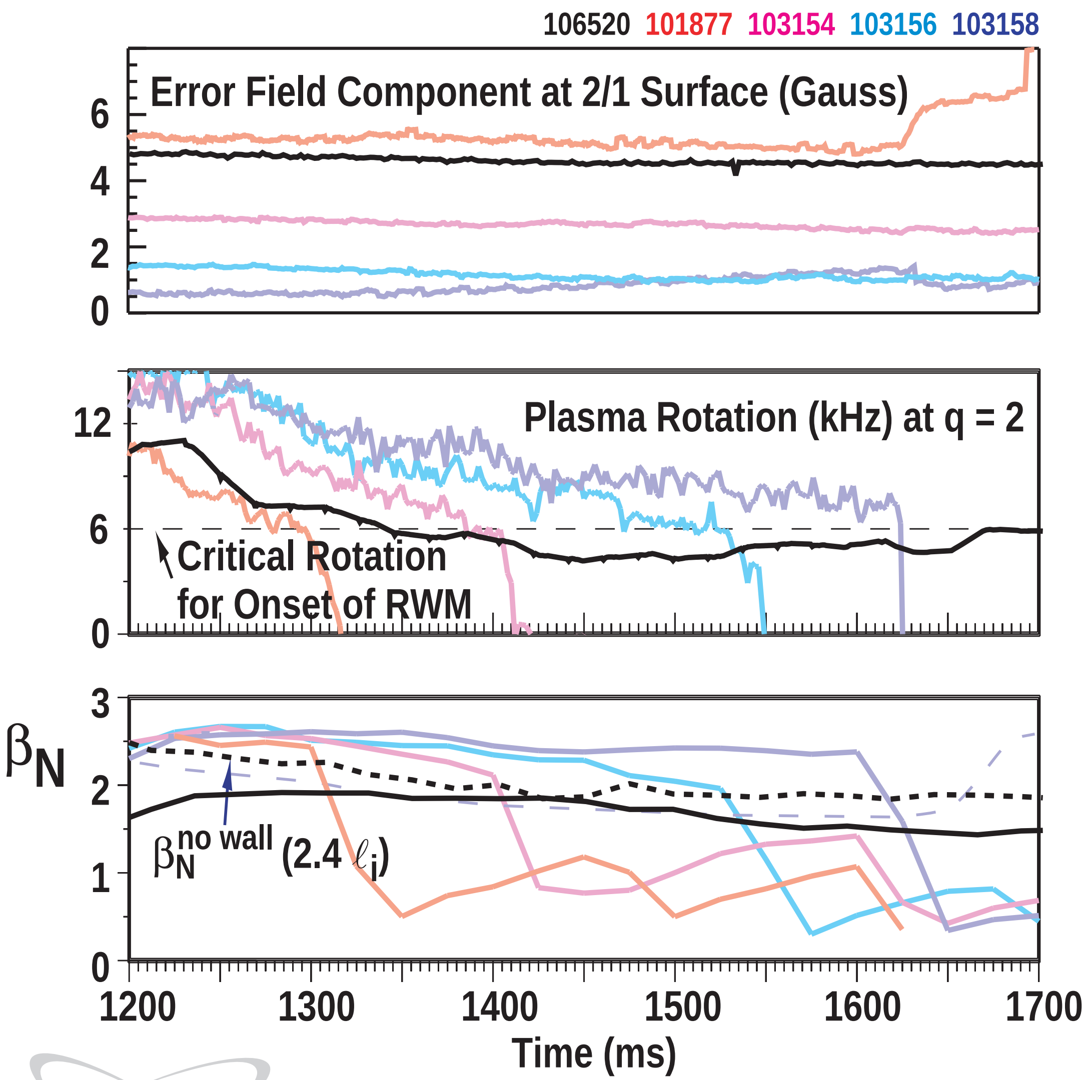
PLASMA ROTATION DECREASES MORE SLOWLY WITH DECREASING ERROR FIELD AMPLITUDE



- Below a critical rotation value, RWM becomes unstable
- At $\beta_N < \beta_N^{no\ wall}$ rotation is maintained even with large error field

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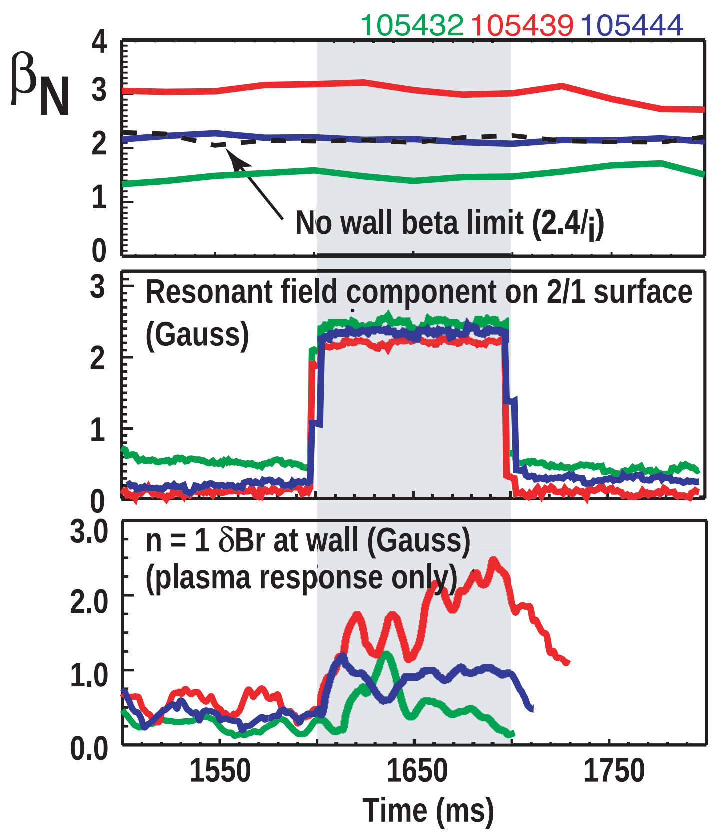
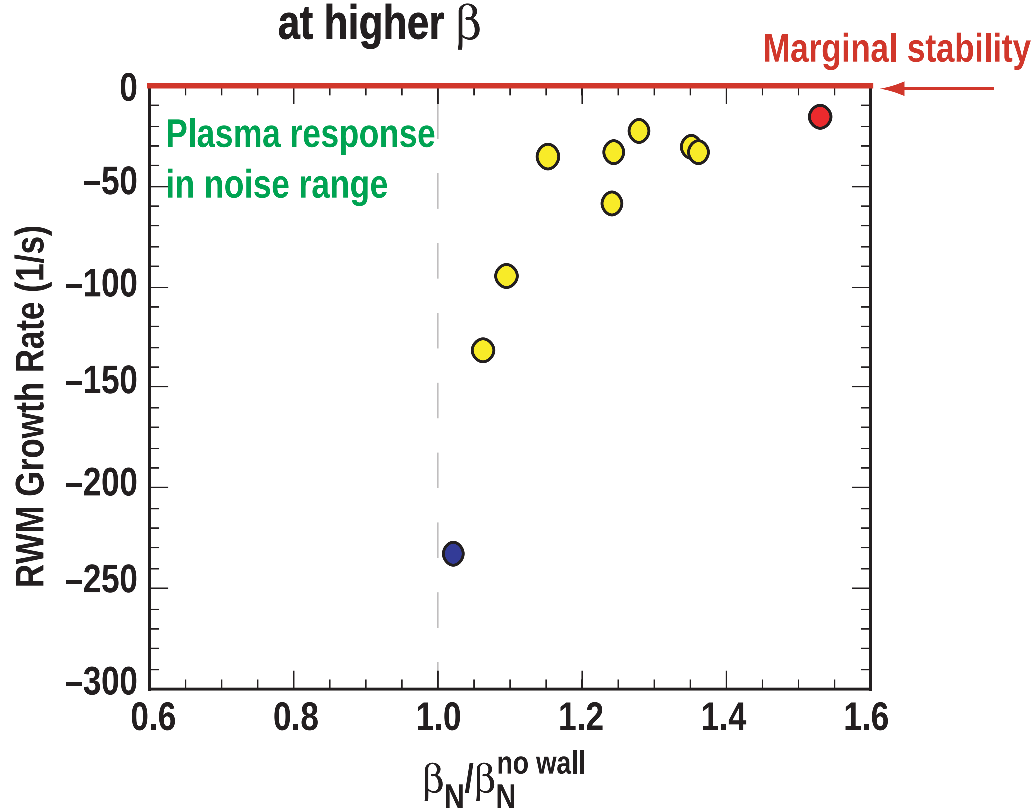
AT β ABOVE THE NO-WALL LIMIT A WEAKLY DAMPED RWM "AMPLIFIES" ANY APPLIED RESONANT FIELD

- RWM is nearly stationary n = 1 mode ⇒ can resonate with n = 1 static resonant field
  - Predicted in A. Boozer, PRL (2001)



- Rotational stabilization gives, in general, only weak damping
  - RWM is strongly damped just above no-wall limit
  - RWM quickly becomes weakly damped at higher β



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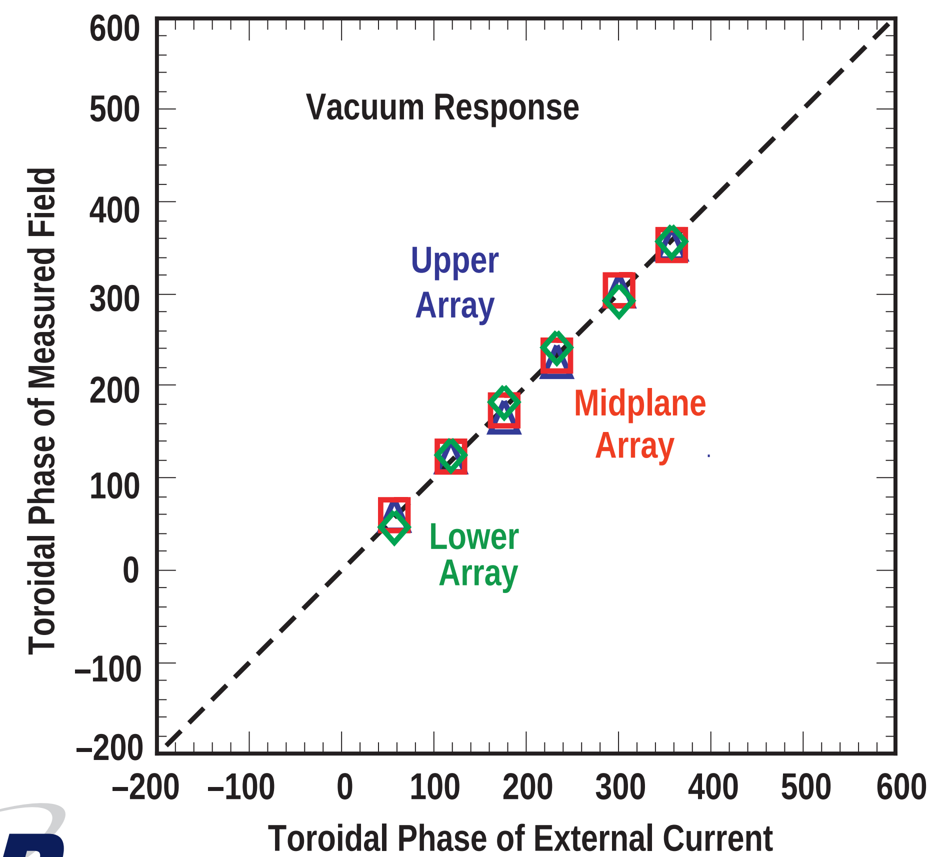
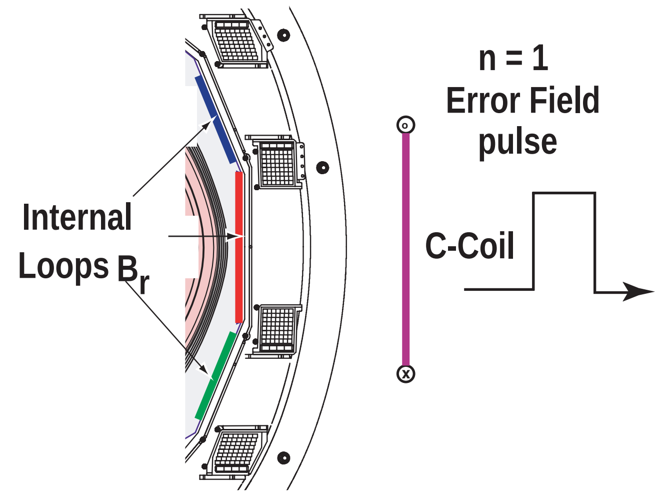
CLEAR EVIDENCE OF RESONANT RWM-ERROR FIELD INTERACTION IS FOUND IN MEASUREMENT OF HELICAL PLASMA RESPONSE

- Applied n = 1 field pulse from C-coil has no helicity
  – Same toroidal phase at three arrays





- Three toroidal arrays of saddle loops are at different poloidal locations

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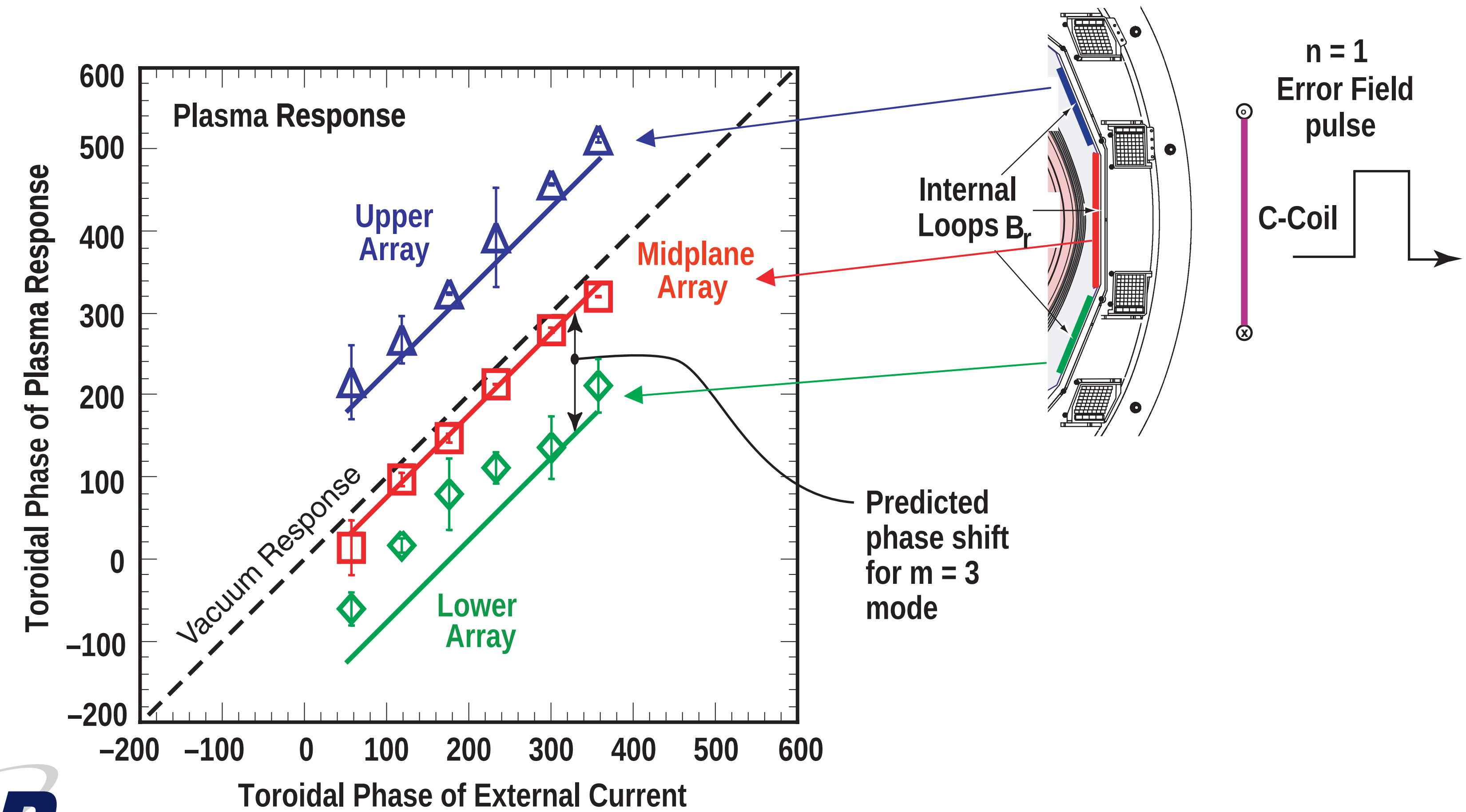
CLEAR EVIDENCE OF RESONANT RWM-ERROR FIELD INTERACTION IS FOUND IN MEASUREMENT OF HELICAL PLASMA RESPONSE

- Plasma response shows a distinct helicity
  — Toroidal phase shift between arrays consistent with m = 3 mode



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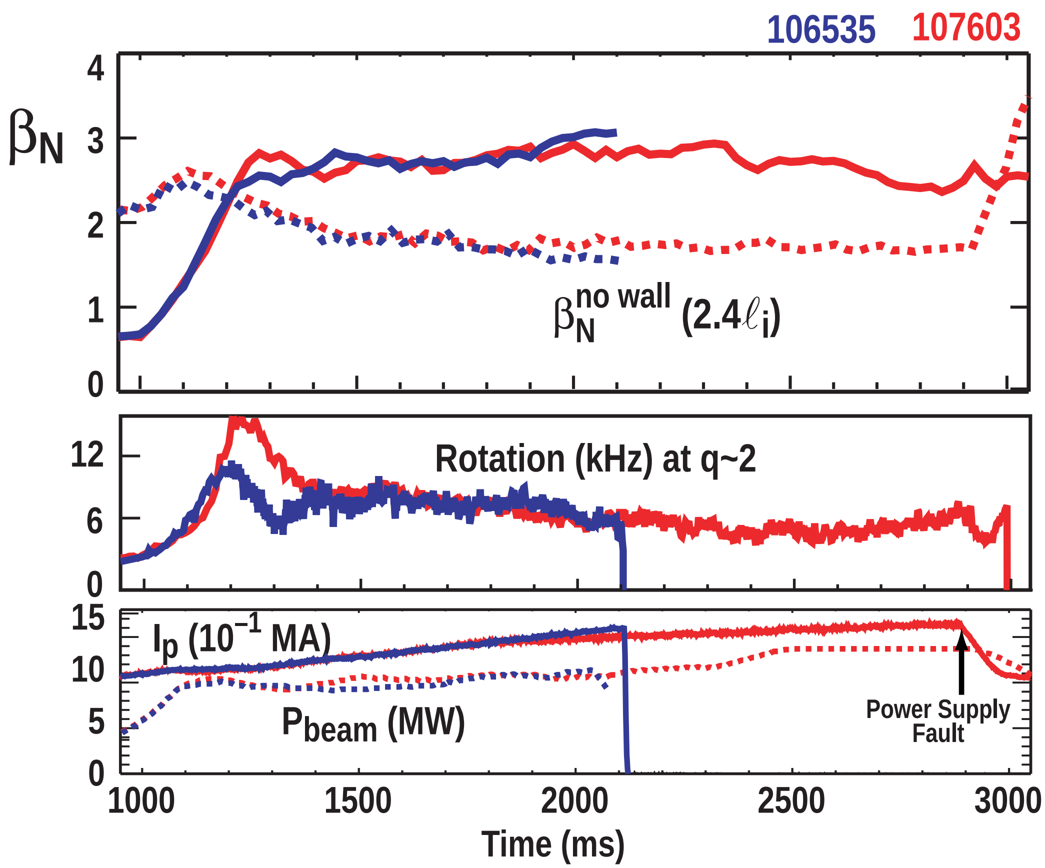
REDUCED RESONANT FIELDS ⇒ SUSTAINED ROTATION ⇒ STABILIZATION OF THE RWM ⇒ RELIABLE OPERATION ABOVE THE NO-WALL LIMIT



- $\beta_N \sim 2\ \beta_N^{no\ wall}$
  - β = 3.7%
- $\beta_N \lesssim \beta_N^{ideal\ wall}$
  - The best theoretically possible
- Feedback control of NBI power keeps β_N below stability limit (107603)
- No other large scale instabilities encountered (NTM, n=2 RWM, . . .)

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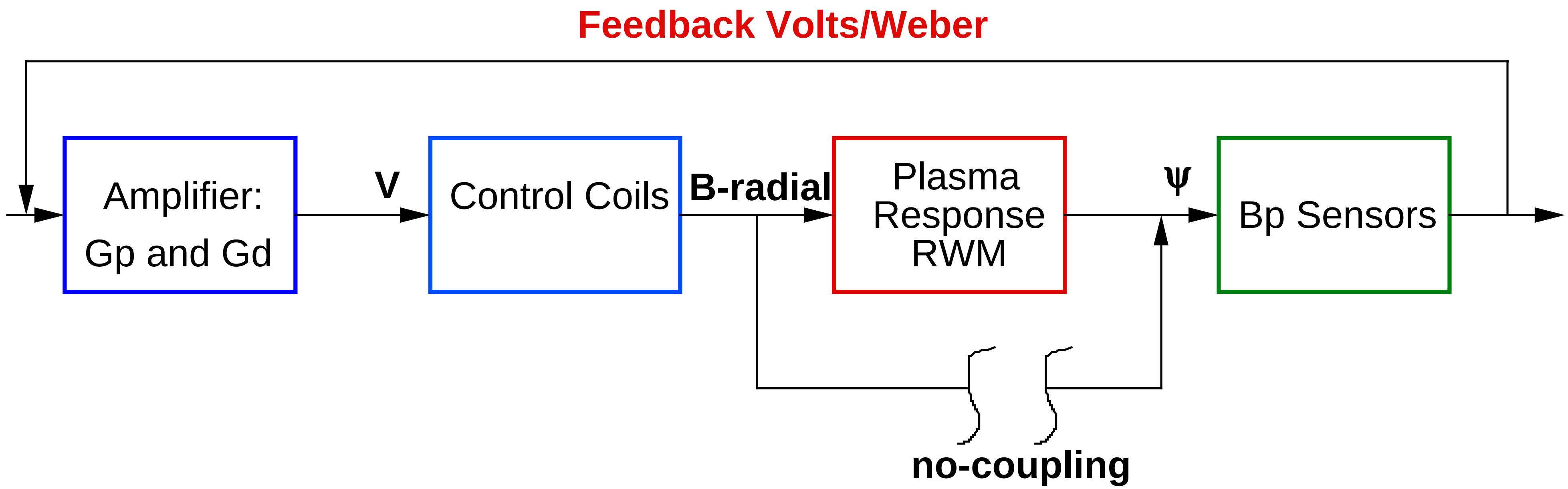
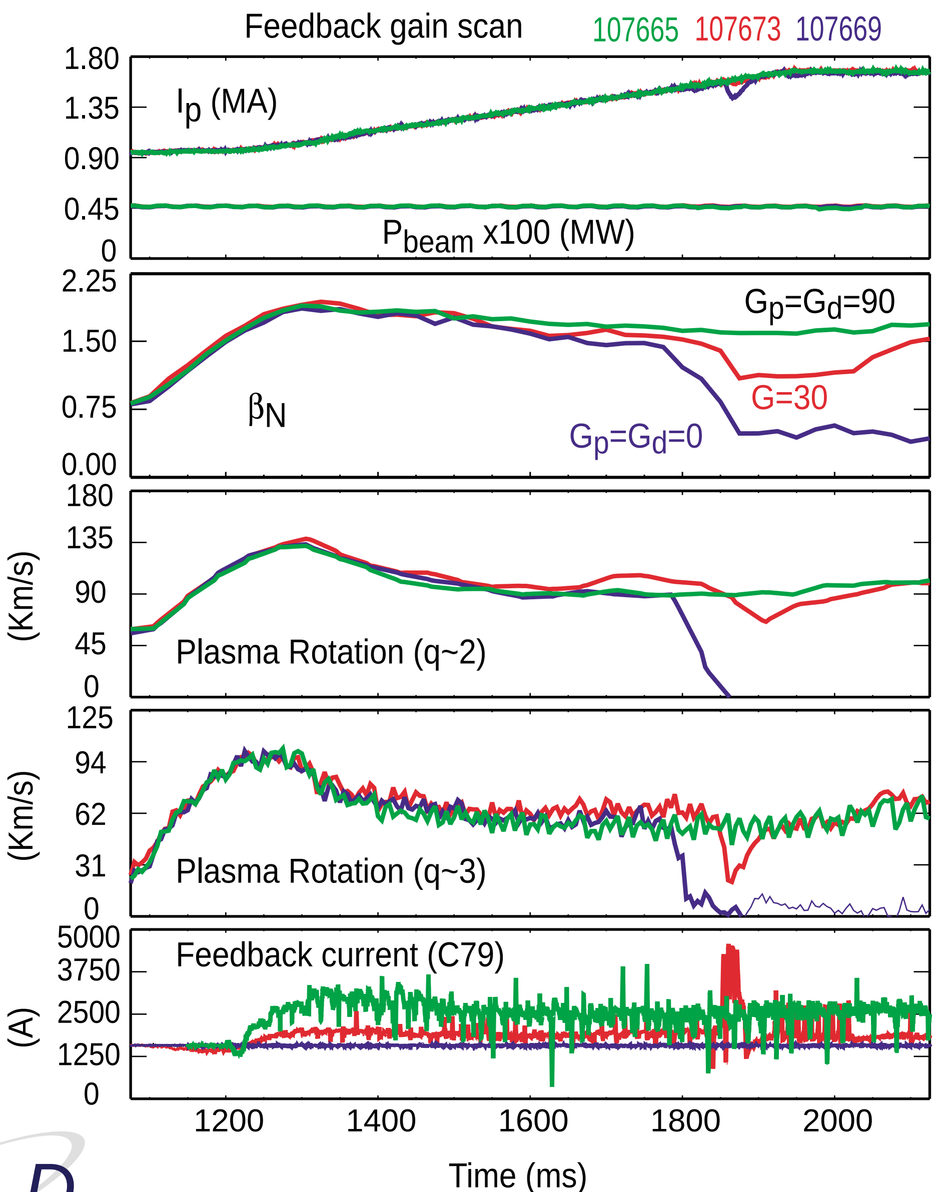
Basic Feedback Control Loop for RWM Control
with Magnetic Sensors Uncoupled to Control Coils



LOW ROTATION PLASMA RWM FEEDBACK STUDIES SHOWS CLEAR EFFECT OF FEEDBACK LOOP GAIN



- Toroidal rotation reduced by 50% compared to typical RWM discharges
- Higher feedback gain removes instability
- No visible effect of feedback field on plasma toroidal rotation, suggesting direct feedback stabilization of the RWM
- Power scan experiments yielded first data for quantitative comparison with VALEN

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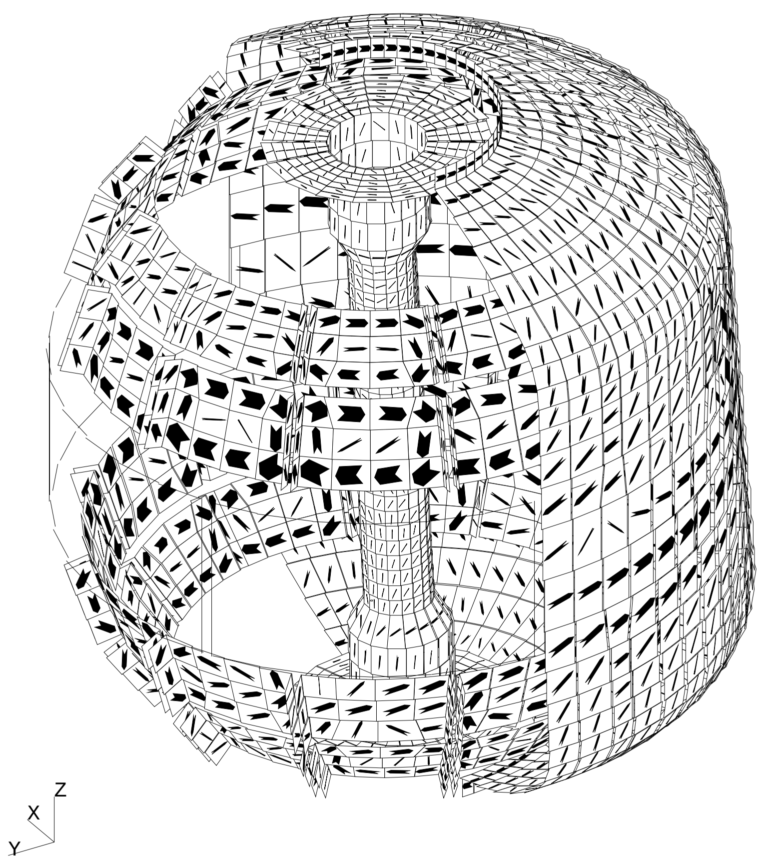
VALEN Feedback Control Model

see PoP **8 (5)**, 2170 (2001) – Bialek J., et al.

- Unstable Plasma Model (PoP Boozer 98)
- General 3D finite element electromagnetic code
- Arbitrary sensors, arbitrary control coils, and most common feedback logic (smart shell and mode control)

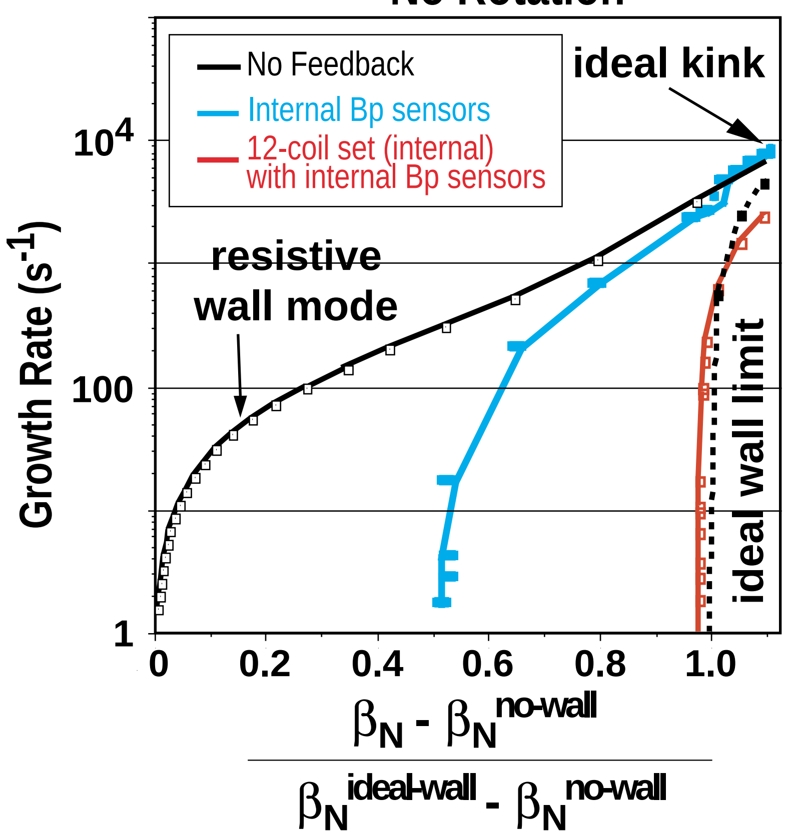


INTERNAL CONTROL COILS ARE BEING TESTED IN DIII-D
PREDICTED TO REACH IDEAL PRESSURE LIMIT w/o ROTATION

- Better matching to resonant field spectrum
- Active feedback stabilization is calculated by VALEN to reach ideal wall limit in plasmas without rotation

Coils Being Installed in DIII–D

No Rotation



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