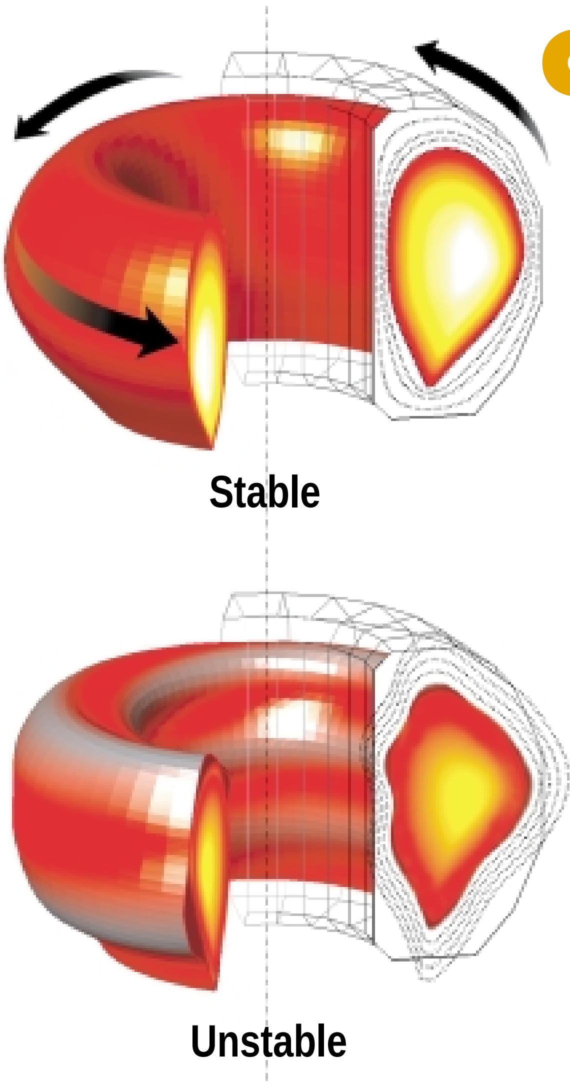
Resistive Wall Stabilization of High Beta Plasmas in DIII–D



by
E.J. Strait

for J. Bialek,* I.N. Bogatu,‡ M.S. Chance,† M.S. Chu, D.H. Edgell,‡ A.M. Garofalo,* G.L. Jackson, T.H. Jensen, L.C. Johnson,† J.-S. Kim,‡ R.J. La Haye, G.A. Navratil,* M. Okabayashi,† H. Reimerdes,* J.T. Scoville, A.D. Turnbull, M.L. Walker, and the DIII–D Team

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GENERAL ATOMICS

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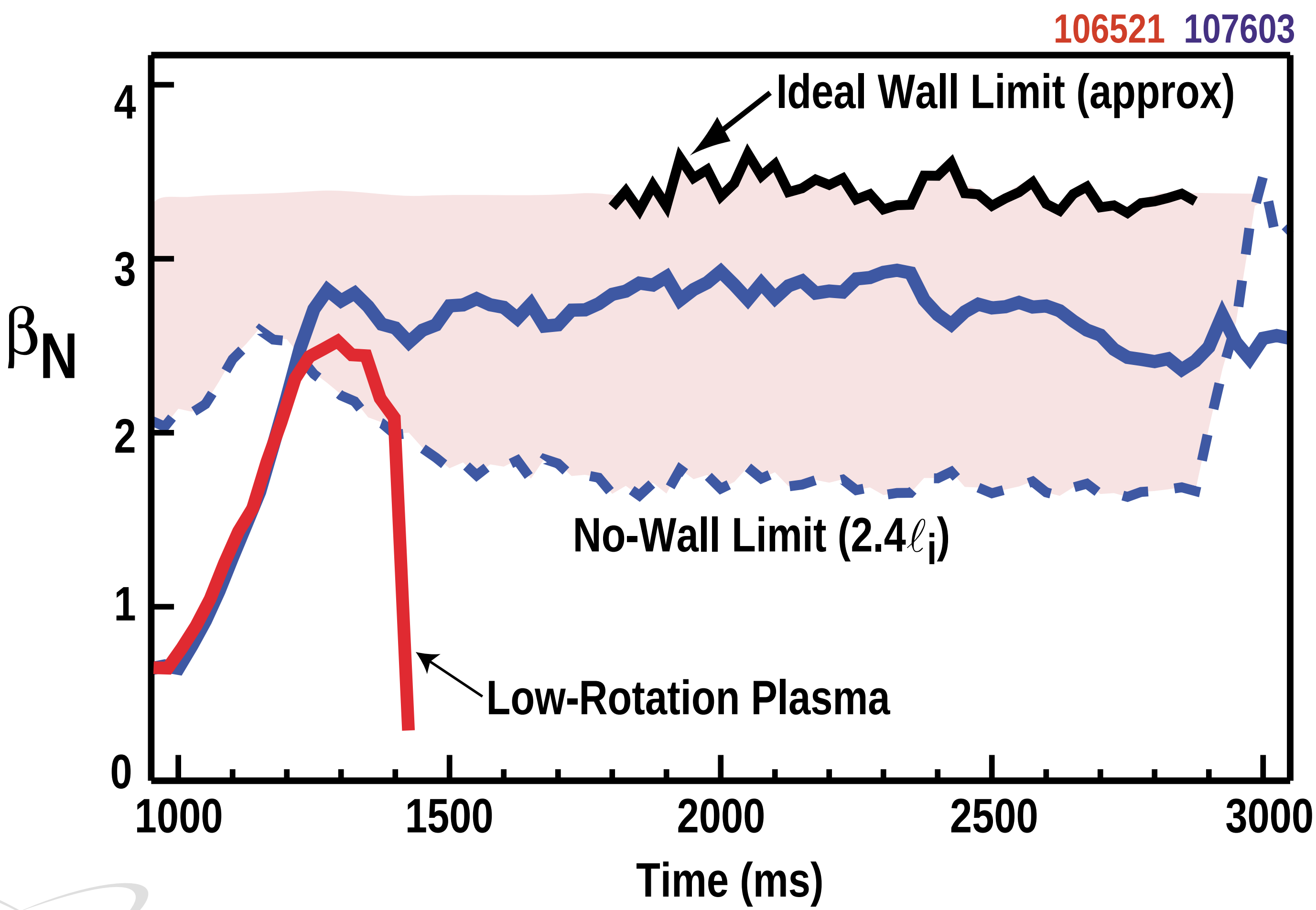
STABLE OPERATION WELL ABOVE THE NO-WALL β LIMIT HAS BEEN SUSTAINED FOR >300 WALL TIMES

- Resistive wall mode stabilized by plasma rotation



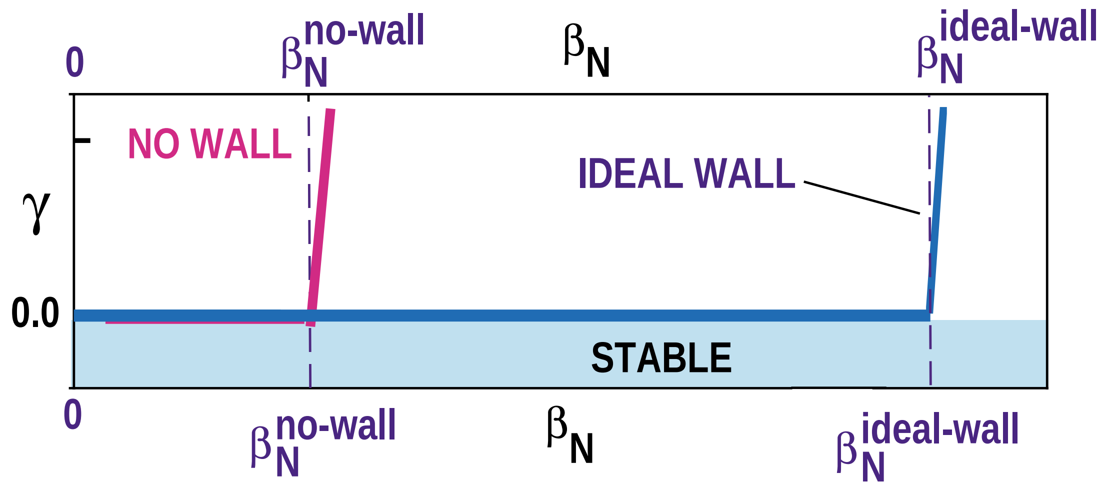
INTRODUCTION

- **Many "advanced tokamak" scenarios rely on wall stabilization of ideal kink modes**
  - Perfectly conducting wall extends stability limits
  - Finite conductivity wall allows a slowly growing resistive wall mode (RWM)
- **Two approaches to providing stability with a resistive wall**
  - Plasma rotation (requires $\Omega \gtrsim 0.02\ \Omega_A$)
  - Active feedback stabilization $\left(\text{possible because } \gamma_{RWM} \sim \tau_{wall}^{-1}\right)$
- **Key discovery: resonant plasma response to non-axisymmetric field enhances rotational drag**
  - Feedback can be applied to minimizing "error field amplification"
- **DIII–D experiments show that ideal kink modes can be stabilized by a resistive wall and plasma rotation, as $\beta \rightarrow$ ideal-wall stability limit**
- **Modeling also predicts high-β stabilization with internal control coils**
  - Needed if rotation frequency is not sufficient in a burning plasma

TH/P3-10: M.S. Chu, "Modeling of Feedback and Rotation Stabilization"

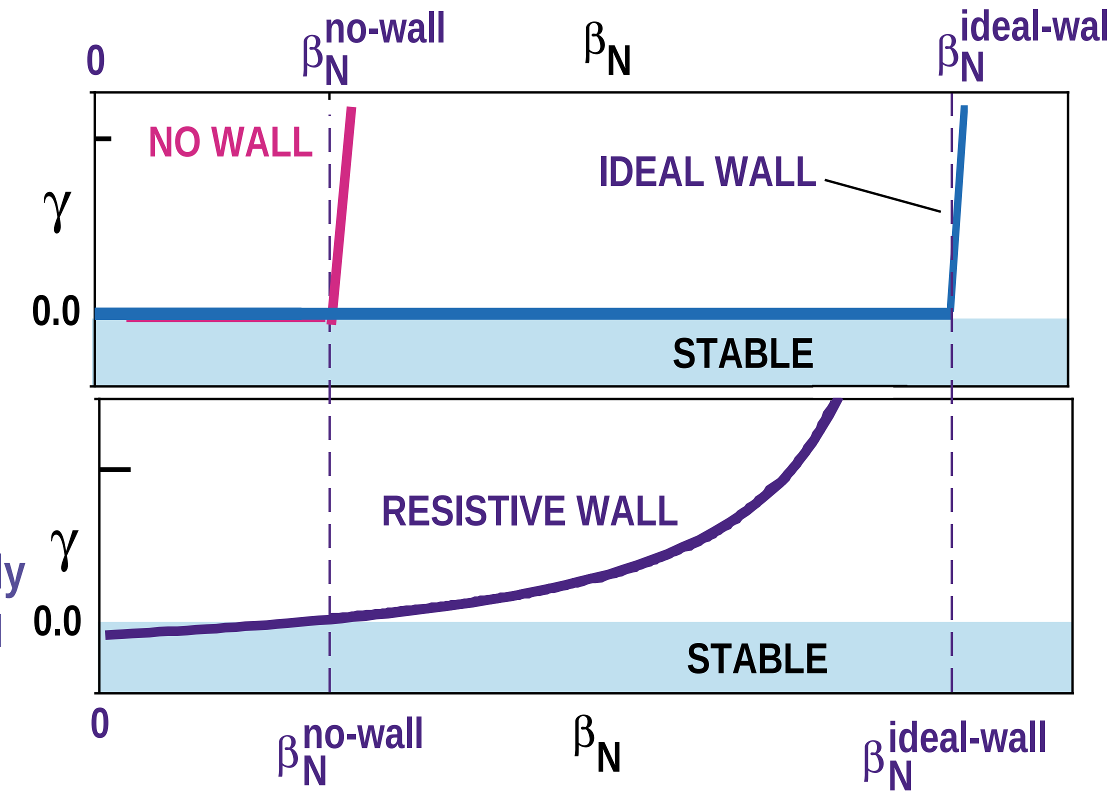
STABILIZATION OF EXTERNAL KINK MODE

- Ideal wall stabilizes external kink



STABILIZATION OF EXTERNAL KINK MODE

- Ideal wall stabilizes external kink
- Finite conductivity allows a slowly growing RWM



STABILIZATION OF EXTERNAL KINK MODE

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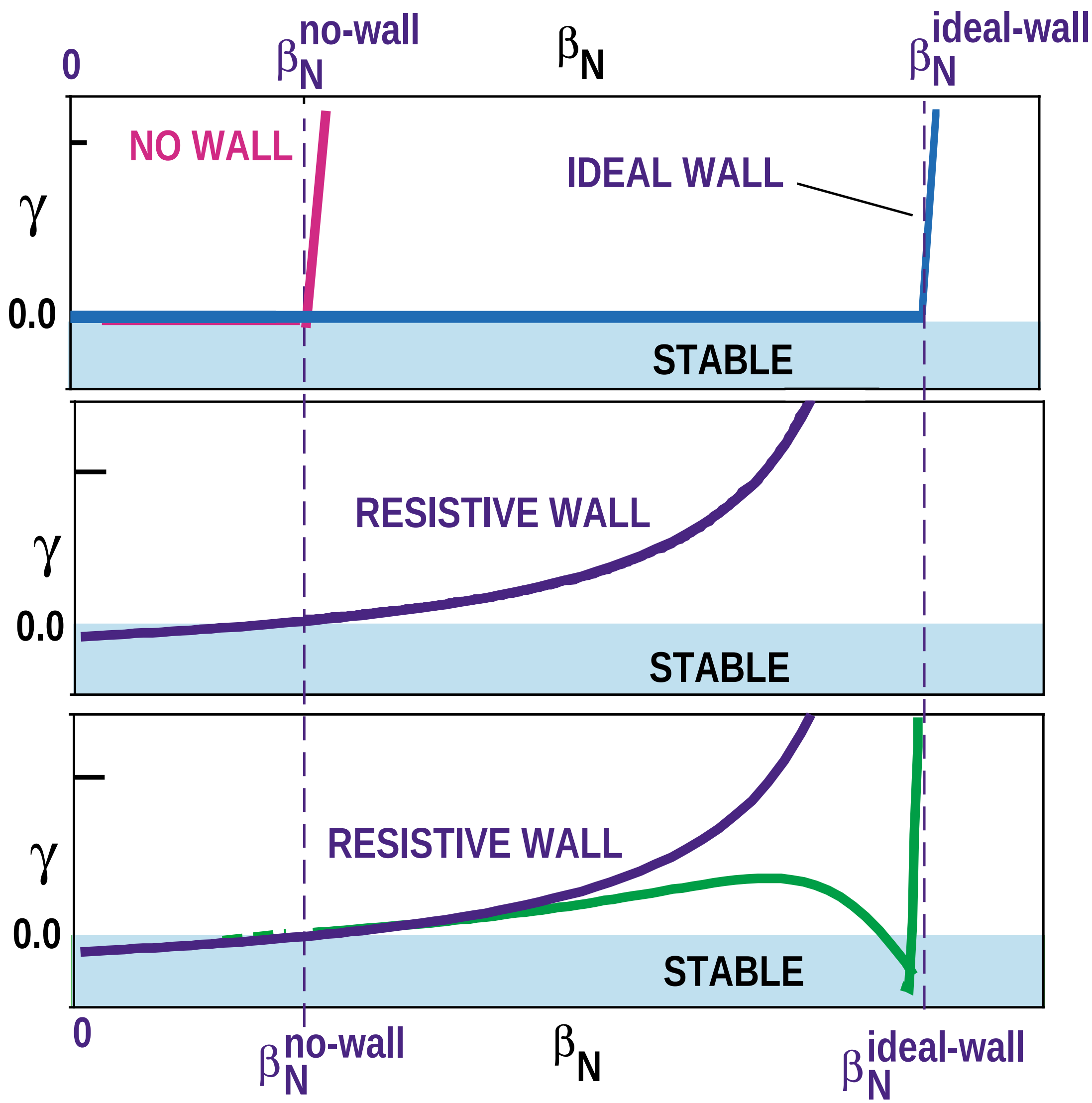

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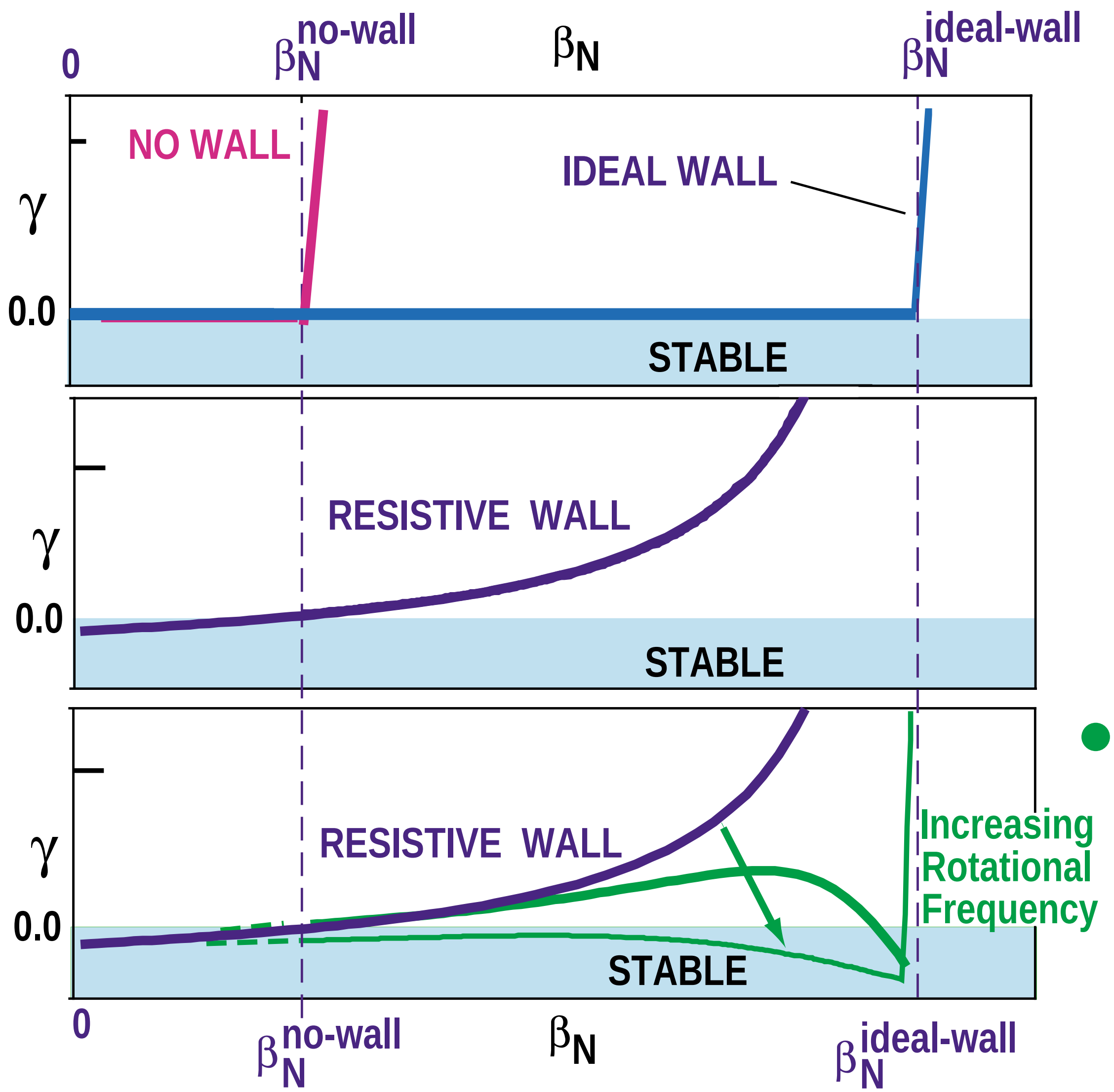

- Rotational stabilization

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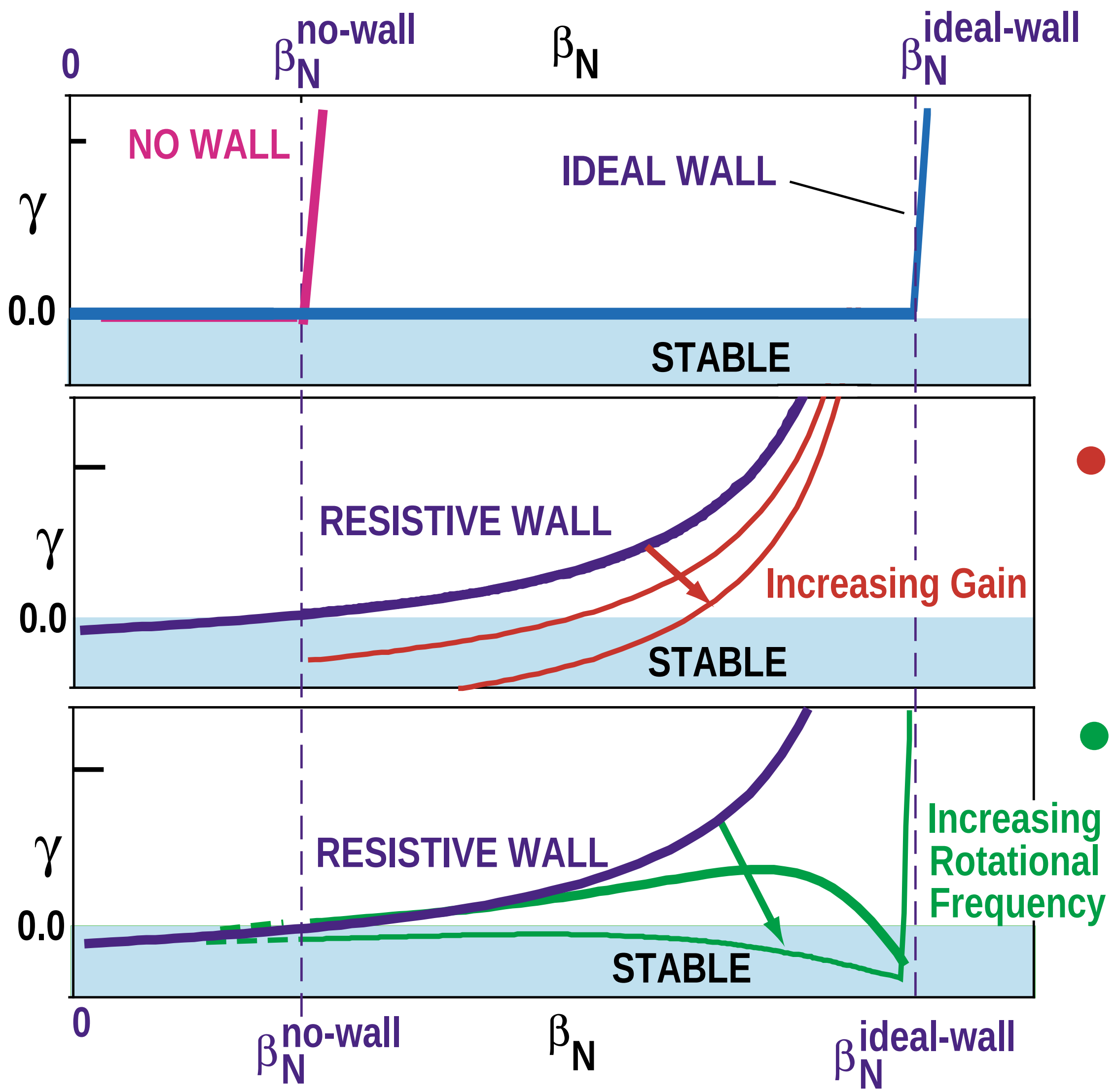

- Magnetic feedback stabilization
- Rotational stabilization

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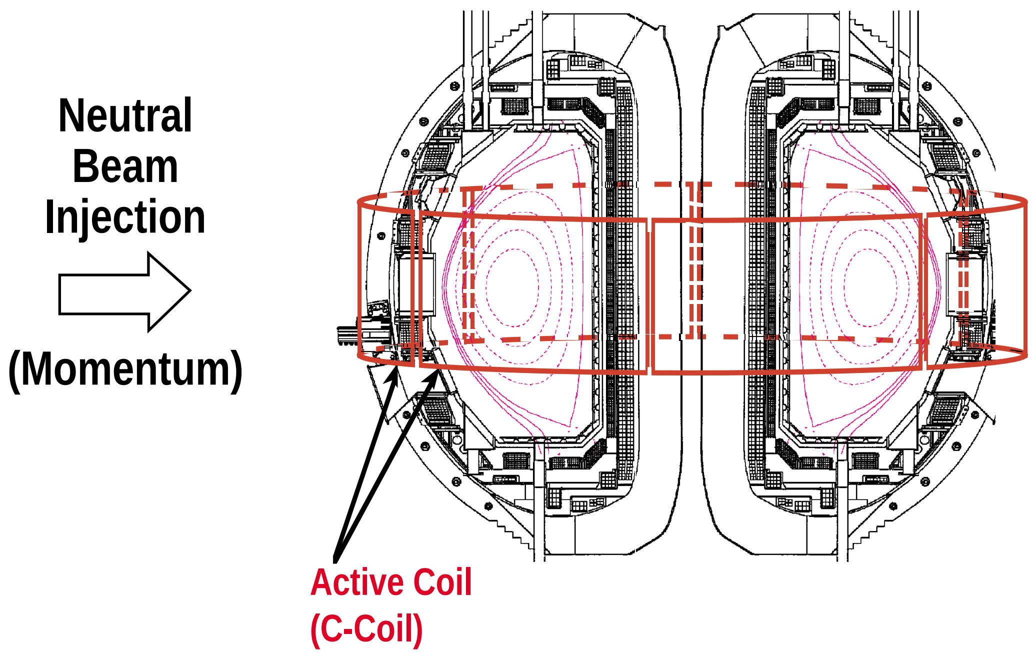
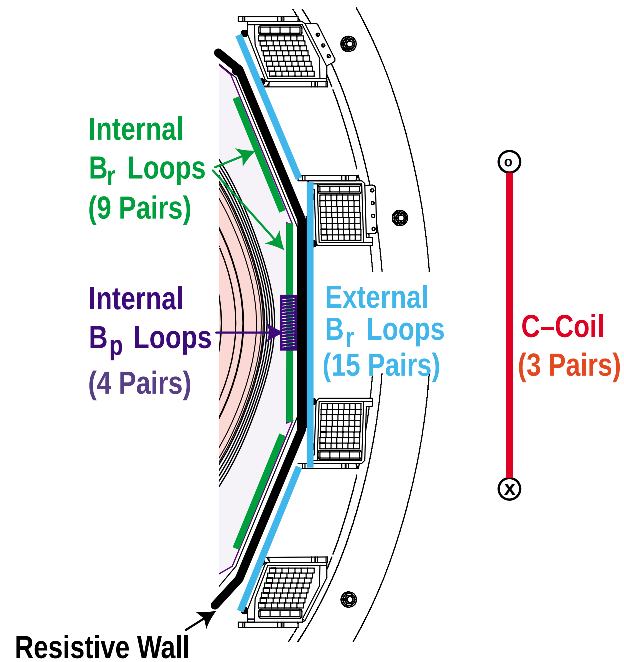
NON-AXISYMMETRIC “C-COIL” IS USED FOR ERROR FIELD CORRECTION AND RWM FEEDBACK CONTROL

- Six midplane coils (C–coil) connected in three pairs for n=1 control
- External and internal saddle loops measure δB_r
- Poloidal field probes measure δB_p with reduced coupling to the control coils

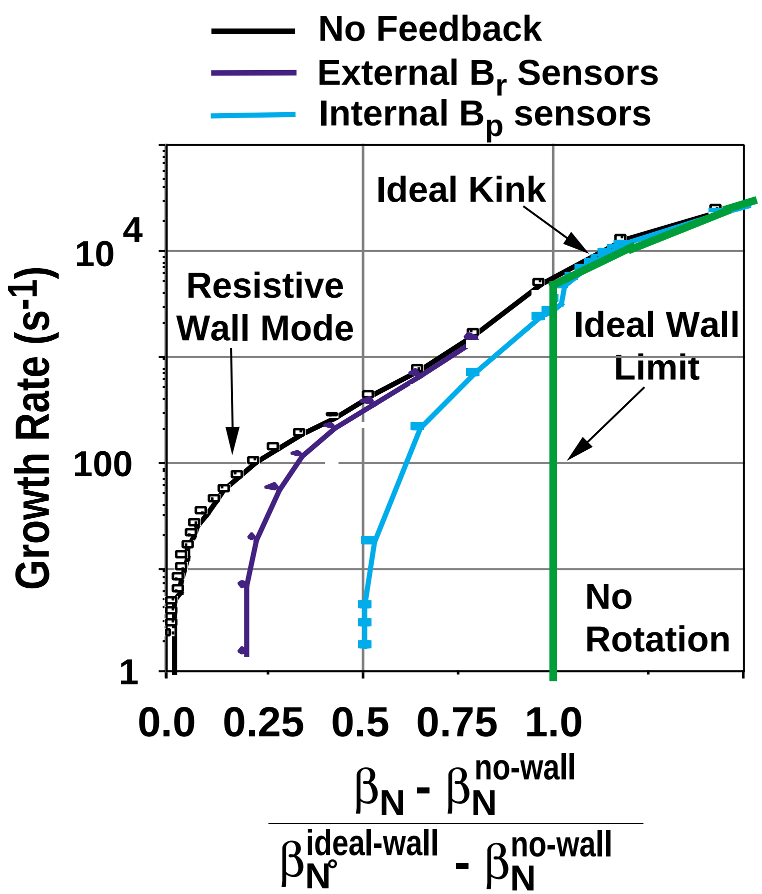




VALEN 3-D FEEDBACK CONTROL MODEL PREDICTS IMPROVED β LIMIT WITH EXISTING 6 COIL SET

- External B_r sensors in basic "smart shell" control algorithm allow 20% increase towards ideal wall β_N limit

- Internal B_p sensors allow 50% increase towards ideal wall beta
  - Faster time response
  - Decoupled from C–coil



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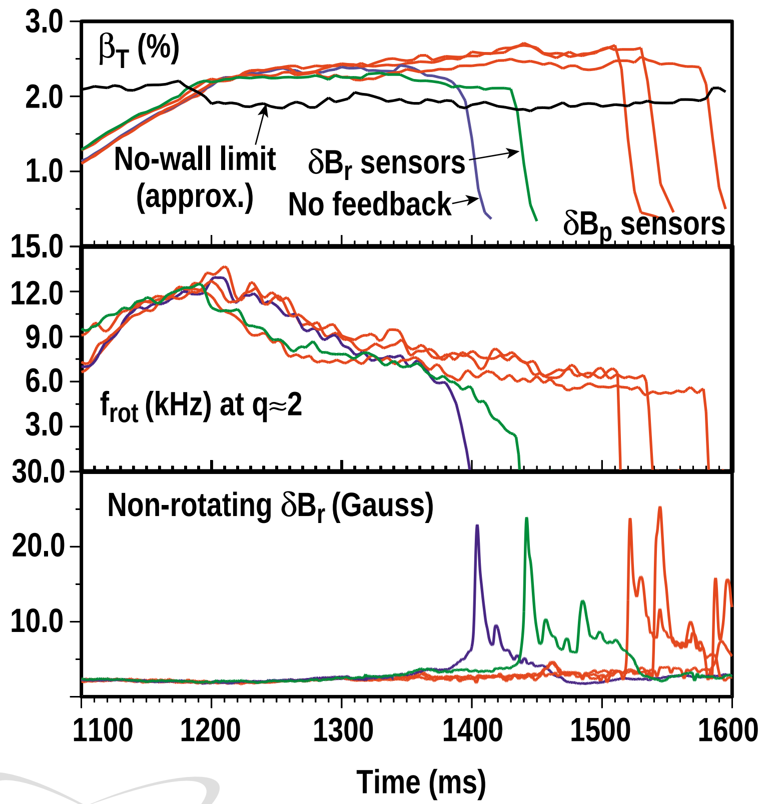
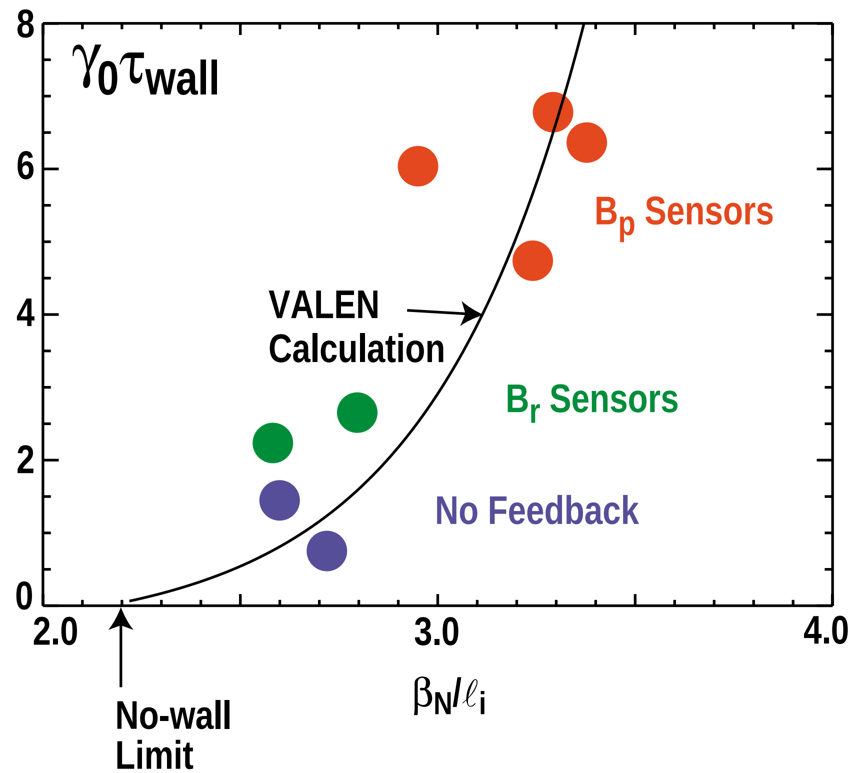
INTERNAL B_p SENSORS IMPROVE ACTIVE CONTROL OF THE RWM

- Stable duration and $\beta/\beta^{no\text{-}wall}$ increase with internal B_p sensors
- Internal B_p sensors stabilize RWM with larger open-loop growth rate γ_0
- Measured open-loop growth rate is consistent with VALEN prediction





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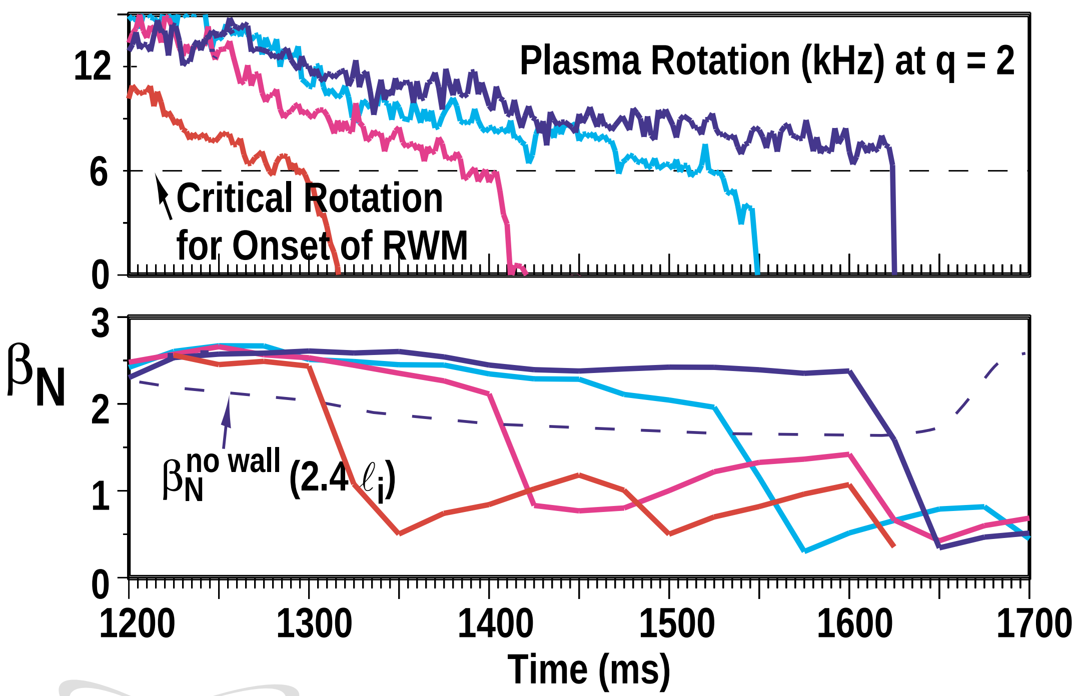
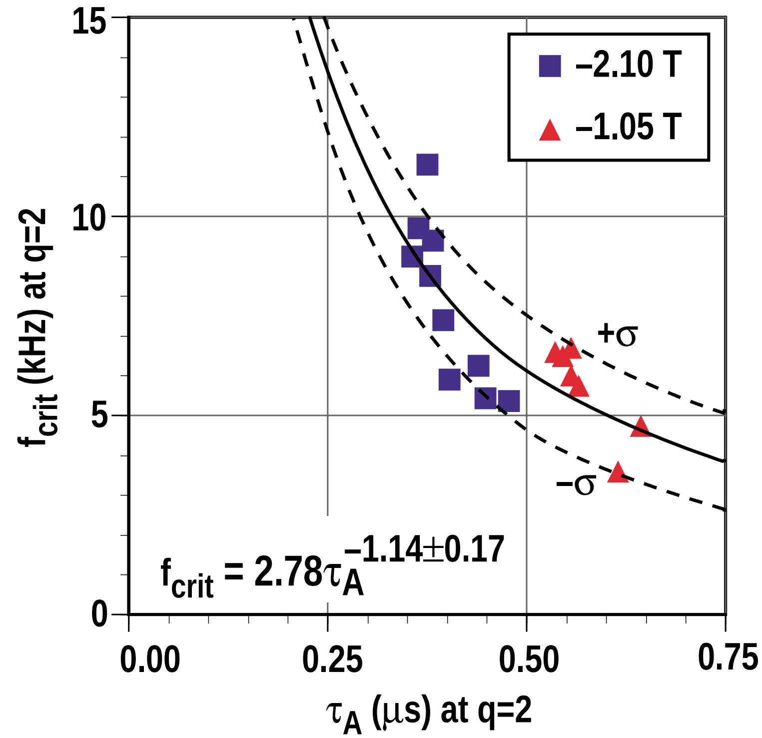
PLASMA ROTATION STABILIZES THE RWM

- Below a critical rotation frequency, RWM becomes unstable

- Critical rotation frequency varies as $\Omega_{crit} \sim 0.02\ \Omega_A$
  - Magnitude consistent with MHD predictions (Bondeson & Ward, 1994)
  - Data could also fit a sound speed scaling





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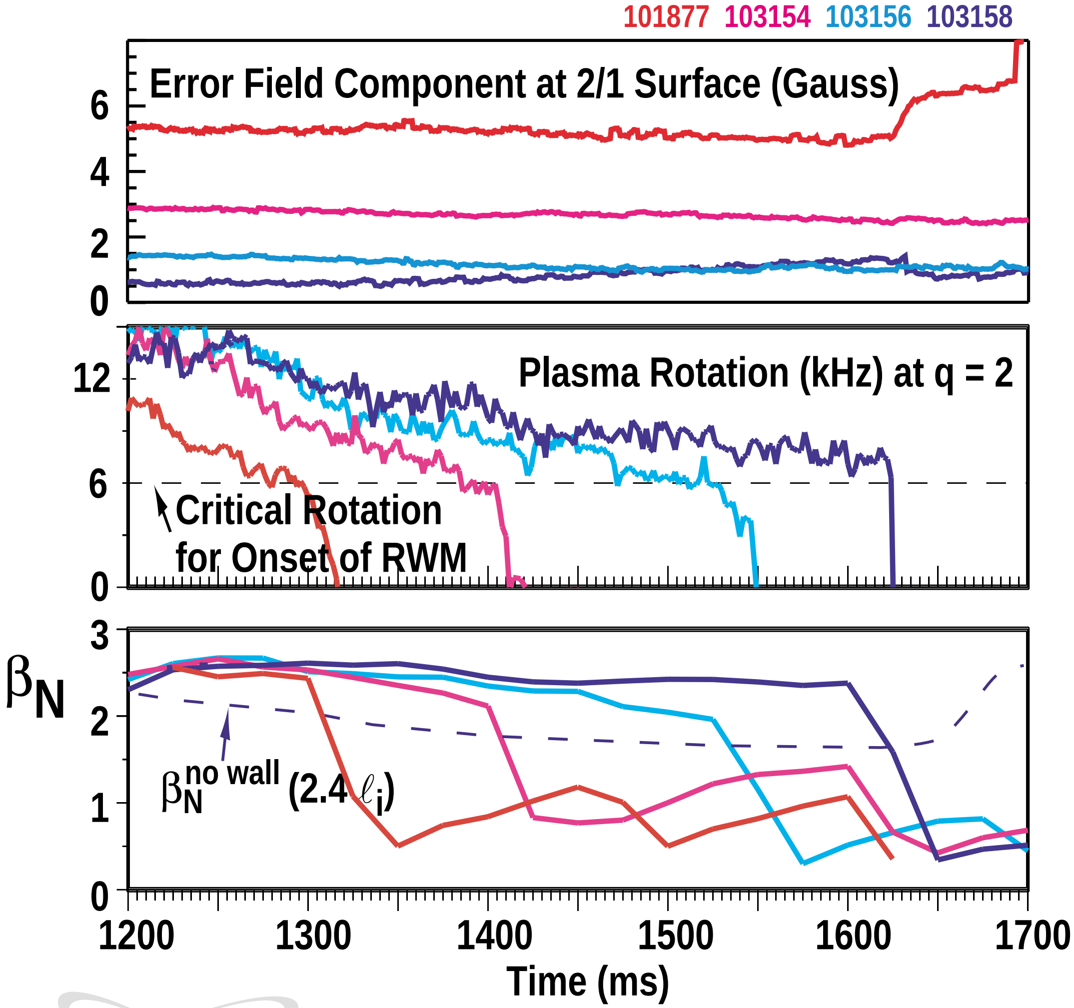
INCREASING n=1 ERROR FIELD AMPLITUDE CAUSES DECAY OF PLASMA ROTATION



- Static n=1 error field is varied with the C–coil

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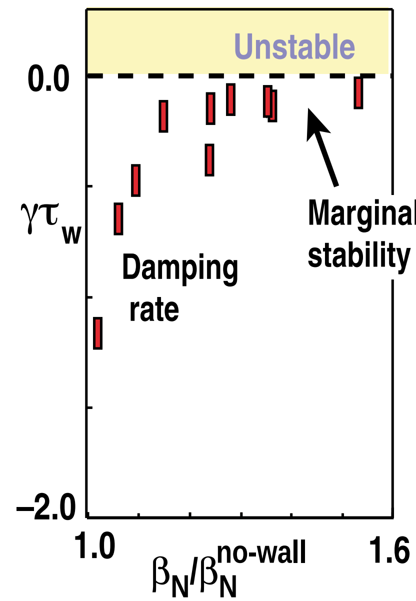
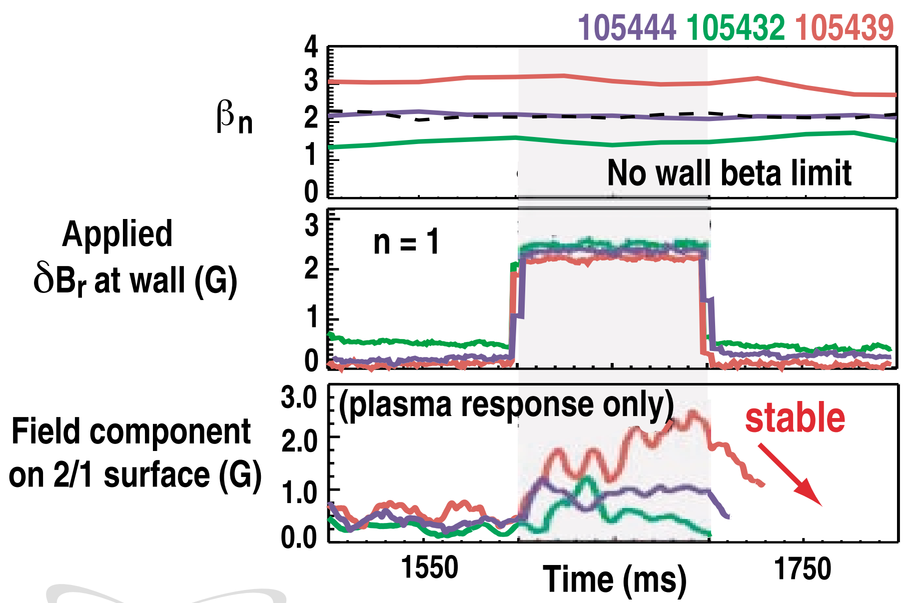
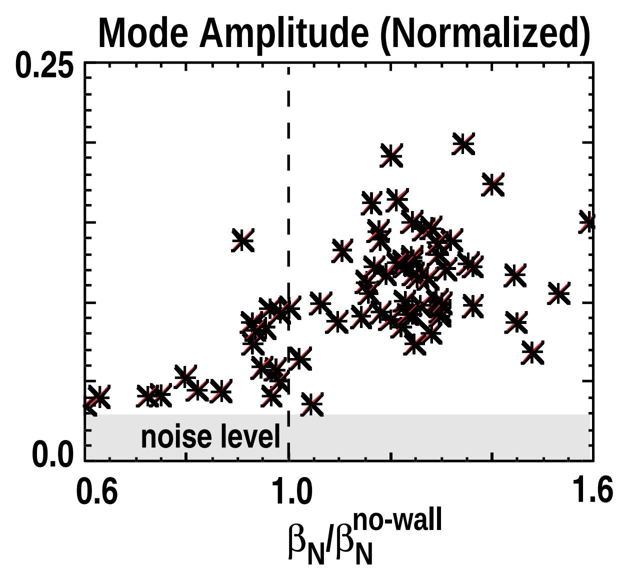
ROTATION-STABILIZED PLASMA HAS A RESONANT RESPONSE TO EXTERNAL MAGNETIC PERTURBATIONS

- Weakly damped oscillator responds when driven near resonant frequency
  - ω_{res} ~ 0 for RWM
- Amplitude of response to n=1 perturbation increases strongly for $\beta > \beta^{no\text{-}wall}$
- Damping rate decreases for $\beta > \beta^{no\text{-}wall}$
- "Error field amplification" by marginally stable RWM can cause slowing of rotation (A. Boozer, PRL 2001)







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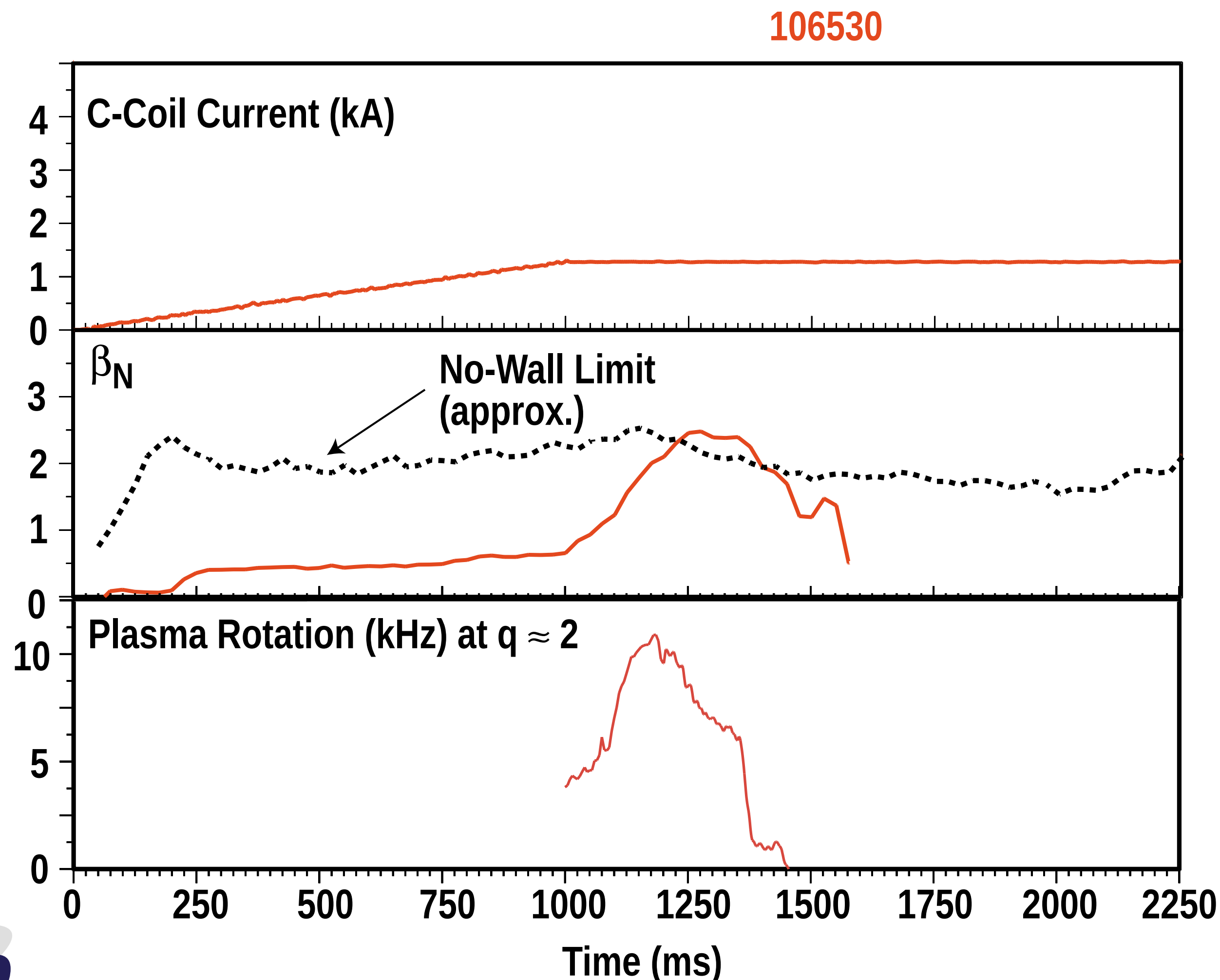
FEEDBACK CONTROL USING INTERNAL B_p SENSORS MAINTAINS WALL STABILIZATION UP TO β_N ~ TWICE THE NO-WALL LIMIT



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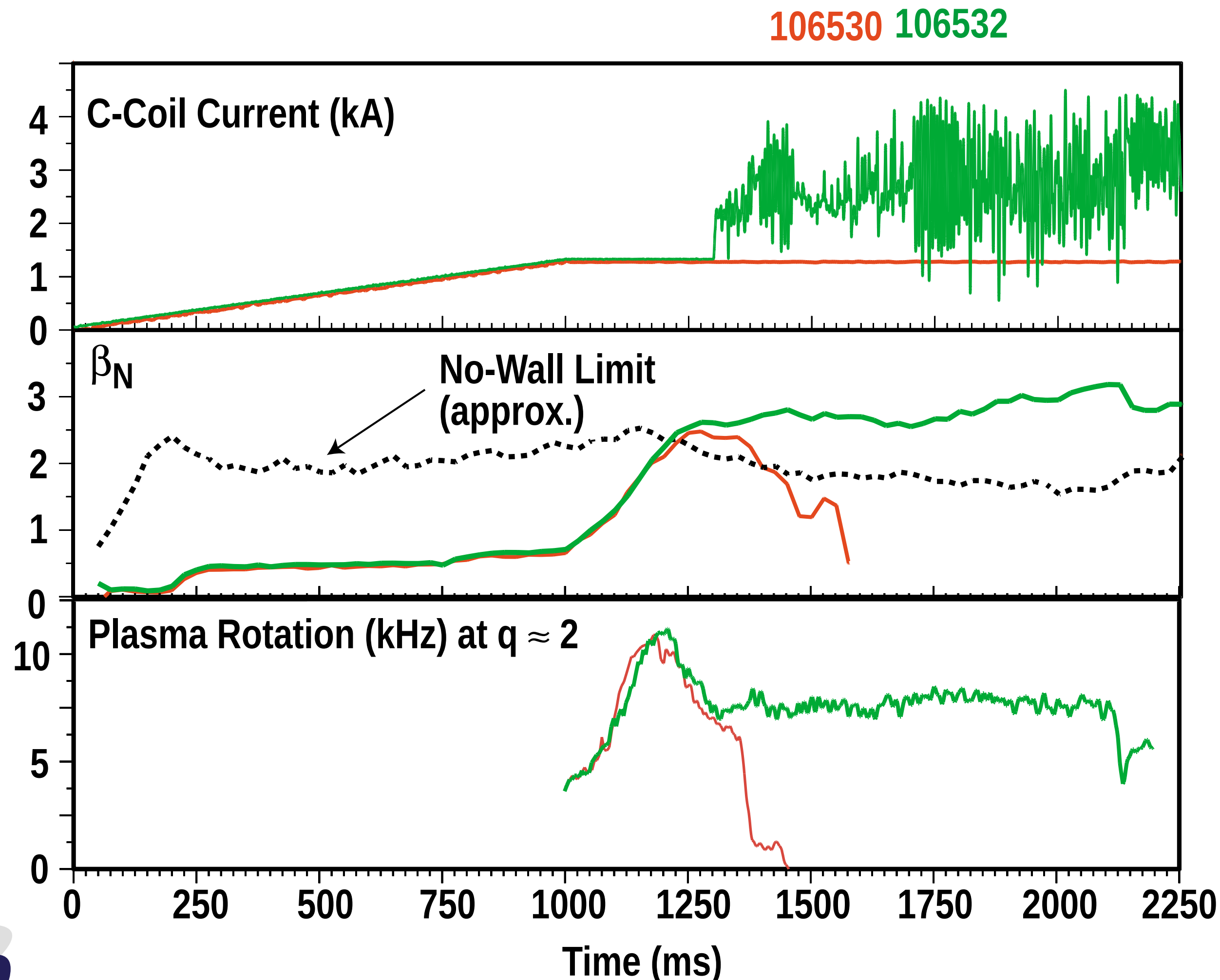
FEEDBACK CONTROL USING INTERNAL B_p SENSORS MAINTAINS WALL STABILIZATION UP TO β_N ~ TWICE THE NO-WALL LIMIT

- Improvement is due to feedback-driven "dynamic error correction" in this case



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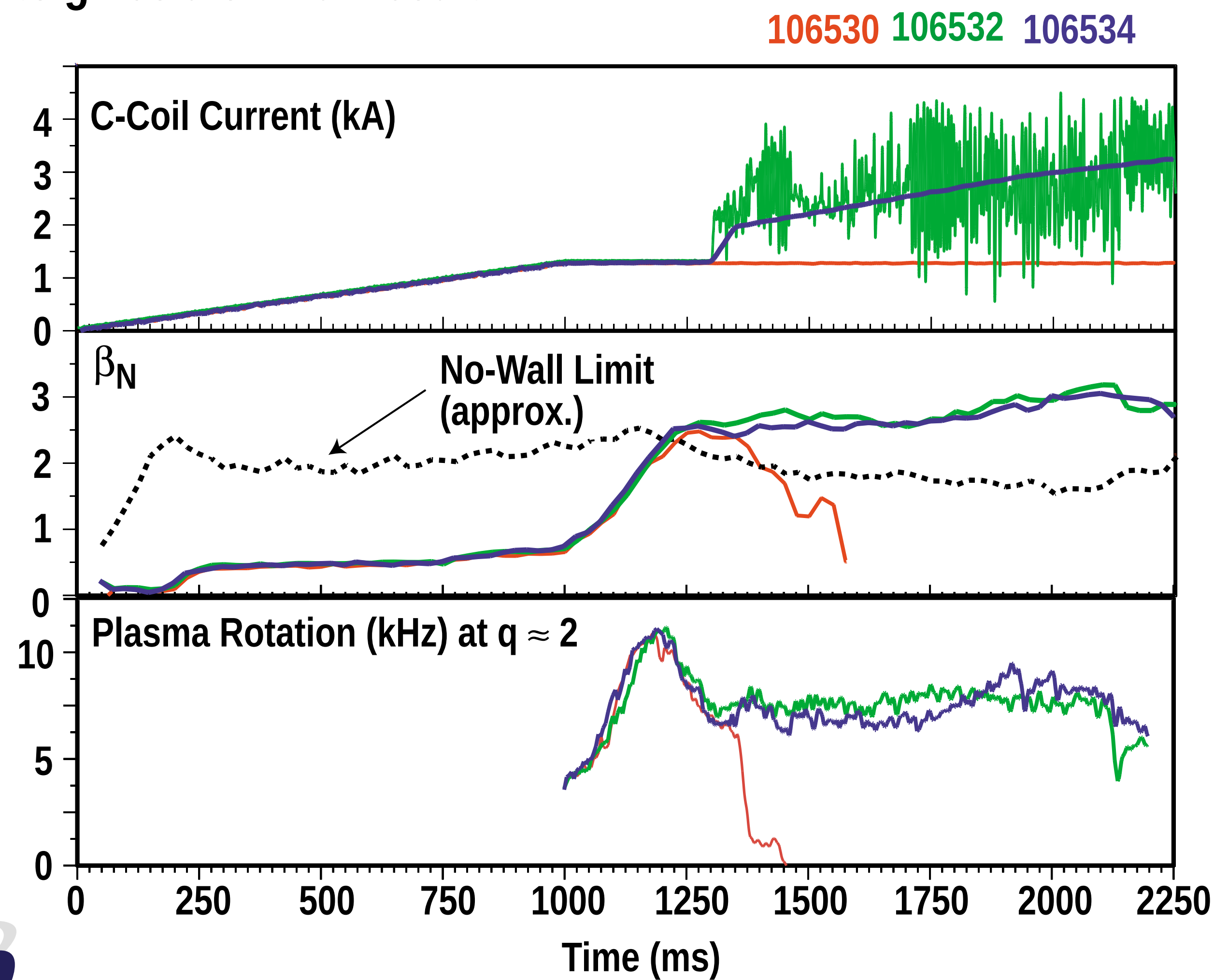
FEEDBACK CONTROL USING INTERNAL B_p SENSORS MAINTAINS WALL STABILIZATION UP TO β_N ~ TWICE THE NO-WALL LIMIT

- Improvement is due to feedback-driven "dynamic error correction" in this case
  - Pre-programming the error correction currents to match feedback-controlled currents gives a similar result



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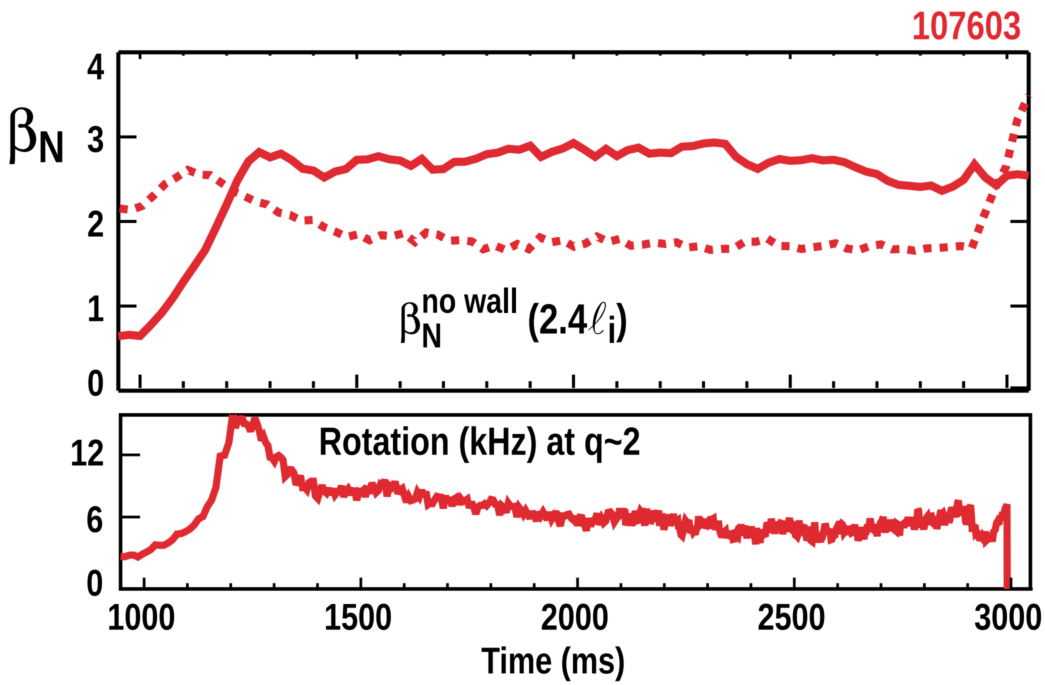
REDUCED ERROR FIELDS ⇒ SUSTAINED ROTATION ⇒ RELIABLE OPERATION ABOVE THE NO-WALL LIMIT



- 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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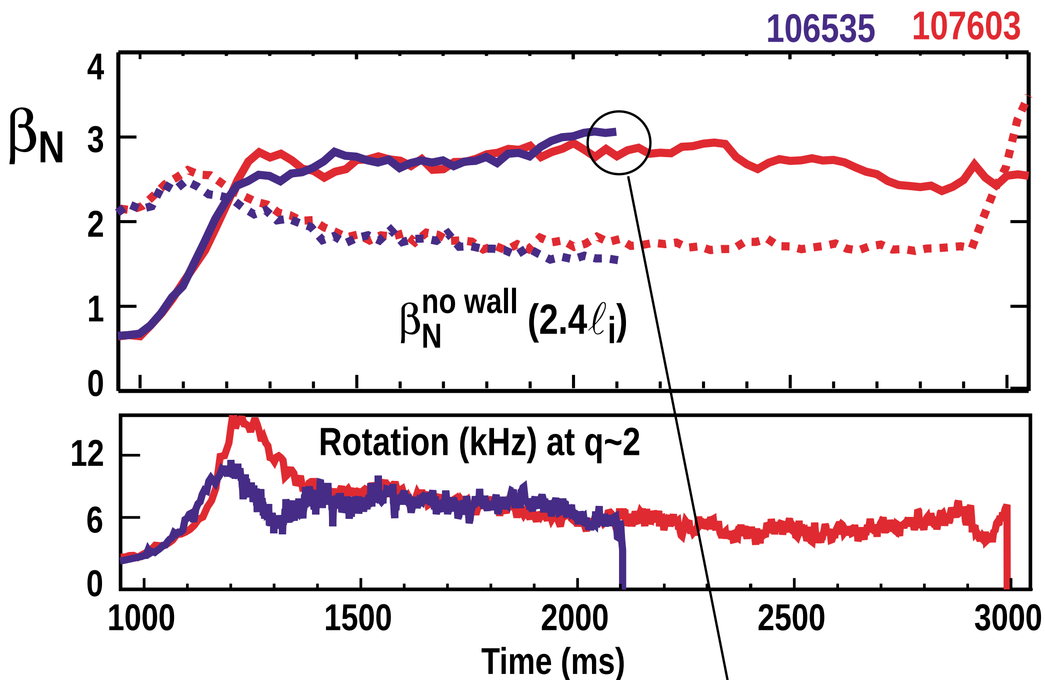

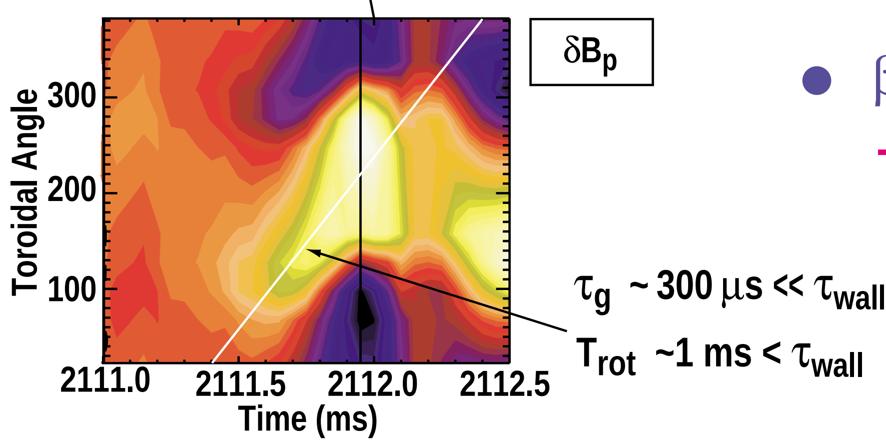

- Feedback control of NBI power keeps β_N below stability limit (107603)
- No other large scale instabilities encountered (NTM, n=2 RWM, . . .)
- Ideal n=1 kink observed at the wall-stabilized β limit
- $\beta_N \sim 2\ \beta_N^{no\text{-}wall}$
  — β = 3.7%

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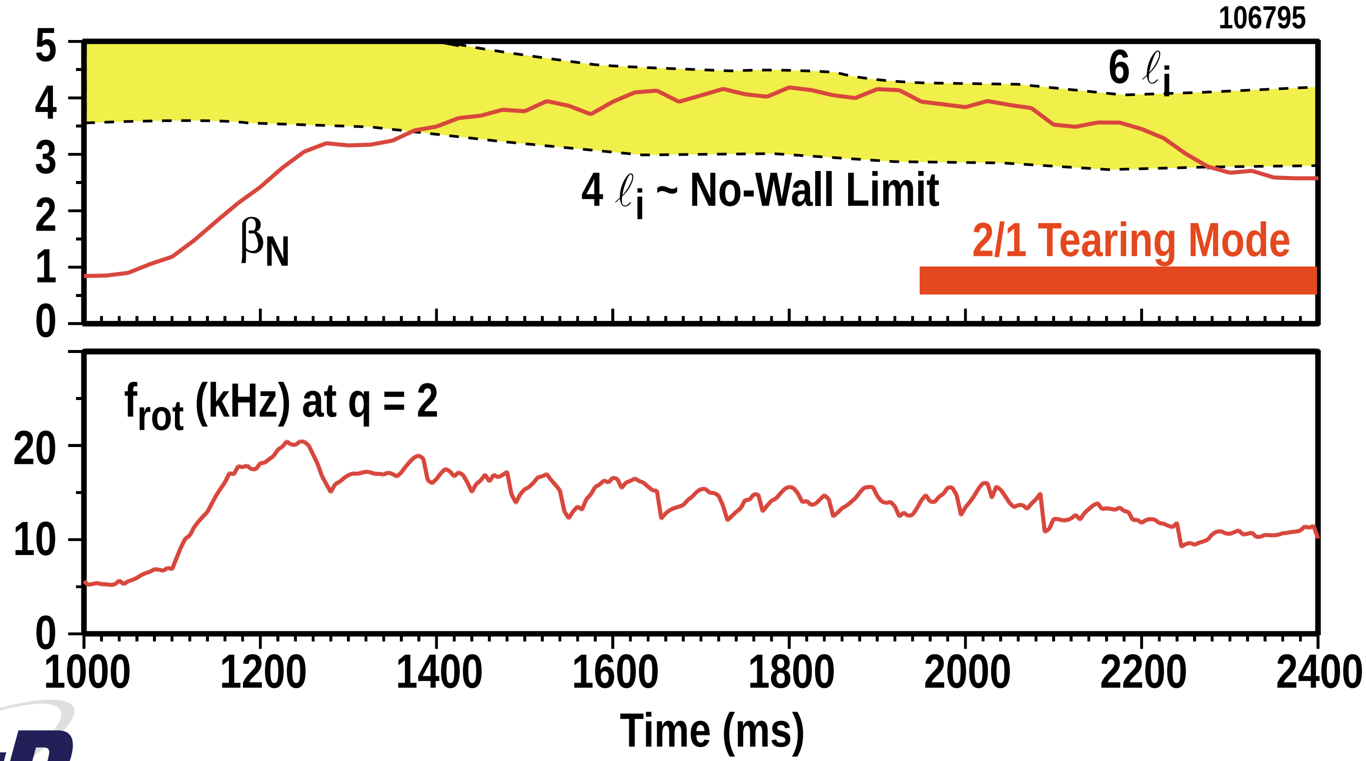
ERROR CORRECTION OPTIMIZATION ALLOWS SUSTAINED HIGH BETA IN ADVANCED TOKAMAK PLASMAS

- Dynamic error correction by feedback control sustains high plasma rotation and high beta
- Negative central shear plasma with 85% noninductive current (65% bootstrap current), and $\beta_T \gtrsim 4\%$
- Large (2,1) tearing mode limits duration of high performance phase



SUMMARY

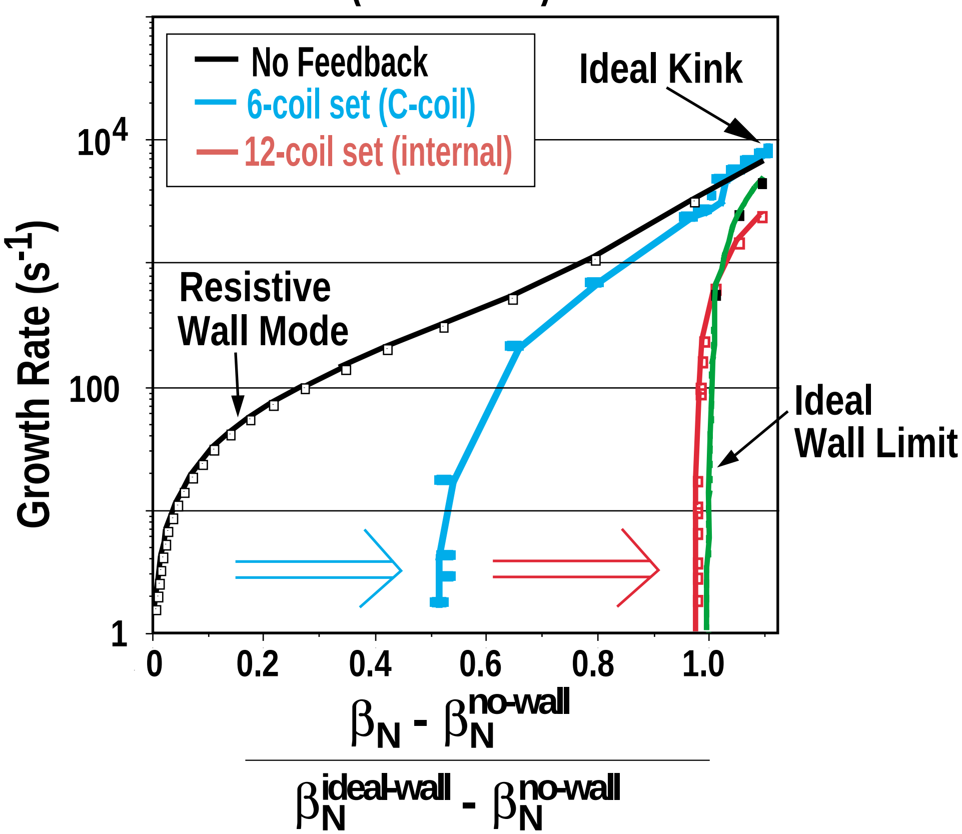
- DIII–D experiments show that ideal kink modes can be stabilized at high beta by a resistive wall, with sufficient plasma rotation
- Resonant response of a marginally stable RWM to non-axisymmetric fields can cause strong damping of rotation
- Feedback control can improve RWM stability in two ways
  - Minimization of the n=1 error field to sustain rotation
  - Direct stabilization at rotation below the critical frequency
- RWM stabilization has improved plasma performance
  - β significantly above the no-wall MHD stability limit sustained for 1.5 s (>300 τ_W)
  - β up to twice the no-wall limit, approaching the ideal-wall stability limit
  - Stable operation at β_N up to 4.2, with 85% noninductive current and β ~ 4%

INTERNAL CONTROL COILS WILL BE AN EFFECTIVE TOOL FOR PURSUING BOTH ACTIVE AND PASSIVE STABILIZATION OF THE RWM

- Off-midplane coils allow better matching to poloidal spectrum of error field or RWM
- Feedback stabilization is calculated to open high beta wall-stabilized regime to plasma without rotation (may be important for burning plasma)

12-coil internal set available for experiments 2003

(VALEN 3-D)



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