RESISTIVE WALL MODE CONTROL ON THE DIII-D DEVICE

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Joint Conference of the 12th International Toki Conference and
The 3rd General Scientific Assembly of Asia Plasma and Fusion Association
on "Frontiers in Plasma Confinement and Related Engineering/Plasma Science"
December 11-14, 2001, Ceratopia Toki, Toki, Gifu, Japan

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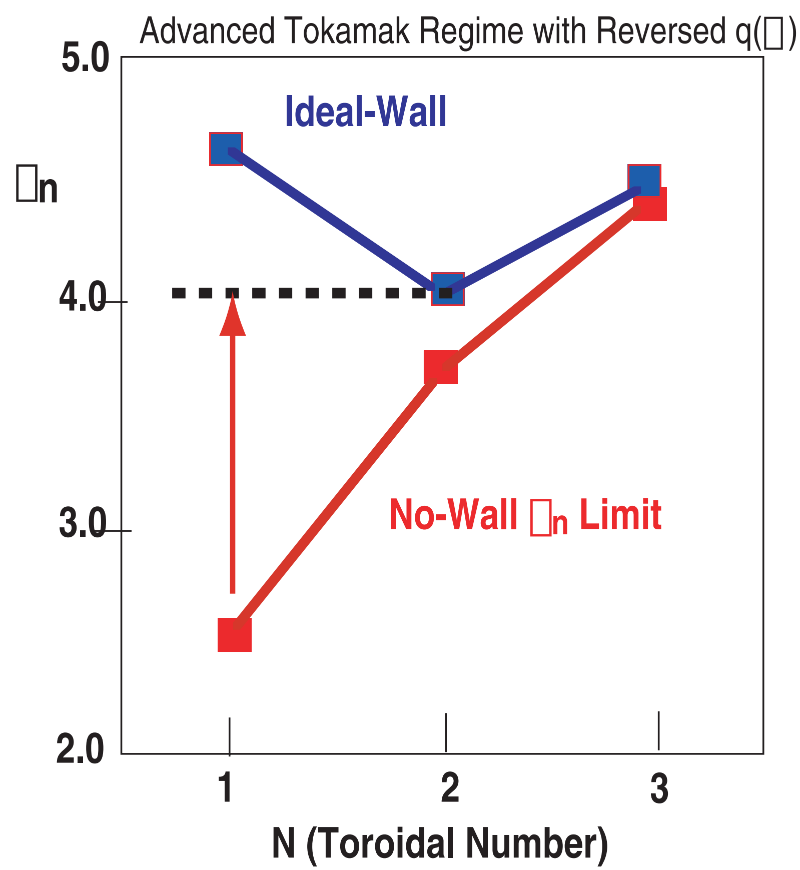
SUCCESSFUL RESISTIVE WALL MODE (RWM) CONTROL IS A PREREQUISITE FOR SUSTAINING IGNITION IN REACTOR ORIENTED DEVICES - HIGH □n PROVIDES HIGH BOOTSTRAP CURRENT CONFIGURATION

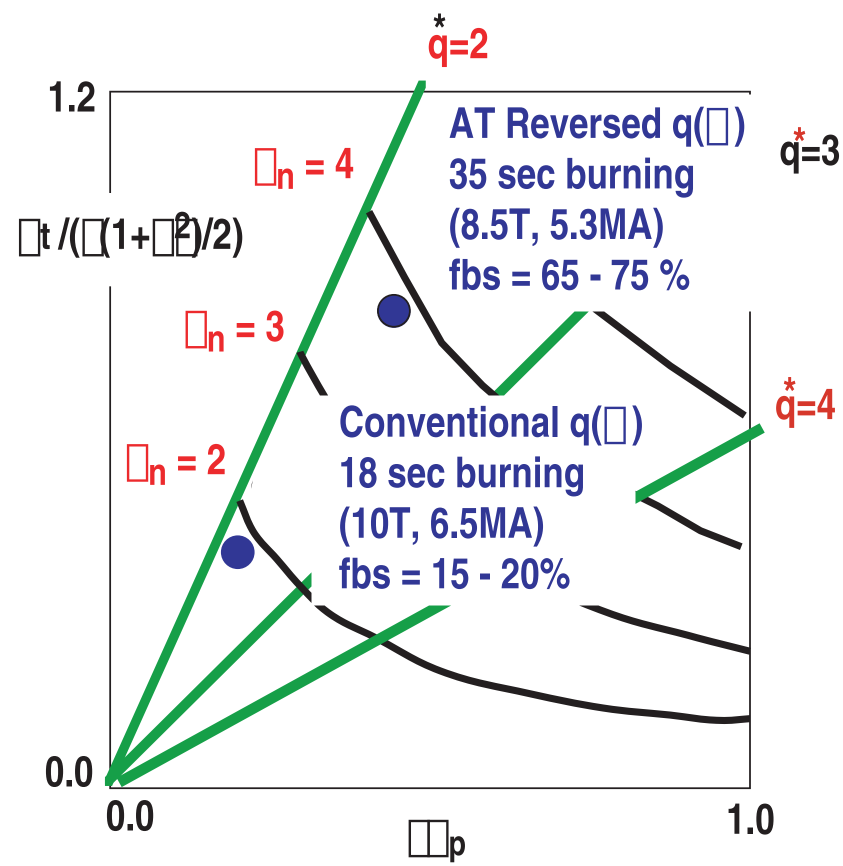
(Example: **F**usion **I**gnition **R**eseach **E**xperiment device)

External kink □n limit

□n = □/(Ip/aBt)



Performance



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OUTLINE

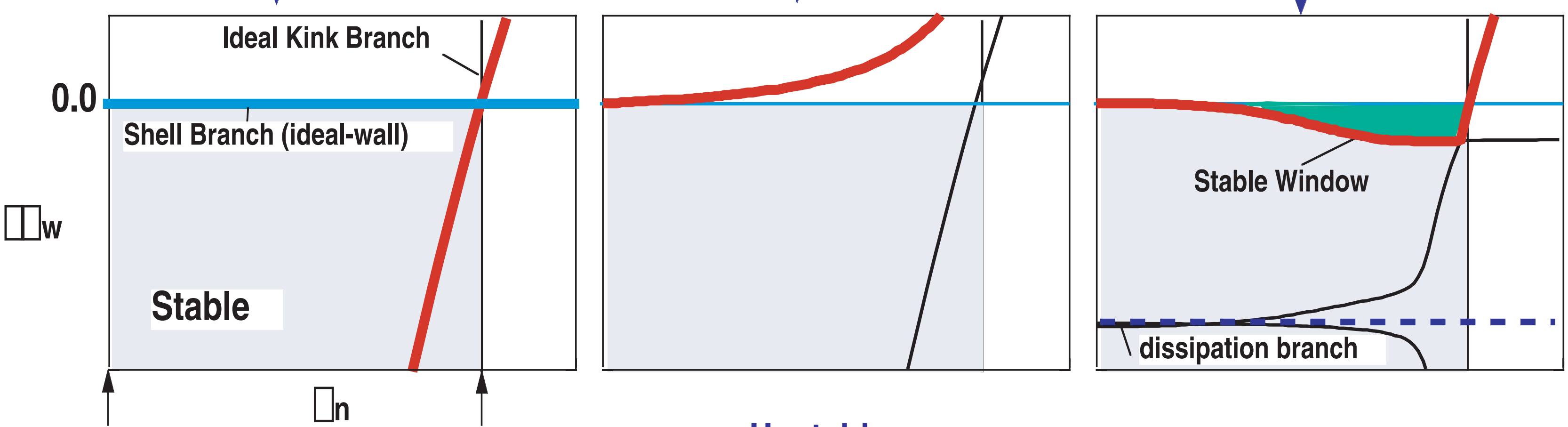
- **Introduction**
  - RWM characteristics
  - Two RWM control approaches
    - Plasma rotation and magnetic feedback
- **Recent RWM control experiments**
  - Magnetic feedback compensates residual error field, increasing rotation and plasma pressure
- **Achievement**
  - Normalized Beta β_n reached twice the no-wall limit, $\beta_n^{no\text{-}wall}$
  - β_n is near the ideal-wall β_n limit, $\beta_n^{ideal\text{-}wall}$
- **Improvement of RWM physics**
  - Discovery of error field amplification (EFA)
- **Modeling**
- **Future plan**
- **Summary**

RESISTIVE WALL MODE
- AN EXTERNAL KINK BRANCH WITH RESISTIVE WALL

δW Formulation

Ideal Kink		Resistive Shell		Plasma Dissipation (Plasma Rotation)	
δW_p	+	$\dfrac{(\delta W_v^b\, \gamma\tau_w + \delta W_v)}{(\gamma\tau_w + 1)}$	+	$(\gamma\tau_w + i\, N\Omega\, \tau)\, D$	$= 0$

τ_w: Wall Skin Time



Stable with Ideal-Wall

Unstable with Resistive-wall

Dissipation Stabilizing

$\beta_n^{no\text{-}wall}$ $\beta_n^{ideal\text{-}wall}$

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RWM CHARACTERISTICS PREDICTED BY THEORY

Mode structure:

- Retains mostly ideal MHD global mode structure

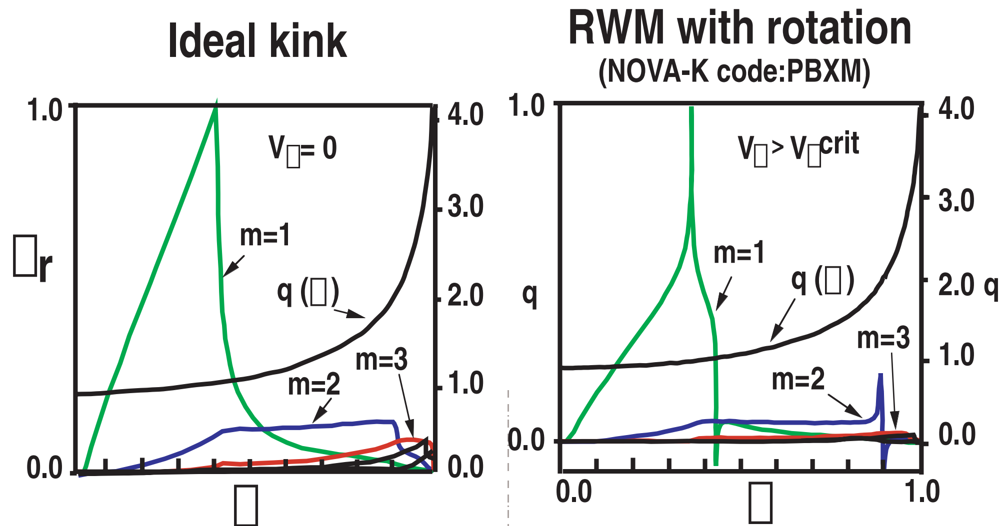
Growth time:

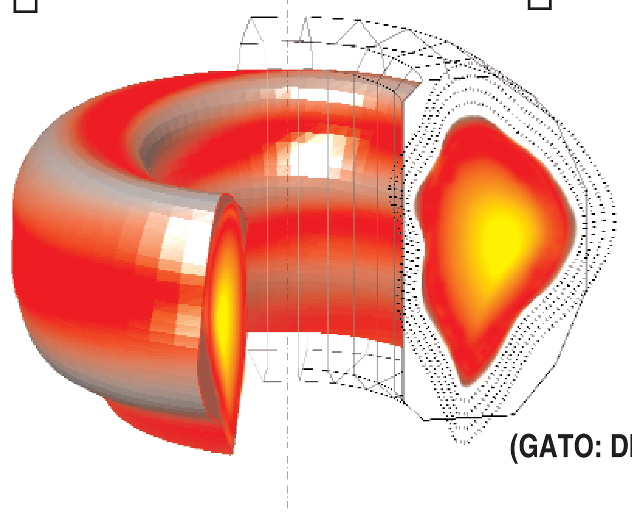
- wall skin time

Toroidally quasi-stationary

No magnetic islands

-> "Slowly evolving quasi-helical equilibrium"





(GATO: DIII-D)

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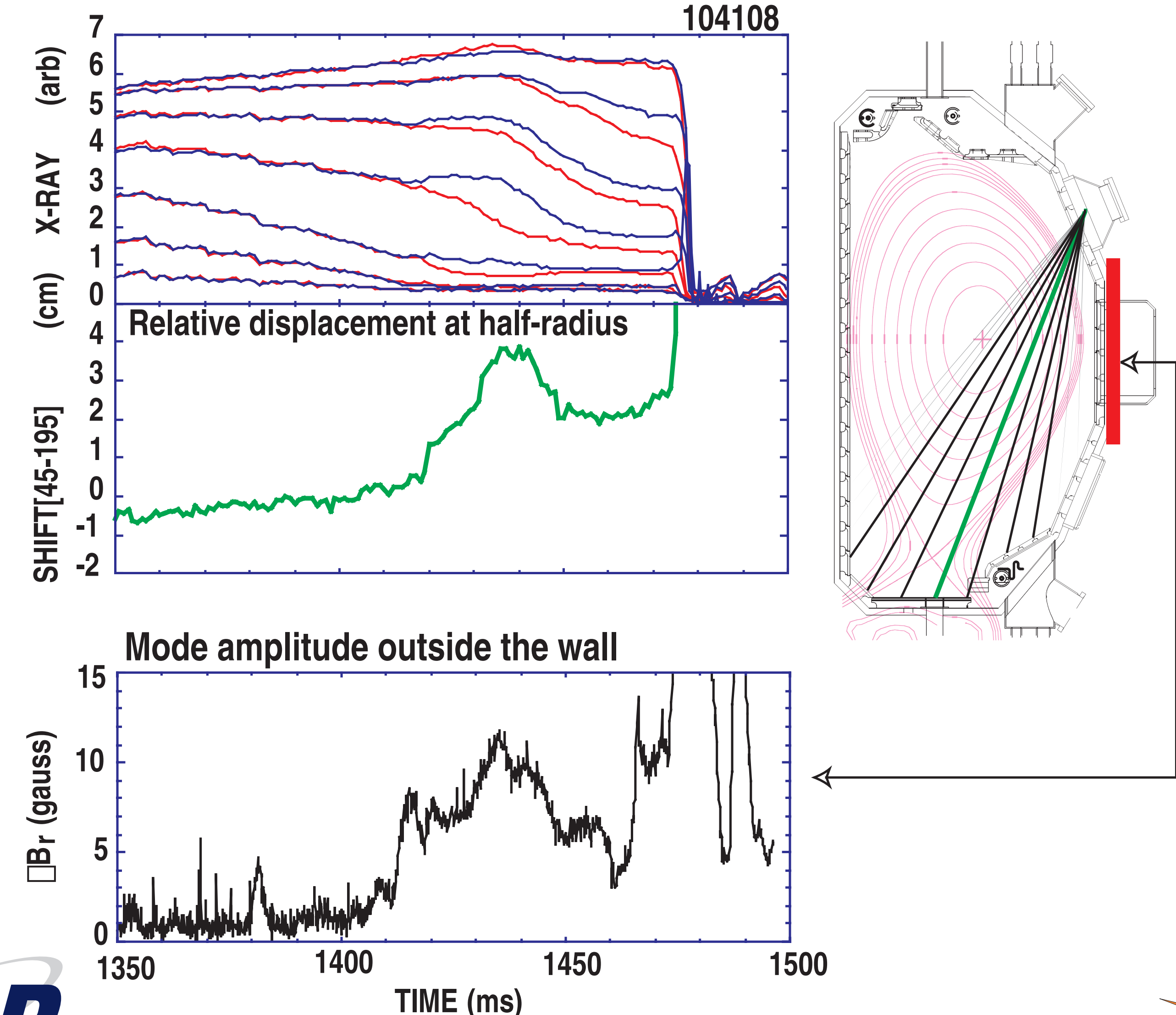
EXPERIMENT SHOWS THAT THE RW MODE STRUCTURE EXTENDS FROM PLASMA CORE TO OUTSIDE THE VACUUM VESSEL

SXR at two toroidal locations separated by 150°



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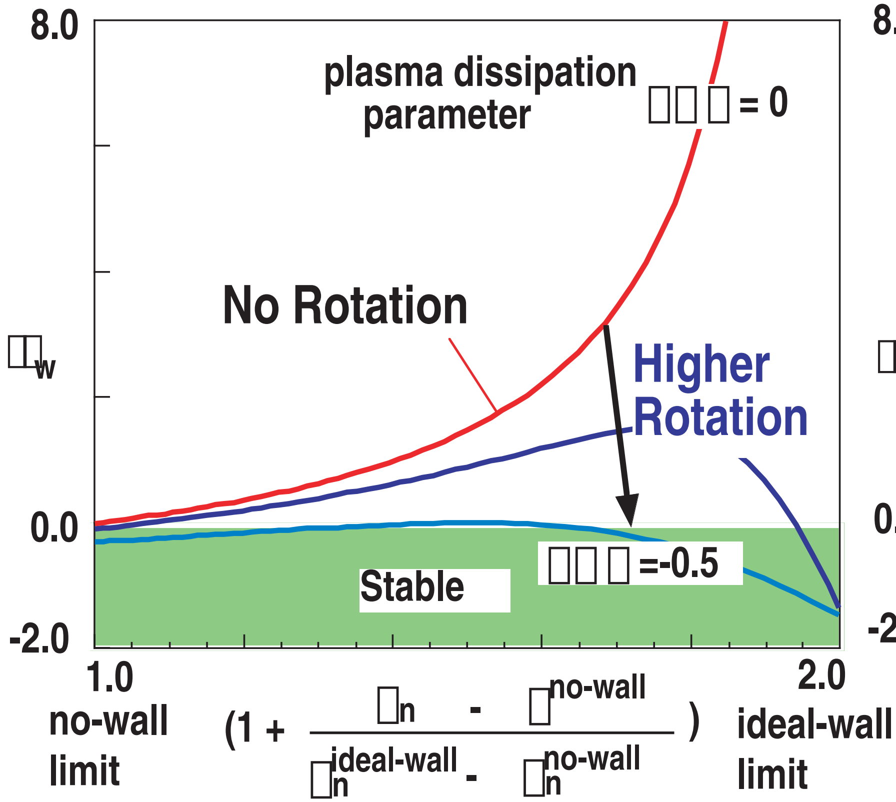
TWO DISTINCT APPROACHES FOR RWM CONTROL HAVE BEEN PROPOSED

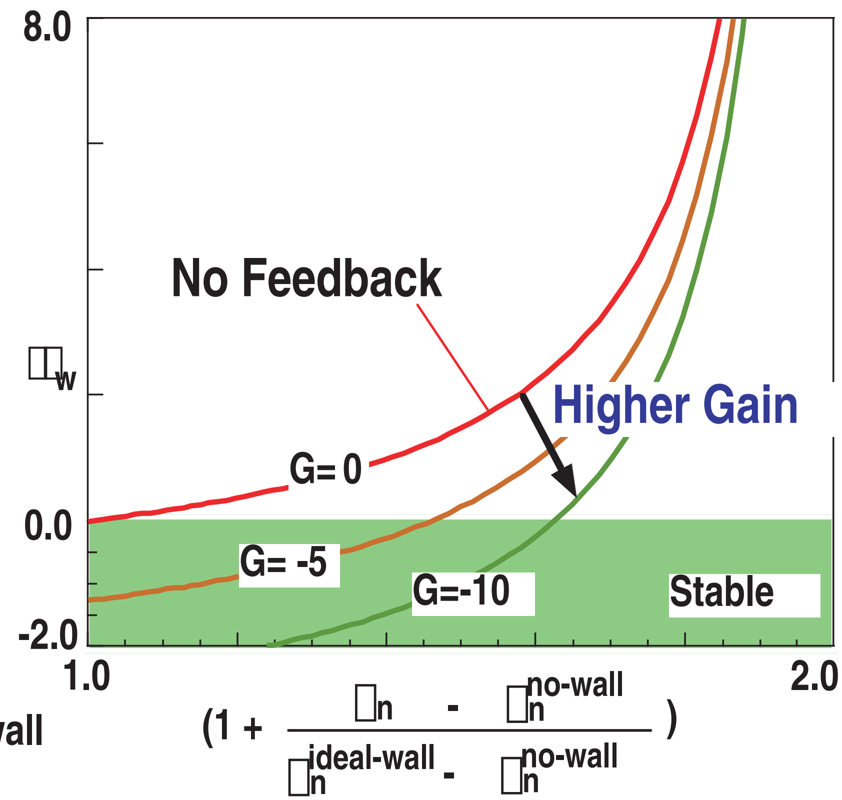
Use of Dissipation (Plasma Rotation: by Bondeson)

Critical rotation velocity for stability a few % of Alfven velocity



Magnetic Feedback

Required power level is modest



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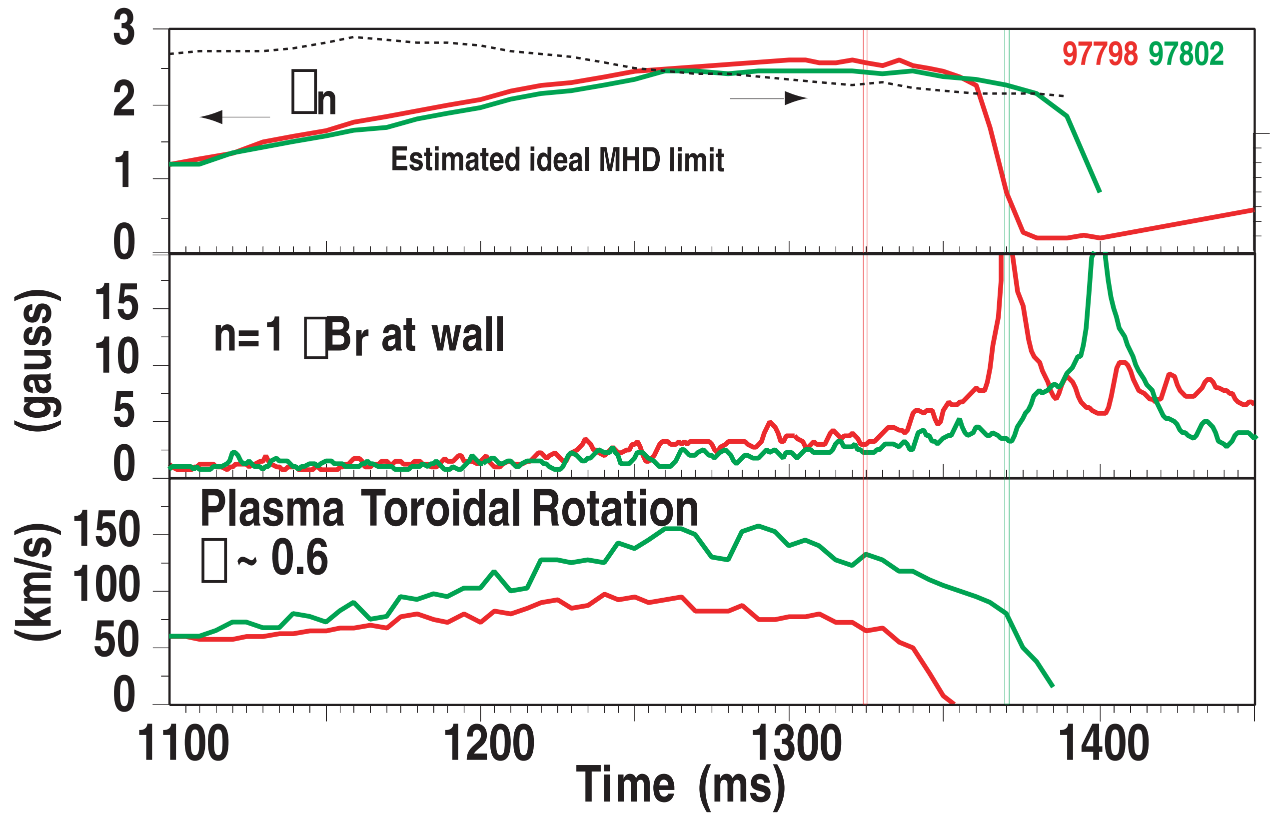
PLASMA ROTATION DELAYS RWM ONSET

A decrease in rotation with $\beta_n > \beta_n^{no\text{-}wall}$, leading to rapid RWM growth

Small amplitude RWM near threshold may cause rotational drag



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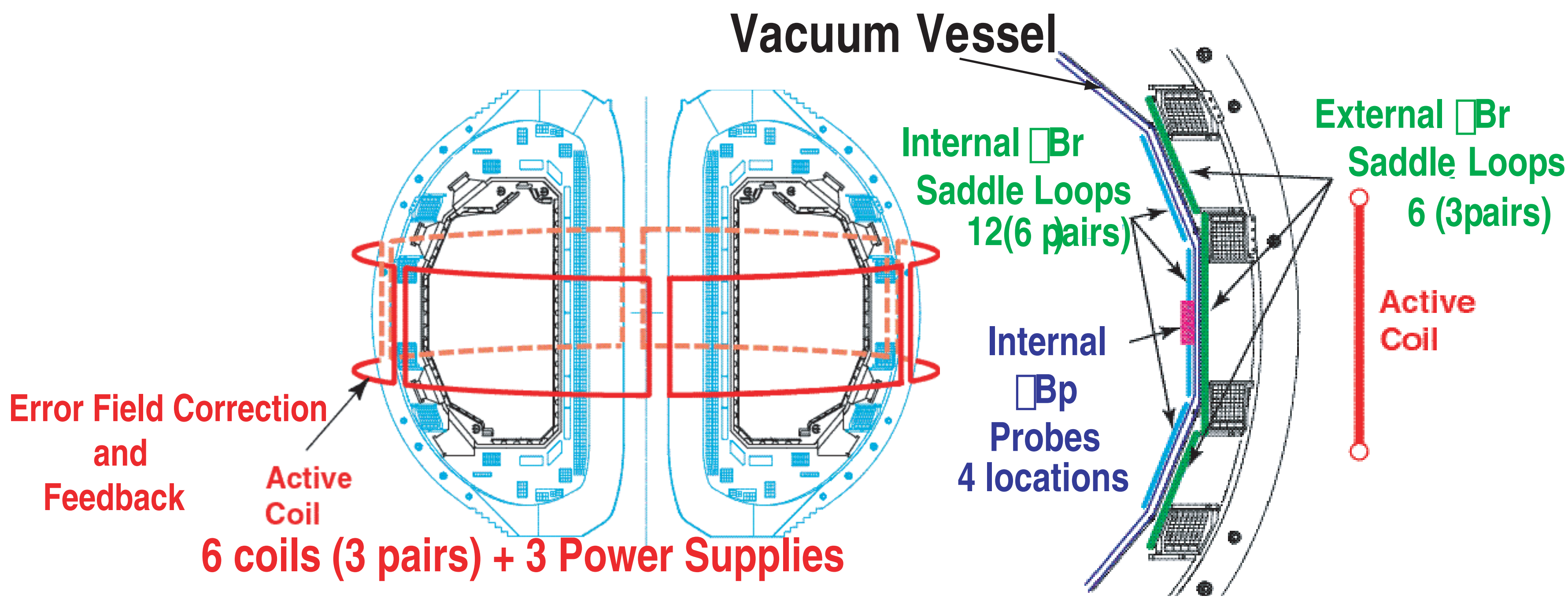
RWM MAGNETIC CONTROL HARDWARE ON DIII-D



Feedback Logic	control	sensors
Smart Shell (Virtual Ideal Shell)	Total leakage flux	□Br Saddle Loop
Mode control	Mode-only flux	□Bp Probe

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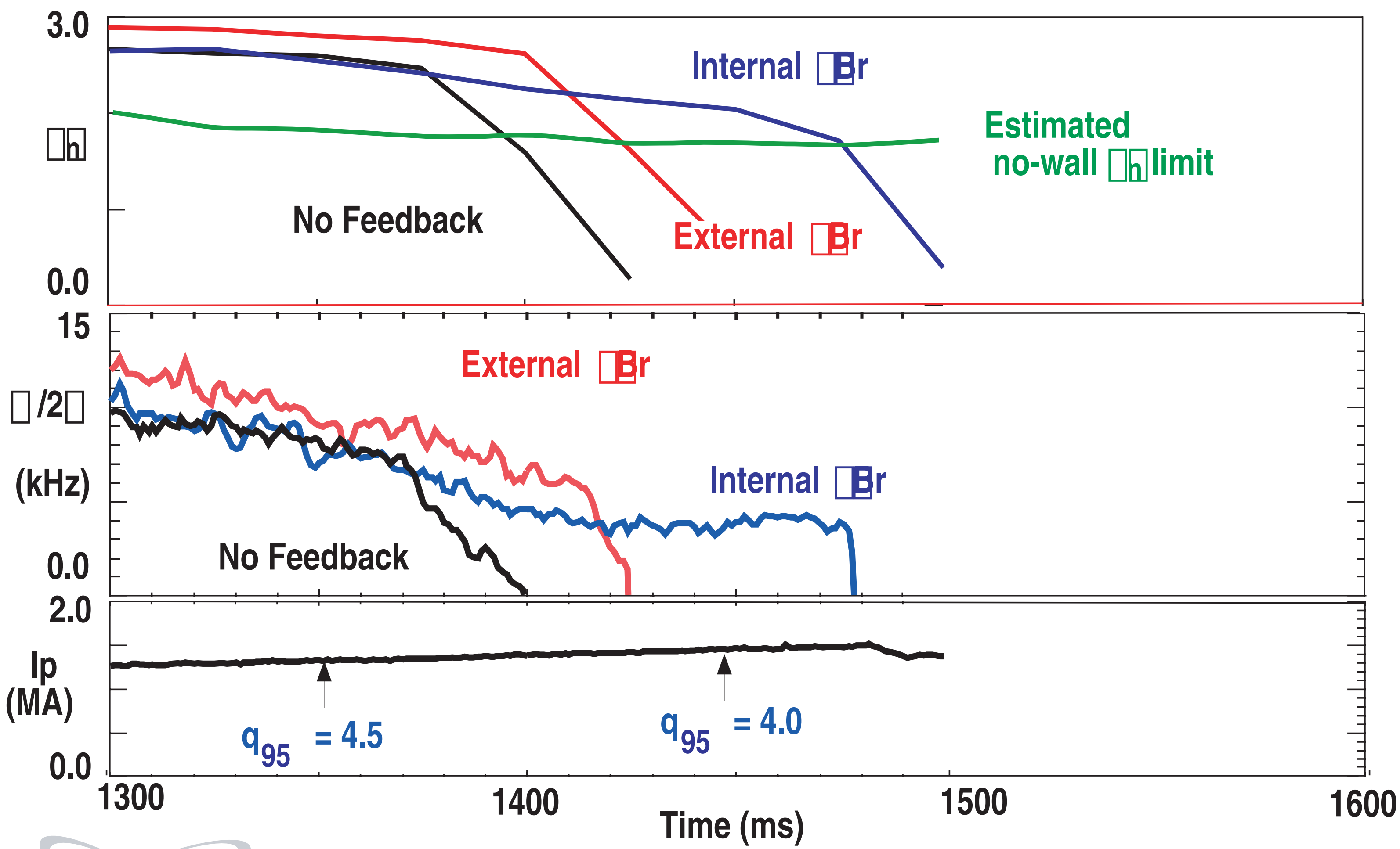
INTERNAL LOOPS ARE MORE EFFECTIVE THAN EXTERNAL LOOPS

- Comparison of □Br loops with smart shell logic
  - Experiment agrees with theoretical predictions
  - Ip ramp is used to maintain no-wall □N limit roughly constant in time



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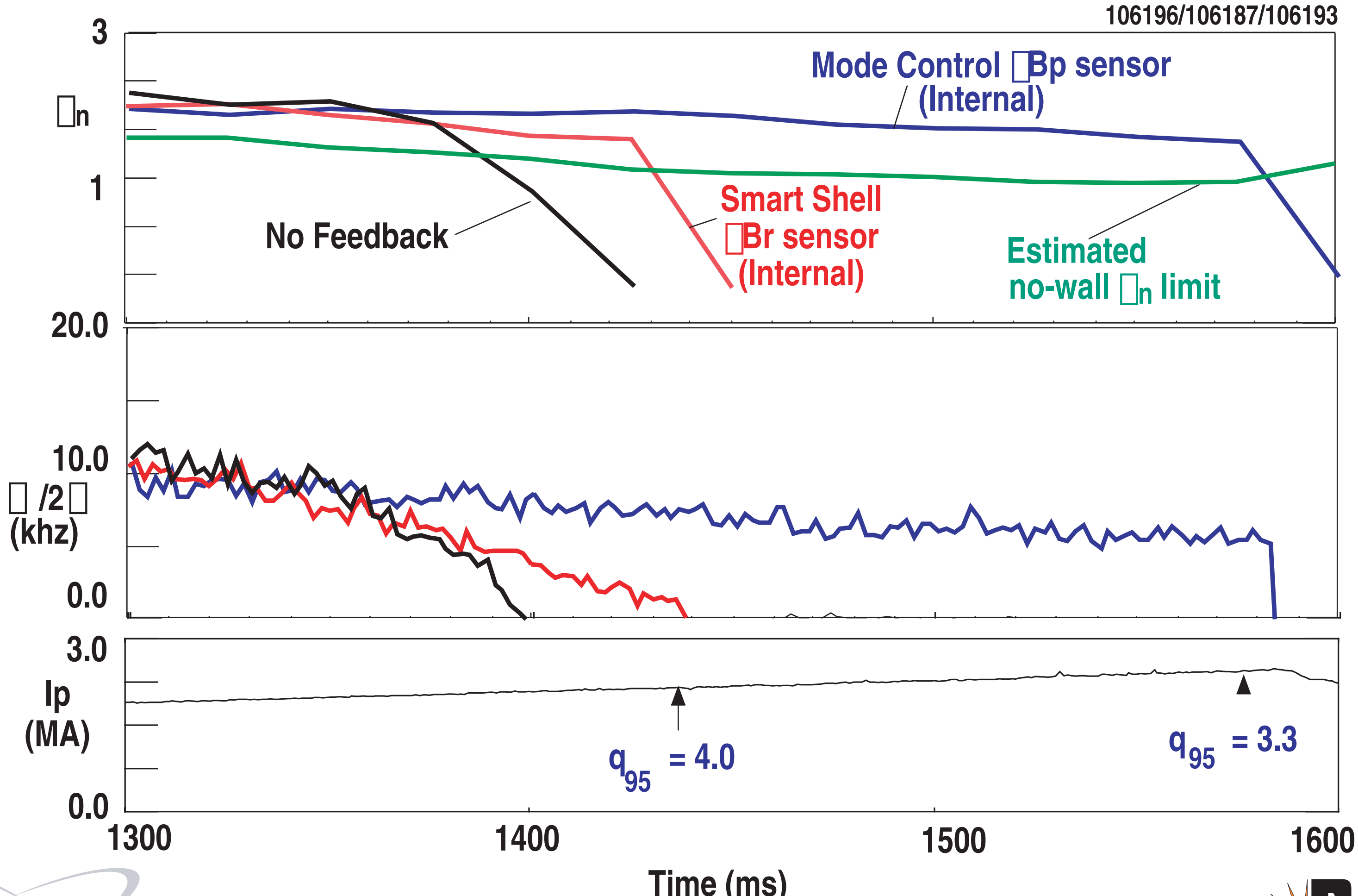
□Bp "MODE CONTROL" IS FAR SUPERIOR TO □Br "SMART SHELL LOGIC"

- **Plasma rotation was well maintained over a longer duration in spite of lowering edge-q**



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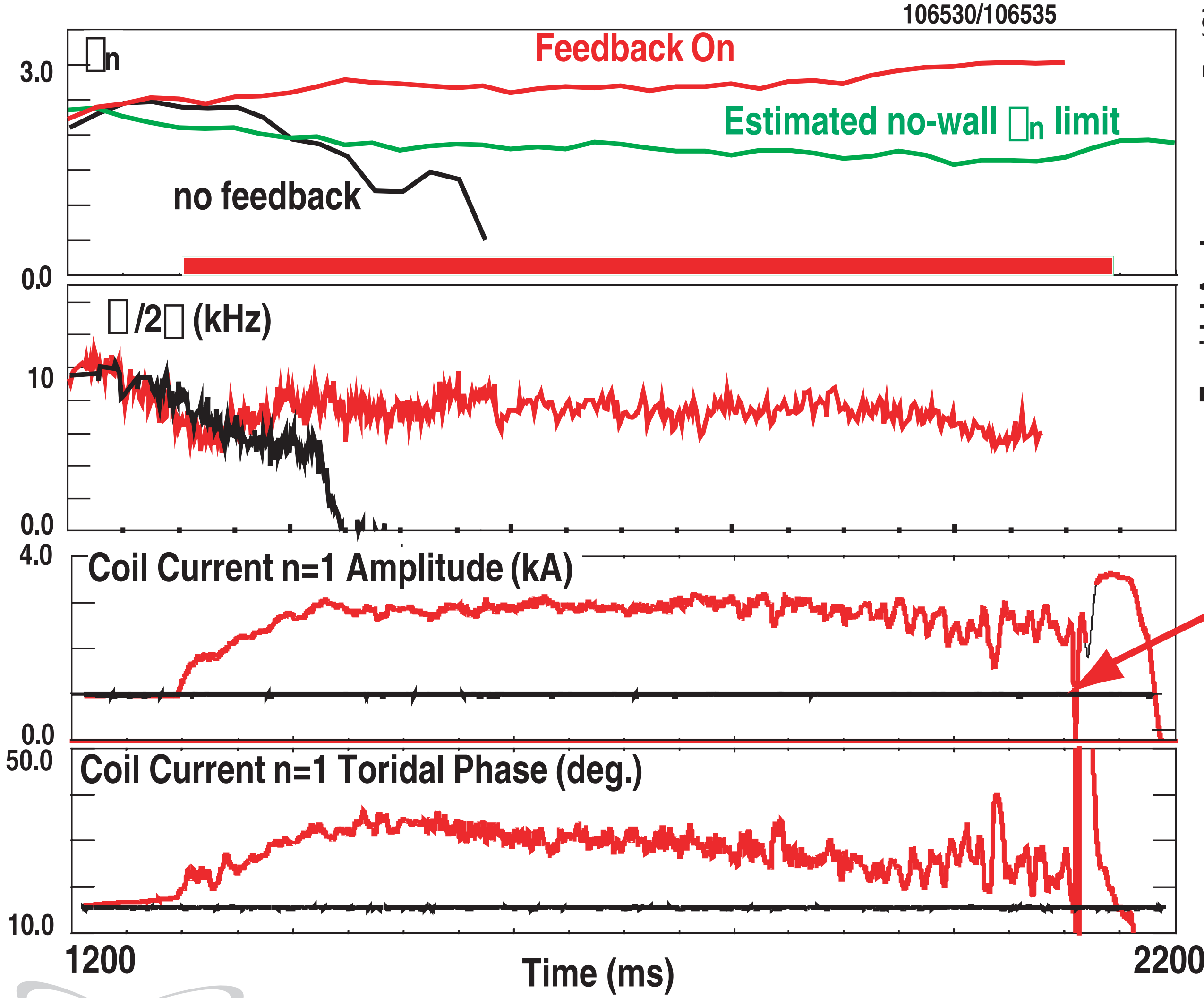
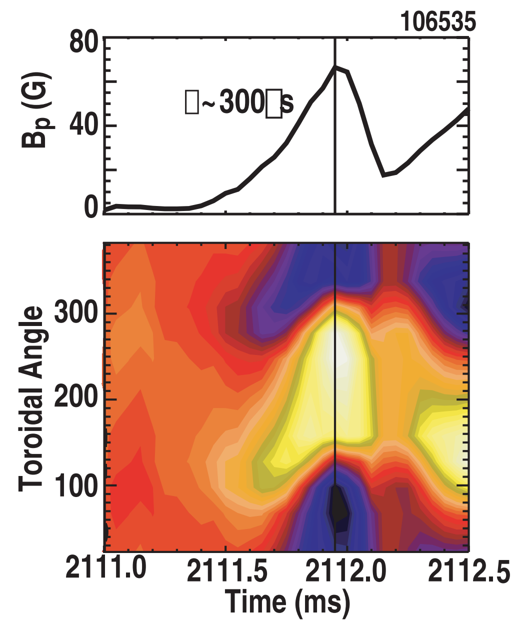
HIGH β_n DURATION WAS EXTENDED BY > 500 ms

β_n reached twice the $\beta_n^{no\text{-}wall}$, close to β_n ideal-wall (GATO-code)

MHD at collapse is ideal kink like behavior

(With δB_p sensor and modest Ip ramp operation)





Rotation Period ~1 ms <

- Ideal MHD Like Behavior

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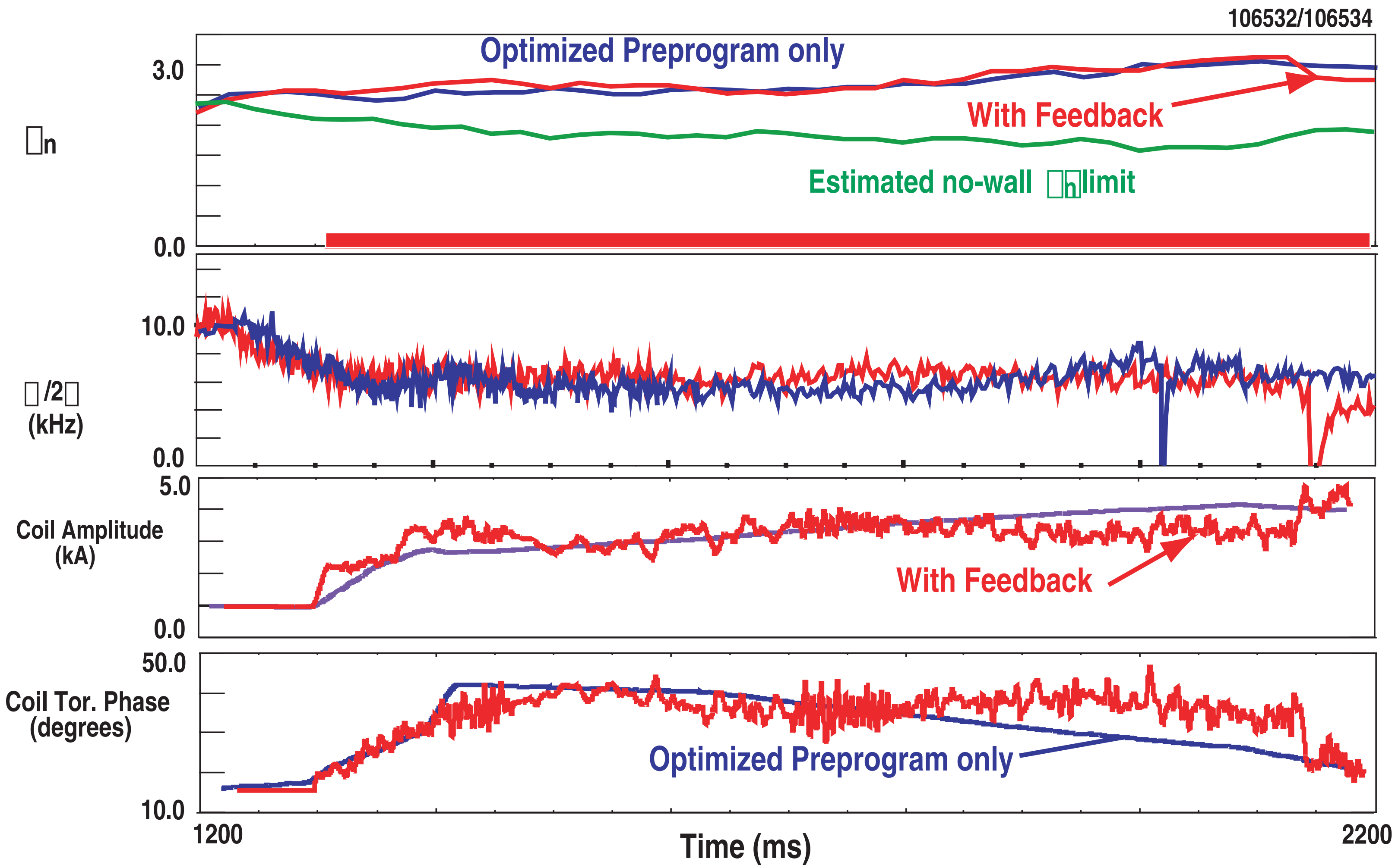
FEEDBACK COMPENSATES RESIDUAL ERROR FIELD

- Preprogramming coil currents without feedback, matched to currents with feedback, produce similar □n and rotation



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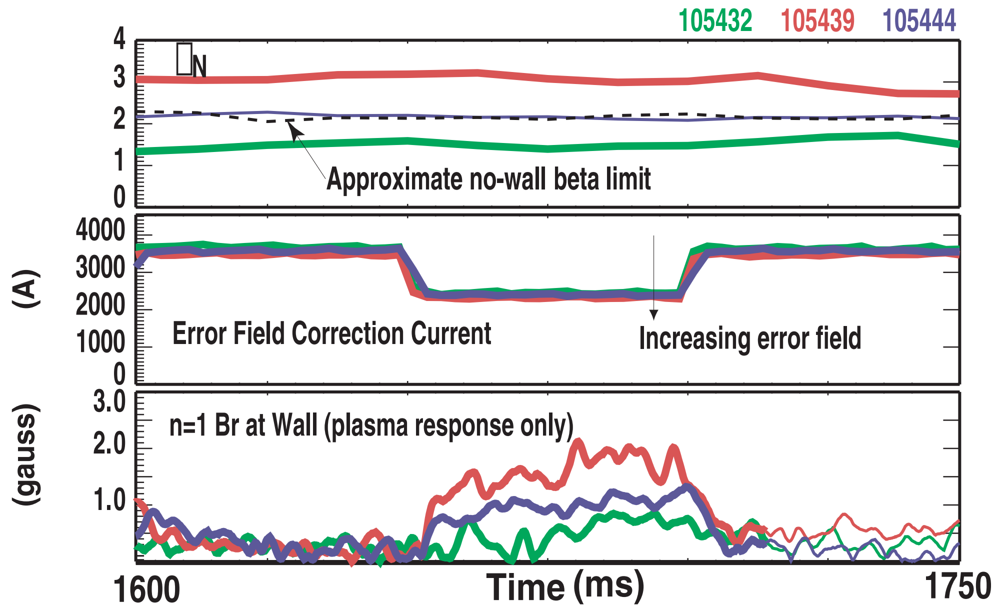
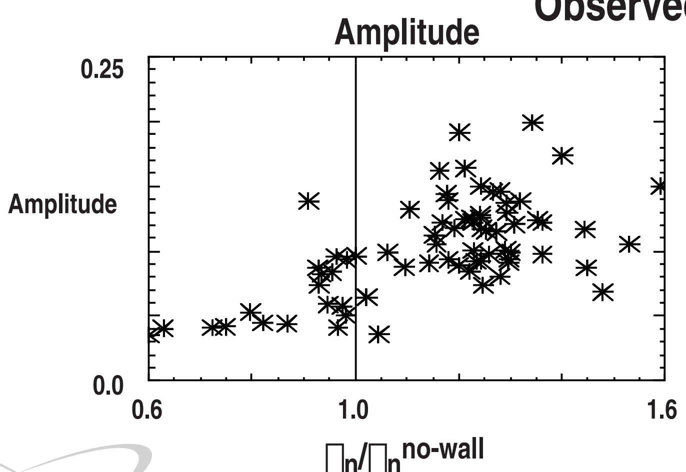
ERROR FIELD AMPLIFICATION (EFA) INCREASED AT $\beta_n > \beta_n^{\text{no-wall}}$

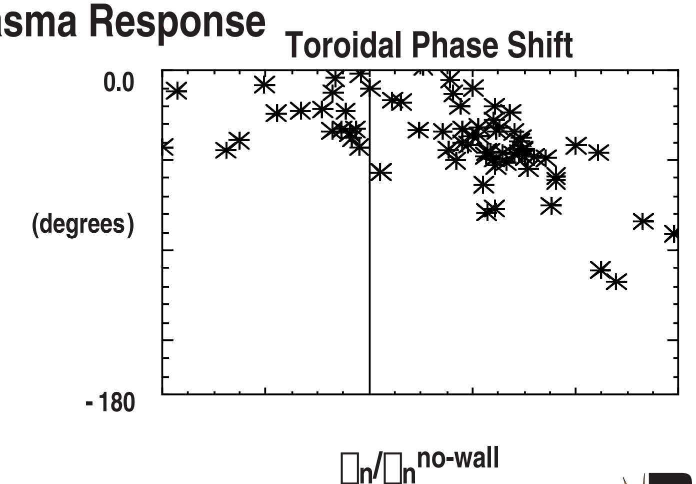
• Helical resonance to non axi-symmetric magnetic field



- First predicted by A. Boozer
Phy. Rev. Lett. 86, 1176 (2001)

Observed Plasma Response





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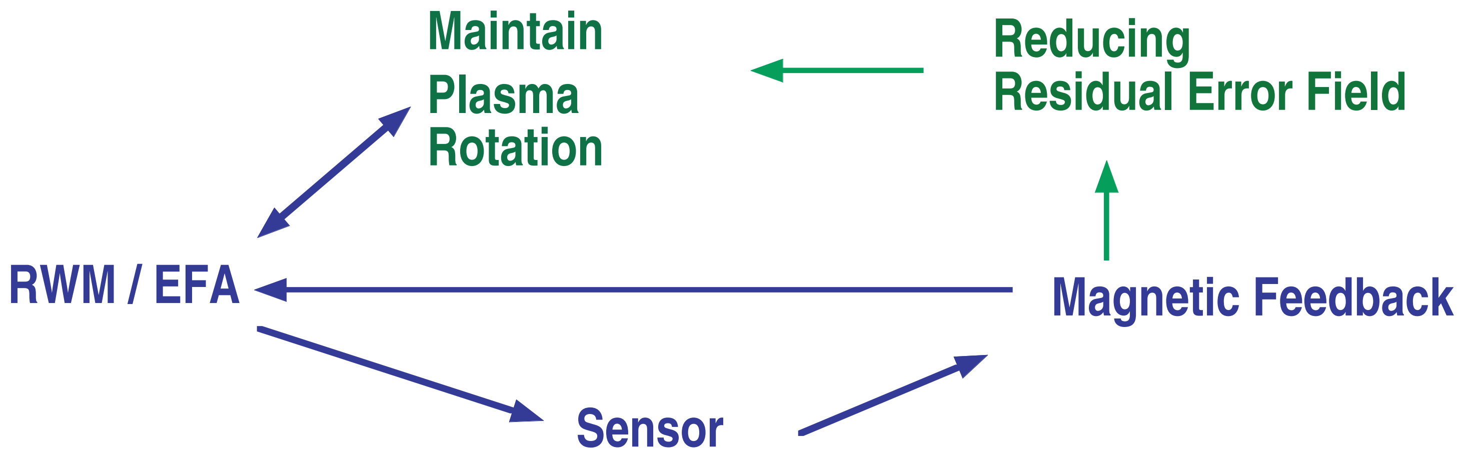
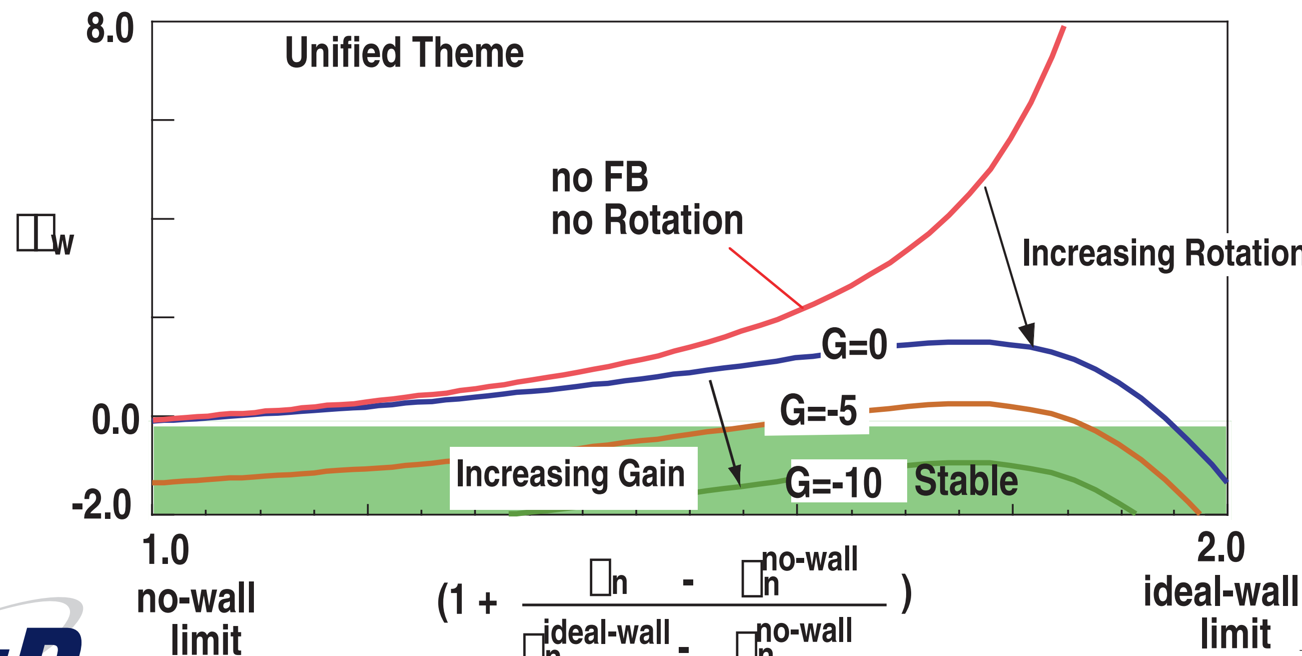
TWO PROCESSES: ROTATIONAL STABILIZATION AND MAGNETIC FEEDBACK HAVE BEEN UNIFIED IN A SYNERGISTIC MANNER, OPENING A PATH TO IDEAL-WALL β_n LIMIT





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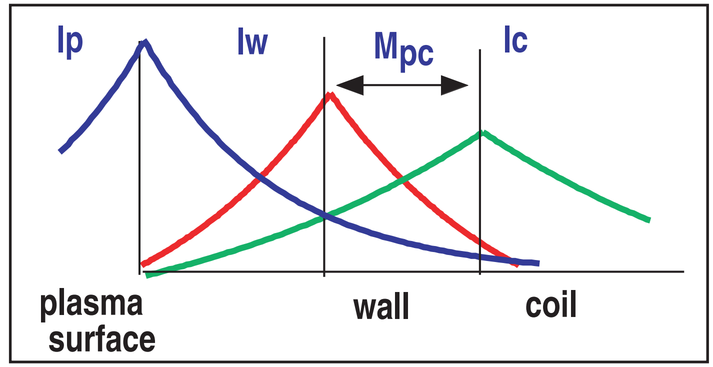
LUMPED PARAMETER FORMULATION

- Explicit Presentation of Boundary Condition



□W approach

Dissipation — Plasma — Resistive Wall

$\square(\square\square_w + i\square\,\square) + \square W_p \;+\; (\square W_v{}^b\,\square\square_w + \square W_v)/(\square\square_w + 1) = 0$

Lumped formulation

Ideal MHD

$[(\square o - 2/f) + \square\,(\partial/\partial t + (\square\,\square)\partial/\partial\square)]\;\square(a)$
$= (a/m)\, d\square/dr_{|r=a}$
$f = m - nq$

Plasma surface

$\square_j = M_{jk}\, I_k$

$M_{wp}\,\partial/\partial t(I_p) + L_w\,\partial/\partial t\,(I_w) +$
$M_{wc}\,\partial/\partial t\,(I_c) + R_w I_w = 0$

Wall surface

Slow time limit:

$L_{eff}\, I_p + M_{pw}\, I_w + M_{pc}\, I_c = 0$:

$$L_{eff} = \frac{(\square_h - 1 + i\square\square + \square\square^2)}{(\square_h + 1 + i\square\square + \square\square^2)}, \quad \square_h = 2/f - 1$$

EFA Amplitude $\quad 1/L_{eff}$

L_{eff} : equivalent to "magnetic decay index" of vertical instability (Ip <-> □Zp)

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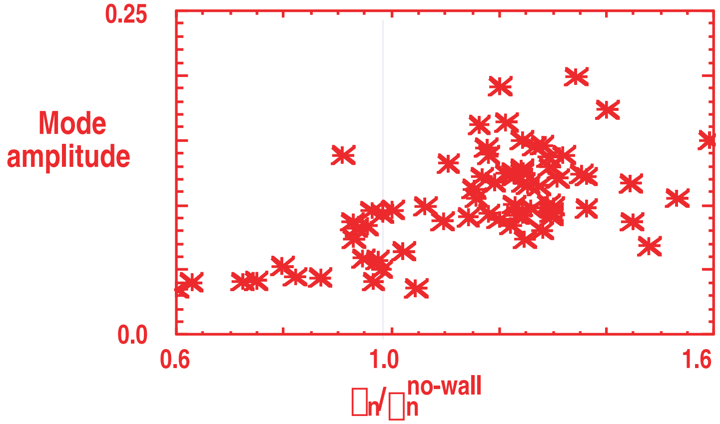
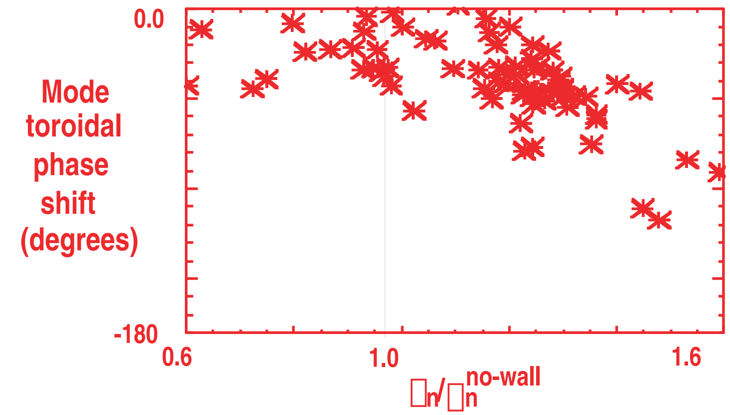
EFA RESPONSE TO PULSED FIELD IS QUALITATIVELY CONSISTENT WITH MODEL ESTIMATE

Observed Plasma Response to

Amplitude

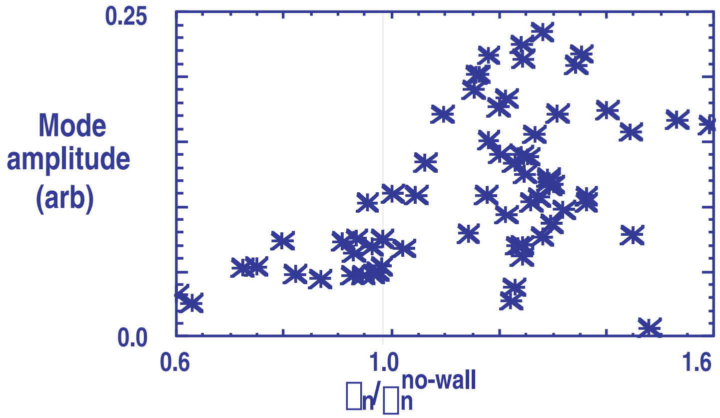


Toroidal phase

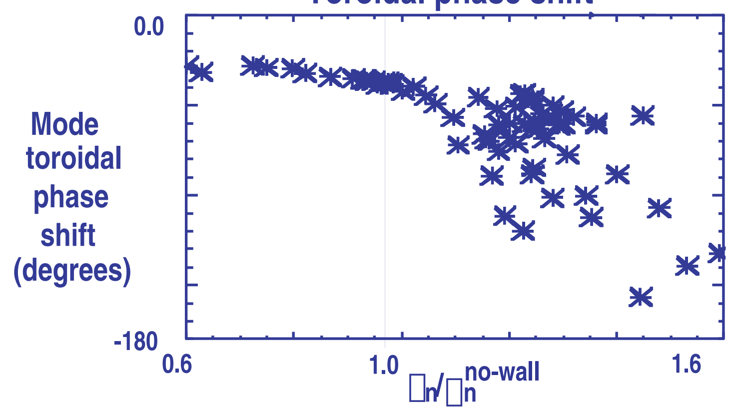


Estimate with Lumped Parameter Model

Amplitude



Toroidal phase shift



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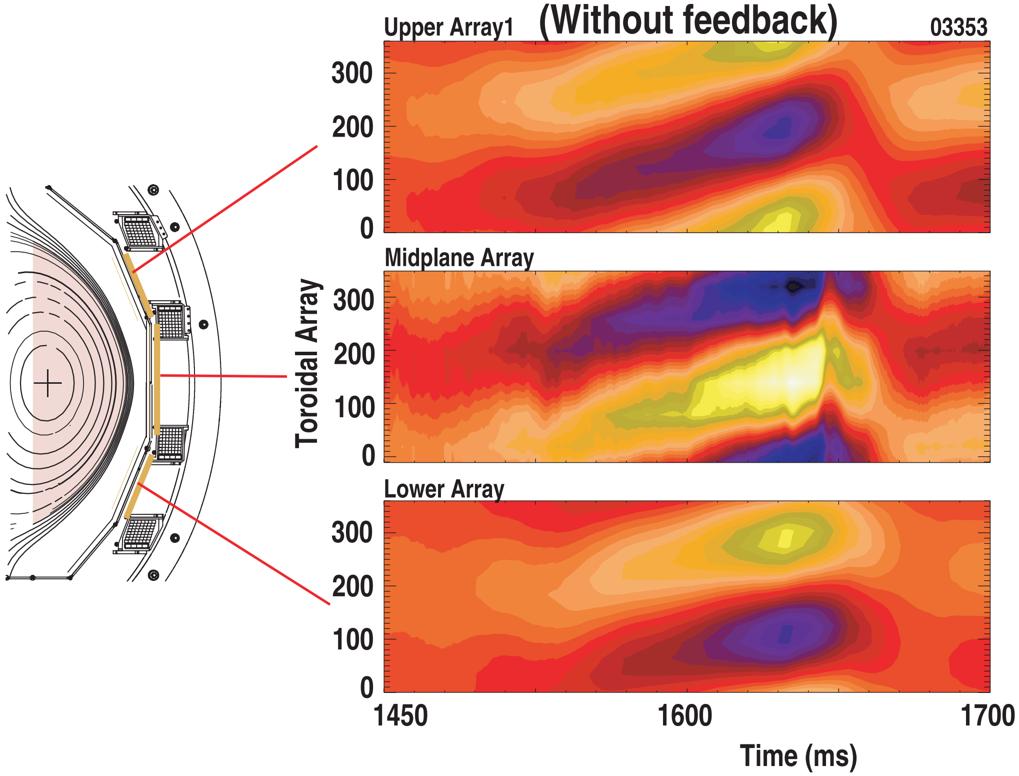
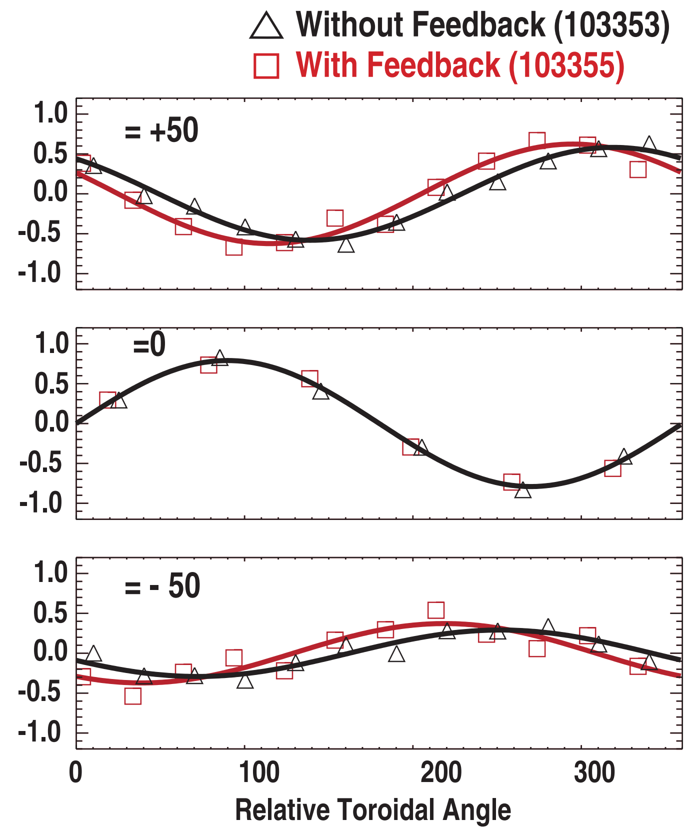
EXPERIMENTS SUPPORT "RIGID DISPLACEMENT" MODE STRUCTURE

- Simplify model development of RWM like Lumped parameter formulation and VALEN code

Three Toroidal Arrays of Saddle Loops Provide Poloidal Mode Structure



Mode Structure Relative to Midplane



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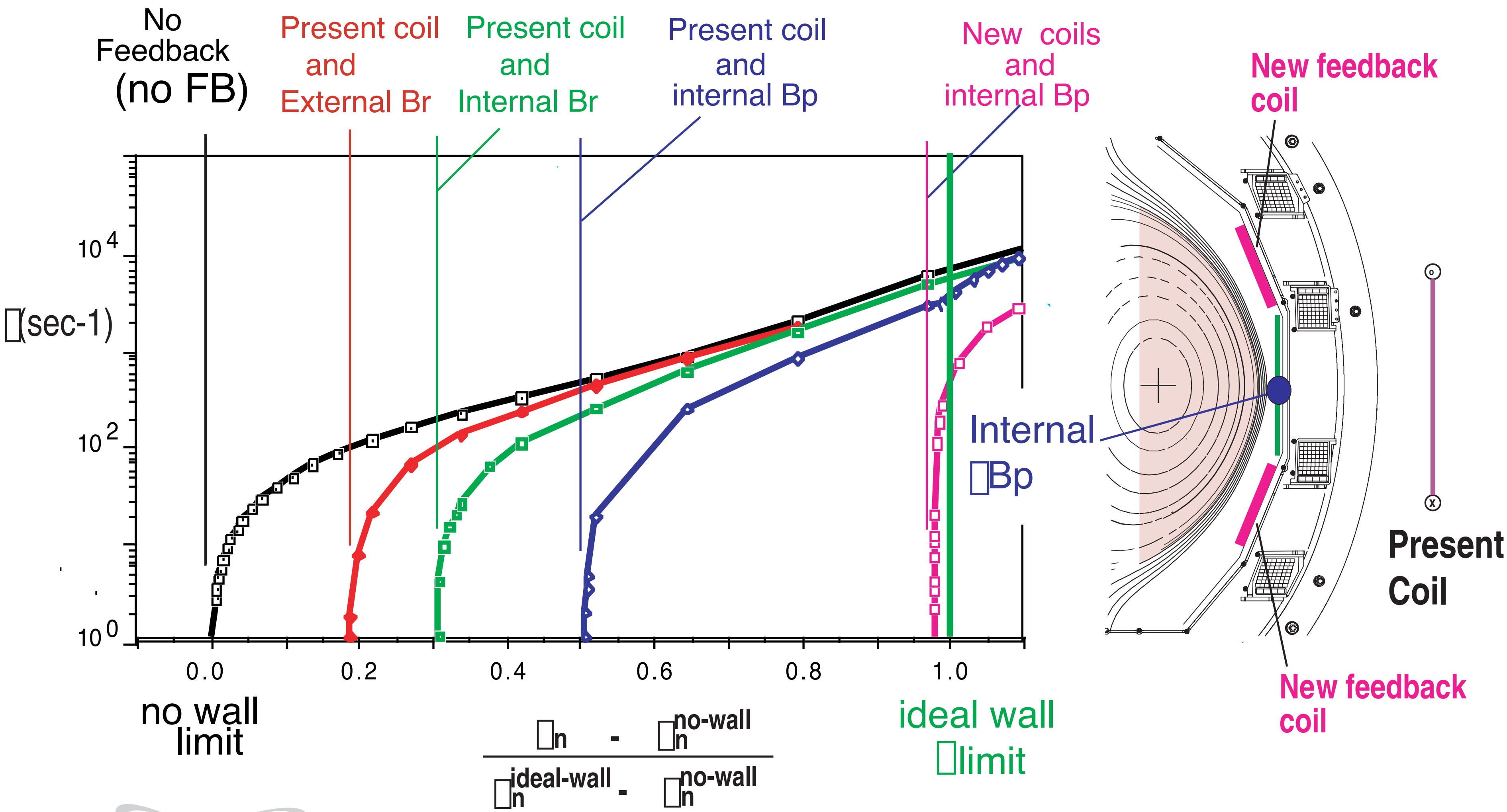
PROPOSED IMPROVEMENT OF RWM FEEDBACK ON DIII-D

Additional six upper- and six lower- coils and internal Bp sensors increase achievable very close to ideal-wall limit (VALEN CODE / no rotation)



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SUMMARY

RWM control

- Two schemes, rotational stabilization and magnetic feedback, previously considered distinct, now function as a unified process in a synergistic manner
- Feedback process tracks and compensates the residual error field, maintains the rotation, and achieves high β_n
- A key to this success is the use of Bp sensors inside the vessel and mode control logic
- High β_n condition is also achievable with optimized error field correction without feedback

High β_n achievement

- Achievement of twice the no-wall β_n limit close to ideal-wall β_n limit consistent with experimental MHD observation

Understanding of RWM physics

- Greatly improved by the discovery of Error Field Amplification

Future plans

- New coils will be installed for achieving high β_n over wide parameter ranges

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