Active Feedback Stabilization of the Resistive Wall Mode on the DIII–D Device

by

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PPPL PRINCETON PLASMA PHYSICS LABORATORY

INTRODUCTION

- From the beginning of fusion research, ideal MHD modes have been considered as a dangerous mode preventing us for achieving high performance plasmas
- Ideal kink plays a significant role on the operational limit in tokamak, RFP, Sphromak and FRC
- In tokamak, a perfectly conducting wall allows high beta operation, $\beta_N = \beta/I/aB \approx 5$–6, favorable for the steady state advanced tokamak
- Finite resistivity of the actual wall converts the ideal kink mode into a branch of resistive wall mode (RWM) and the mode can be unstable
- The RWM has been observed in DIII–D (M. Wade CI2.001), PBX-M and HBT-EP
- Proof of principle experiment of magnetic feedback stabilization of RWM has been carried out to demonstrate the ability of RWM control

OUTLINE

1. Resistive Wall Mode (RWM)
   — Mode characteristics
2. Stabilization approach
   — Plasma rotation and feedback stabilization
3. Experimental results of RWM feedback experiment
   — RWM successfully suppressed,
   — Duration of $\beta > \beta_{wall}^{no}$ extended over 50 times τ_w
   — Lumped parameter formulation is successful for feedback analysis
   — Mode rigidity was observed
4. Full MHD code includes the field from the feedback field
   — Mode structure is consistent with experiment
5. Future plan
   — New poloidal B_p sensors
   — Additional off midplane coil options (VALEN J. Bialek GI1.004)
6. Summary

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Details:
ORAL session M01 Wed. Morning
Poster session NP1 Wed. Afternoon

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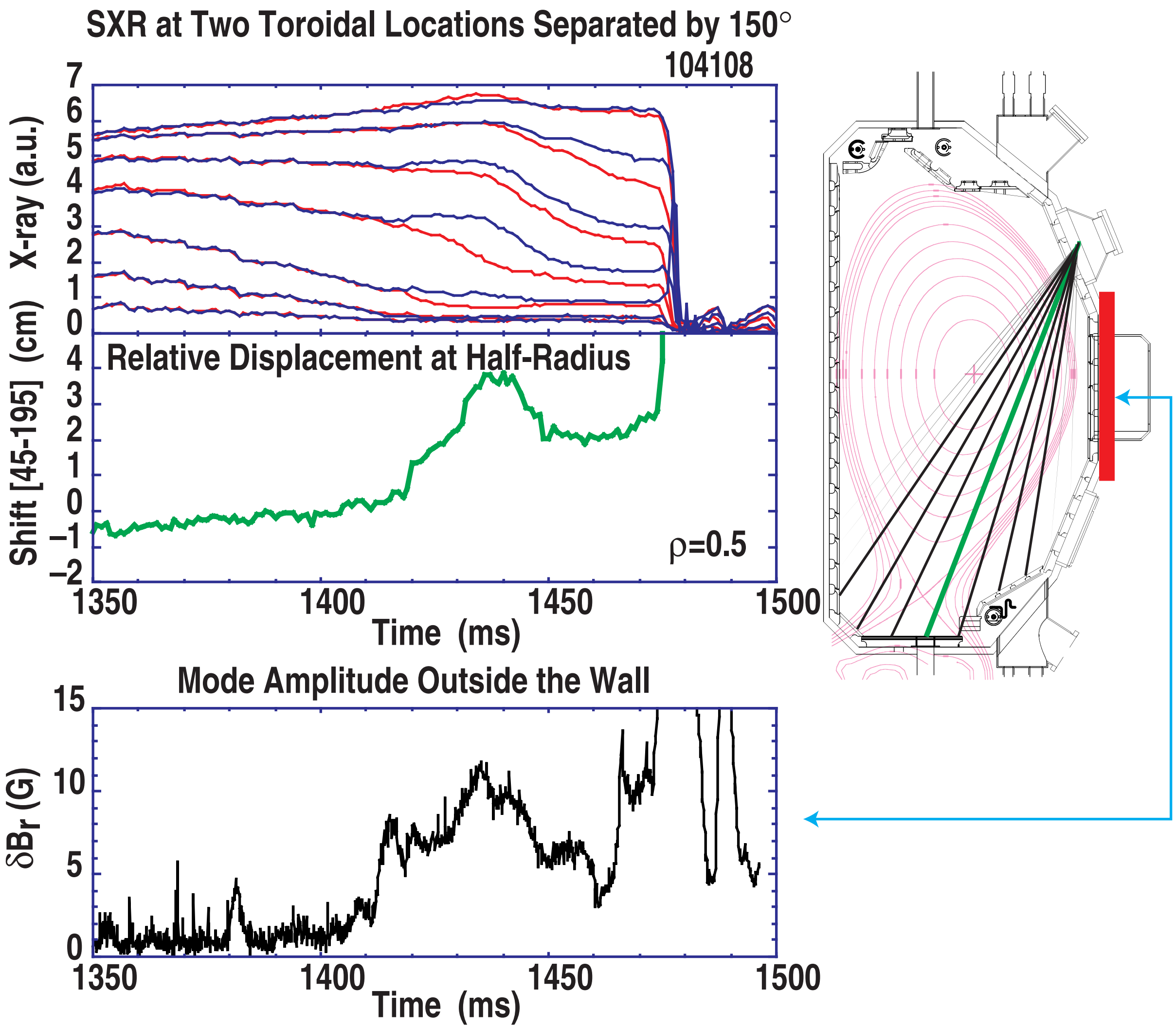
RWM IS A GLOBAL KINK WHERE THE MODE STRUCTURE EXTENDS FROM PLASMA CORE TO OUTSIDE VACUUM VESSEL



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Poster NP1.083
L.C. Johnson et al.,

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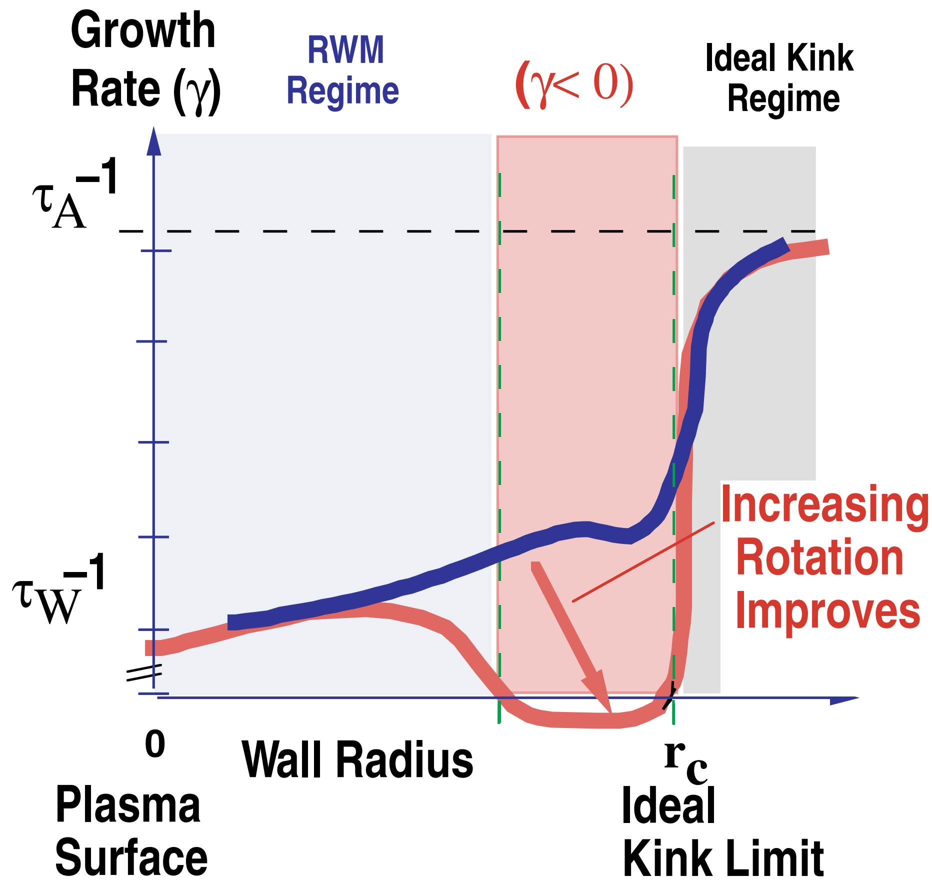
TWO STABILIZATION APPROACHES HAVE BEEN EXPLORED ON DIII–D

- **Rotation Stabilization**
  - Stable window exists when $\Omega >> \Omega_c$
  - $\Omega_c \approx$ a few percent of Alfvén transit frequency
- **Magnetic Feedback Stabilization**
  - Slow growth time makes feedback practical



• Originally proposed by Bondeson and D. Ward 1994

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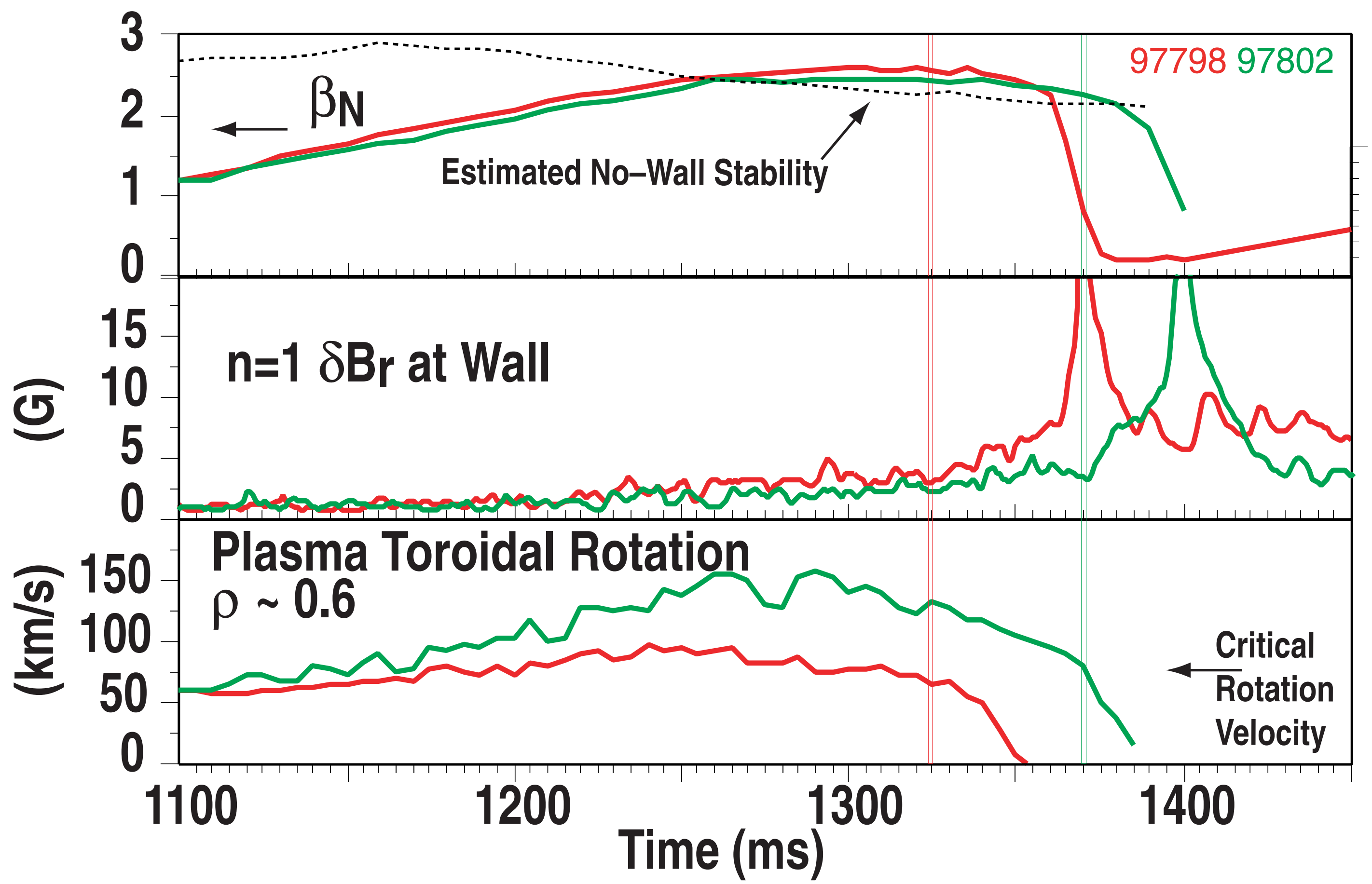
INCREASING PLASMA ROTATION DELAYS RWM ONSET

- Momentum input varied by changing beam energy at constant power



- Feedback control may be needed for complete stabilization

MO1.003 E.J. Strait
MO1.004 A.M. Garofalo
NP 1.084 G.A. Navratil
NP 1.086 J.T. Scoville

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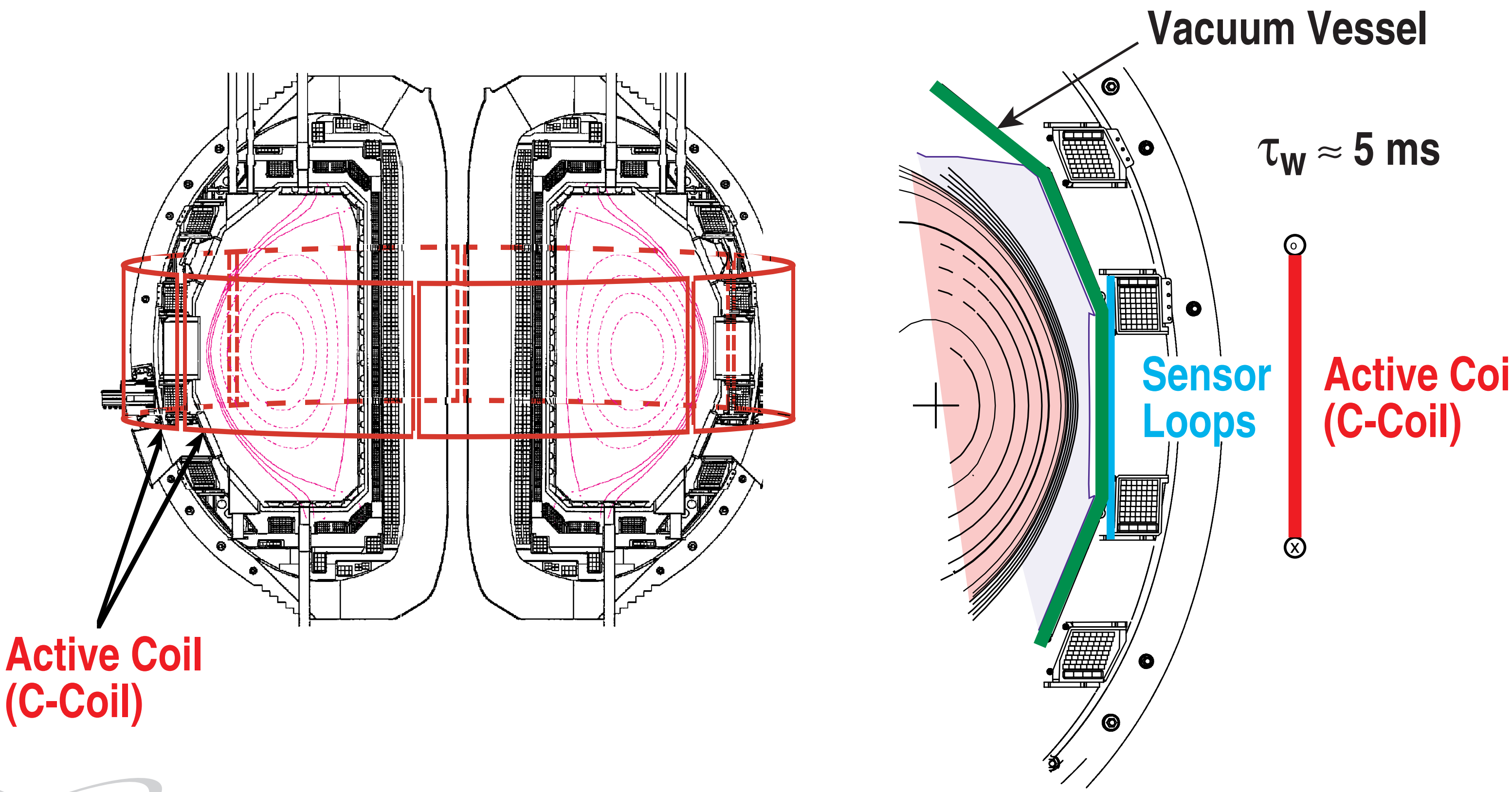
RWM FEEDBACK EXPERIMENT ON DIII–D

- Six midplane coils (C-Coil)
- Six Sensors

} Connected in anti-parallel for n=1 control

- Three Power supplies
  - dc - 100 Hz, 5 kA
  - Shared with error field correction



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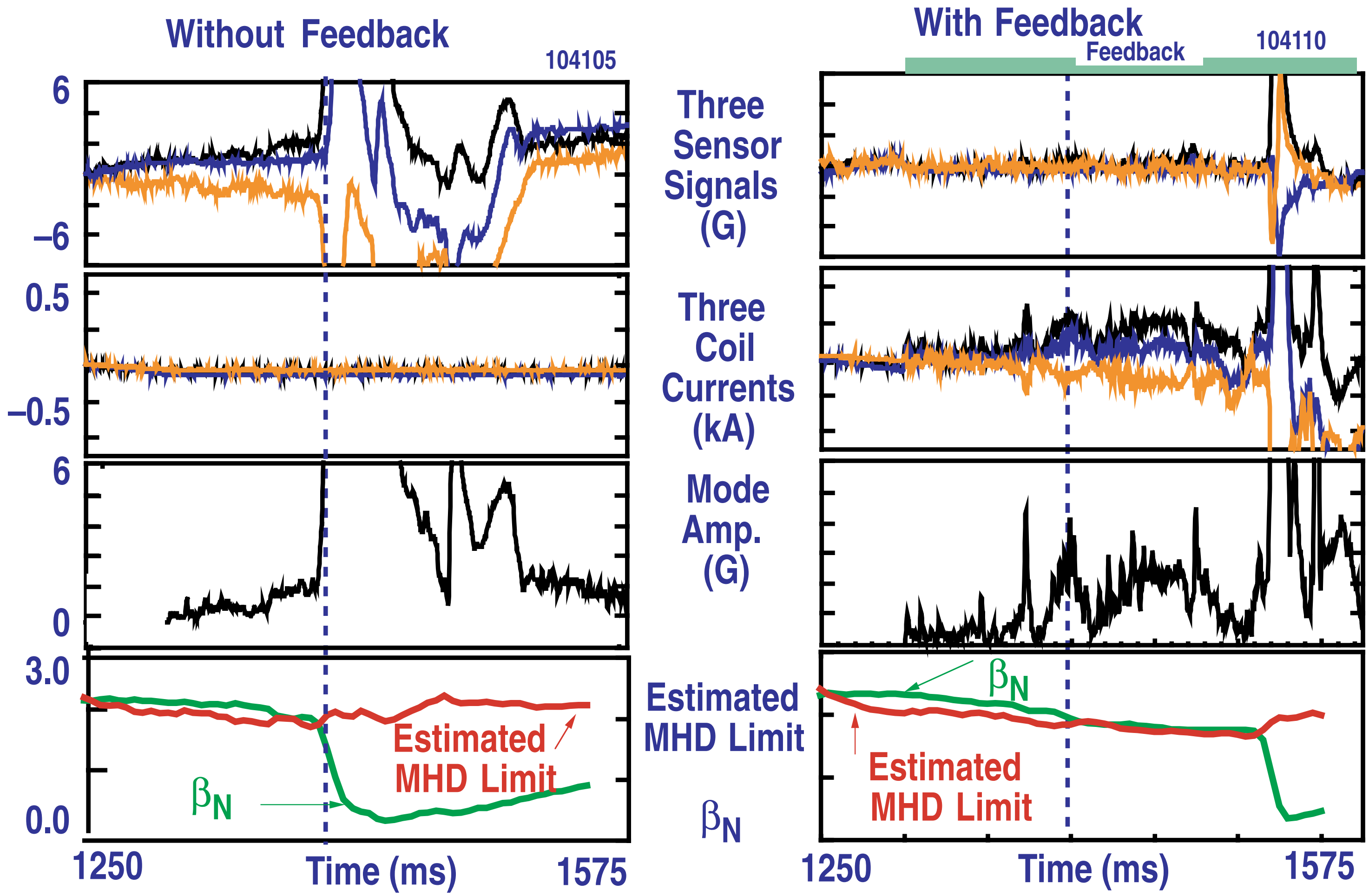
FEEDBACK CONTROL LIMITS RWM GROWTH AND EXTENDS THE DISCHARGE DURATION



- These discharges were prepared with I_p ramp for low ℓ_i

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MO1.004 A.M. Garofalo

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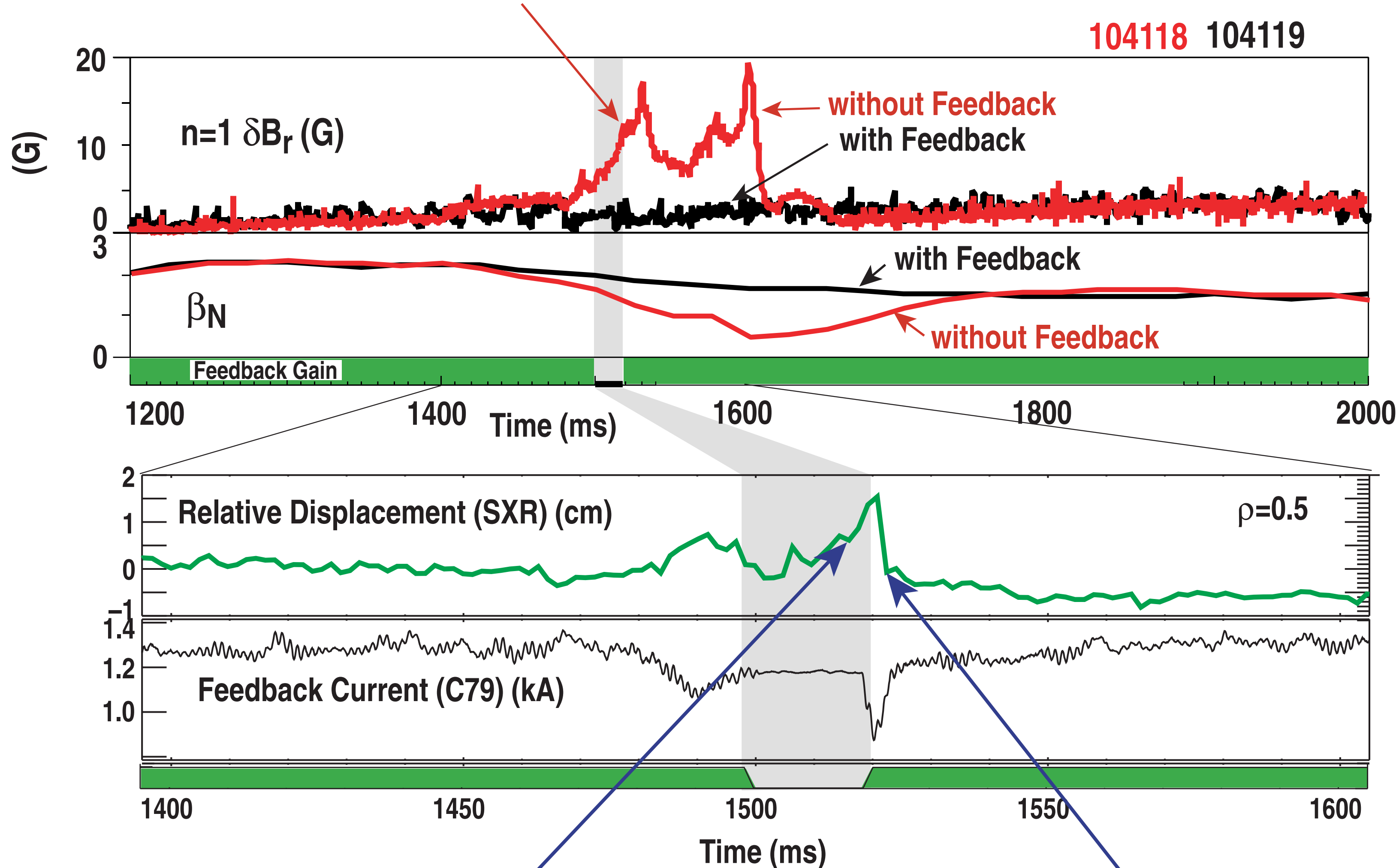
GATING FEEDBACK OFF DEMONSTRATES STABILIZATION

- Large instability in comparison case without feedback



- Rapid RWM growth when feedback is switched off
- Prompt suppression of RWM when feedback resumes

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Np1.083 L.Johnson et al.,

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THEORY AND MODELING PROVIDE THE FOUNDATION FOR DESIGN OF RWM FEEDBACK EXPERIMENTS

- Analytic formulation: resistive flux loss compensation
  - Applicable even to reactors

    C. Bishop 1989
    R. Fitzpatrick 1996, and T. Jensen 1998

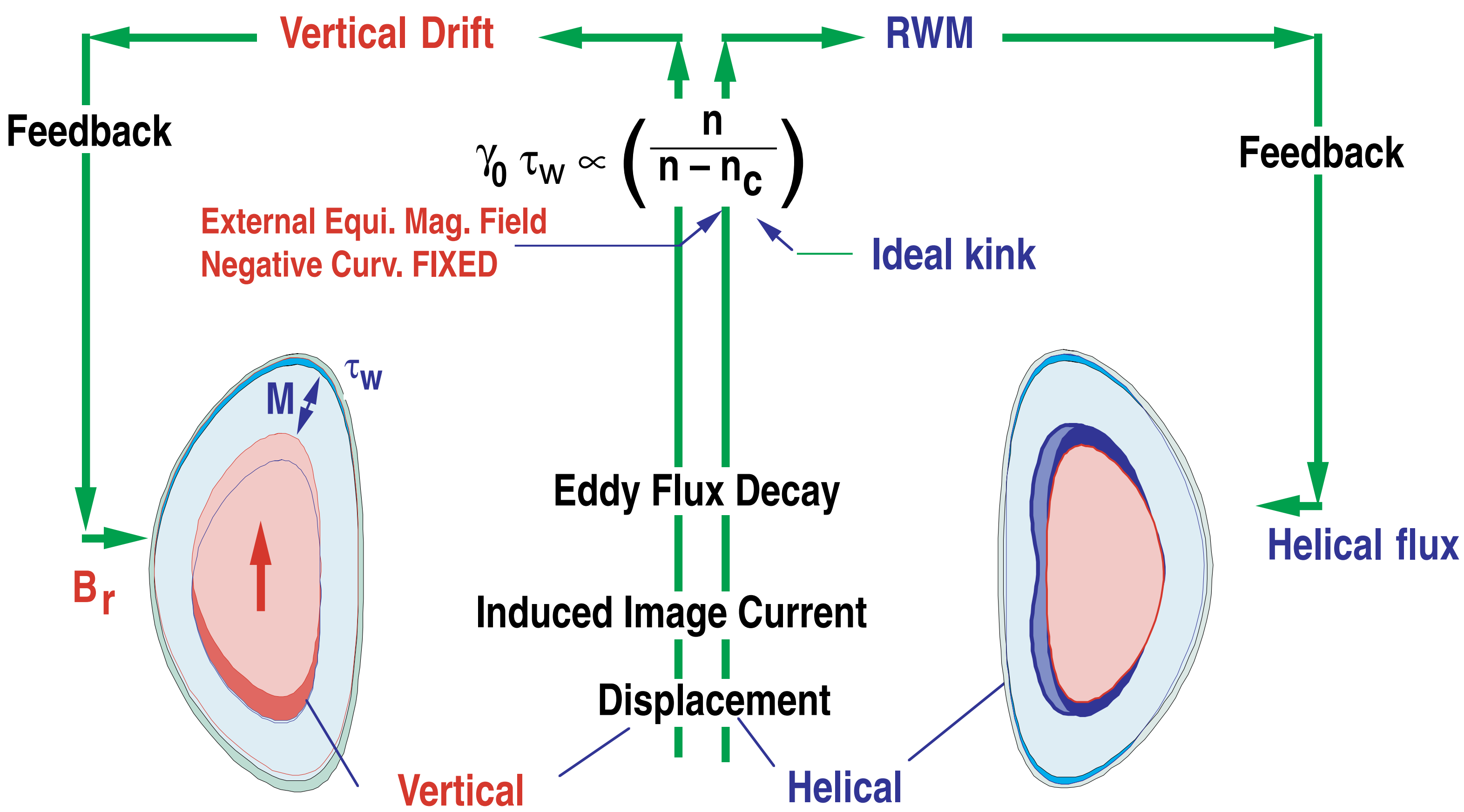
- 1–D models
  - Lumped parameter circuit modeling
  - Instructive, however, qualitative

    A. Boozer 1998
    M. Okabayashi, N. Pomphrey and R. Hatcher 1998
    T. Jensen and A. Garofalo 1999

- Full MHD models
  - With finite wall resistivity
  - Ideal MHD mode interacting with the actual resistive wall

A. Bondeson and Y. Liu 2000	MARS code
J. Bialek and A. Boozer (1998, GI1.004)	VALEN code
M. Chance and M. Chu (MP1.085)	GATO + VACUUM

RWM FEEDBACK CONTROL IS THE n=1 HELICAL ANALOG TO THE n=0 VERTICAL POSITION CONTROL



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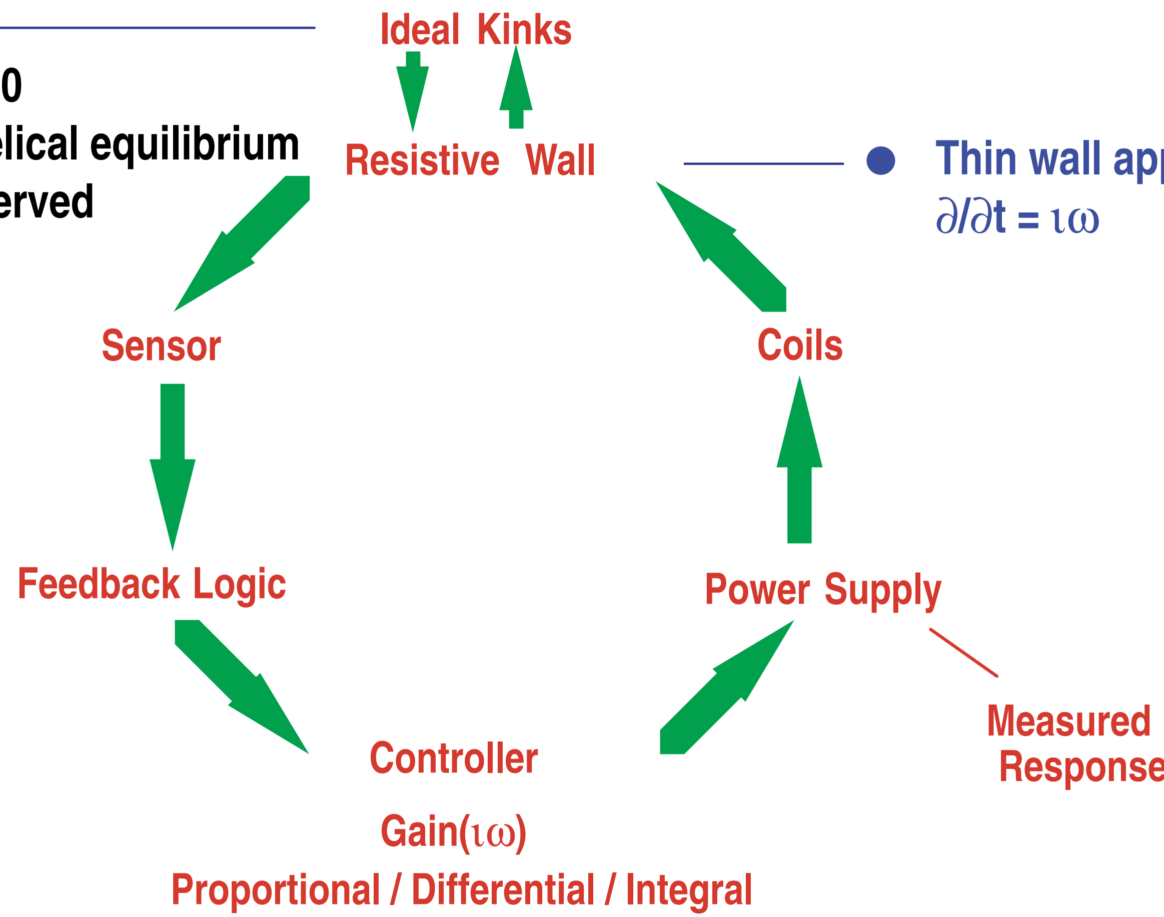
LUMPED PARAMETER FORMULATION PROVIDES SIMPLE MODEL FOR THE RWM FEEDBACK PROCESS

- Helical skin current
  - $\tau_w >> \tau_{alf}$, $\partial/\partial t = 0$
  - Instantaneous helical equilibrium
  - Helical flux conserved

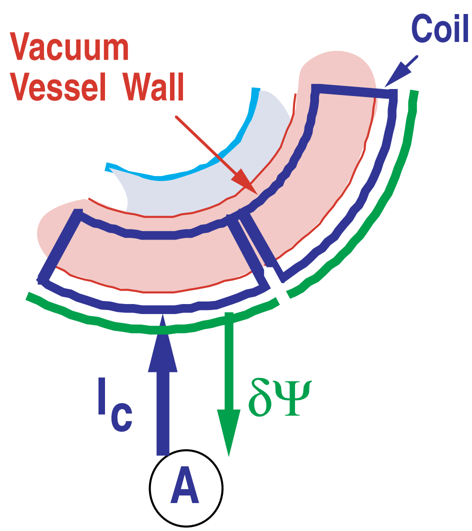
- Thin wall approx.
  $\partial/\partial t = \iota\omega$



- Lumped parameter model used on DIII–D analysis
  - Jensen/Garofalo model 1998, 1999
  - Skin-current-model Okabayashi/Pomphrey/Hatcher 1998

FEEDBACK LOGIC FOR RWM FEEDBACK STABILIZATION

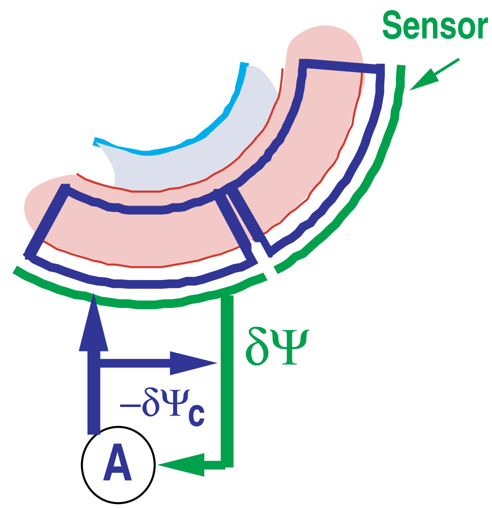
Smart Shell



$A = G\ \delta\Psi$

Feedback knows
the total flux at sensor

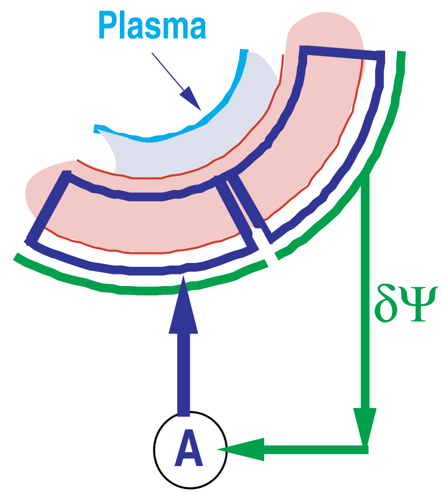
Explicit Mode Control



$A = G\,(\delta\Psi - M\,I_c)$

Feedback knows
the flux from MHD mode

Fake Rotating Shell
(R. Fitzpatrick and T. Jensen)



$A = G\ \delta\Psi$

Toroidal phase shift is
added to simulate the
toroidal wall rotation

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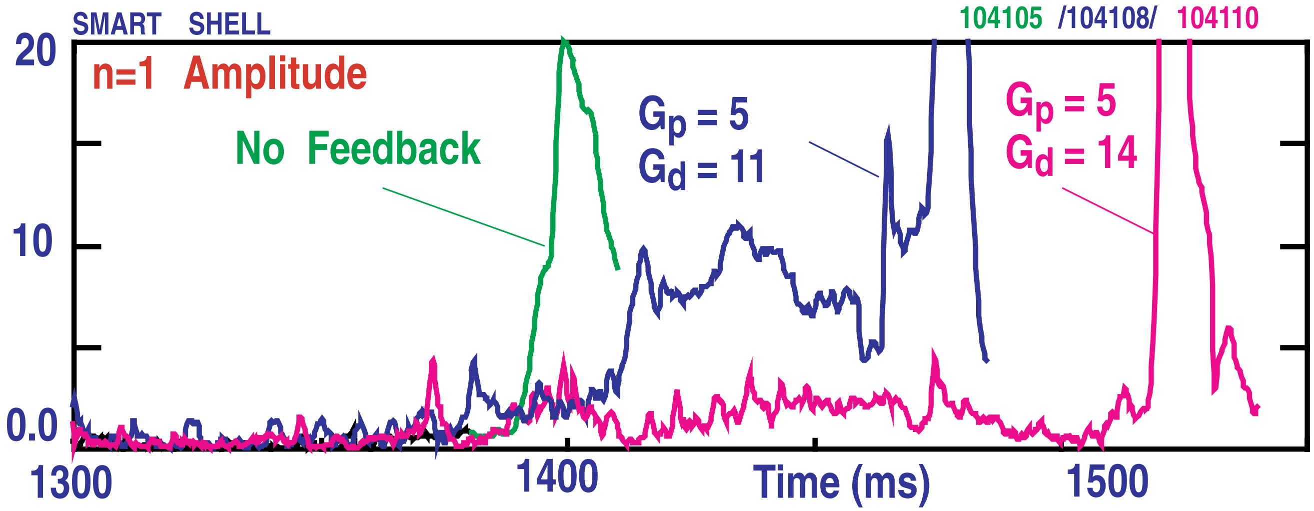
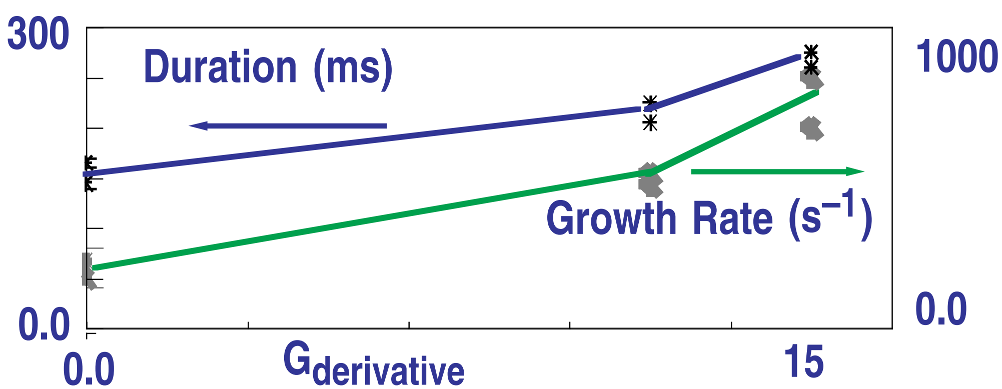
DERIVATIVE GAIN [Gd(dψ_{obs}/dt)] IMPROVES FEEDBACK PERFORMANCE

- Smart shell with proportional and derivative gain
- Duration above no-wall beta limit is extended
- Growth rate at the limit of stabilization increases





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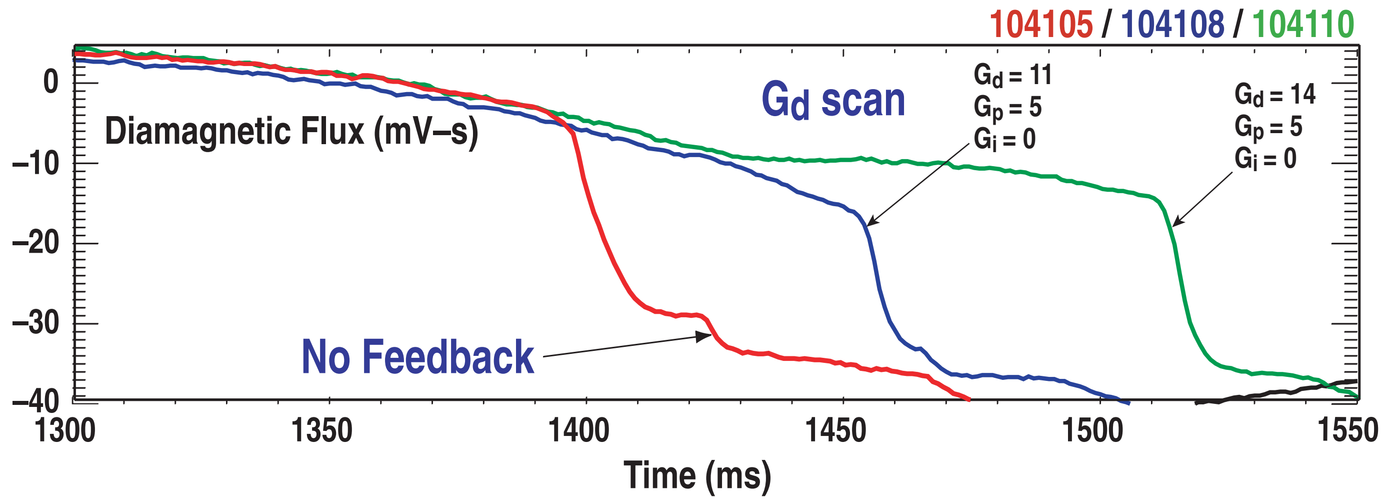
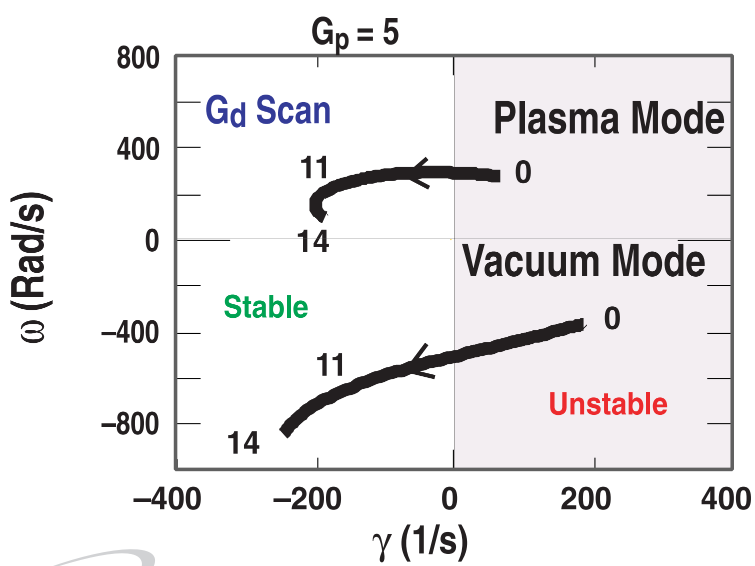
LUMPED PARAMETER MODEL PREDICTS THE DEPENDENCE ON GAIN



- Derivative gain is stabilizing



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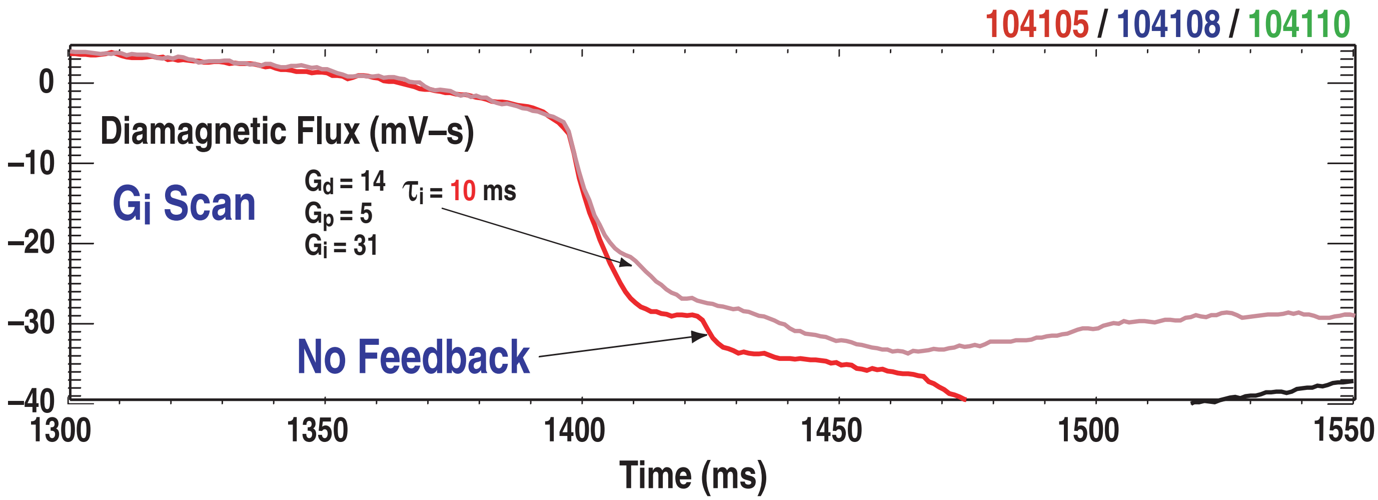
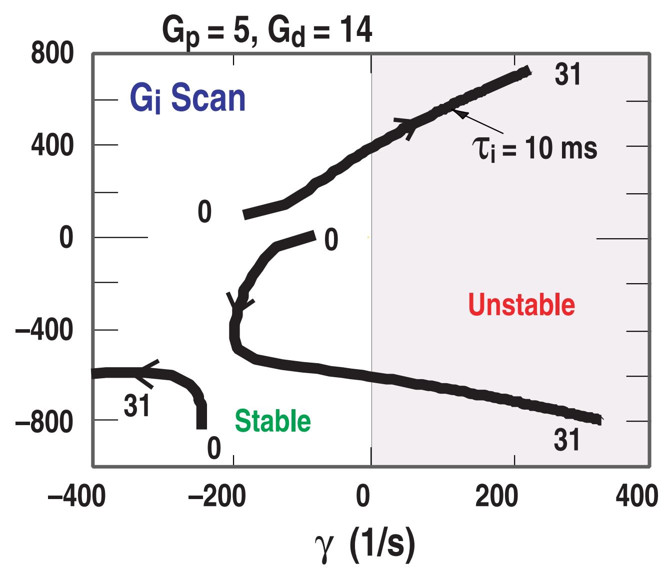


- The integral gain is destabilizing



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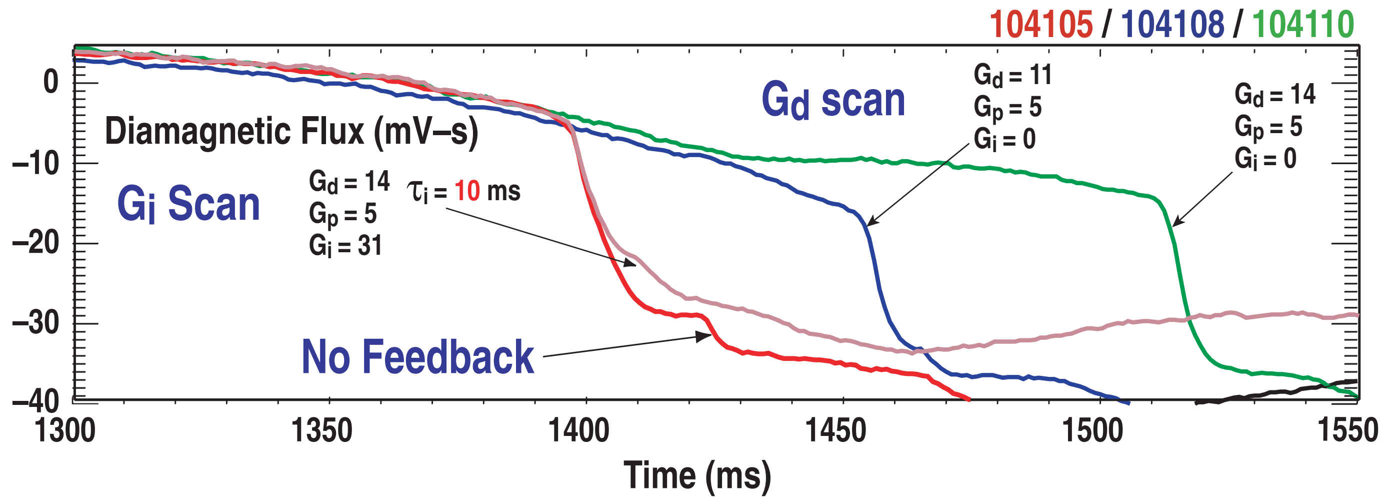
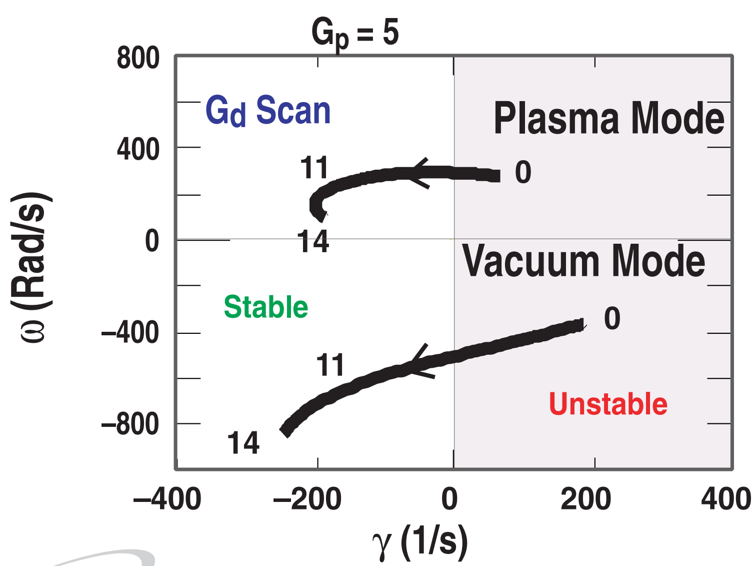
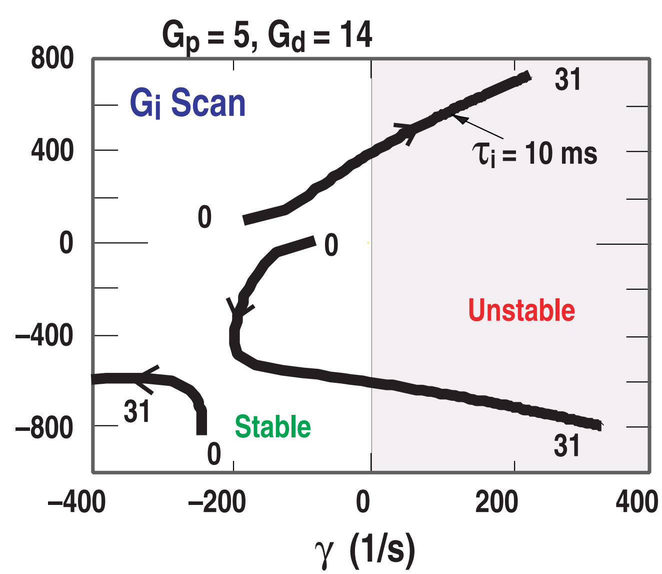


- Derivative gain is stabilizing
- The integral gain is destabilizing





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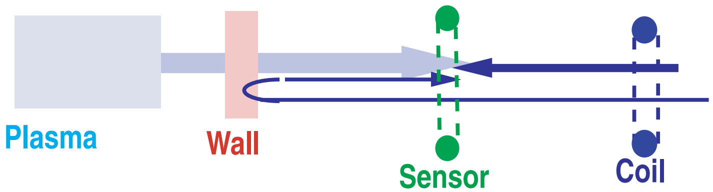
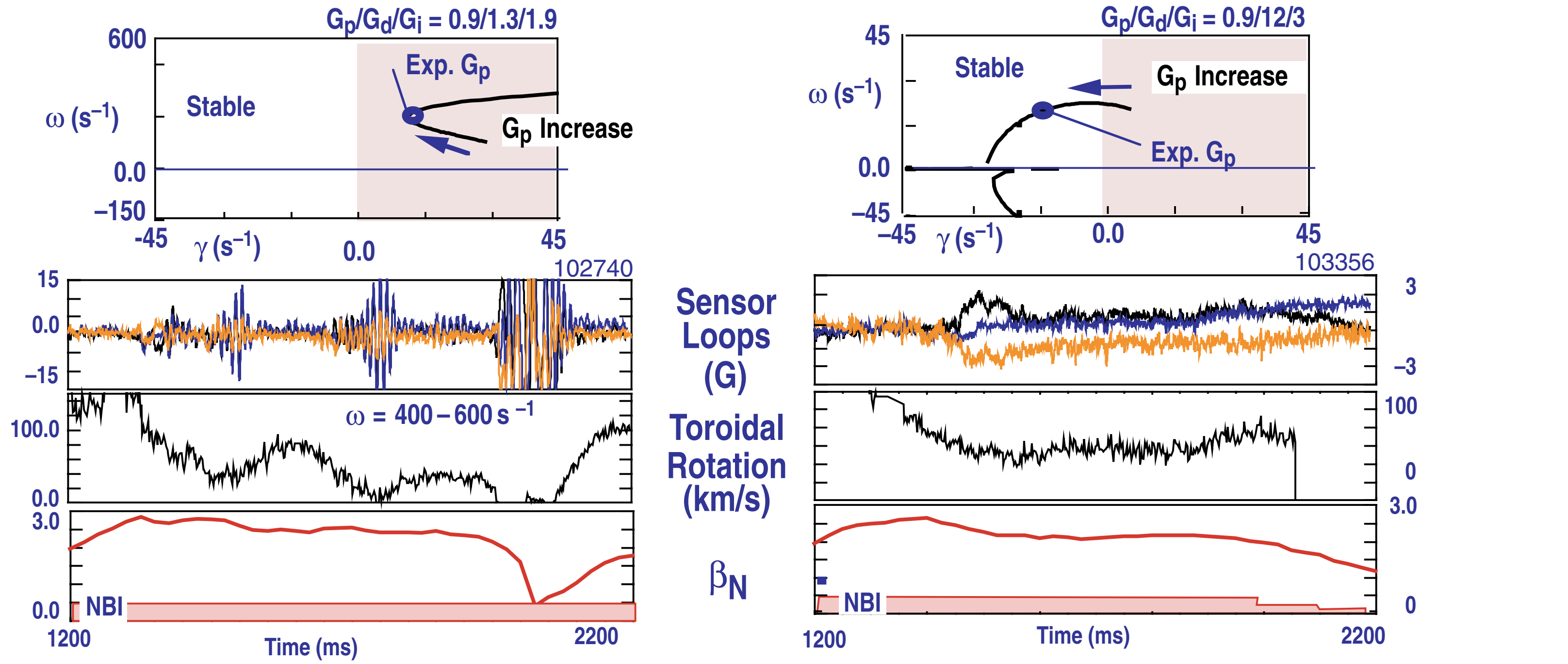
EXPLICIT MODE CONTROL ALLOWS LONG DURATION OF STABILIZATION

- Sensitive to plasma response



- Compensation for direct coupling
- Oscillation and incomplete stabilization

- Compensation for coil and eddy currents
- RWM stabilized for 700 ms



- This indicates advantages of (1) Sensor sensitive to plasma response and (2) B–poloidal sensor

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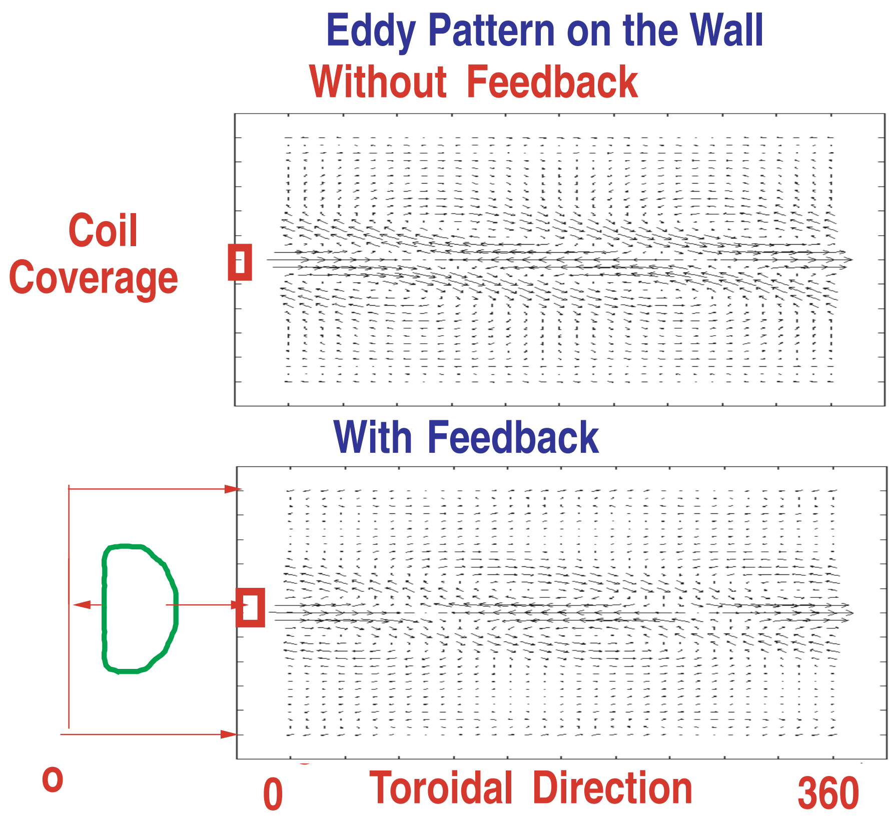
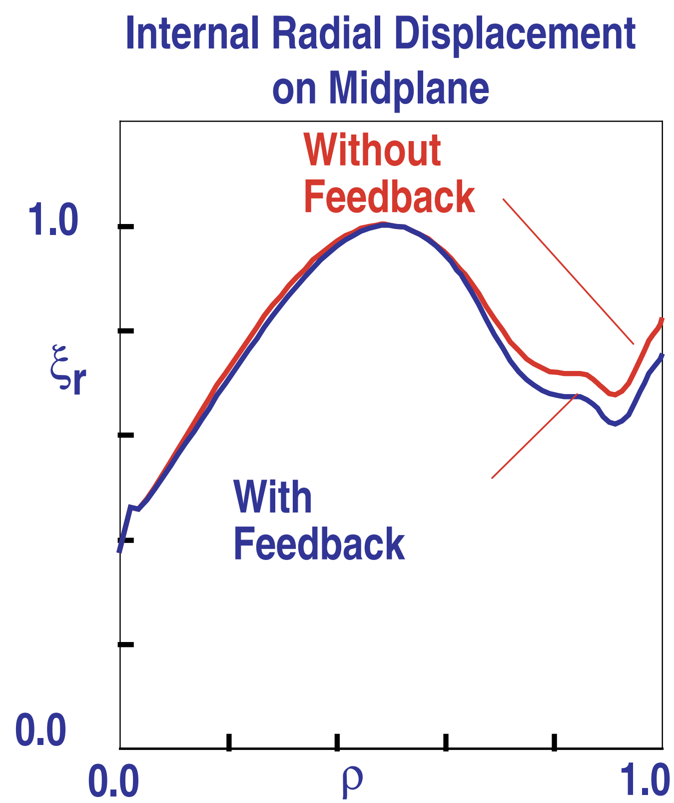
MODELING PREDICTS MODE STRUCTURE IS NOT CHANGED SIGNIFICANTLY WITH FEEDBACK

- Self-consistent MHD calculation including feedback field (VACUUM + GATO)





- With midplane coil only, the total eddy current pattern was not changed significatly
- Internal mode structure was unchanged, except slightly peaked with feedback

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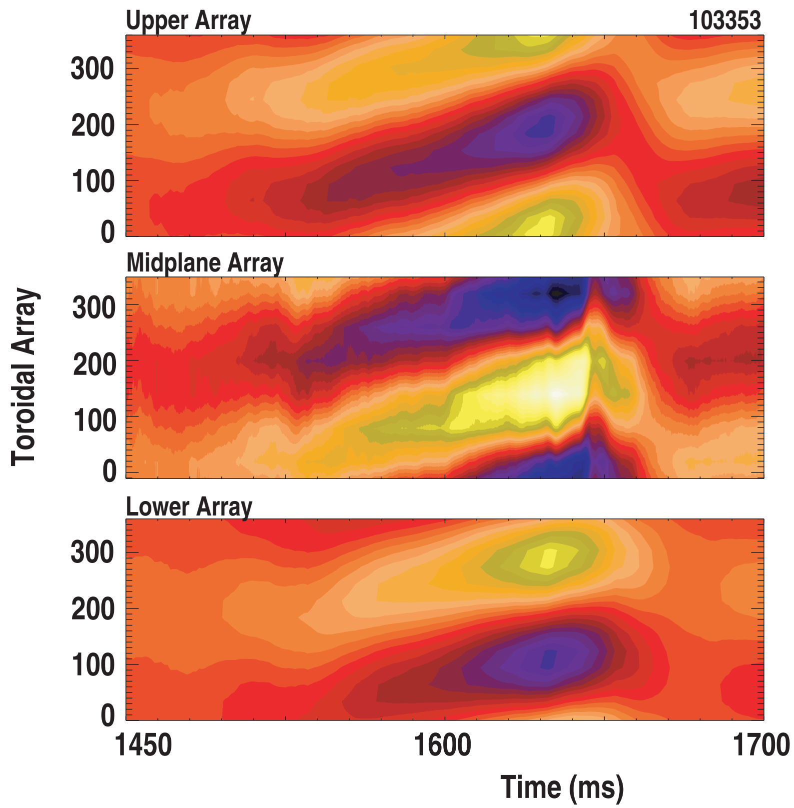
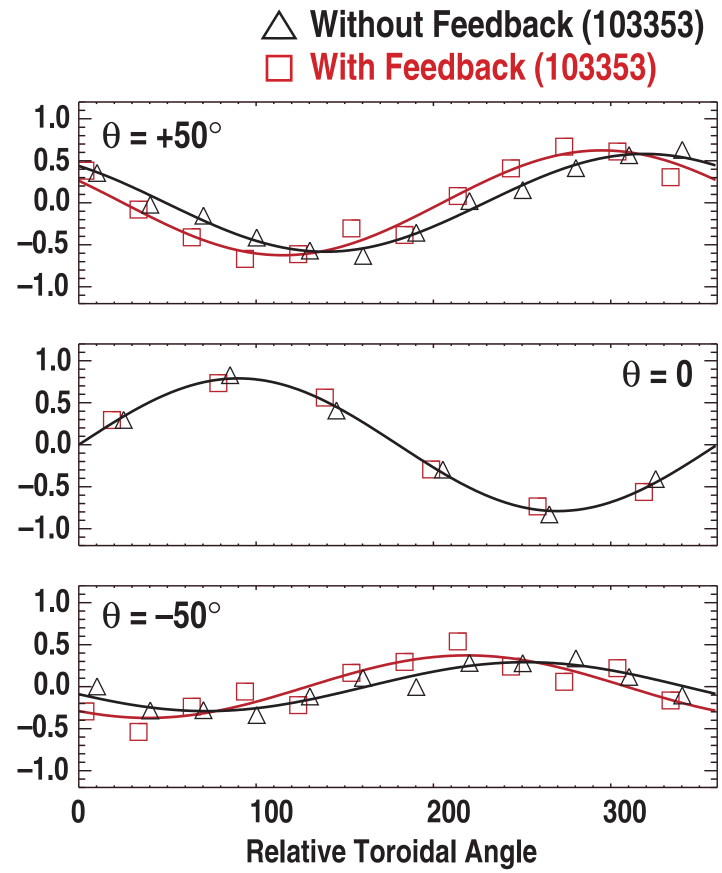
EXPERIMENT SHOWS MODE STRUCTURE OUTSIDE THE WALL IS NOT CHANGED SIGNIFICANTLY WITH/WITHOUT FEEDBACK

Three Toroidal Arrays of Saddle Loops Provide Poloidal Mode Structure



Mode Structure Relative to Midplane



- Qualitatively consistent with VACUUM/GATO prediction
- Supports "rigid displacement assumption" used in lumped parameter formulation and 3D feedback codes

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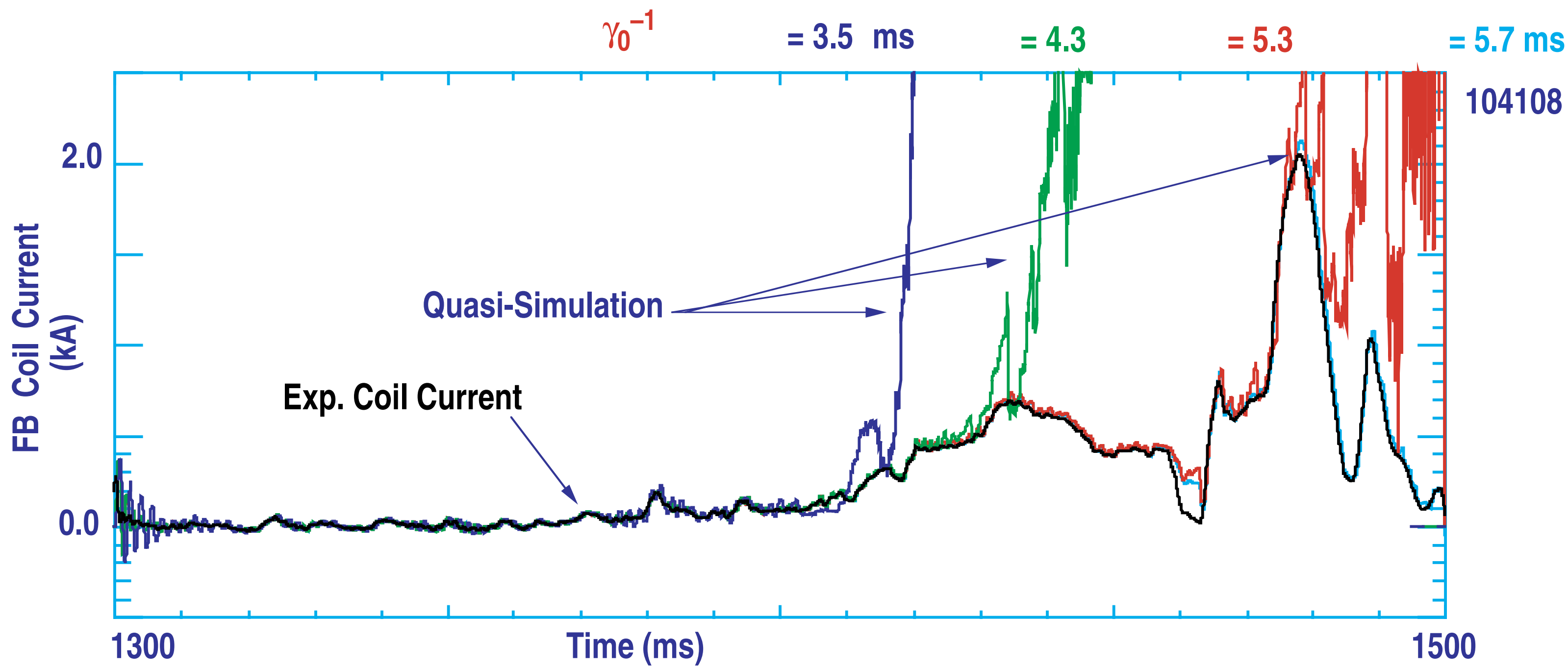
PRESENT RWM FEEDBACK PERFORMANCE LIMIT IS $\gamma_0 \tau_w \lesssim 1$

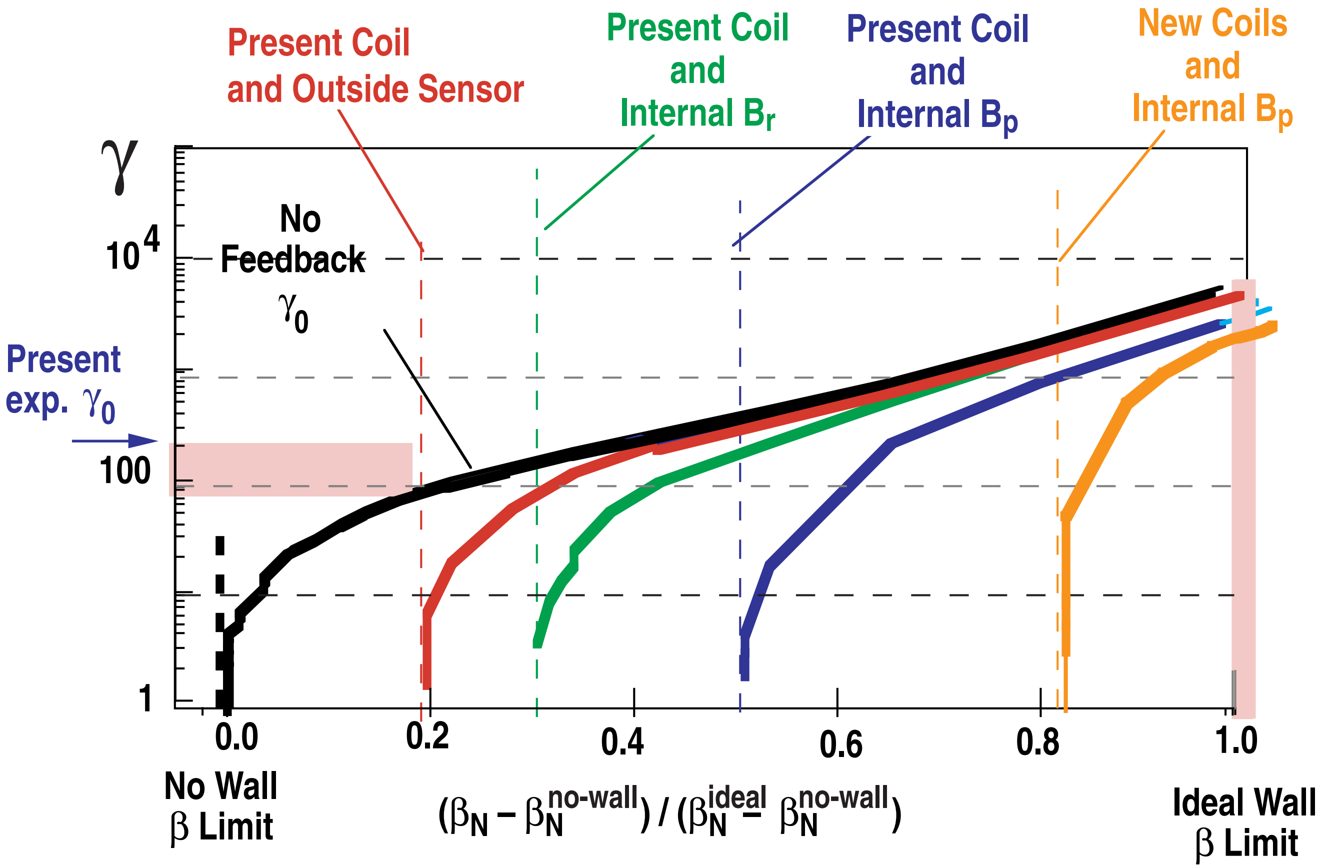
Growth rate without feedback: γ_0

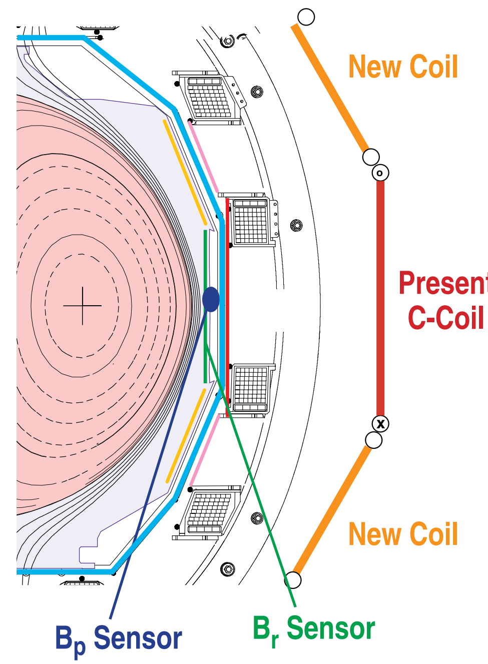
- Quasi-simulation code allows us to estimate no feedback mode growth rate γ_0 using experimental data
- Simulation reproduces mode onset time when γ_0^{-1} = 5.3 ms $\approx \tau_w$
- Planned upgrades should extend stabilization to larger γ_0



PROPOSED IMPROVEMENT OF RWM FEEDBACK ON DIII–D

- Six upper and six lower coil and internal B_p sensors increase achievable β within 20% of ideal MHD limit (VALEN CODE)





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GI1.004 J.Bialek

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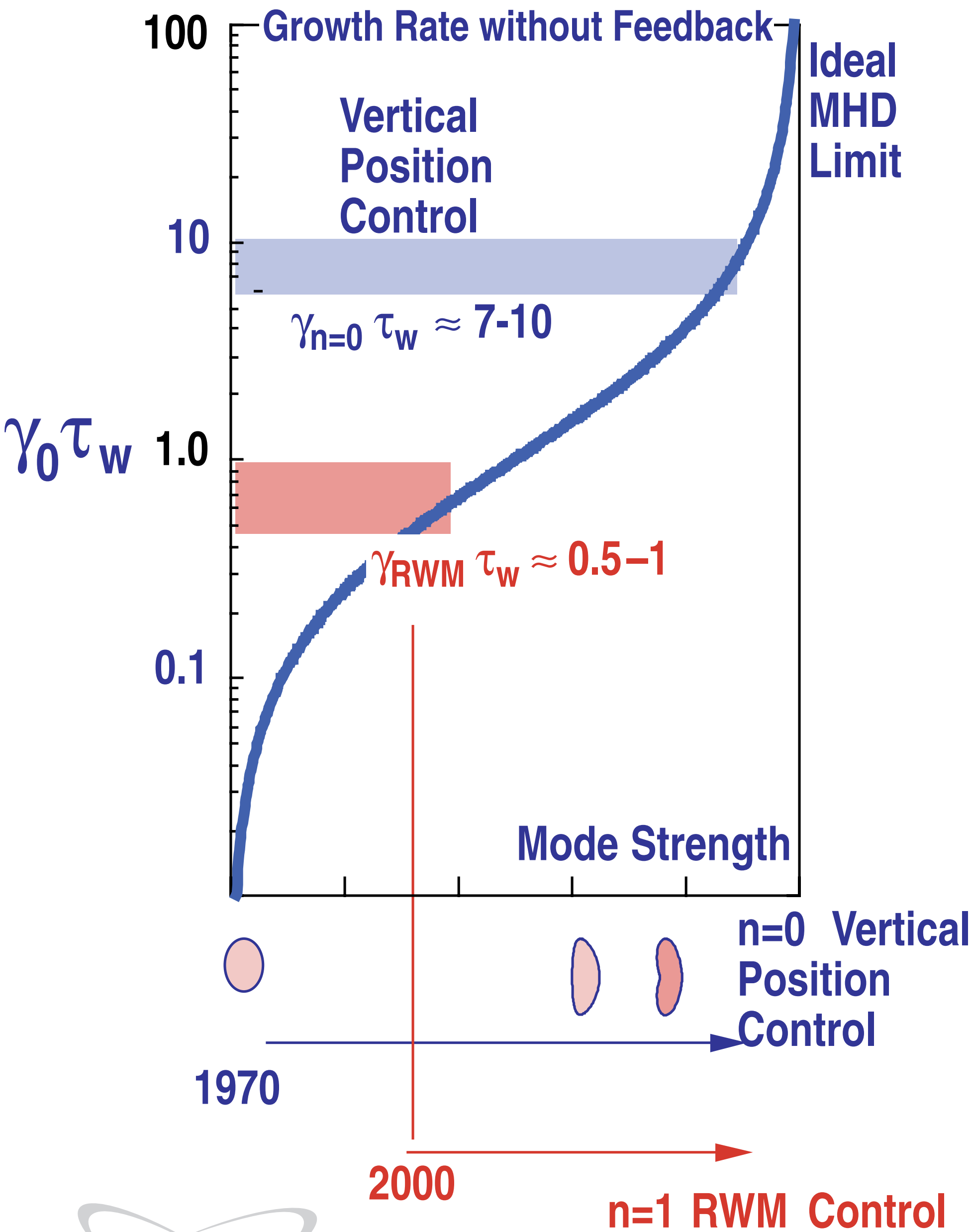
SUMMARY



- RWM can be suppressed by magnetic feedback
- Lumped parameter formulation has been useful, this success will allow us to utilize techniques developed by n = 0 vertical control progress
- Mode rigidity is confirmed by modeling and experiment
- Full MHD codes, VALEN, VACUUM+GATO have become practical tools for quantitative discussion
- This experiment has identified issues and prepared for next step

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