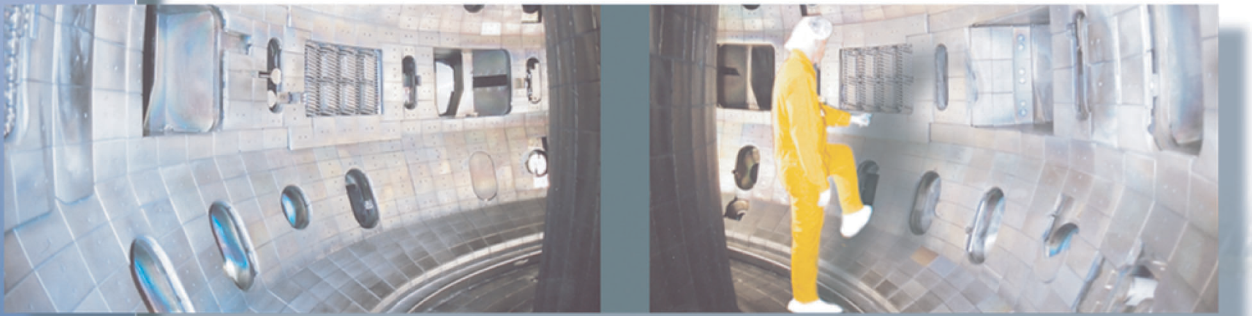

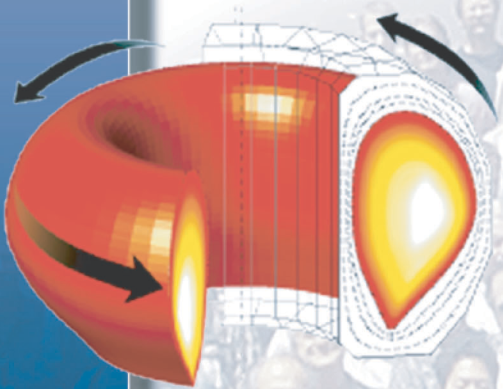

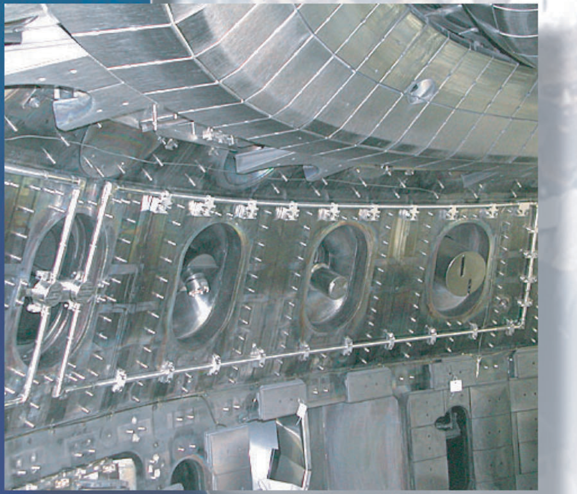

Control of the Resistive Wall Mode with Internal Coils in the DIII–D Tokamak (EX/3-1Ra)

Active Measurement of Resistive Wall Mode Stability in Rotating High Beta Plasmas (EX/3-1Rb)

by
M. Okabayashi

Presented at
20th IAEA Fusion Energy Conference
Vilamoura, Portugal

November 1st - 6th, 2004

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PPPL
PRINCETON PLASMA PHYSICS LABORATORY

248-04/MRW//rs

EX/3-1Ra

CONTROL OF THE RESISTIVE WALL MODE WITH INTERNAL COILS IN THE DIII–D TOKAMAK

**M. Okabayashi,[1] J. Bialek,[2] A. Bondeson,[+] M.S. Chance,[1] M.S. Chu,[3] D.H. Edgell,[4]
A.M. Garofalo,[2] R. Hatcher,[1] Y. In,[4] G.L. Jackson,[3] R.J. Jayakumar,[5] T.H. Jensen,+
O. Katsuro-Hopkins,[2] R.J. La Haye,[3] Y.Q. Liu,[6] G.A. Navratil,[2] H. Reimerdes,[2] J.T. Scoville,[3]
E.J. Strait,[3] H. Takahashi,[1] M. Takechi,[7] , A.D. Turnbull,[3] I.N. Bogatu,[4] P. Gohil,[3] J.S. Kim,[4]
M.A. Makowski,[5] J. Manickam,[1] and J. Menard[1]**

1 Princeton Plasma Physics Laboratory, Princeton, New Jersey, 08543-0451,USA

2 Columbia University, New York, New York, USA.

3 General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA.

4 Far-Tech, Inc., San Diego, California 92121, USA.

5 Lawrence Livermore National Laboratory, Livermore, California, USA.

6 Chalmers University of Technology, Goteborg, Sweden.

7 Japan Atomic Energy Research Institute, Ibaraki, Japan

+deceased

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20th IAEA Fusion Energy Conference, Vilamoura, Portugal 2004

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EX/3-1Rb

ACTIVE MEASUREMENT OF RESISTIVE WALL MODE STABILITY IN ROTATING HIGH BETA PLASMAS

H. Reimerdes,[1] J. Bialek,[1] M.S. Chance,[2] M.S. Chu,[3] A.M. Garofalo,[1]
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[1] Columbia University, New York, New York, USA
[2] Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
[3] General Atomics, San Diego, California, USA
[4] Lawrence Livermore National Laboratory, Livermore, California, USA
[5] Chalmers University of Technology, Göteborg, Sweden

+ deceased

20th IAEA Fusion Energy Conference, Vilamoura, Portugal 2004

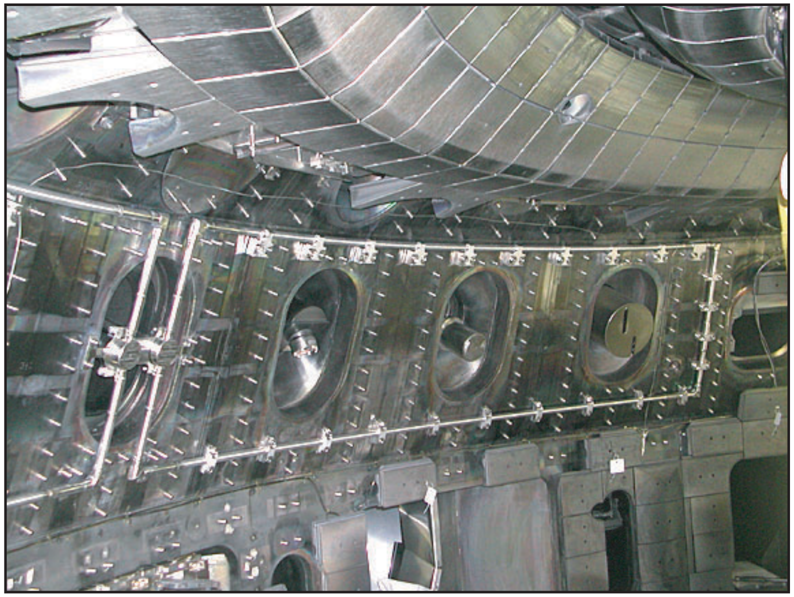
EXTERNAL KINK CONTROL WITH RESISTIVE WALL

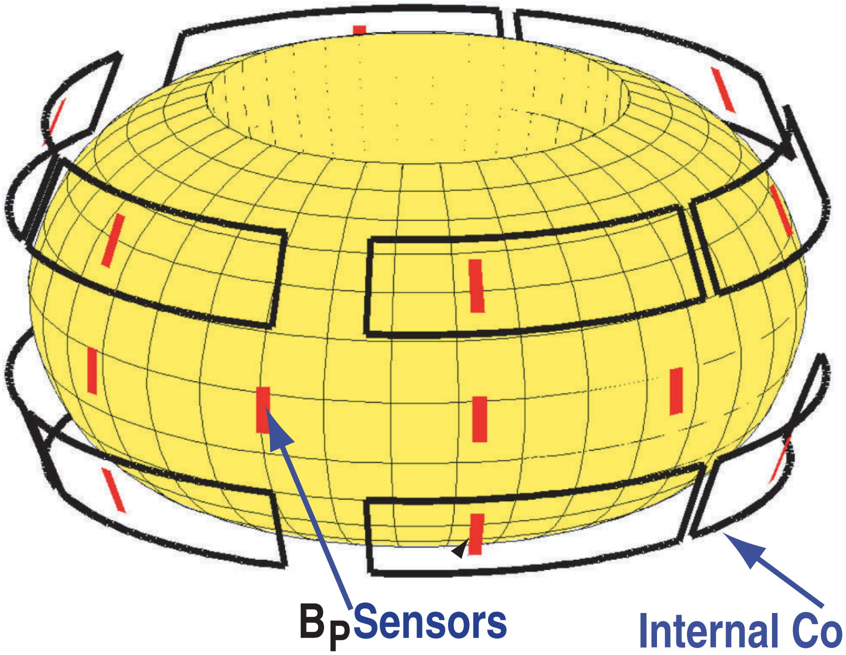
- Steady state advanced tokamak scenarios need wall stabilization of external kink modes
  - for operation at high beta with a high fraction of bootstrap current
- Finite-conductivity wall
  - Does not completely stabilize ideal kink mode,
  - Converts it to a slowly-growing Resistive Wall Mode (RWM)
- Two approaches to RWM stabilization
  - Passive: fast plasma rotation (EX/3-1Ra)
  - Active: magnetic feedback control (EX/3-1a)
- New Internal coils installed just after the last IAEA conference: Very productive for RWM physics studies and active control of RWMs
  - Active MHD spectroscopy with applied rotating field:
    RWM stability physics
  - Plasma rotation sustained by feedback-controlled error field correction:
    Long duration high β plasmas
  - Direct feedback control :
    RWM stability at higher beta below critical rotation

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

- Inside vacuum vessel: Faster time response for feedback control

  Closer to plasma, flexible magnetic field pattern: more efficient coupling





- 12 "picture-frame" coils
- Single-turn, water-cooled
- 7 kA max. rated current
- Protected by graphite tiles
- 10 gauss/kA on plasma surface

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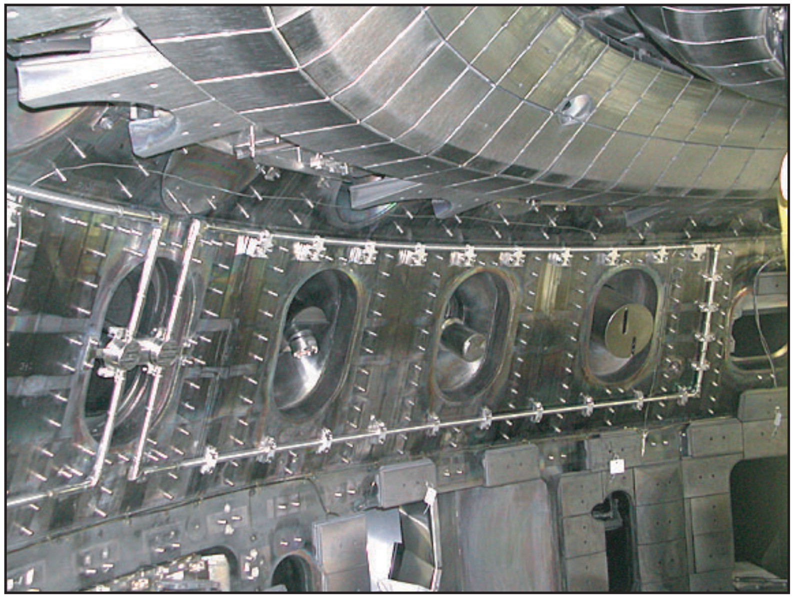

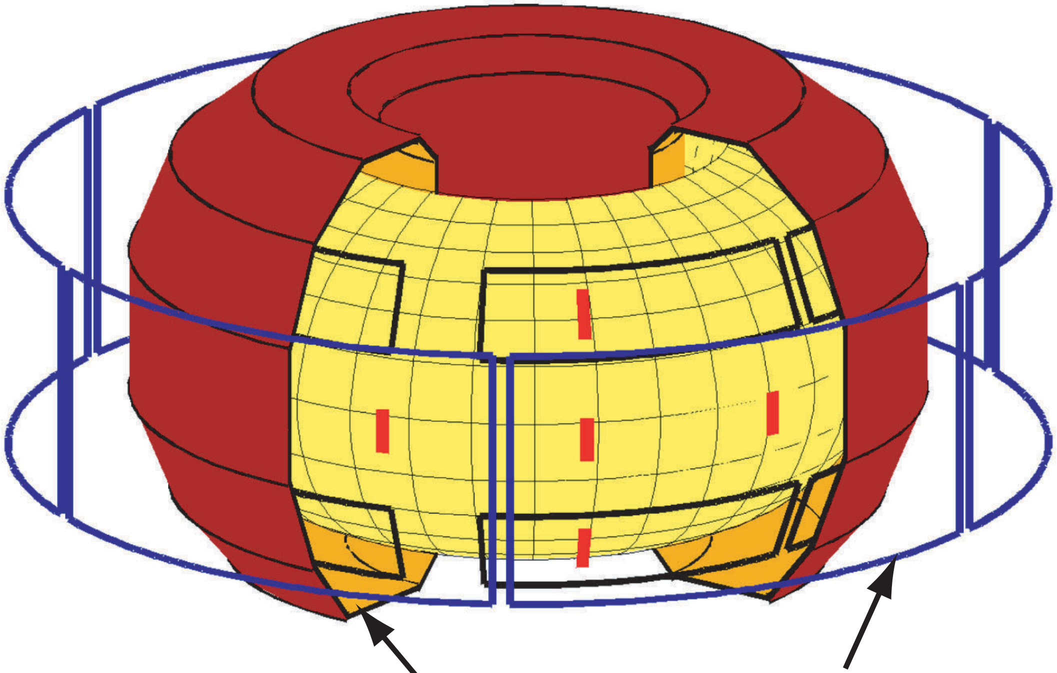

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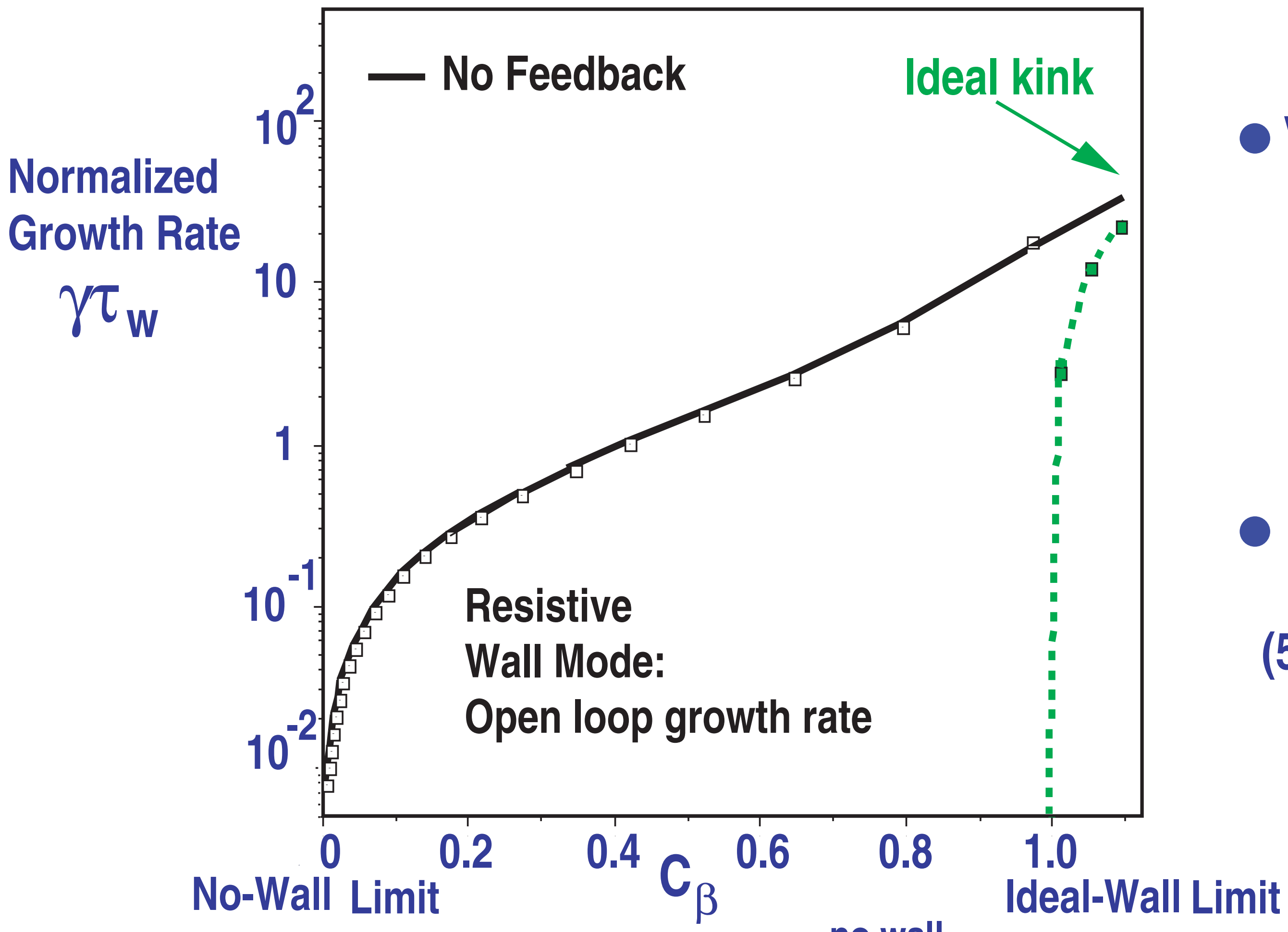
FEEDBACK WITH I-COILS INCREASES STABLE PLASMA PRESSURE TO NEAR IDEAL-WALL LIMIT

- VALEN code prediction

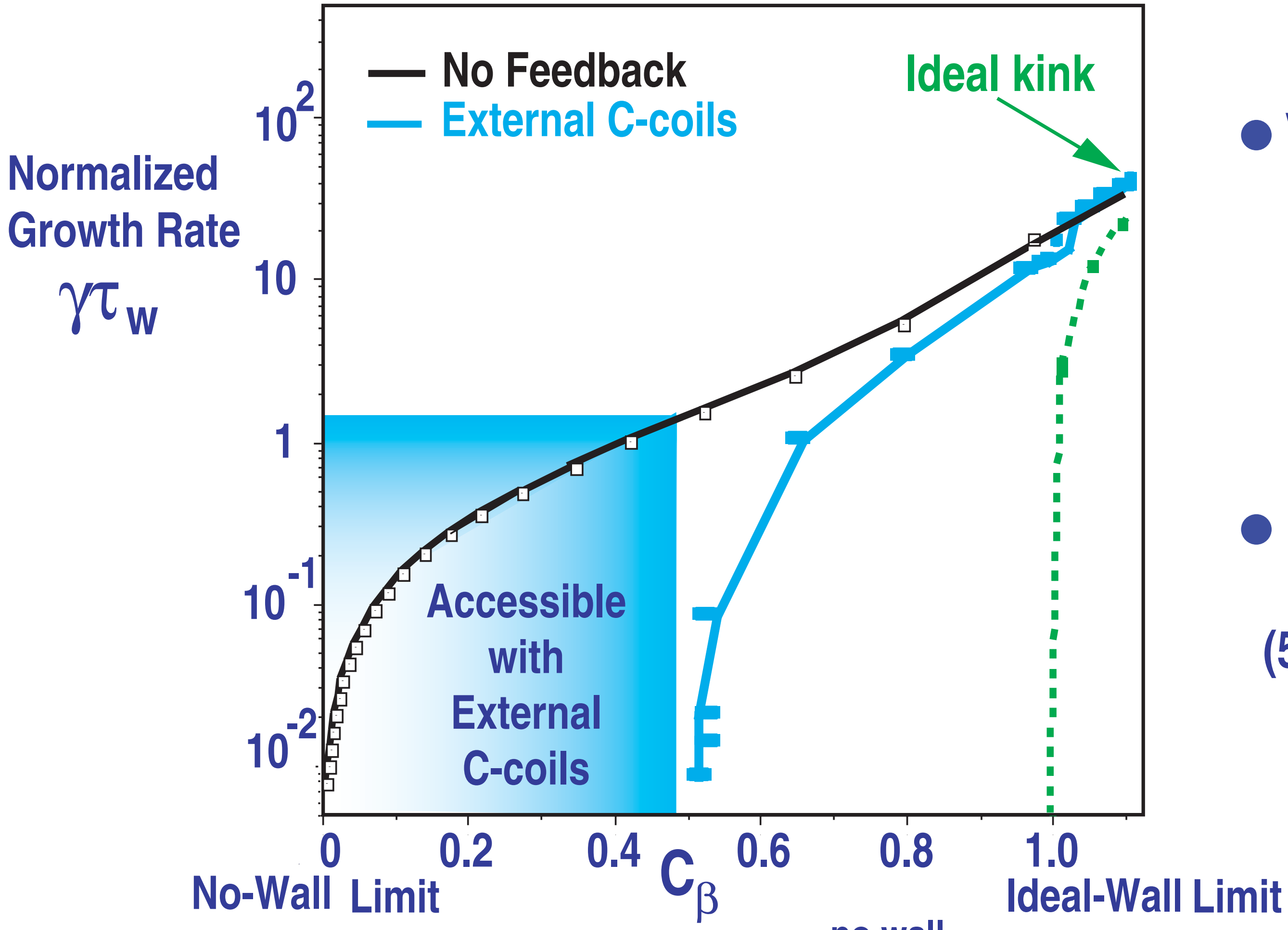


$$C_\beta = \frac{\beta - \beta^{no.wall}}{\beta^{ideal.wall} - \beta^{no.wall}}$$

- VALEN code:
  - DCON MHD stability
  - 3D geometry of vacuum vessel and coil geometry
- τ_W is the vacuum vessel flux diffusion time (5 ms is used in VALEN code)

FEEDBACK WITH I-COILS INCREASES STABLE PLASMA PRESSURE TO NEAR IDEAL-WALL LIMIT

- C-coil stabilizes slowly growing RWMs



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- VALEN code:
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  - 3D geometry of vacuum vessel and coil geometry

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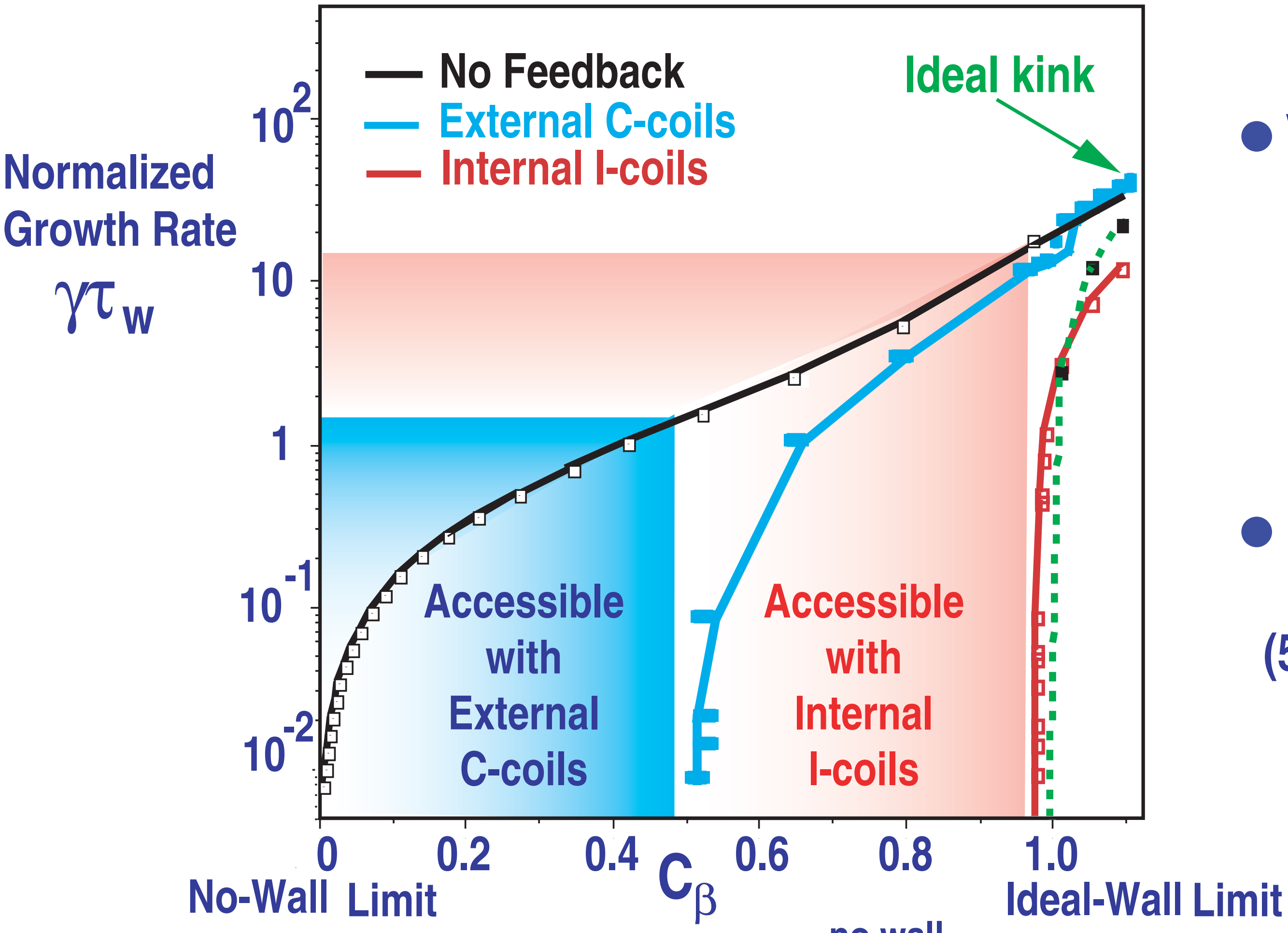
FEEDBACK WITH I-COILS INCREASES STABLE PLASMA PRESSURE TO NEAR IDEAL-WALL LIMIT

- I-coil stabilizes RWMs with growth rate 10 times faster than C-coils



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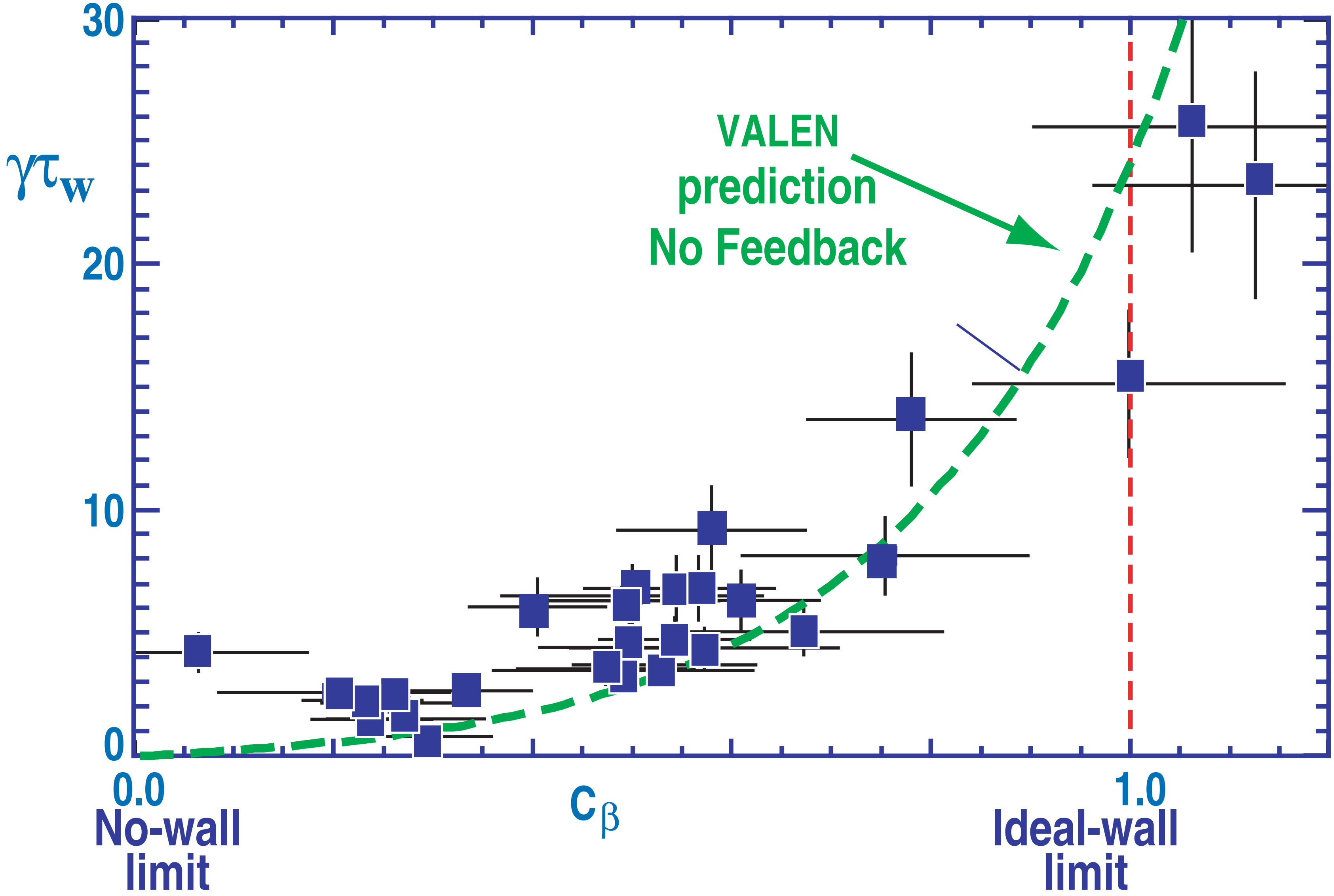
OBSERVED OPEN LOOP GROWTH RATES AGREE WITH VALEN PREDICTION



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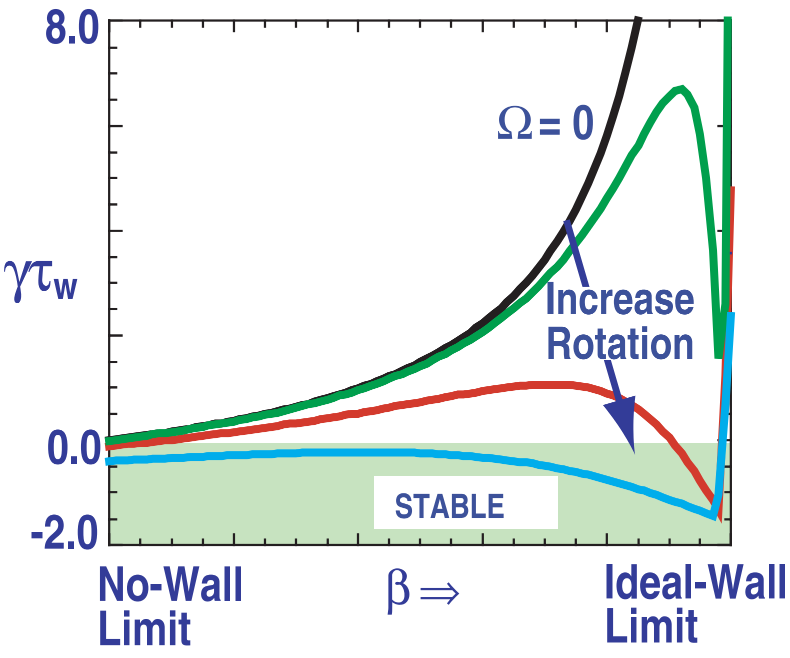
TWO DISTINCT STABILIZATION APPROACHES HAVE BEEN PROPOSED

Plasma Rotation

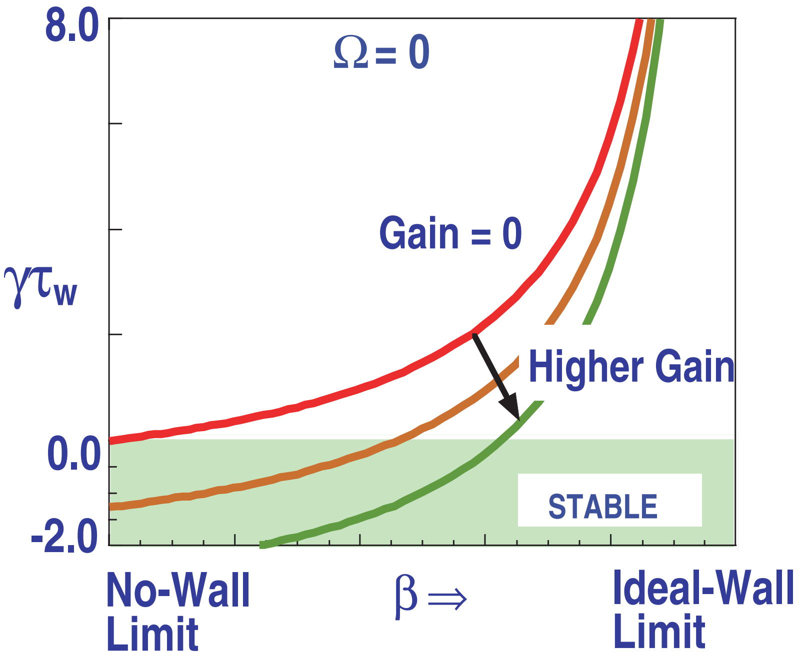
- **Required:** A few % of Alfvén velocity



Exp/3-1Rb

Magnetic Feedback

- **Required:** Practical power level
- System stability limits gain



Exp/3-1Ra

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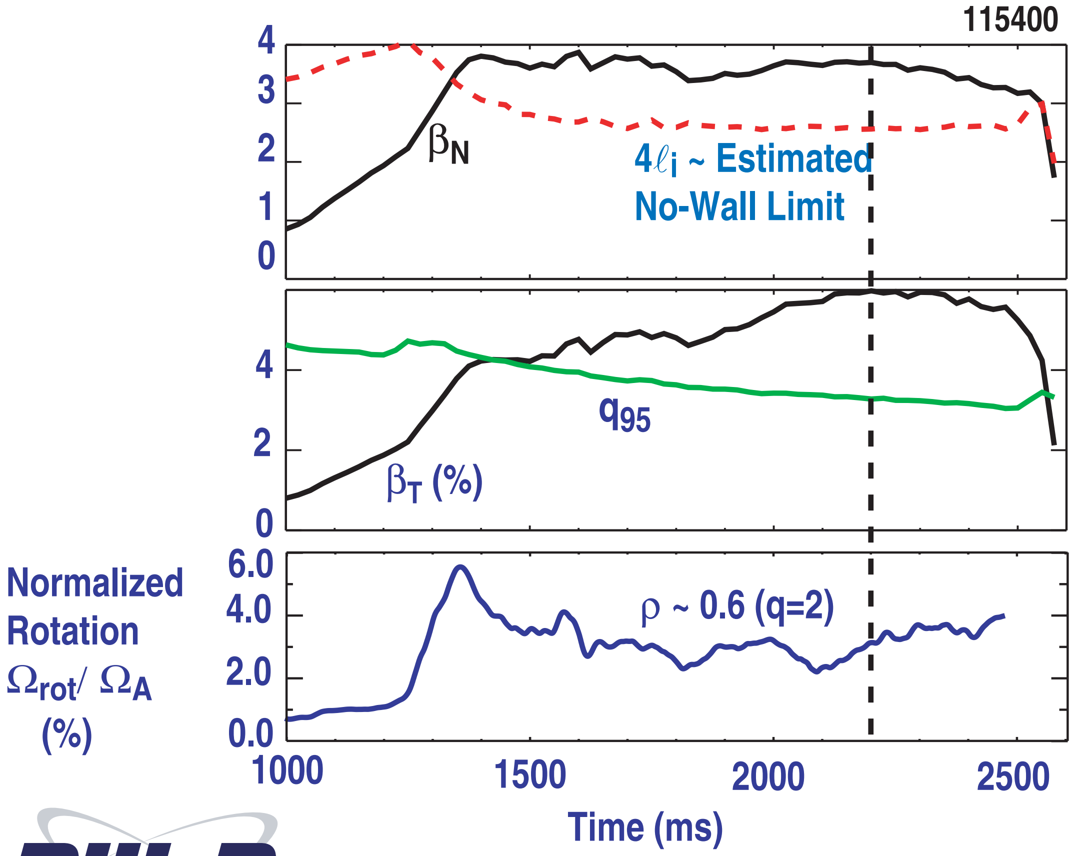
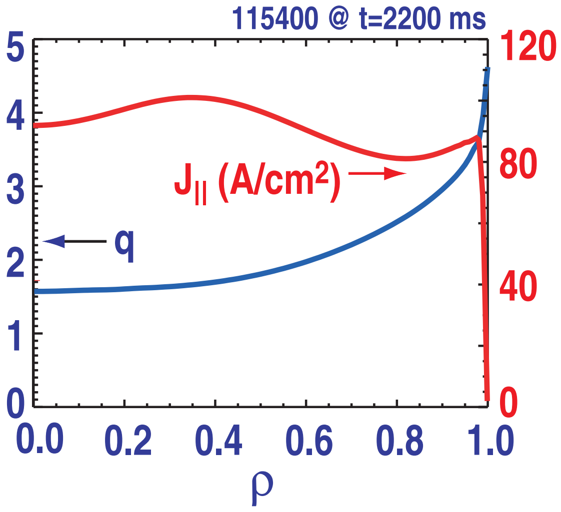
WALL STABILIZATION WITH ROTATION ALLOWS HIGH BETA OPERATION

- Stable at $\beta_N \approx 6\ \ell_i$ and β_T reaching to 6%
- Beta exceeds estimated no-wall limit for >1s (> 200 τ_w)



- Broad current profiles can greatly benefit from wall stabilization



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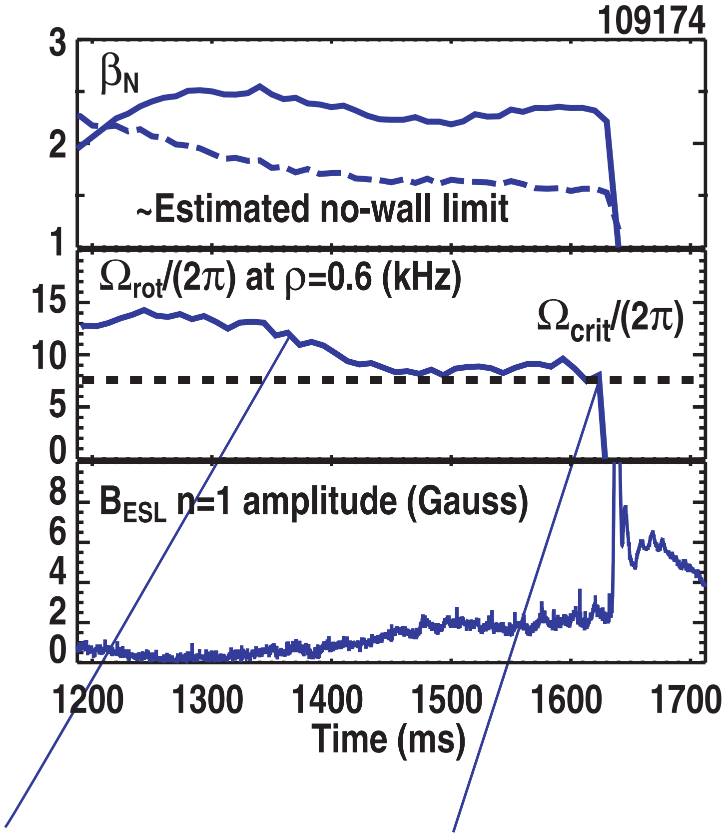
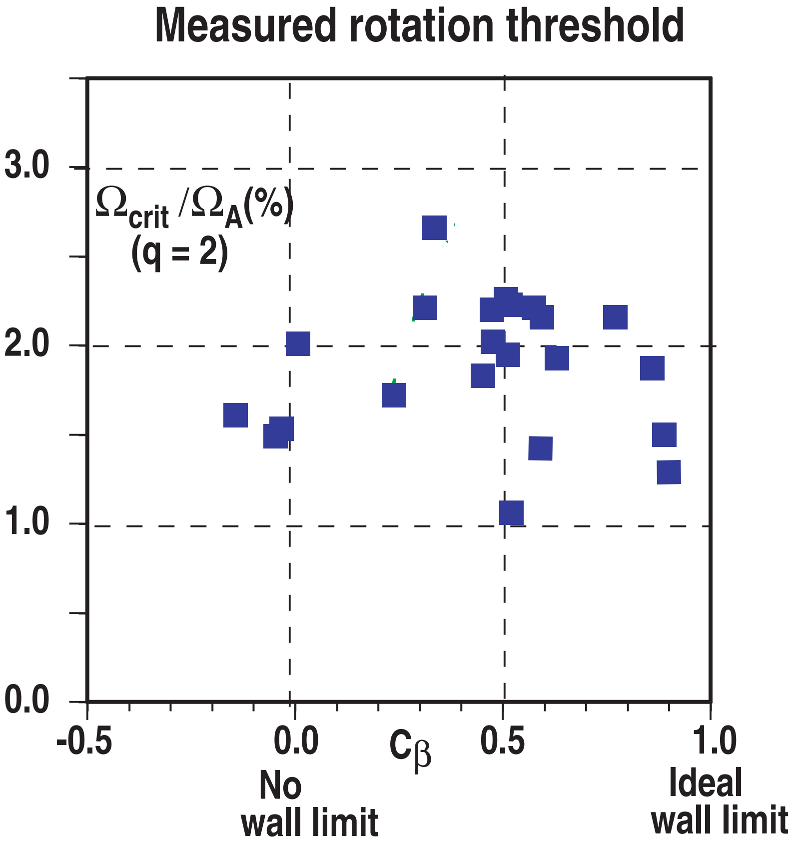
HOW MUCH PLASMA ROTATION IS REQUIRED TO STABILIZE THE n=1 RWM?



Measured rotation threshold



Insufficient
error field correction
causes slow-down

Onset of RWM
marks
critical rotation Ω_{crit}

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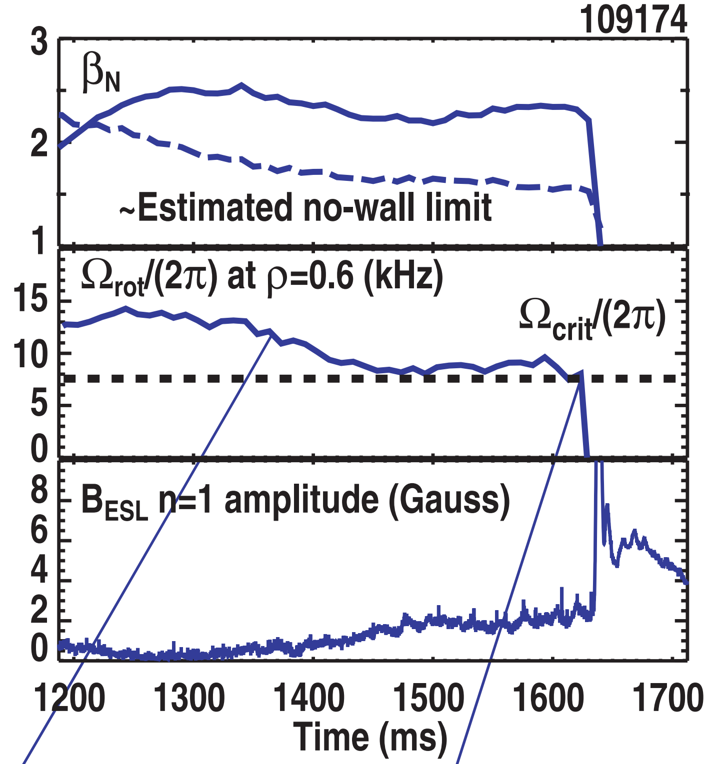
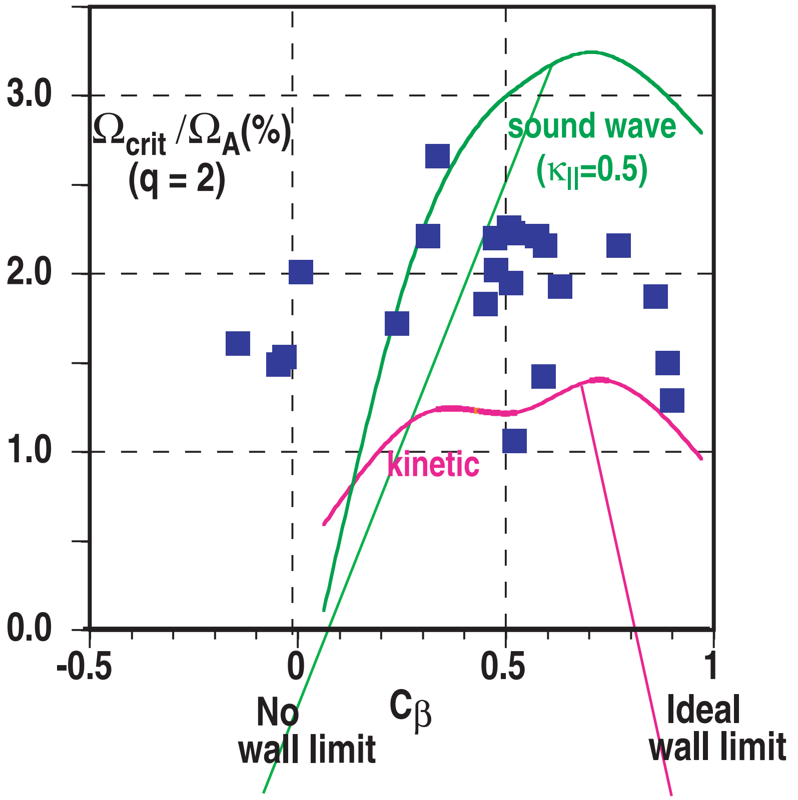


Insufficient error field correction causes slow-down

Onset of RWM marks critical rotation Ω_{crit}

- **Comparison with MARS calculation with experimental rotation profile**



Soundwave damping overestimates the critical rotation

Kinetic damping underestimates the critical rotation

- **MARS includes rotation and viscous dissipation**

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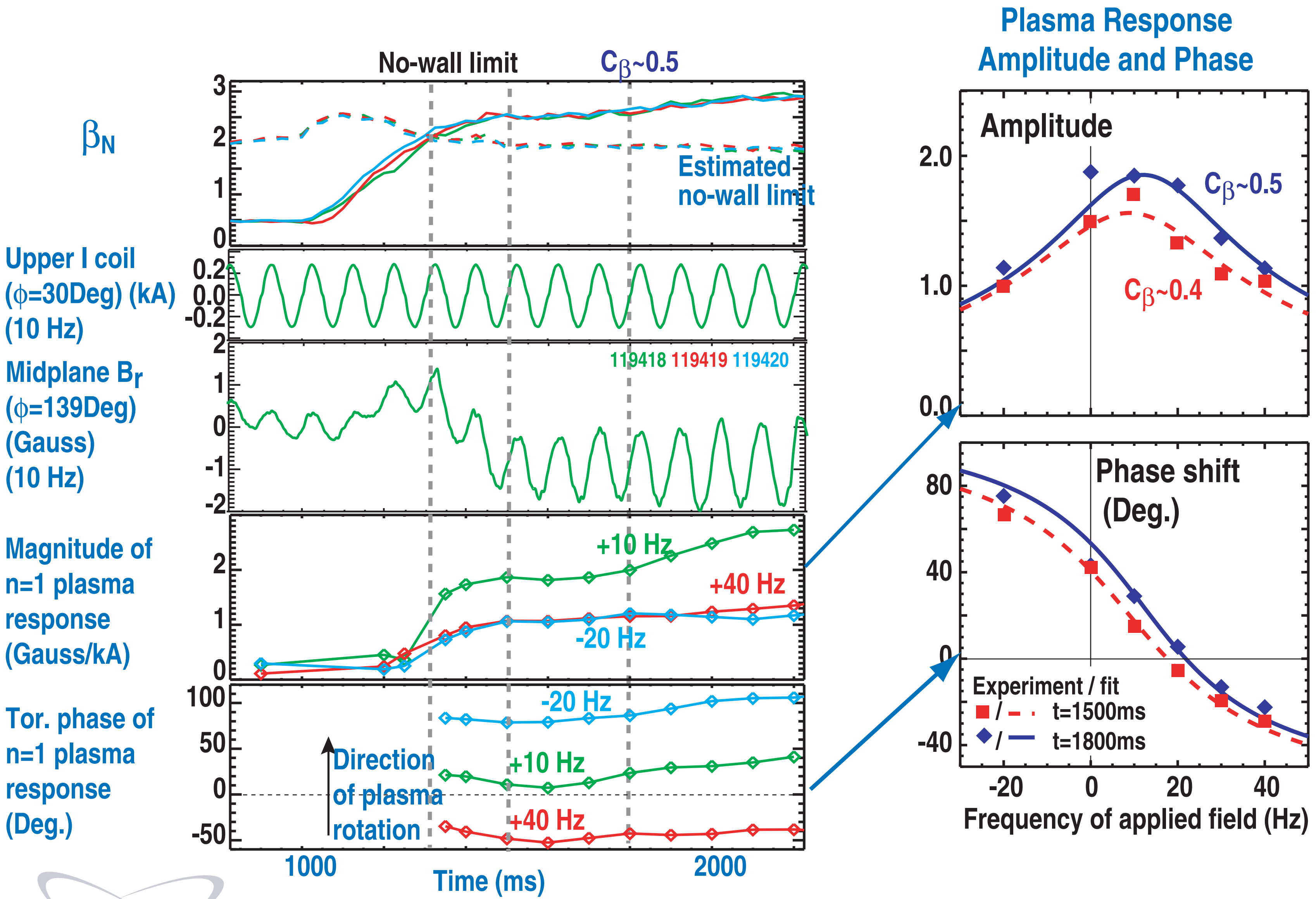
MHD SPECTROSCOPY PROBES THE RWM STABILITY WHILE THE PLASMA REMAINS STABLE



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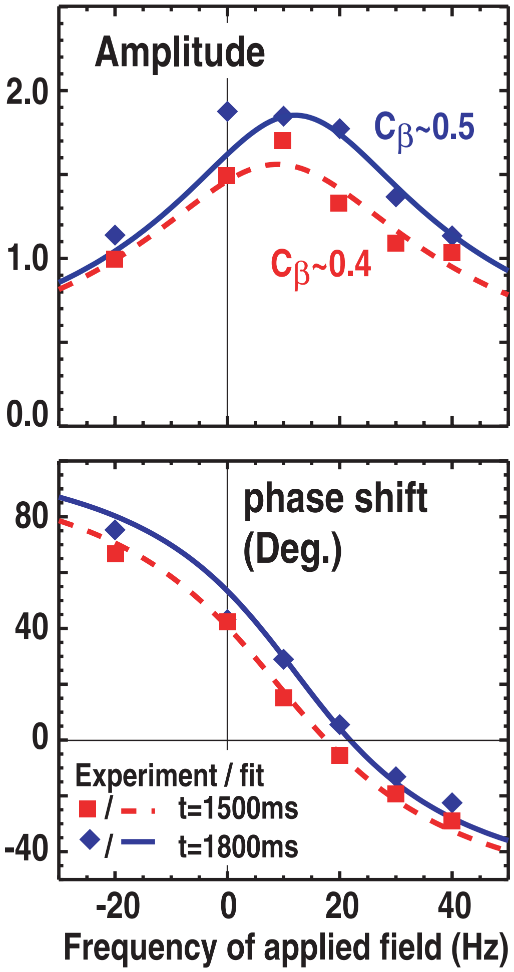
SPECTRUM REVEALS GROWTH RATE AND MODE ROTATION FREQUENCY OF THE STABLE RWM



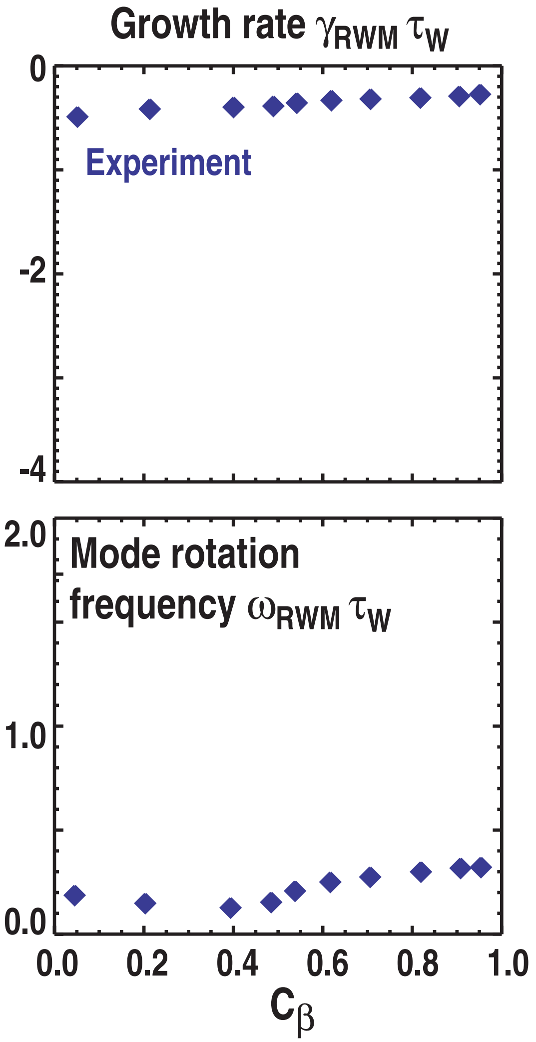
- Spectrum Analysis with a Single Mode Model

$$\gamma_0 = \gamma_{RWM} + i\,\omega_{RWM}$$

- Amplification Factor

Coupling between external field and RWM

$$= \frac{M\,(1+\gamma_0\tau_w)}{(i\omega_{ext}\tau_w - \gamma_0\,\tau_w)}$$



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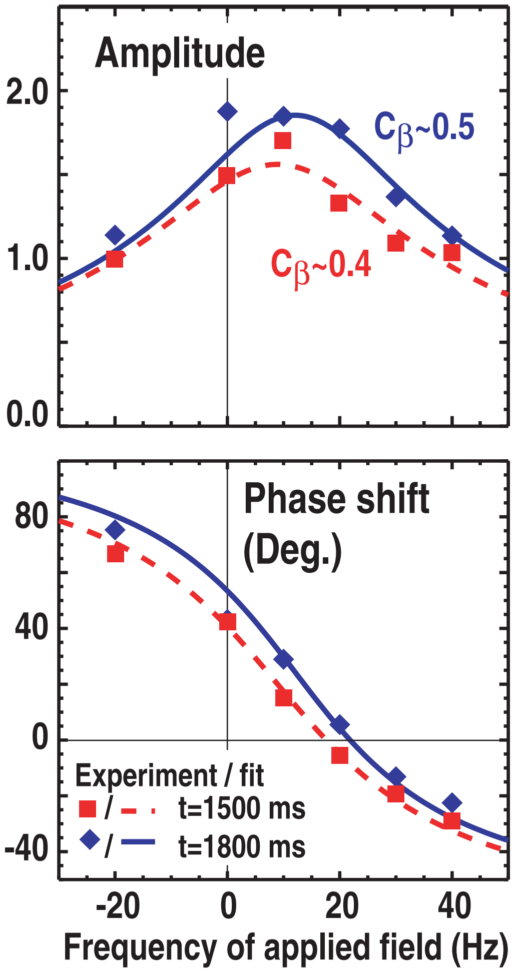


- **Spectrum Analysis with a Single Mode Model**

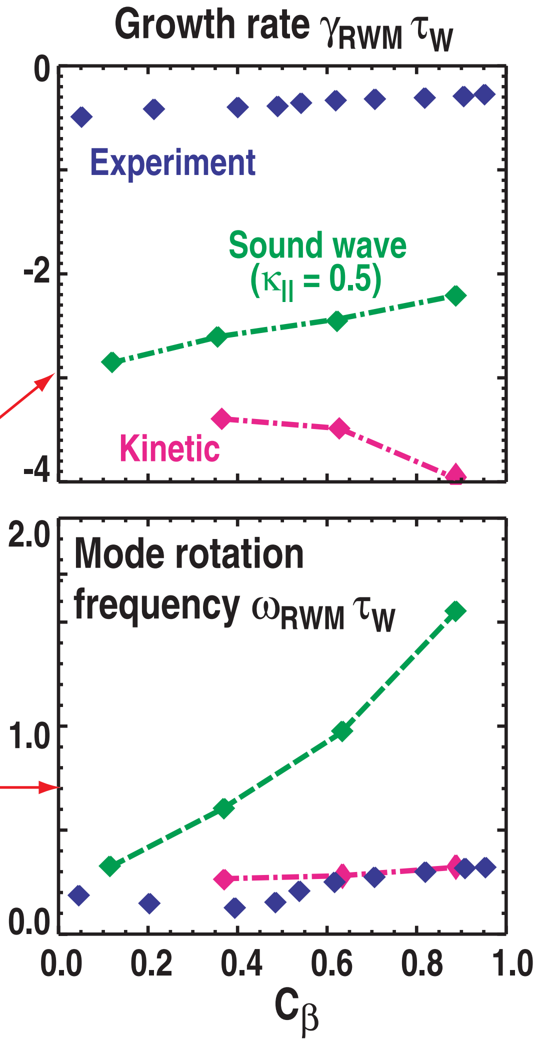
$$\gamma_0=\gamma_{RWM} + i\,\omega_{RWM}$$

- **Amplification Factor**

Coupling between external field and RWM

$$= \frac{M\,(1+\gamma_0\tau_w)}{(i\omega_{ext}\tau_w - \gamma_0\,\tau_w)}$$

- **MARS Comparison**
  - Growth rate
    - sound wave / kinetic overestimates stabilizing effect
  - Mode rotation frequency
    - kinetic : agreement
    - sound wave damping underestimate coupling



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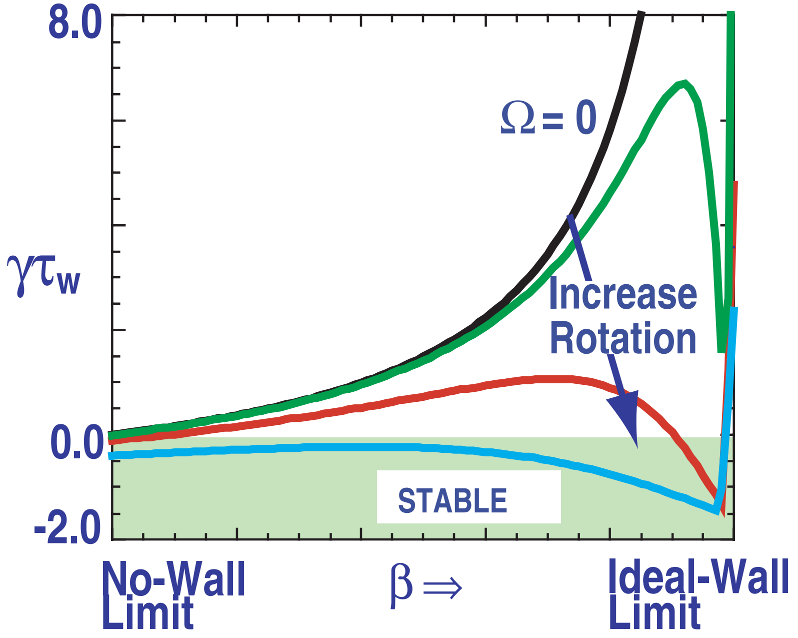
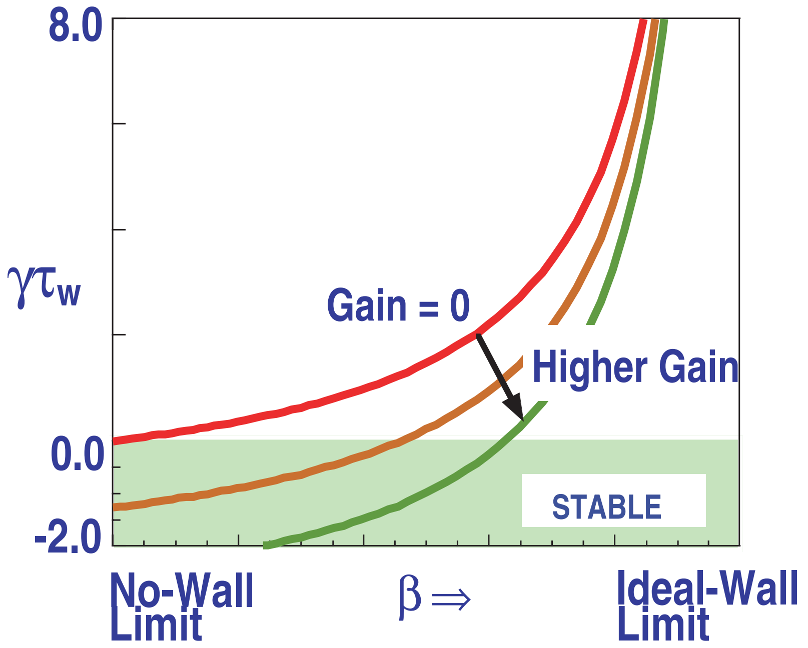


$\Omega_{rot} > \Omega_{crit}$

Magnetic Feedback

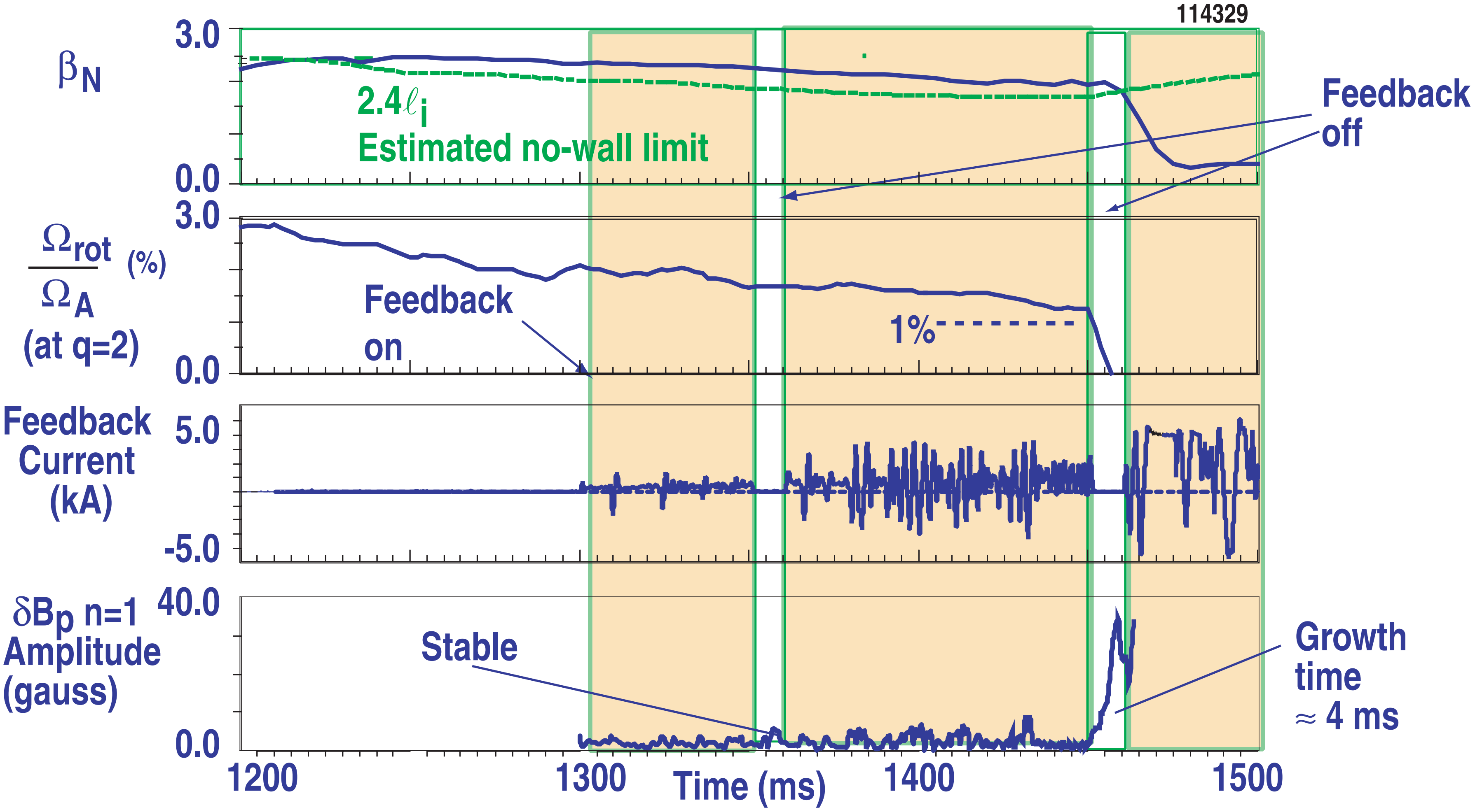
- **Required:** Practical power level
- System stability limits gain



$\Omega_{rot} < \Omega_{crit}$

- Rational surface damping mechanism –> Ω at q=2 as a measure of rotations

DIRECT MAGNETIC FEEDBACK SUSTAINS BETA ABOVE NO-WALL LIMIT EVEN WHEN $\Omega_{rot} < \Omega_{crit}$



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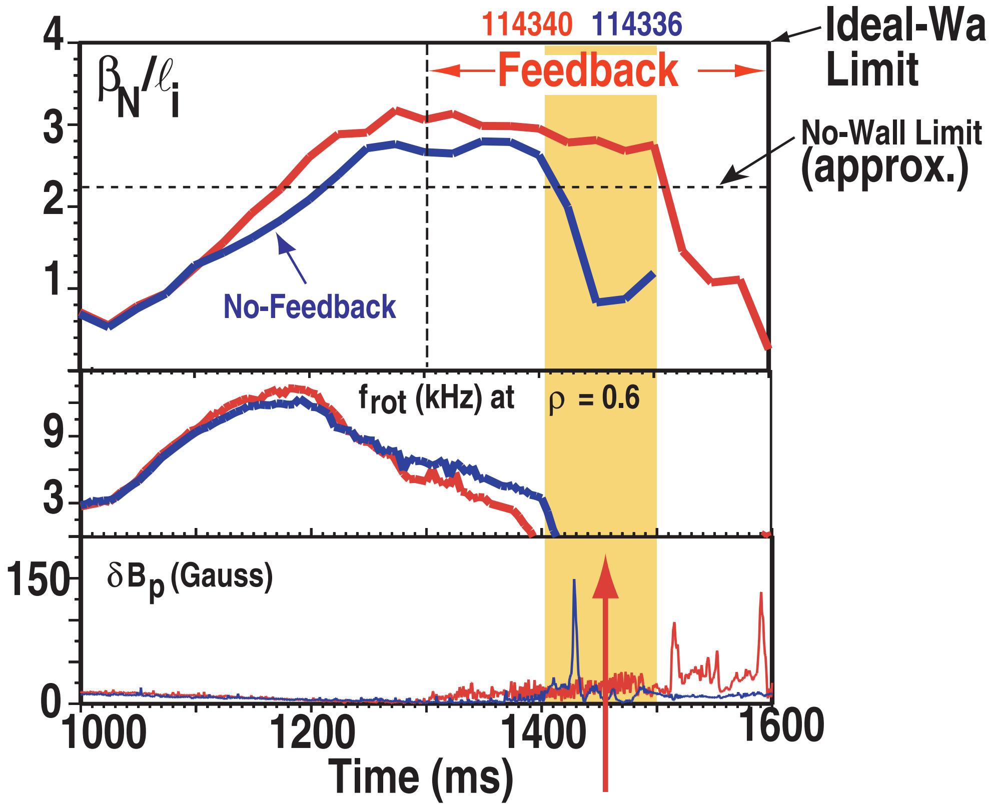
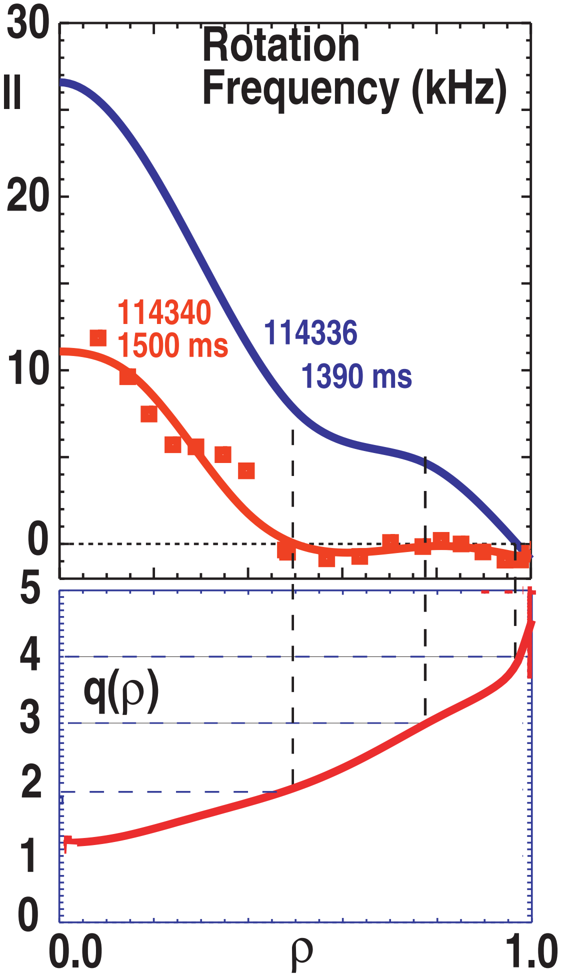
FEEDBACK SUSTAINS A DISCHARGE WITH NEAR-ZERO ROTATION AT ALL n=1 RATIONAL SURFACES

- Comparison case without feedback is unstable even with lower beta and faster rotation

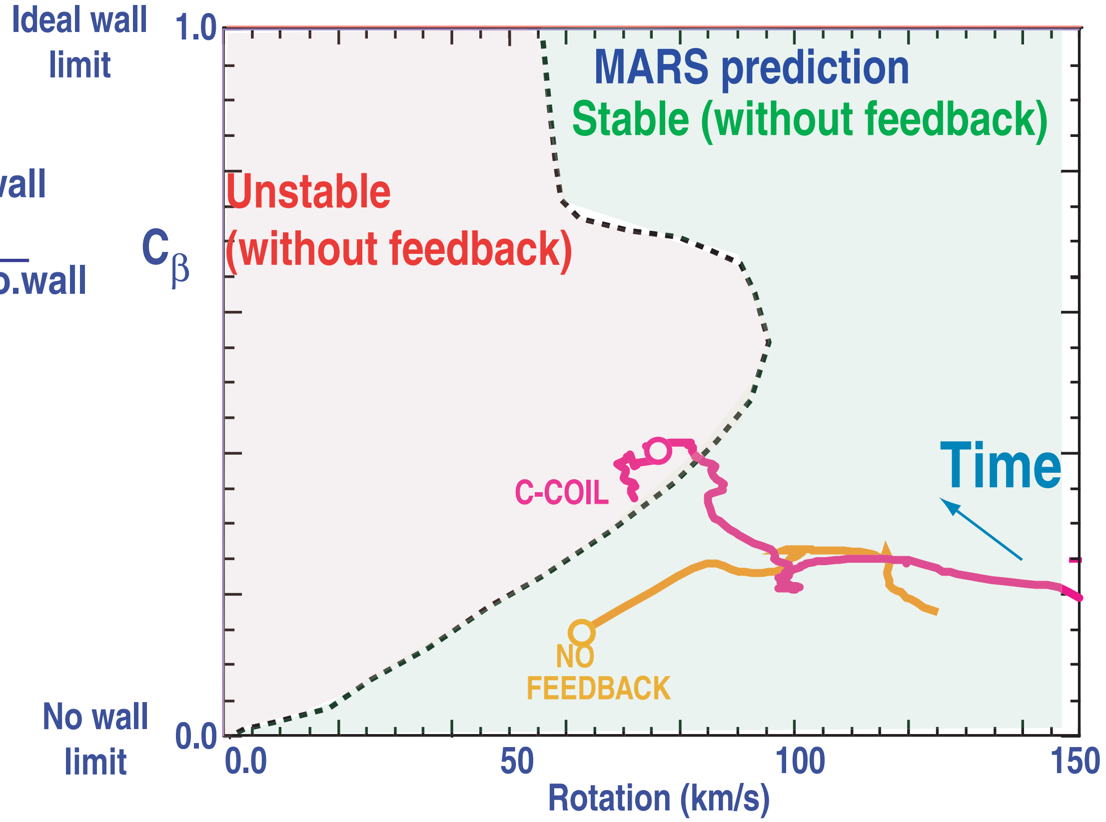


Feedback Stabilized with Low Rotation



FEEDBACK WITH I-COILS HAS ACHIEVED HIGH β_N AT ROTATION BELOW CRITICAL PREDICTED BY MARS

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



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FEEDBACK WITH I-COILS HAS ACHIEVED HIGH β_N AT ROTATION BELOW CRITICAL PREDICTED BY MARS

- With near zero rotation, C_β is near the maximum set by control system characteristics

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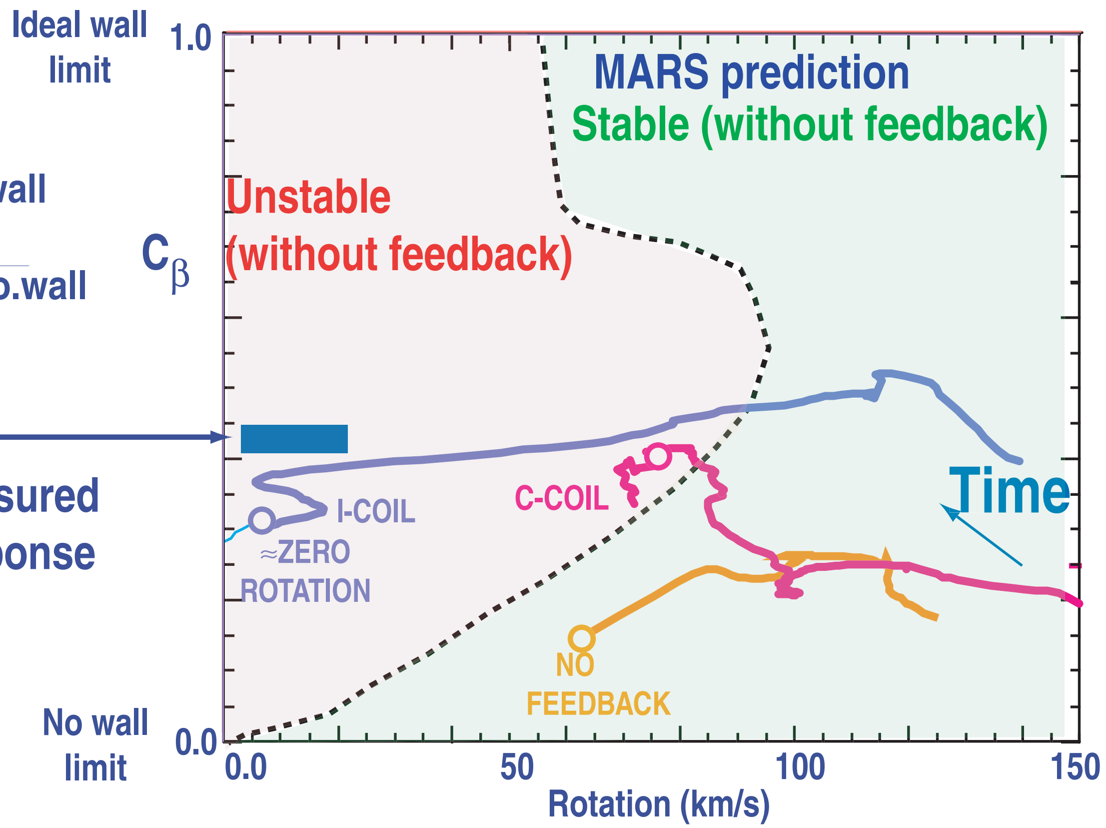


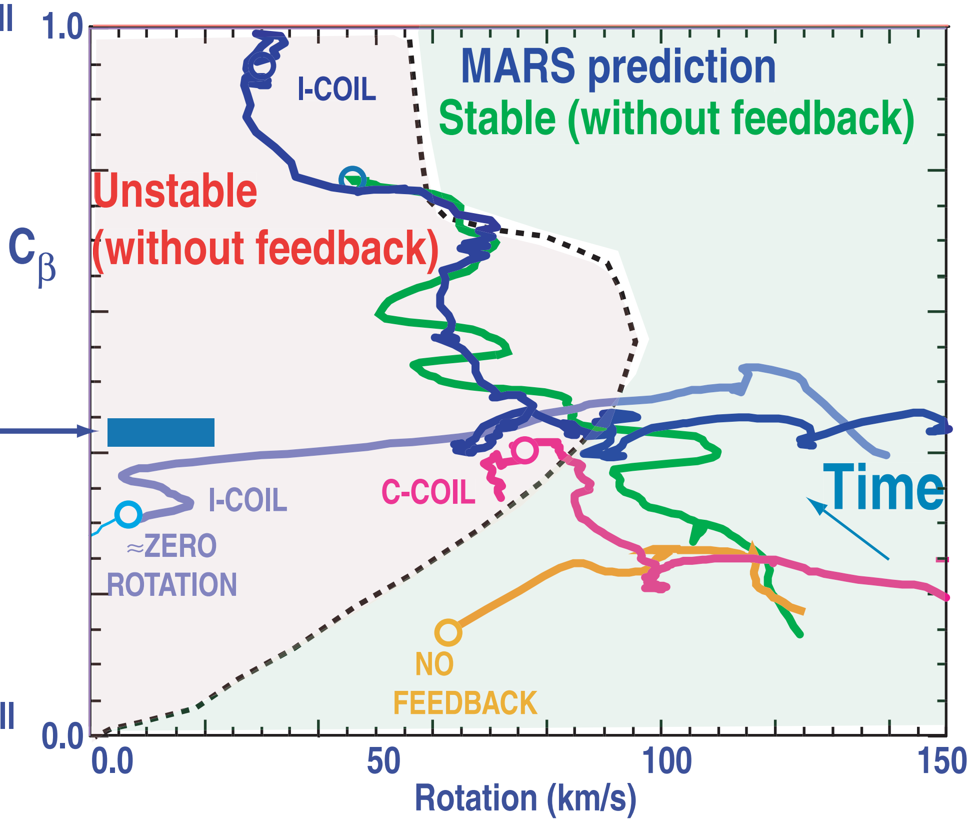
MARS /VALEN prediction for zero rotation, with measured feedback system time response

FEEDBACK WITH I-COILS HAS ACHIEVED HIGH β_N AT ROTATION BELOW CRITICAL PREDICTED BY MARS

- With near zero rotation, C_β is near the maximum set by control system characteristics
- Feedback with I-coils attained C_β higher than with C-coils

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

MARS /VALEN prediction for zero rotation, with measured feedback system time response



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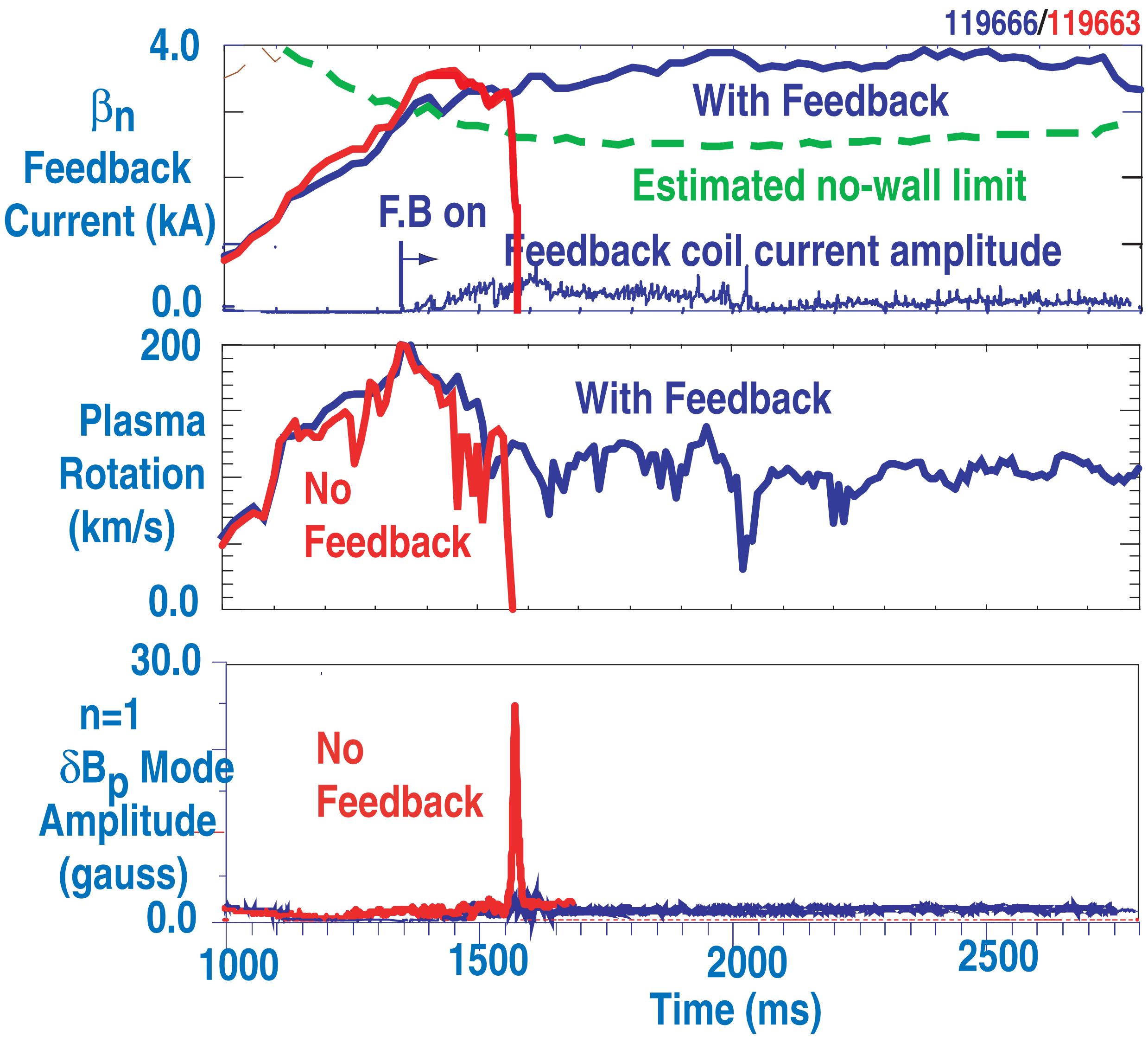
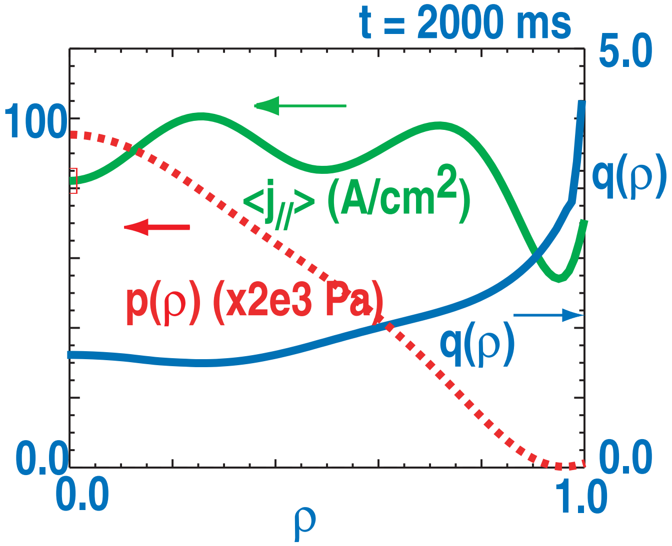
RWM FEEDBACK ASSISTS IN EXTENDING $\beta_N \approx 4$ ADVANCED TOKAMAK DISCHARGE MORE THAN 1 SECOND





- The rotation is similar for both cases

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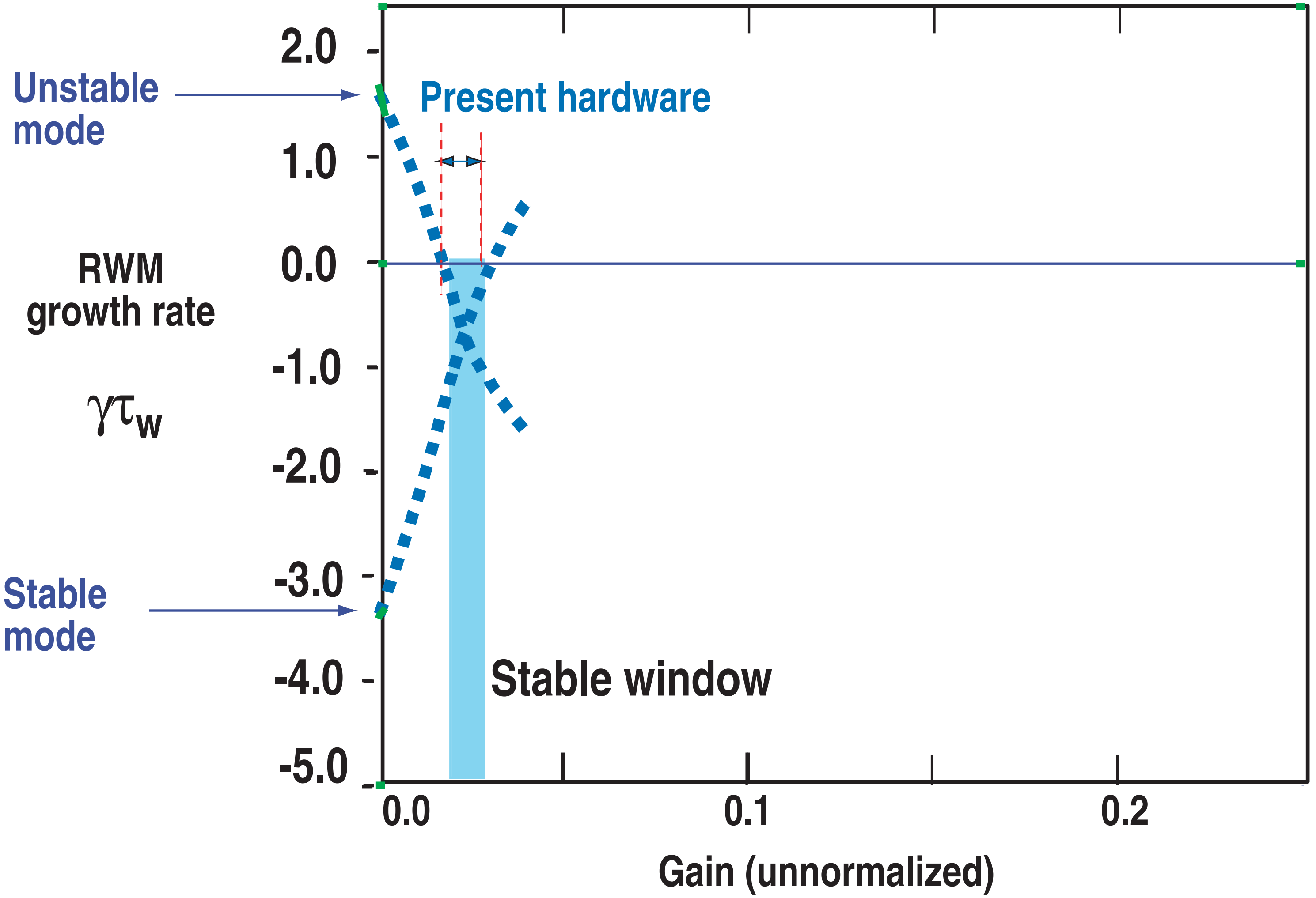
MARS ANALYSIS PREDICTS THAT STABLE FEEDBACK GAIN RANGE IS NARROW

- With experimental profiles and present hardware
- Stable mode becomes unstable with higher gain due to finite feedback time response



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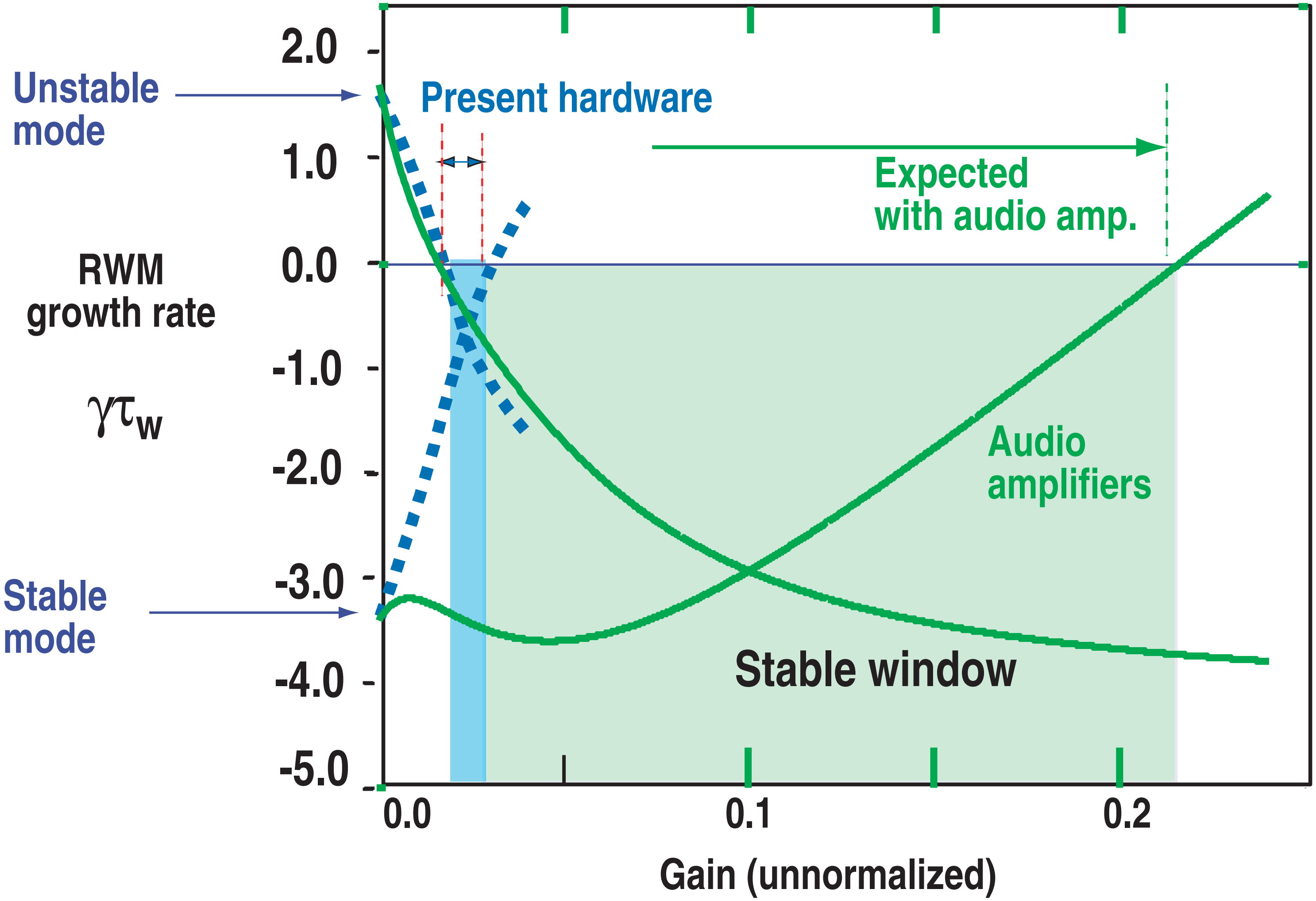
- τ_w is 2.5 ms in MARS-F

MARS ANALYSIS PREDICTS THAT STABLE FEEDBACK GAIN RANGE IS NARROW

- High-bandwidth audio amplifiers are being installed to increase the range of stable operation



- τ_w is 2.5 ms in MARS-F

OVERALL SUMMARY

- Active MHD Spectroscopy has been developed to investigate RWM stability (EX/3-1Rb)
  - Detailed comparison of experiments with damping models are now possible
  - Sound wave and kinetic damping model results are comparable to experimental values
  - Further improvements of models are needed for a quantitative comparison
- Direct magnetic feedback with I-coils has been demonstrated as an essential tool for achieving high β plasmas (EX/3-1Ra)
  - Internal Coils are more effective and efficient than External Coils
  - High β_n close to ideal-wall limit has been achieved with $\Omega_{rot} < \Omega_{crit}$
  - Feedback has assisted in sustaining advanced tokamak discharges with $\beta_n \approx 4$ over 1 second
  - High-bandwidth audio-amplifiers are being installed to increase the range of stable operation