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*RWM Stabilization in DIII-D Using I-Coils With High Speed Actuators**

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A new prototype actuator system driving 12 internal coils (I-coils) was used to help stabilize resistive wall modes (RWMs) up to beta_N~4. This approach is an alternative to rotational stabilization, which may not be adequate for fusion devices. VALEN modeling shows that as beta_N approaches the ideal wall limit, higher bandwidth and lower system delay time are required to stabilize the larger RWM growth rates. This actuator system consists of 6 transistor amplifiers (dc-40kHz), configured in 3 pairs, each driving 4 I-coils in an n=1 configuration. Initial experiments include the combination of I-coils for fast RWM stabilization and external C-coils with higher current capability for slower response dynamic error field correction. Effects of noise, maximum actuator current, and feedback system delay time on maximum achievable beta_N will also be presented.

RWM Research in DIII-D Provides Input for the ITER Design

- **Demonstrate RWM stabilization in low rotation plasmas above the no-wall limit and extrapolate to ITER**
- **Evaluate internal vs. external coil sets and their applicability for ITER**

Physics Goals for this Research Require RWM Stabilization at high β_N

- **Sustained, robust stabilization at C_β up to 0.7 and β_N ~ 4, where C_β =1 is the ideal β wall limit**
- **Transient operation at C_β ~ 0.9 or greater**
  - Stabilization of maximum growth rate, $\gamma = 3000\ s^{-1}$ (includes 50% safety margin)

$$[C_\beta = (\beta - \beta_{no\_wall})/(\beta^{ideal\_wall} - \beta_{no\_wall})]$$

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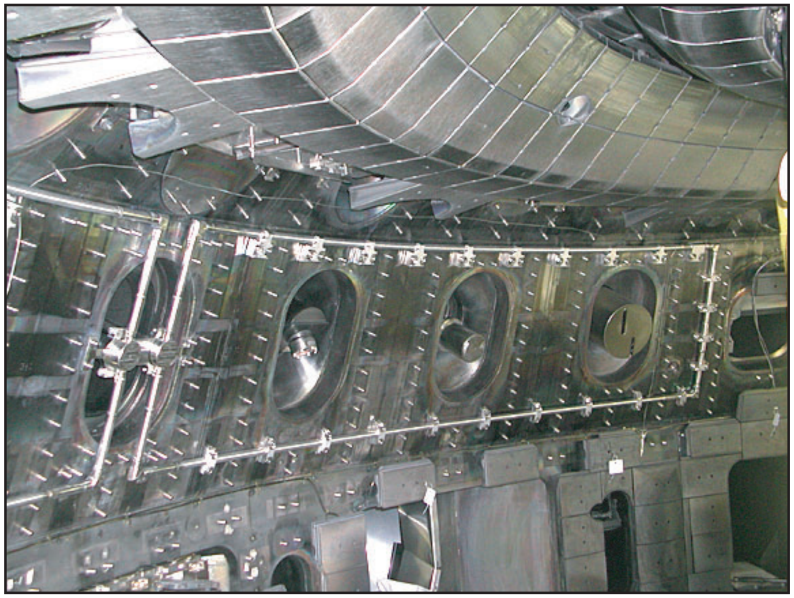
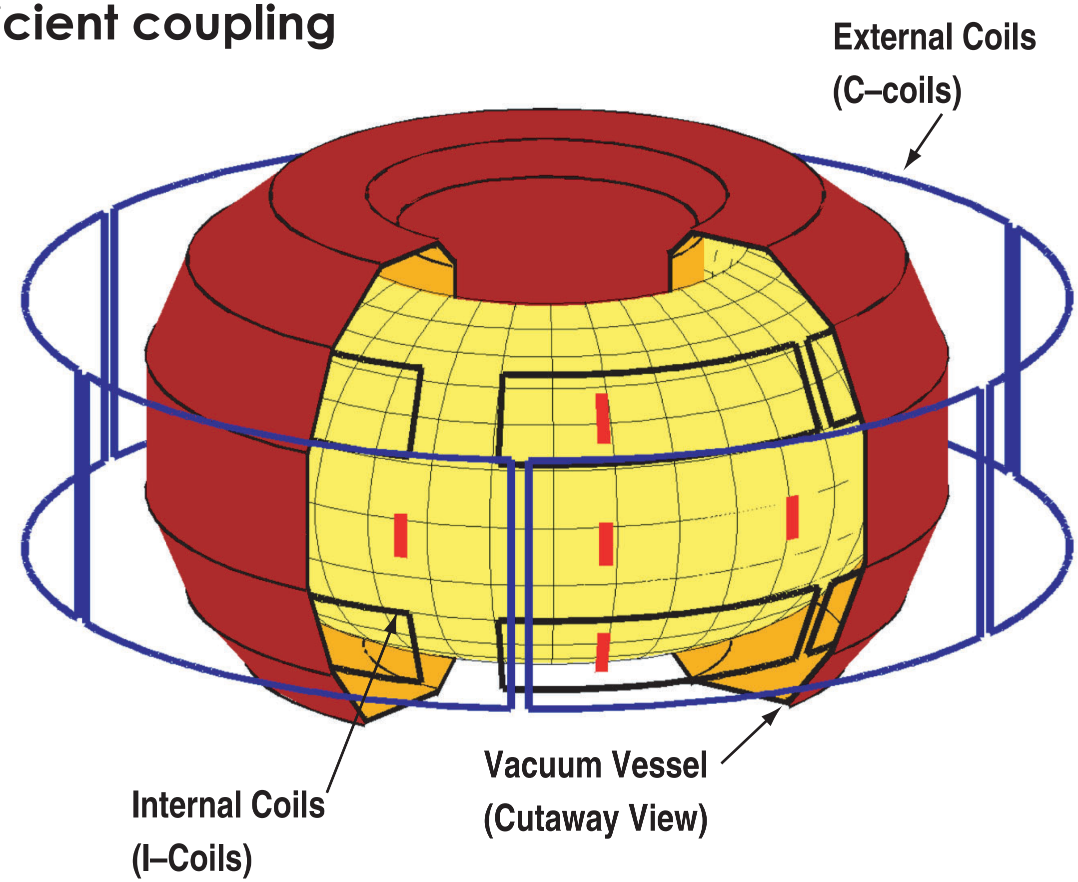
DIII–D's Internal Control Coils are an Effective Tool for Active and Passive Stabilization of the RWM

- Inside vacuum vessel: Faster time response for feedback control
- Closer to plasma: more efficient coupling

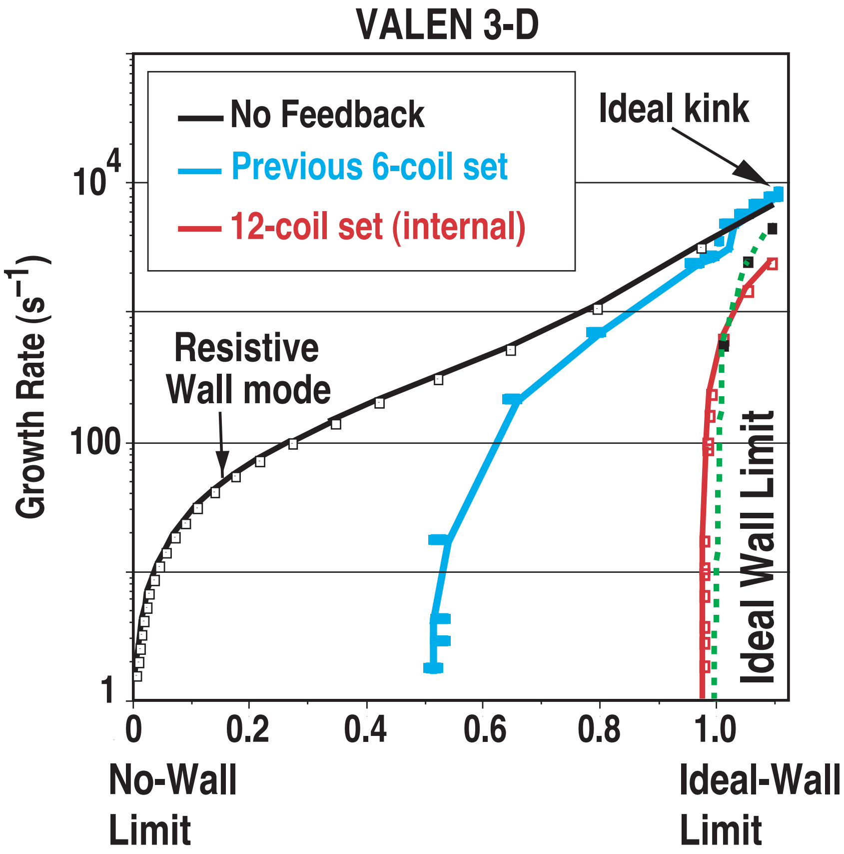


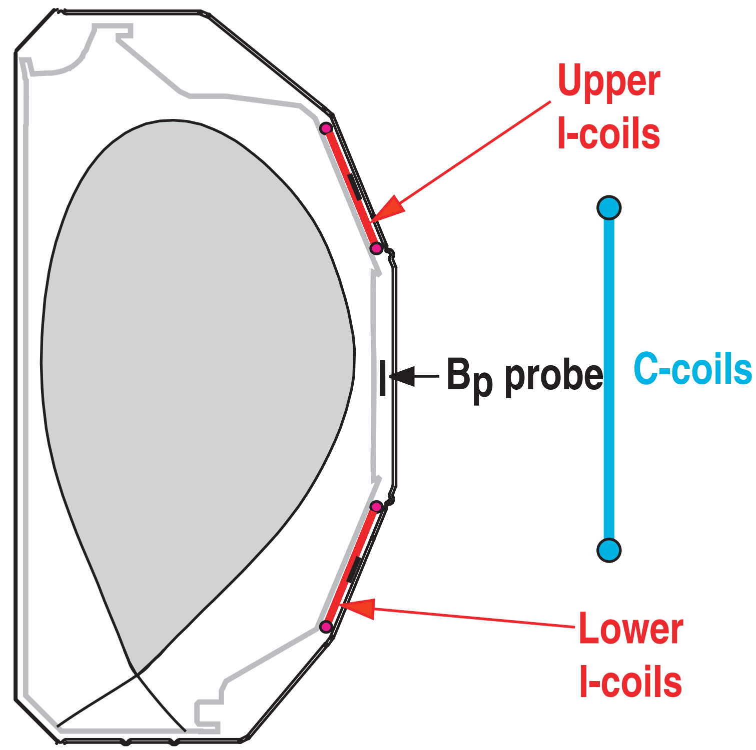


- 12 "picture-frame" coils
- Single-turn, water-cooled
- 7 kA max. rated current
- Protected by graphite tiles

I-coil Should Provide RWM Stabilization Comparable to an Ideal Wall

- **Modeling with VALEN (3D electromagnetics code) using realistic geometry**
  – Idealized amplifiers (optimistic)





MODELING OF THE DIII-D RWM FEEDBACK SYSTEM SHOWED THE NEED FOR HARDWARE UPGRADES

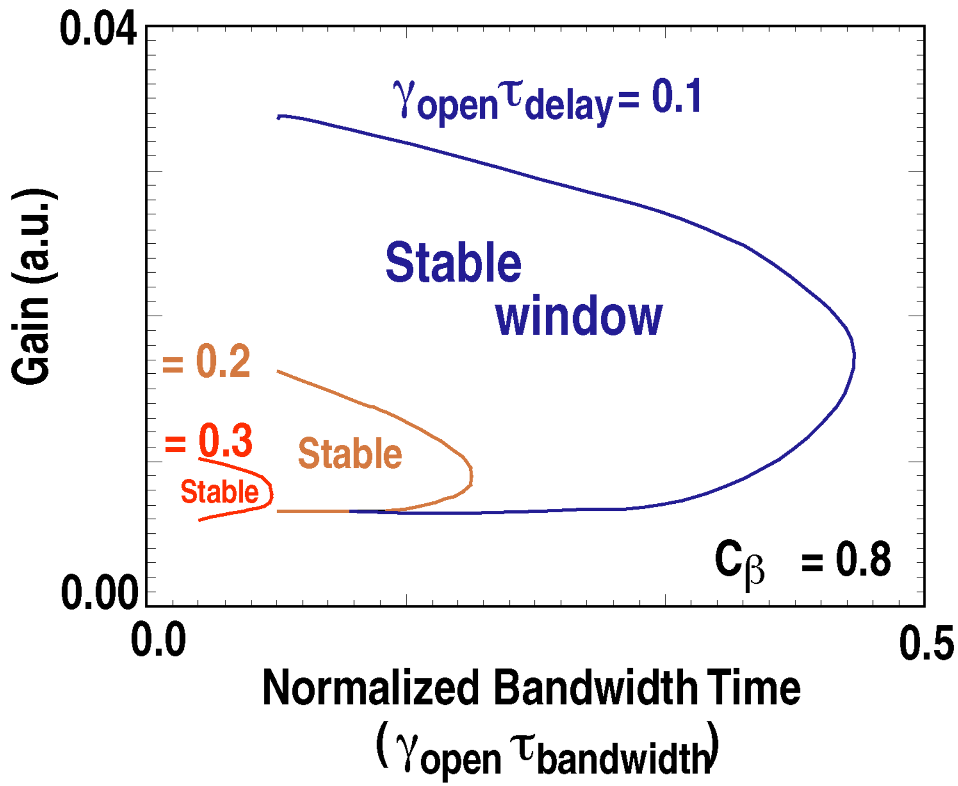
- Larger bandwidth to stabilize RWMs, especially at low rotation or near the ideal wall β limit
  - 20 kHz or higher

- Lower feedback system latency, i.e. shorter time delays
  - 65 μs or lower

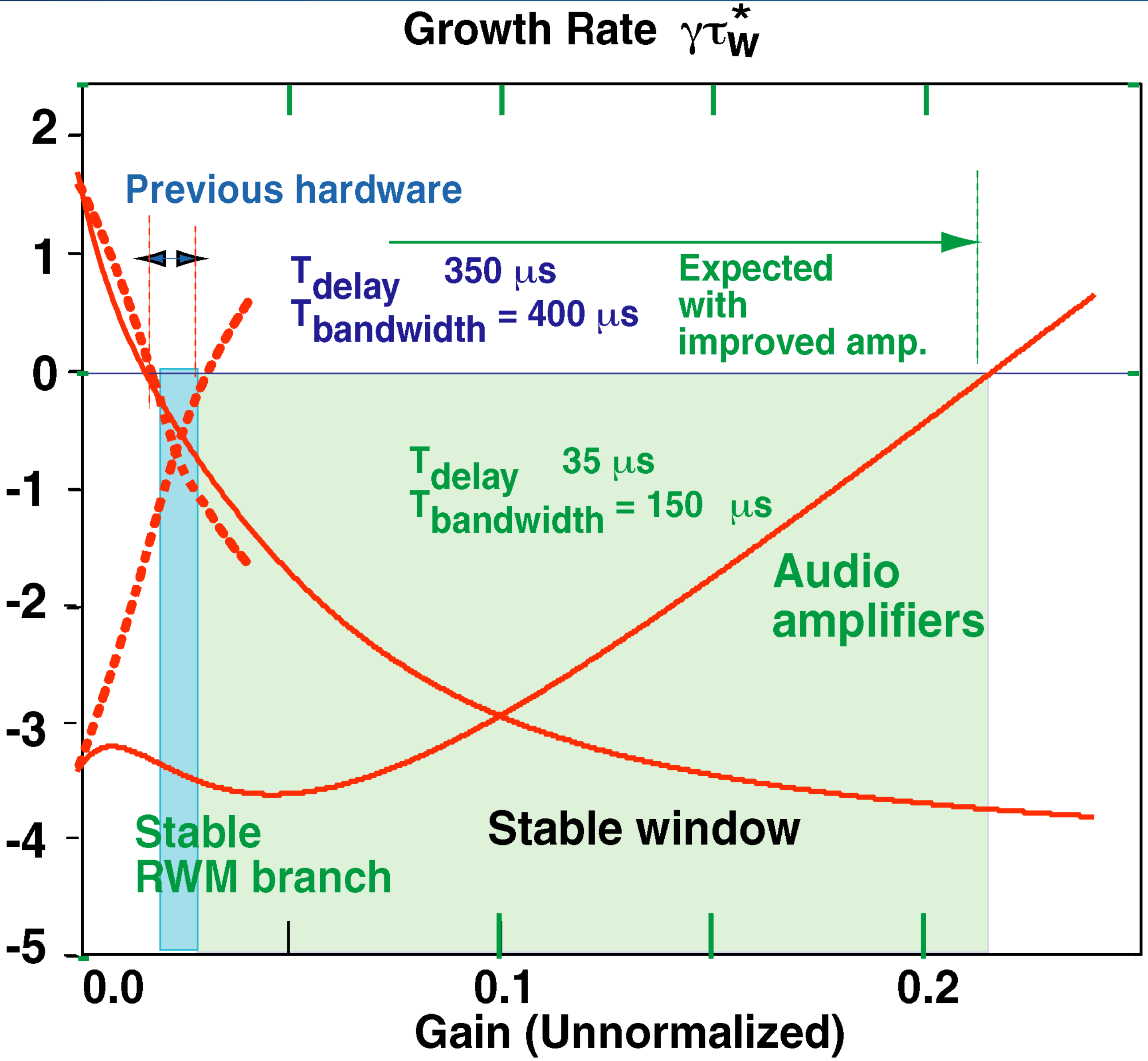
- Required I-coil current determined by system noise
  - 800 A

DIRECT FEEDBACK CONTROL AT HIGH β_N REQUIRES A FAST FEEDBACK SYSTEM

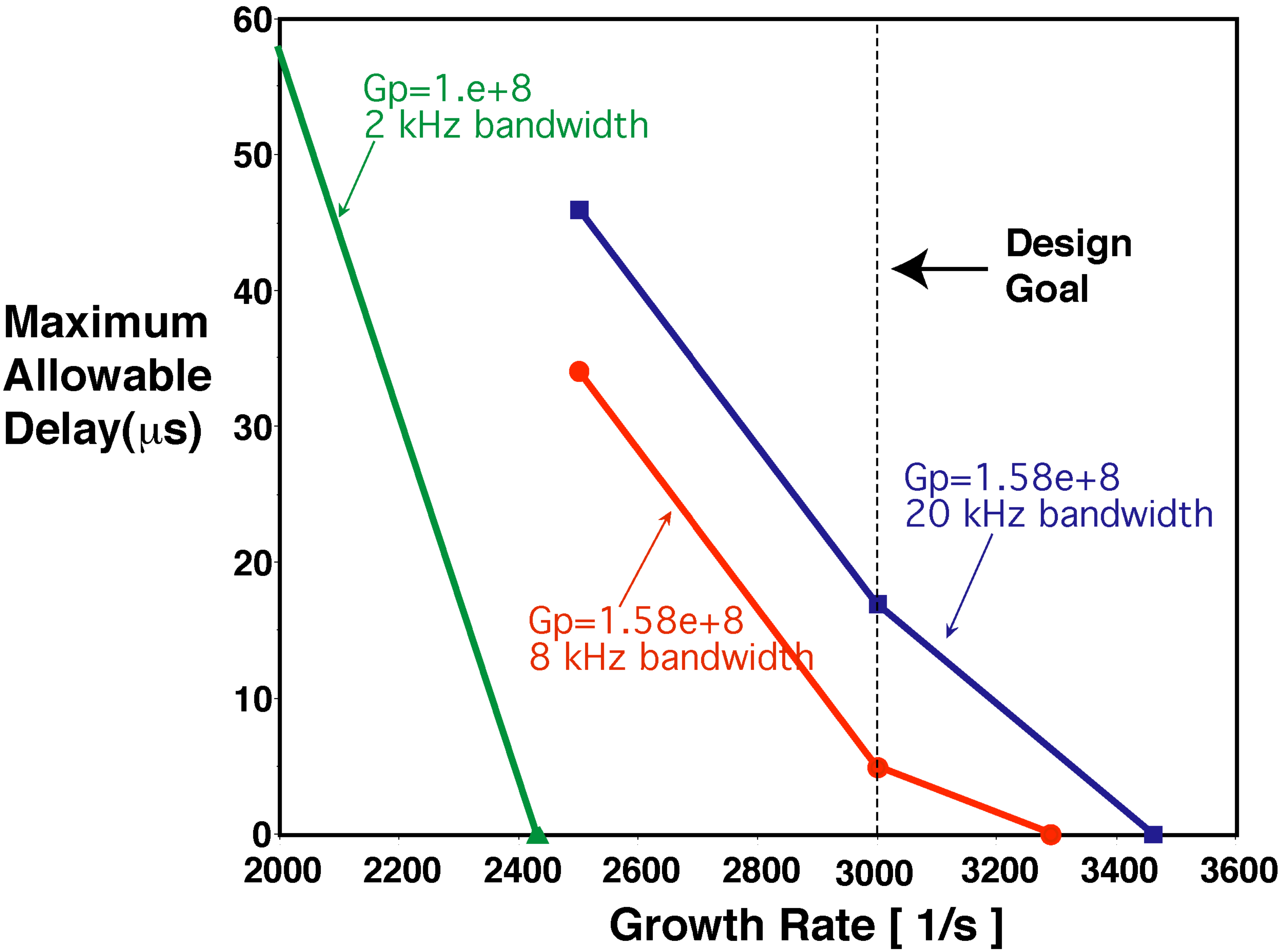
- **MARS-F modeling with amplifier response ~ $\dfrac{\exp(-s\tau_{delay})}{1 + s\tau_{band}}$**
  - No rotation
- **Stable operating window requires:**
  - Short control system delay ($\gamma\tau_{delay} < 0.3$)
  - Large amplifier bandwidth ($\gamma\tau_{band} < 0.4$)



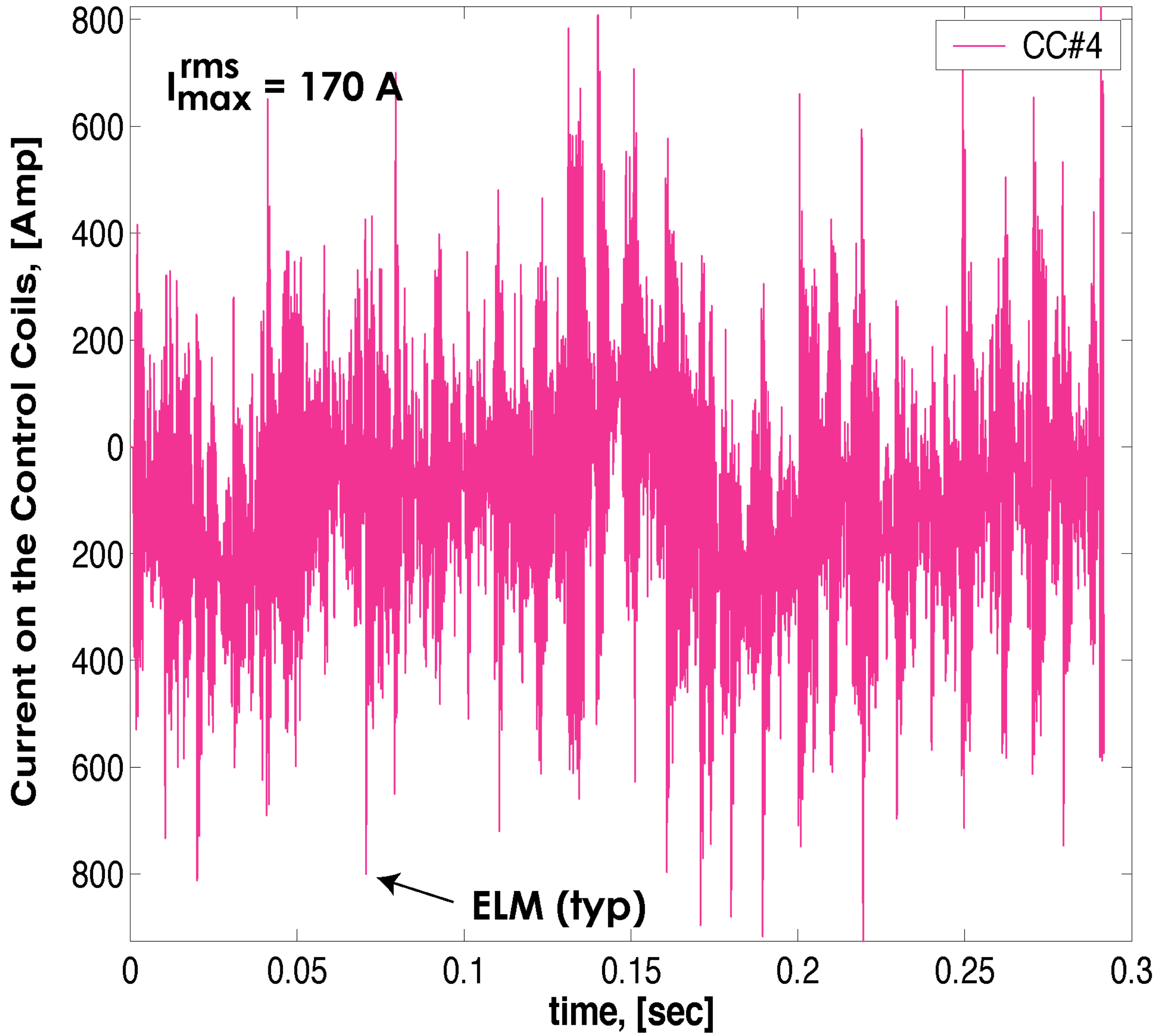
NEW HARDWARE (AUDIO AMPLIFIERS) EXPANDS THE OPERATING SPACE, ALLOWING OPERATION NEAR THE IDEAL WALL LIMIT



HIGHER SYSTEM BANDWIDTH CAN STABILIZE FASTER GROWTH RATES (OCCURRING AT HIGHER C_β)



TIME DEPENDENT VALEN MODELING SHOWS RWMs ARE STABILIZED IN THE PRESENCE OF NOISE AND ELMS



- FEEDBACK RESPONSE MODELED FOR REALISTIC DIII-D CONDITIONS
  - C_β = 0.9
  - B_{noise} = 1.5 G (rms)
  - V_{amp} = 50 V (max)
  - R/L = 2700 s^{-1}
  - Latency = 65 μs
  - G_p = 6.3 10^{+7}

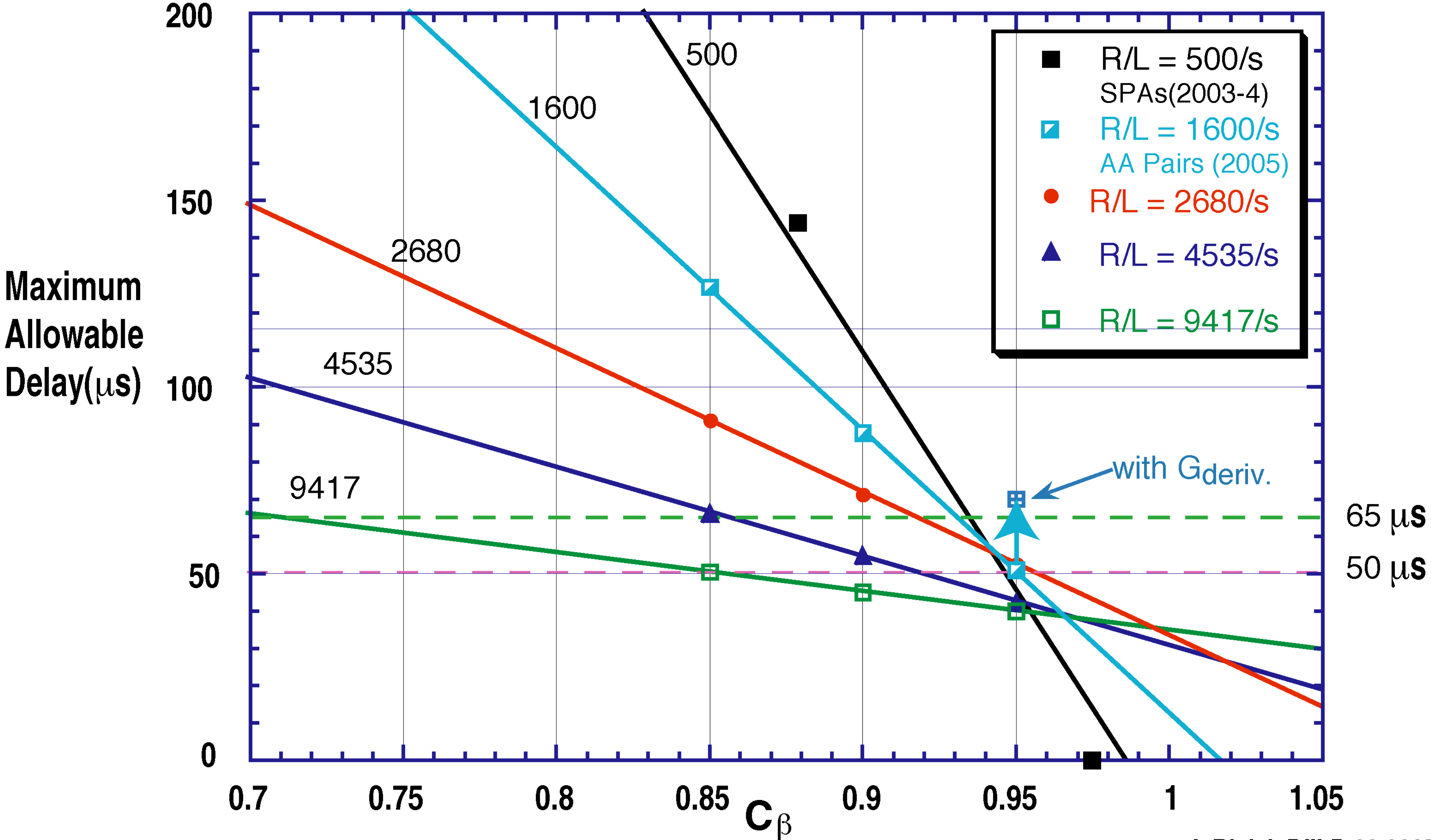
O. Katsuro-Hopkins

HIGH BANDWIDTH TRANSISTOR AMPLIFIERS MEET THE DIII-D DESIGN REQUIREMENTS

Audio Amplifier

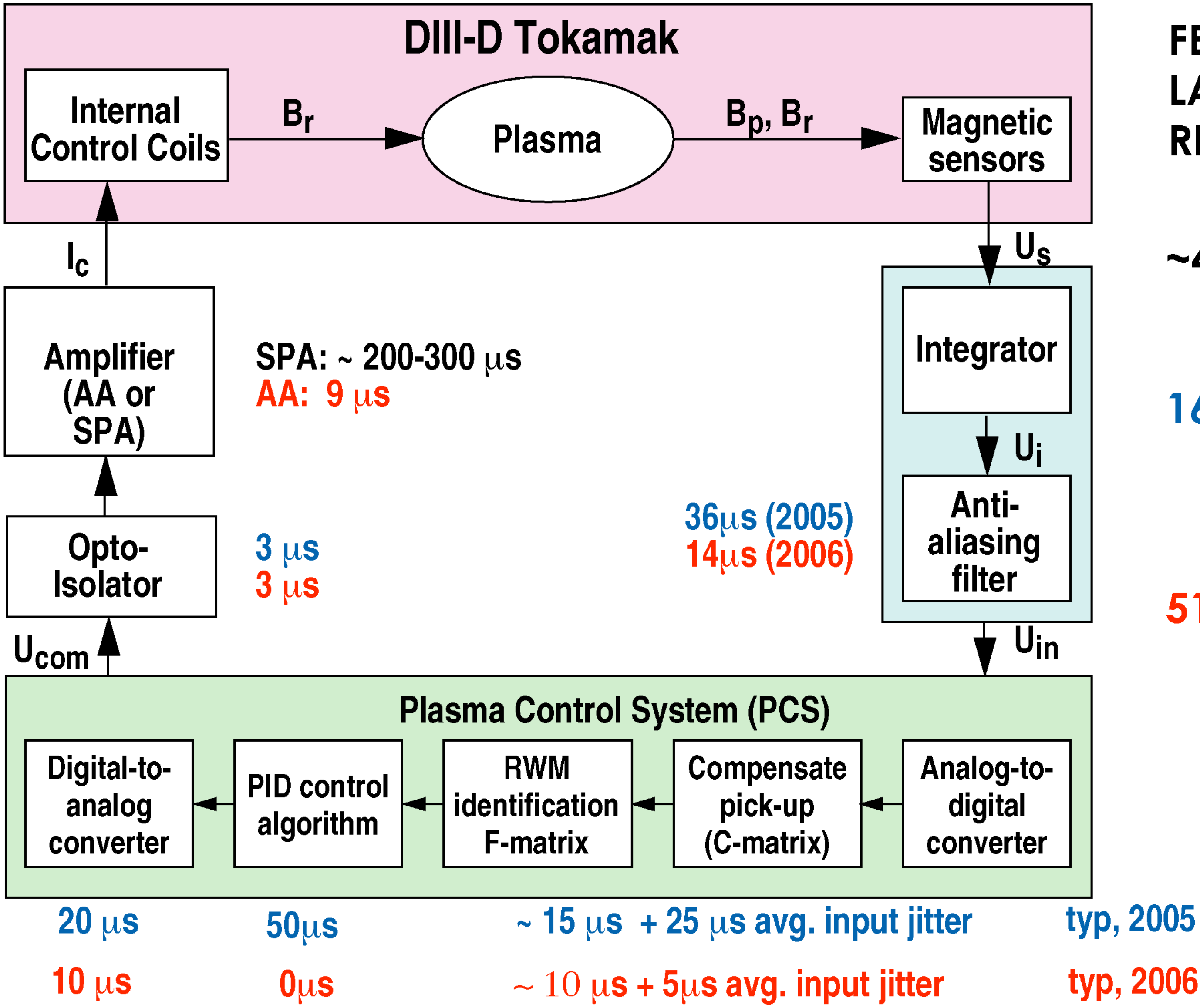
- DIII-D amplifiers derived from audio amplifier technology
  - 100 V peak
  - 200 A peak
  - Voltage Gain ~ 30
  - Parallel operation (up to 6=1200A)
  - DC to >40kHz
  - 8-9 μs amplifier delay time
  - 2 AAs per I-coil quartet used in 2005 experiments

VALEN MODELING SHOWS THAT SYSTEM DELAY MUST BE MINIMIZED FOR STABILIZATION NEAR THE IDEAL WALL LIMIT



J. Bialek DIII-D.09.2005

LOWER SYSTEM LATENCY IN 2006 WILL ALLOW OPERATION NEAR THE IDEAL WALL LIMIT



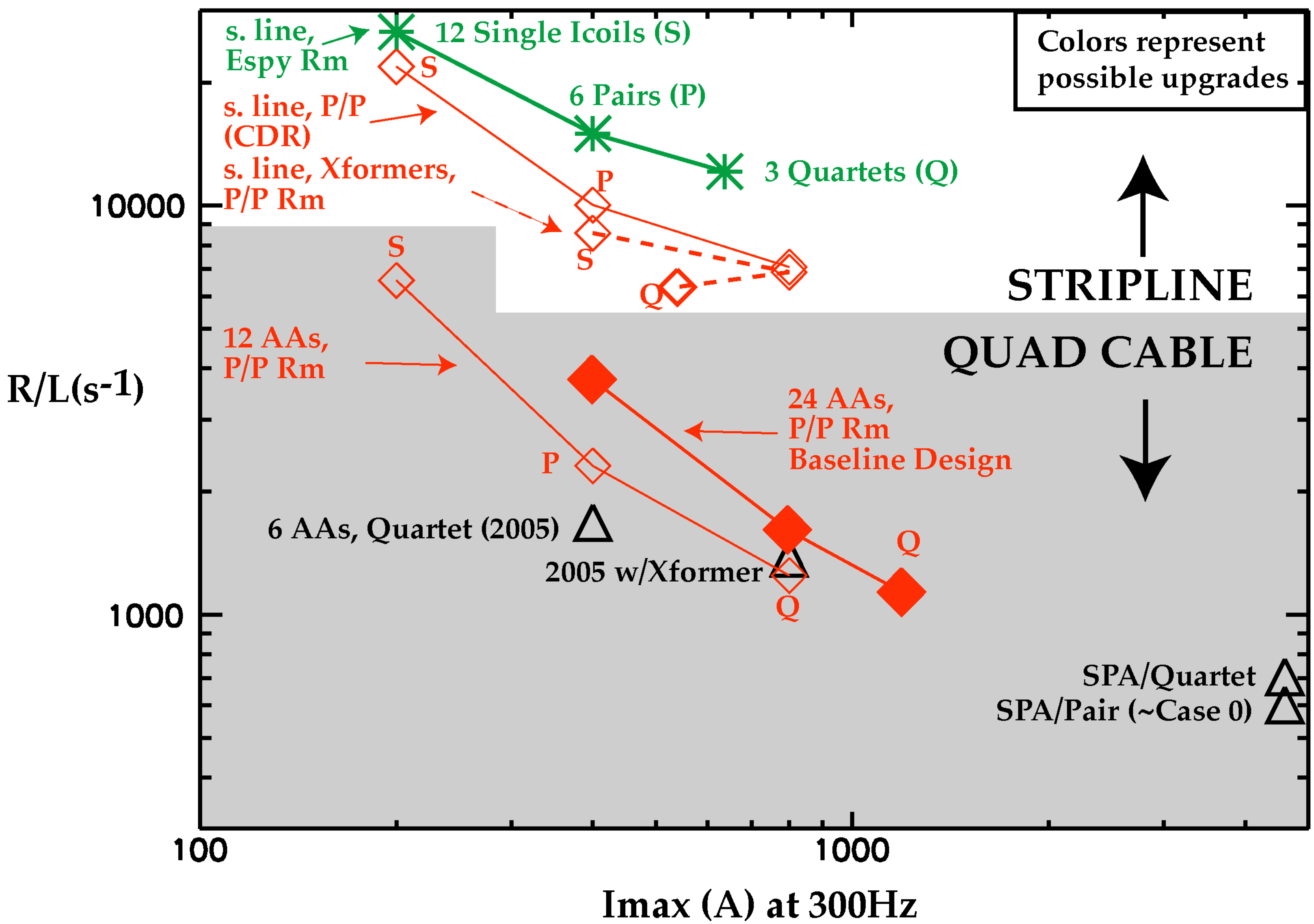
FEEDBACK SYSTEM LATENCY HAS BEEN REDUCED

~400µs with SPAs (2003-2005)

160µs with AAs & Baseline PCS (2005)

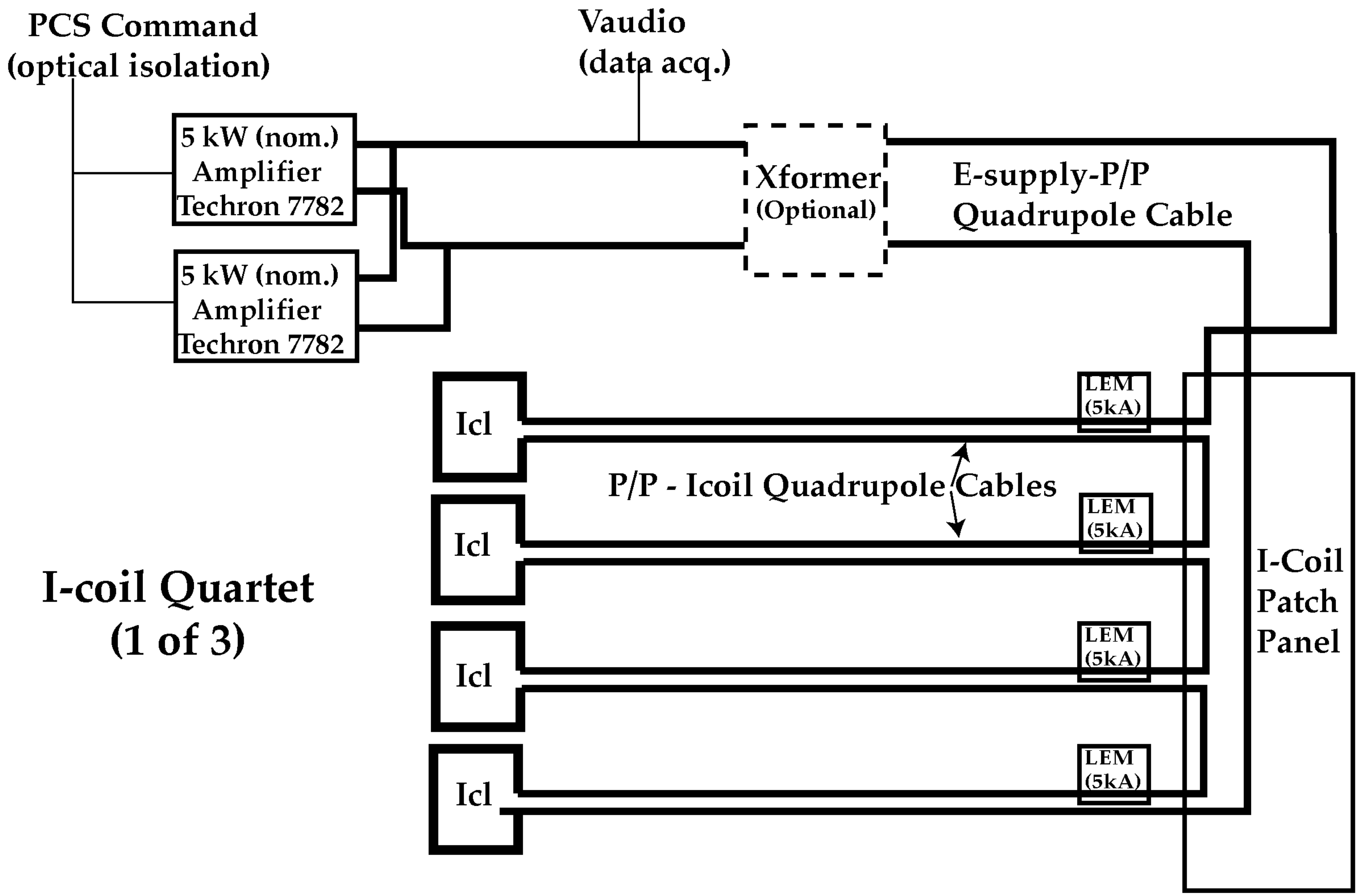
51µs with AAs & upgraded PCS (2006)

A VARIETY OF I-COIL CIRCUIT CONFIGURATIONS ARE POSSIBLE TO OPTIMALLY MATCH WITH SYSTEM LATENCY



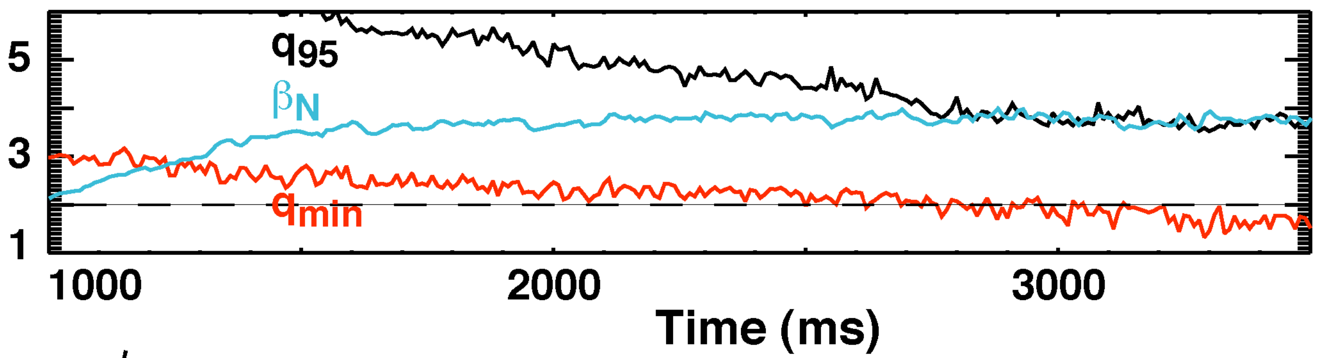
- Stripline dramatically increaseses circuit response
- Stripline R/L is too high for system latency in 2006

AUDIO AMPLIFIERS CAN BE CONNECTED TO I-COILS IN A VARIETY OF CONFIGURATIONS (QUARTET IS TYPICAL)

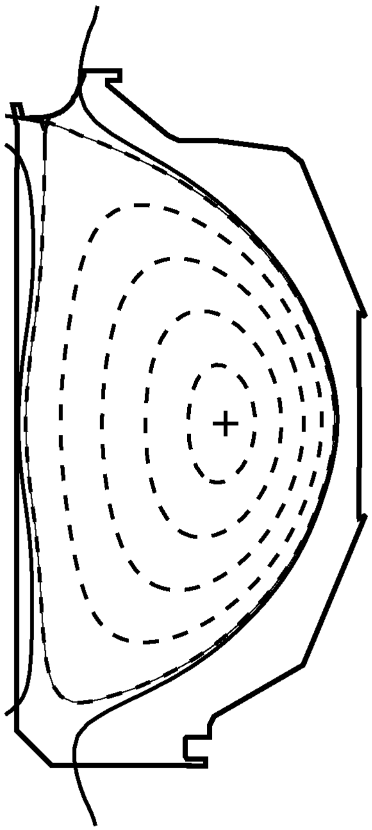


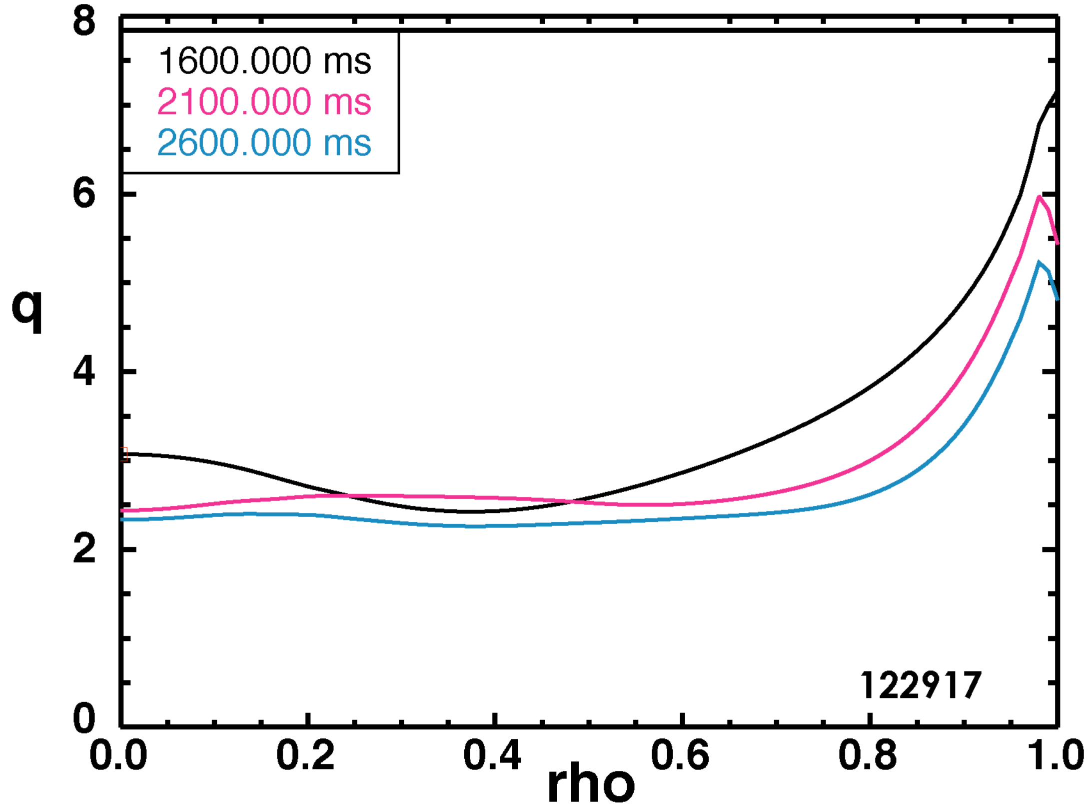
- Prototype system uses existing components whenever possible
- R and L of existing cables good match to PCS latency
  - -R/$L_{quartets}$ = 1130
  - -R/L_{pairs} = 1600
  - -R/$L_{singles}$= 3730
- PCS latency
  - -160μs (2005)
  - - 51μs (2006)

HIGH qmin DISCHARGES ARE A SUITABLE TARGET FOR EVALUATING THE AUDIO AMP PROTOTYPE SYSTEM

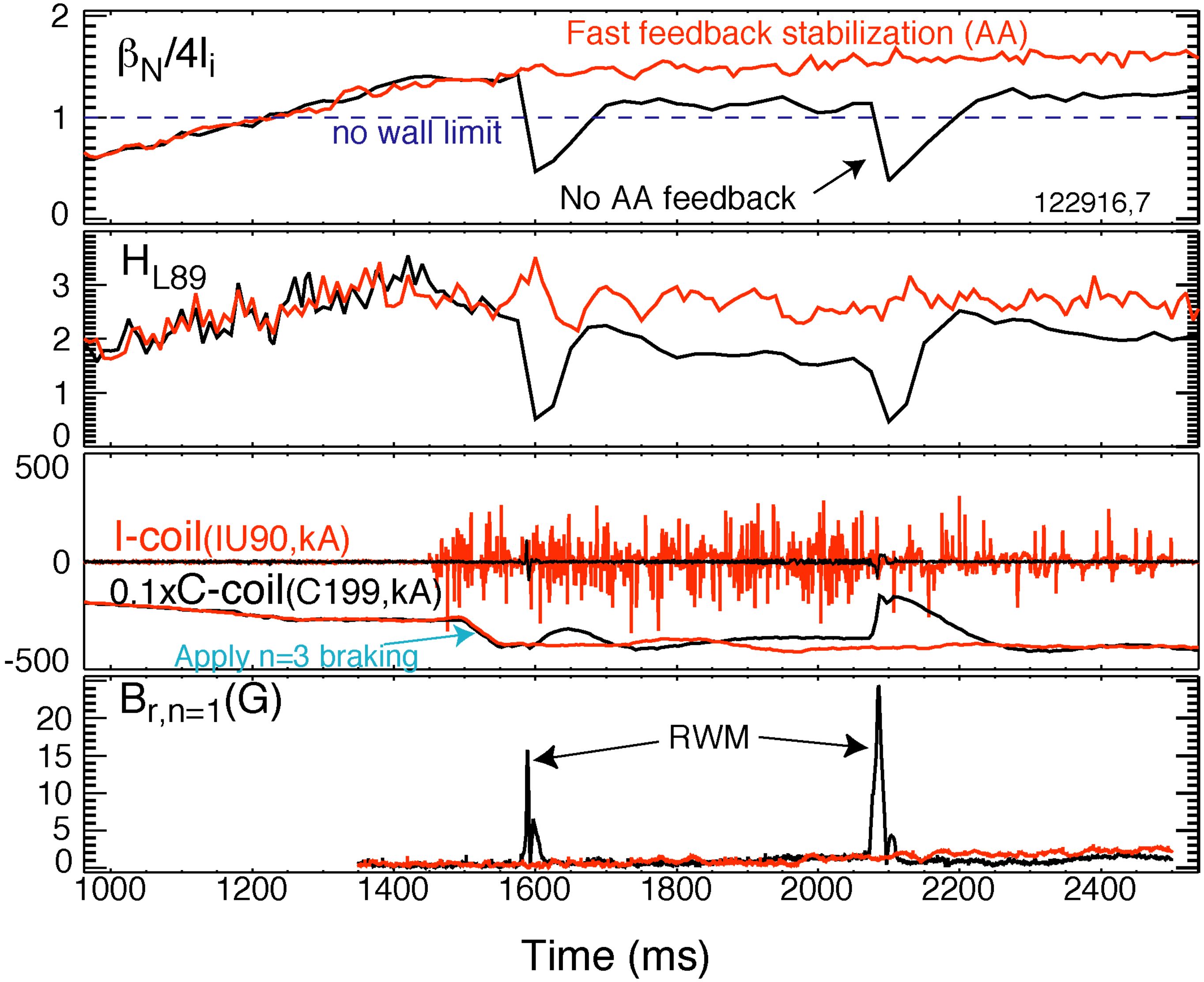


- With AA feedback, $q_{min} > 2$ and $\beta_N > 3.5$ for 1.4 sec
- Above the no wall limit for 2.3 sec
  - Terminated by tearing modes, not RWM





HIGH SPEED AUDIO AMPLIFIERS (AAs) CAN HELP STABILIZE RWMs

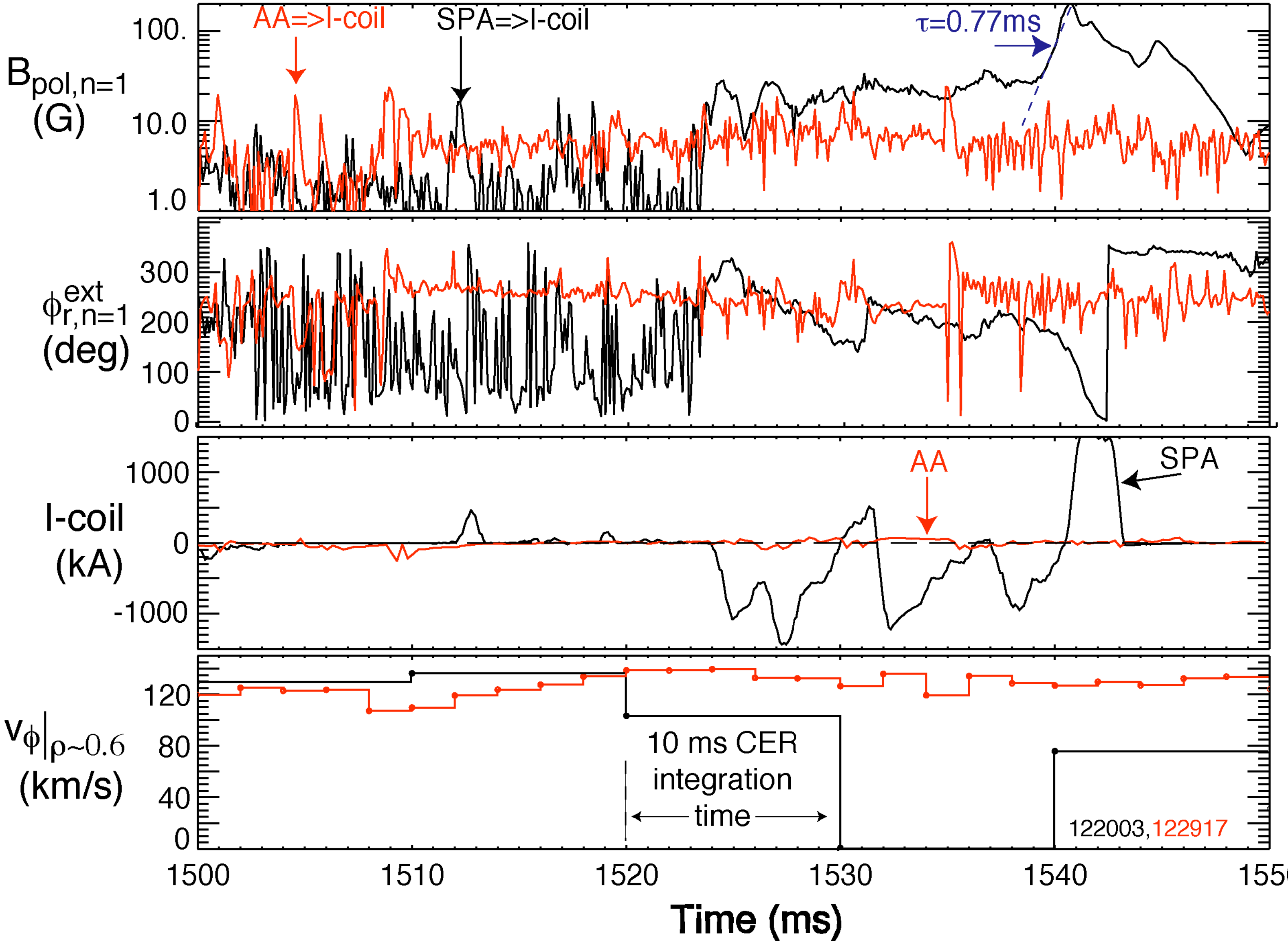


Discharge with AAs (red) remains above $4l_i$ for 2.3 s (terminated by tearing mode, not RWM)

No confinement degradation above the no wall β limit

Fast AAs (I-coils) coupled with slower response switching power amplifiers on C-coils provide effective RWM stabilization well above the no wall β limit

SLOW RWM FEEDBACK (SPA PWR SUPPLIES=>Icoils) REQUIRES LARGER CURRENT FOR STABILIZATION THAN AAs=>Icoils



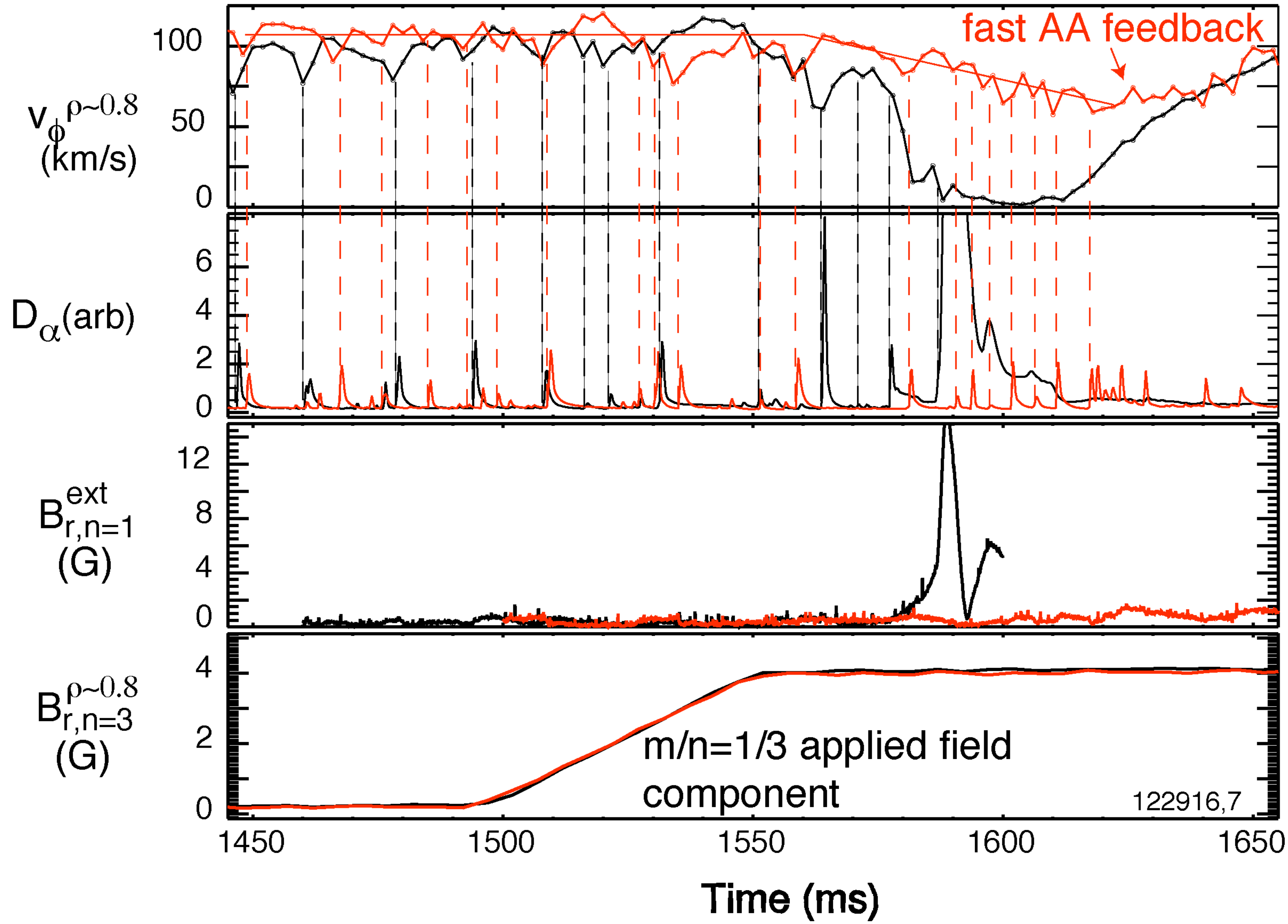
SPA (to Icoils) stabilizes RWM until rotation collapses

Fast Audio Amps (AA,red) assist in RWM stabilization

Icoil currents are lower with AAs and system latency (not shown) is reduced compared to SPAs

Rotation remains high with fast feed-back (AAs)

WITHOUT FEEDBACK, n=3 BRAKING AND ELMs TOGETHER CAN REDUCE ROTATION TRIGGERING AN RWM



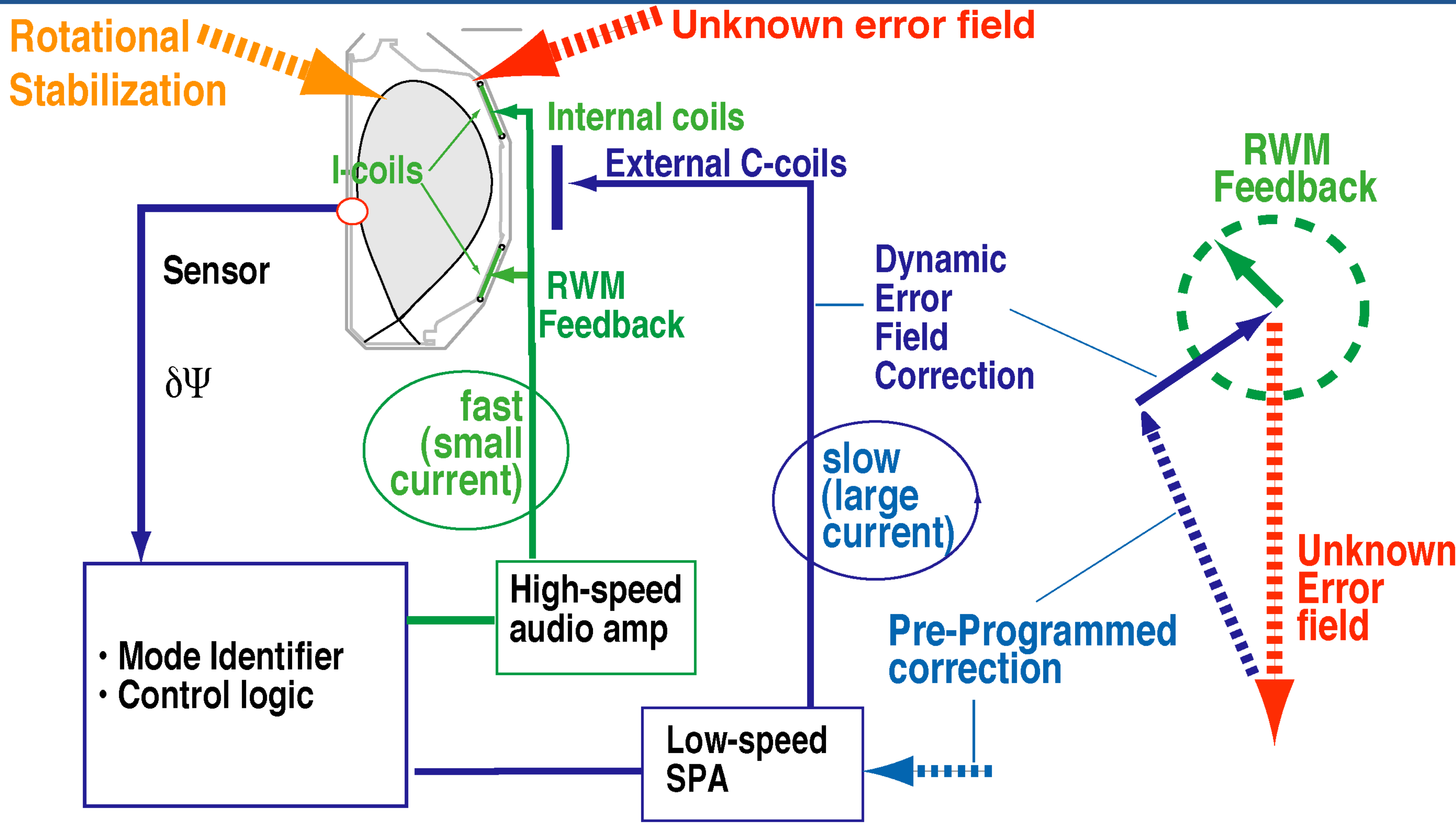
AAs provide feedback stabilization even with decreasing rotation

ELMs transiently reduce rotation while applied n=3 exhibits a longer decay

C-coil used for n=3 braking and slow (~100 ms) n=1 feedback response

Strait CP1.22

Two Independent Power Supply Combination is Effective and Efficient for Improving n=1 RWM Stabilization



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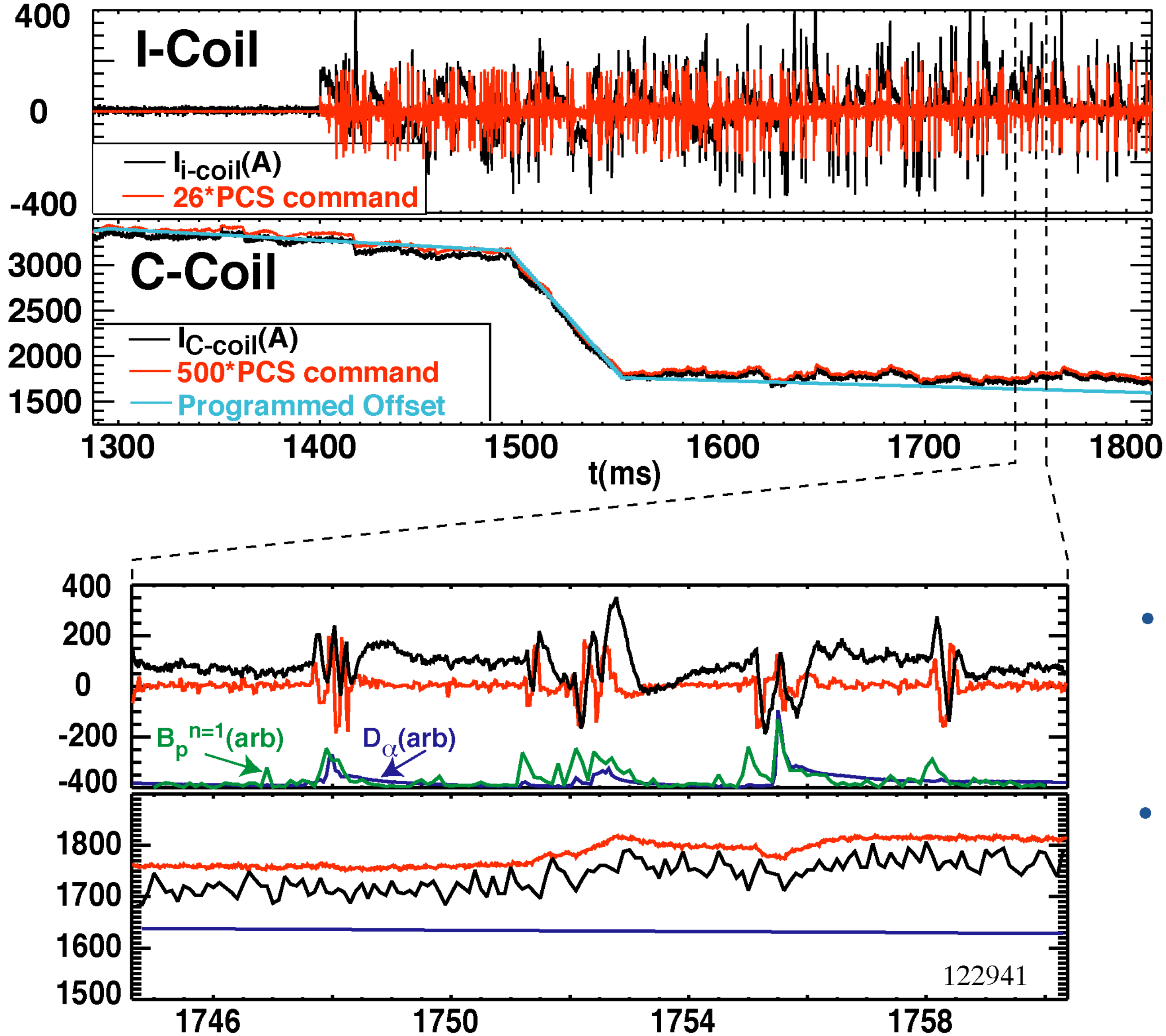
SIMULTANEOUS FEEDBACK (fast I-coil and slow C-coil) HAS SUCCESSFULLY STABILIZED RWMs



- **I-coil uses voltage feedback ($V_{I\text{-coil}} = 26\ V_{PCS\ Cmd}$)**
- **PCS: G_p, G_{deriv} = 16,144**
- **PCS: τ_p, τ_{deriv} = 10,50 μs**

- **C-coil uses current feedback and a programmed offset ($I_{C\text{-coil}} = 500\ V_{PCS\ Cmd}$)**
- **PCS: $G_p = 1$**
- **PCS: τ_p = 10 ms**

- **Fast system responds to ELMs and other n=1 activity**

- **Slow system provides**
  - **- preprogrammed n=1 field**
  - **- n=1 dynamic error field correction**
  - **- n=3 braking**

FUTURE WORK

- Counter beam (2006) will allow experiments with low rotation in an ITER-like scenario
  - Low rotation reproducible target discharges (2002-2005) have been difficult to obtain with high momentum CO injected beams
- Audio Amplifier system upgrade to 24 units (2006) will allow higher current and more flexibility
  - 1200A maximum current (I-coil quartets)
  - Individual I-coil control for n=2 RWM stabilization and smart shell algorithms
- Plasma control system (PCS) upgrade will reduce latency (51 μs) and better match PCS response to AA bandwidth and external circuit R/L
  - Other experiments such as tearing mode control (up to 50 kHz) and TAE excitation are being considered

SUMMARY

- Modeling predicts high speed actuators driving I-coils will allow operation near the ideal wall β limit without rotational stabilization if feedback system latency is sufficiently low (< 65 μs)

- A prototype wide bandwidth audio amplifier system driving I-coil quartets has been used for feedback stabilization of RWMs
  - I_{max} = 700 A (with step-down transformers)
  - System latency ~ 160 μs

- A combination of C-coil (slow feedback) and I-coil (fast feedback) has demonstrated n=1 feedback stabilization and operation above the no wall limit for up to 2.4 sec in high q_{min} discharges, $\beta_n^{max} \sim 4$