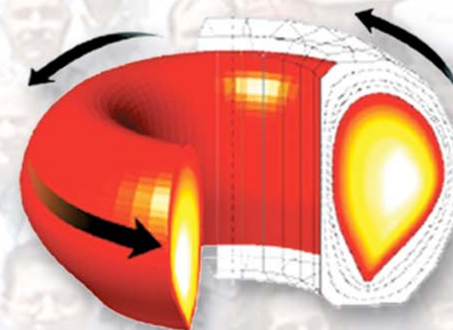
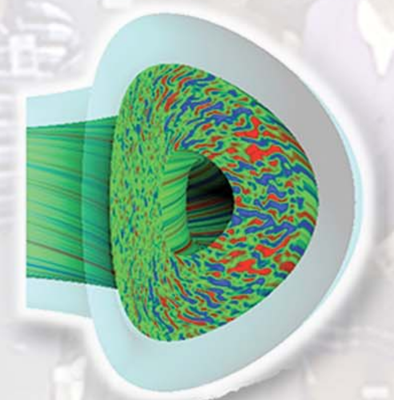
Resistive Wall Mode Control for ITER

by
A. Garofalo



Presented to
DIII–D Program
Advisory Committee



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DIII–D
NATIONAL FUSION FACILITY
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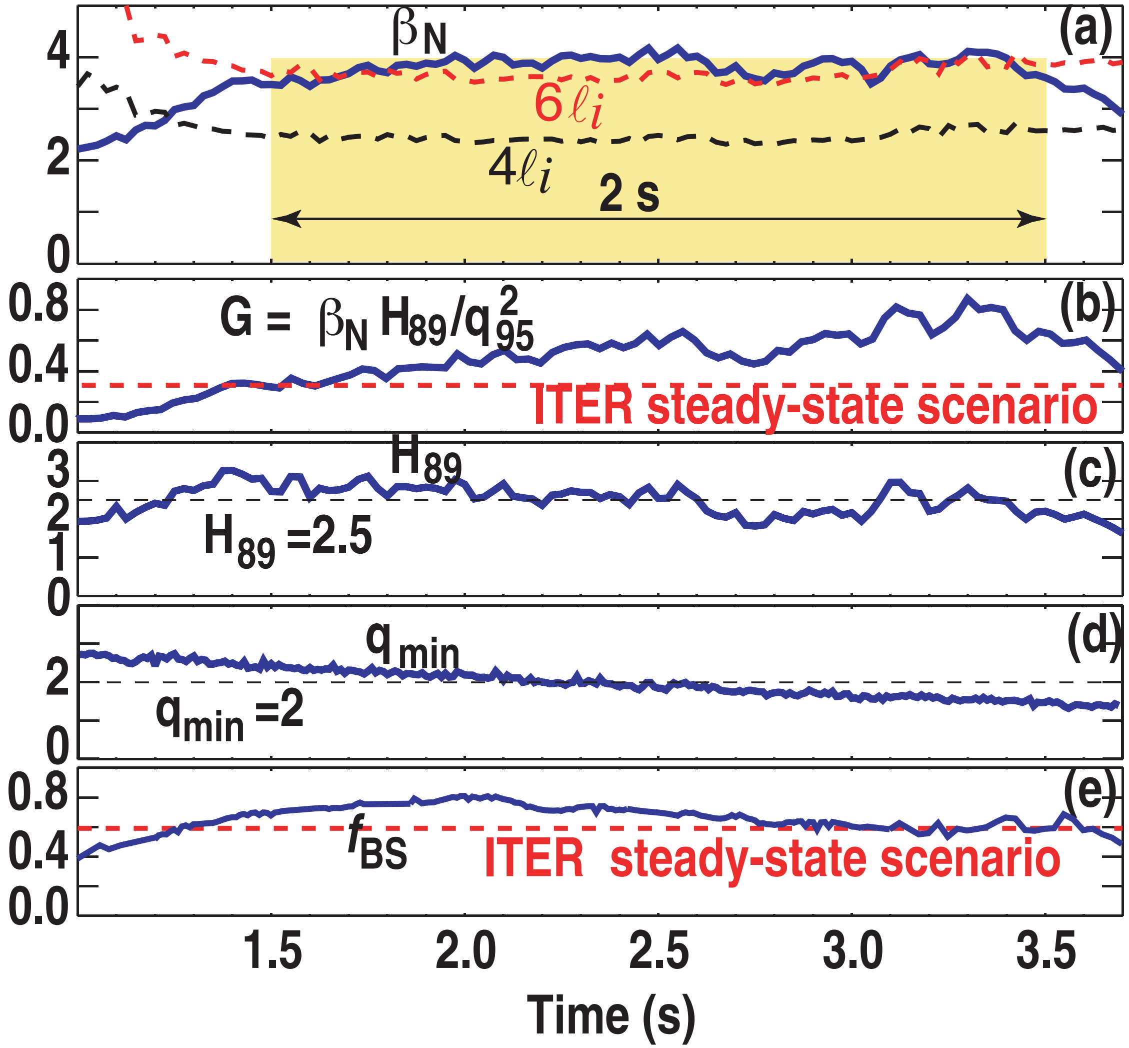
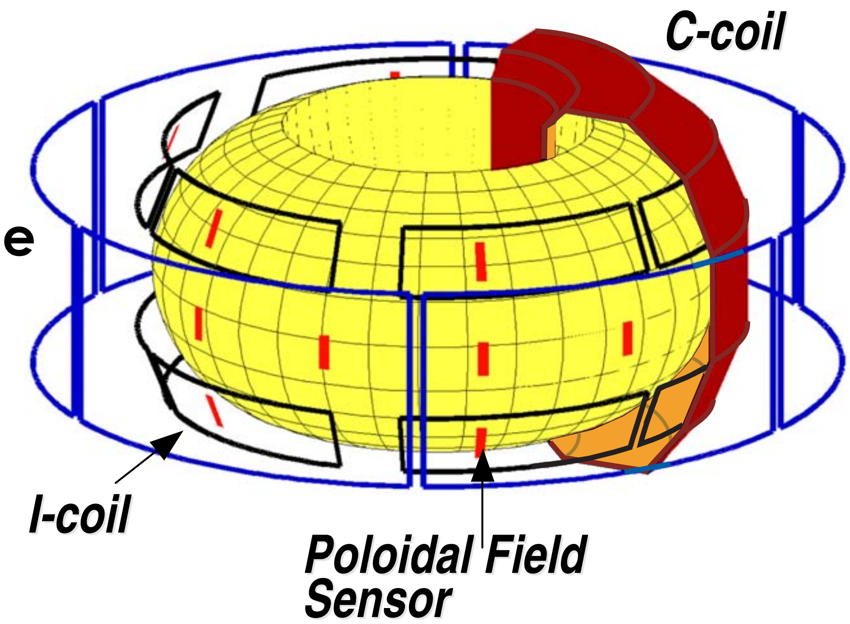
RWM Stabilization Has Opened New Regimes of AT Operation Above the No-Wall Beta Limit

- β_N ~ 4, β_T ~ 4-7%
- $H_{89} \geq 2.5$
- $f_{BS} \geq 60\%$, $f_{NI} \geq 80\%$
- C-coil and I-coil used for simultaneous feedback control of error fields and RWM
- New tools in FY06–07 will help advance the understanding of RWM control
  - Balanced injection for ITER-relevant rotation
  - Additional fast amplifiers for larger control currents with low latency



DIII-D is Uniquely Equipped to Lead on the Path to Predictive Understanding of RWM Stabilization

- Close fitting vacuum vessel for wall stabilization of the ideal kink
- High heating power availability for reliable access into wall stabilized regime
- Separate control of plasma rotation and heating
- Two sets of non-axisymmetric coils for independent control of error fields and RWM
- Extensive diagnostics for equilibrium reconstruction and stability modeling



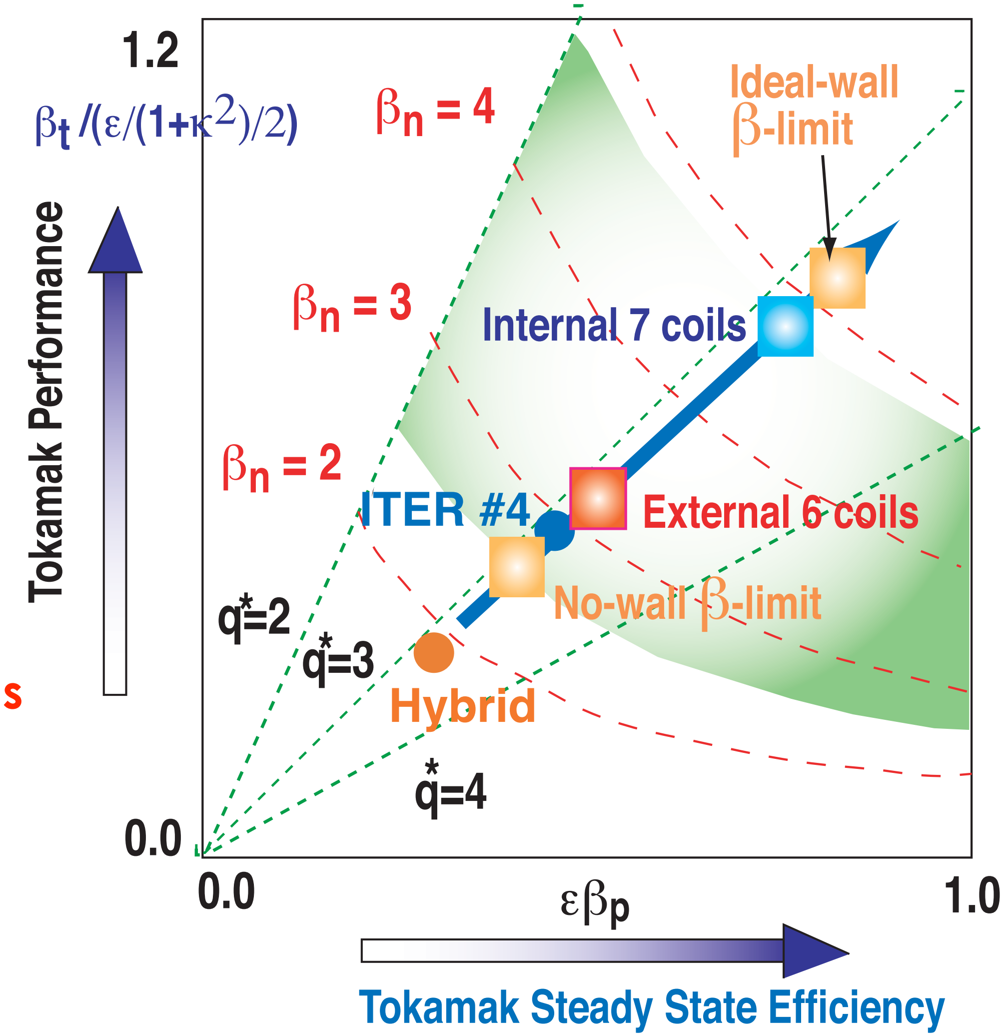
DIII-D is the only machine in the world that can support research on all of:

- Basic RWM physics
- RWM feedback physics
- AT physics at high beta (⇒100% bootstrap)

ITER Steady-State Scenario May Require RWM Feedback Stabilization

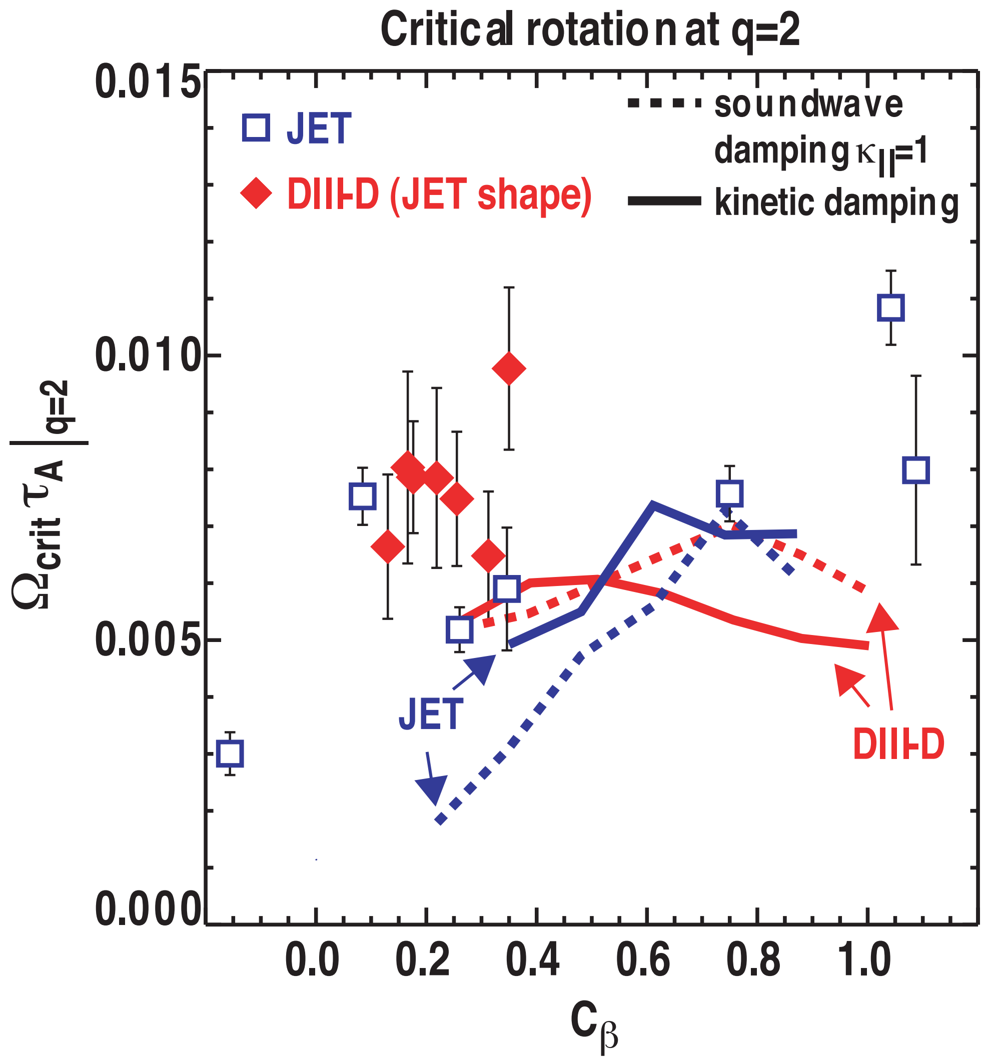
- **ITER steady-state scenario requires RWM stabilization for operation at target β_N ~ 3**
- **Predicted plasma rotation in ITER may be insufficient to provide RWM stabilization without an active feedback system <<-- Need to demonstrate sustained RWM feedback stabilization**
- **Present ITER design of external error field correction coils is possibly not sufficient for RWM feedback stabilization significantly above $\beta_N^{no\text{-}wall}$**
- **DIII-D tokamak is uniquely suited to deliver experimental results needed to benchmark codes and support ITER design modifications**
  - External and internal control coils
  - Capability to produce non-rotating high beta plasmas

VALEN modeling:
ITER with blanket (ports covered)



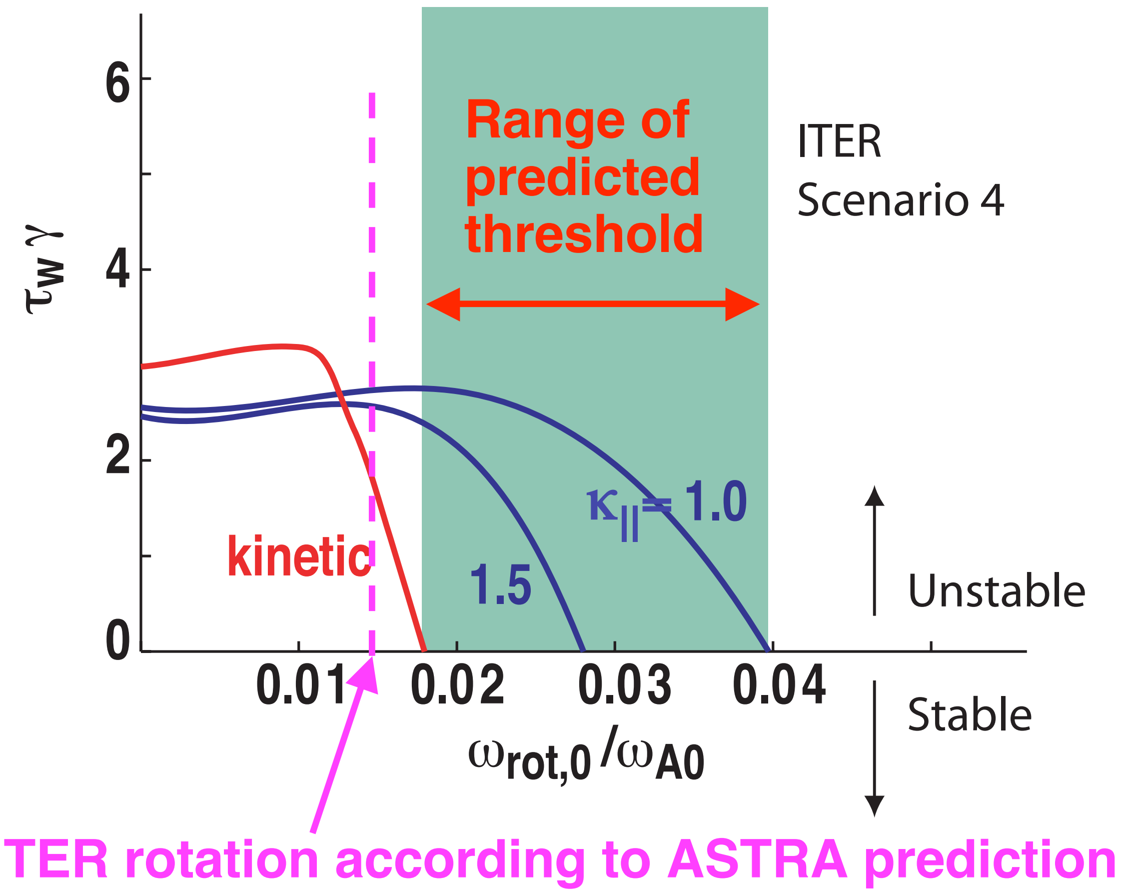
Predictive Capabilities of RWM Theoretical Models Are Qualitatively Correct, but Further Work Is Needed

- **MARS modeling of plasma rotation threshold for RWM stabilization is within a factor of 2 from measurements**
- **Agreement of threshold in similar DIII-D and JET plasmas supports the independence of the stabilization mechanism from machine size**



Modeling of Rotational Stabilization in DIII-D Does Not Extrapolate Favorably to ITER

- **MARS predictions of threshold rotation in ITER is within a factor of 2 for different damping models (sound wave damping, kinetic damping)**
- **Expected plasma rotation in ITER steady-state scenario is predicted to be at best marginal for RWM stabilization**



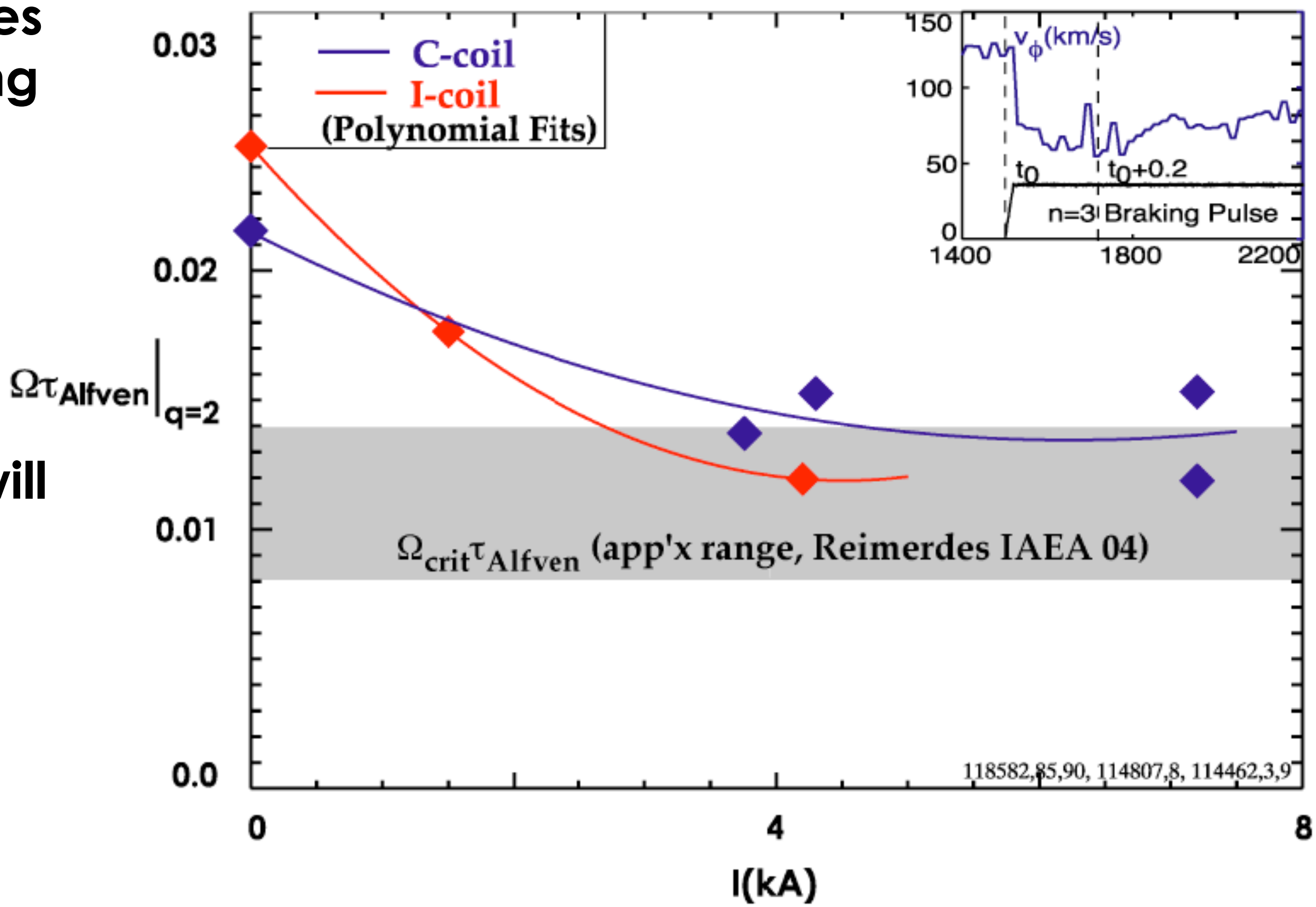
[Q. Liu, et al, *Nucl. Fusion* **44** (2004) 232]

Rotation Control is Needed to Explore Regime of High Beta and Low Rotation

- **Plasma rotation is sufficient to stabilize RWMs in most DIII-D scenarios with co-injected NB**
  - Unidirectional NB heating in high beta plasmas applies strong torque
  - Difficult to test RWM feedback control under realistic reactor conditions
- **Resonant and non-resonant magnetic braking to reduce the rotation have disadvantages**
  - Feedback system tends to respond to applied resonant braking field
  - Fine control is difficult: rotation tends to lock
  - Once locked, braking field may excite islands in the plasma
- **Balanced injection will provide effective rotation control without magnetic perturbations**

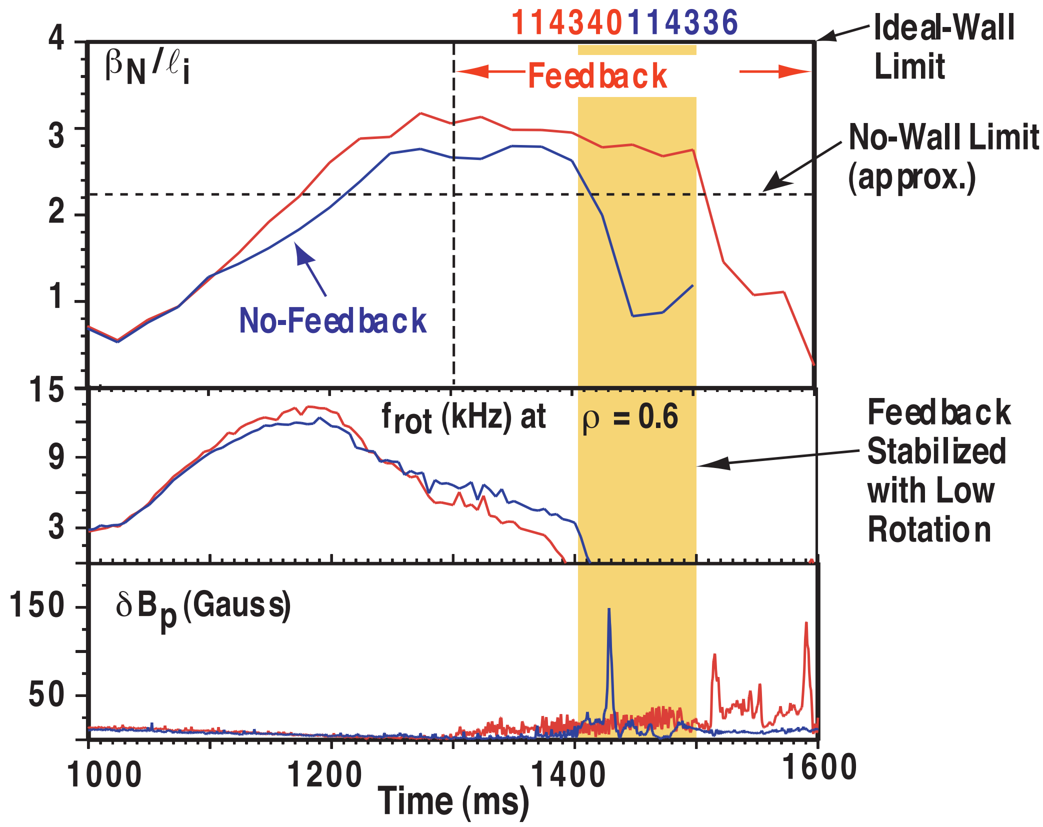
Non-Resonant n=3 Braking Did Not Give Access to the Low-rotation Regime

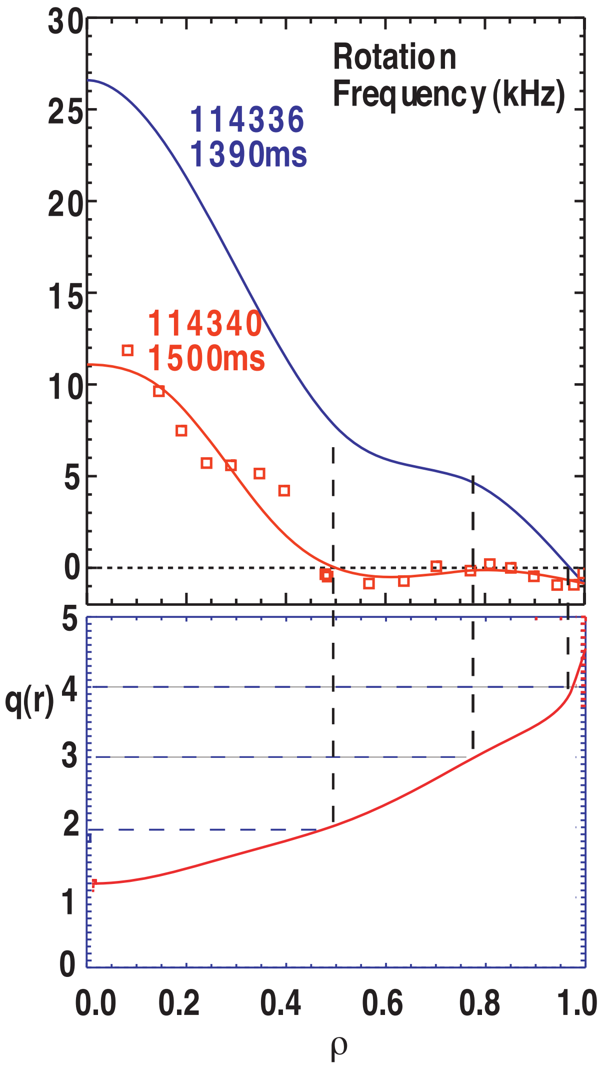
- **Braking effect saturates with increasing braking fields**
  - Plasma rotation remains just above critical value for RWM stabilization
- **Experiments in NSTX will test aspect ratio dependence of non-resonant braking**



Resonant Braking Provides Demonstration of Transient Feedback Stabilization at Low Rotation

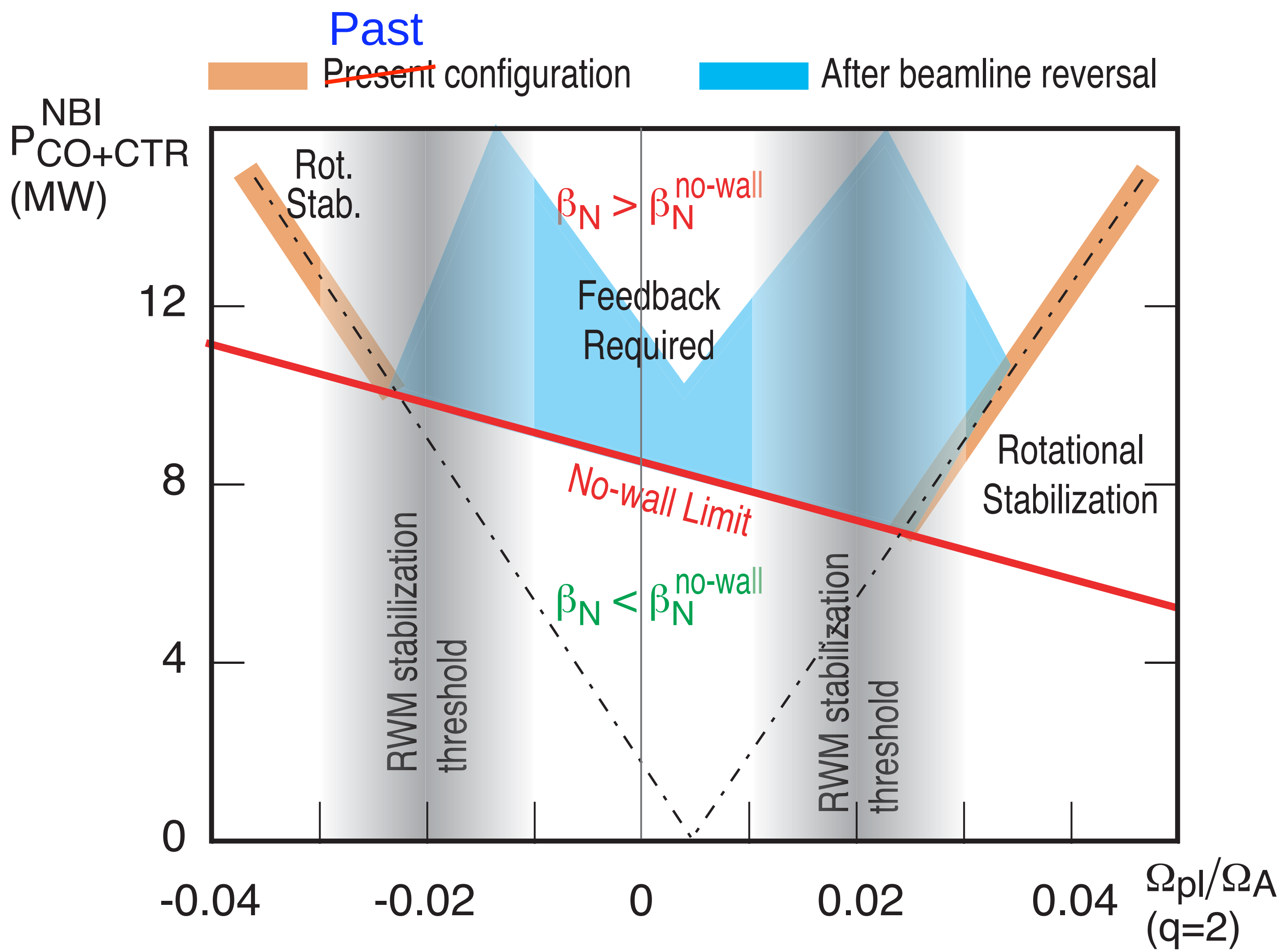
- **I-coil feedback sustains beta in discharge with near-zero rotation at all n=1 rational surfaces**
- **Comparison case without feedback is unstable even with lower beta and faster rotation**



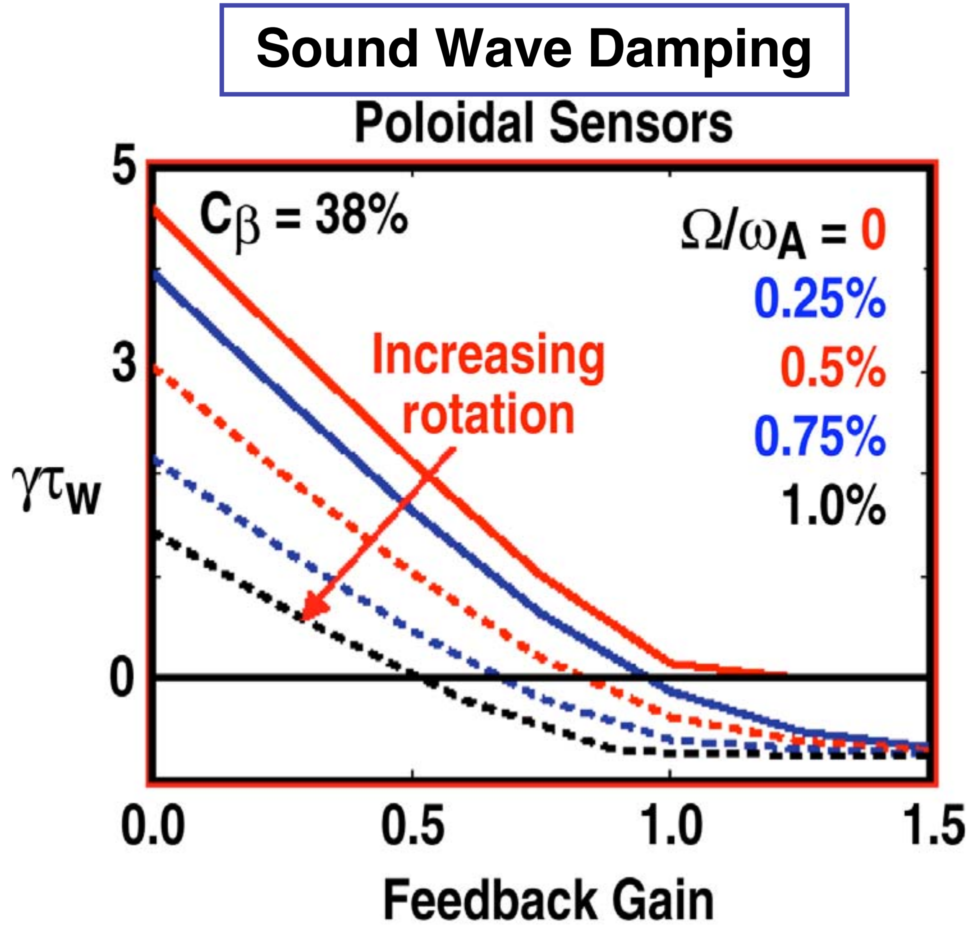


New Beamline Configuration Will Provide Access to High Beta With Near-zero Plasma Rotation

- **Minimum torque (Ω_{pl} ~ 0) achieved with $2_{(CO)}$ + $2_{(CTR)}$ sources ≈ 10 MW**



Balanced Injection Allows Study of Synergistic Effect of Plasma Rotation and Feedback



- **MARS-F simulations show that modest rotation reduces the requirements on the feedback system**

New High Bandwidth Transistor Amplifiers Will Allow High Current, Low Latency RWM Feedback

- **12 (+ 2 spares) TECHRON amplifiers are in-house**
- **100 V peak**
- **200 A peak**
- **Parallel operation (up to 6 =1200 A)**
- **DC to > 40 kHz**
- **8-9 μs delay time**
- **Up to 720 A per I-coil quartet (4 in parallel) in 2006 experiments**
  - 2 AAs per quartet used in 2005

Audio Amplifier

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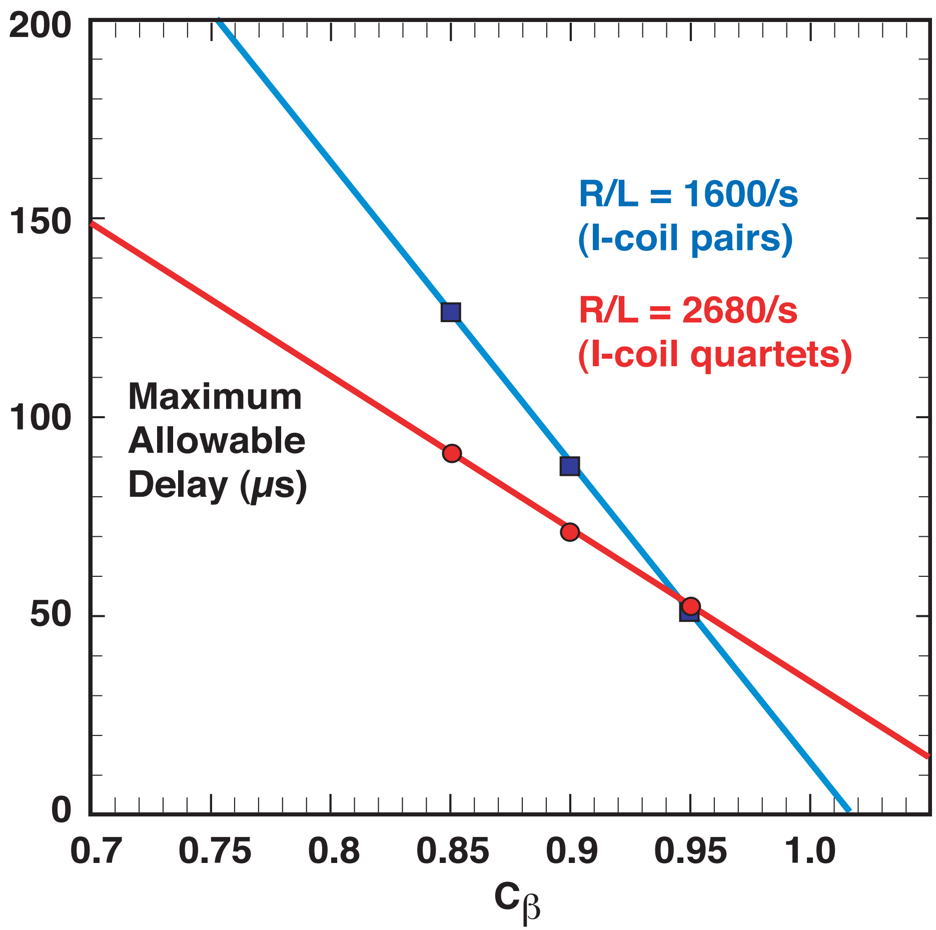
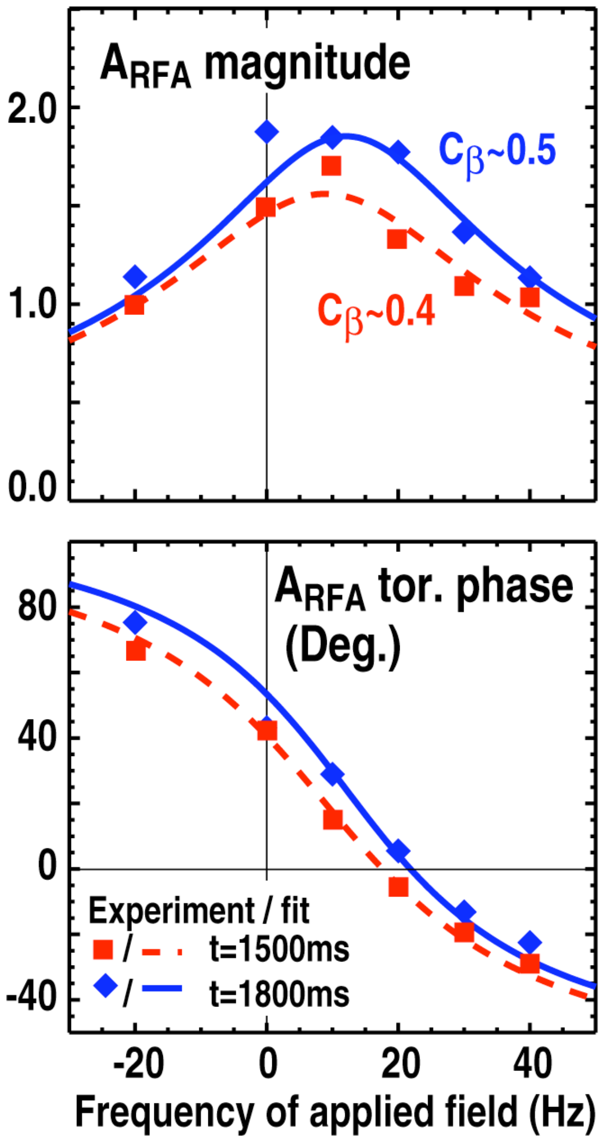
- VALEN modeling shows that system delay must be minimized for stabilization near the ideal-wall limit



Active MHD Spectroscopy Will Probe the RWM Dispersion Relation in Low-rotation Regimes



- Measurements of the stable RWM spectrum yield accurate measurements of the damping rate and mode rotation frequency
- Counter injection will allow measurements of the parametric dependence on plasma rotation
- Active probing of a feedback stabilized plasma under a variety of conditions (e.g. different feedback gains) will allow stringent tests of feedback models

Definition of Near Term and Longer Term Goals

- **Near term goals: Demonstrate RWM feedback for ITER**
  - Verify RWM onset at low plasma rotation without magnetic error fields
  - Demonstrate feedback stabilization at low rotation
  - Validate modeling of RWM feedback with internal vs. external coils
  - Validate models of feedback-rotation synergism
  - Assess noise level requirements for ITER

- **Long term goals: Demonstrate RWM feedback for AT reactor targets**
  - Demonstrate feedback stabilization up to the ideal-wall beta limit with low plasma rotation
  - Characterize impact of feedback activity on high beta, low rotation plasma (ELMs, NTMs, confinement, etc.)

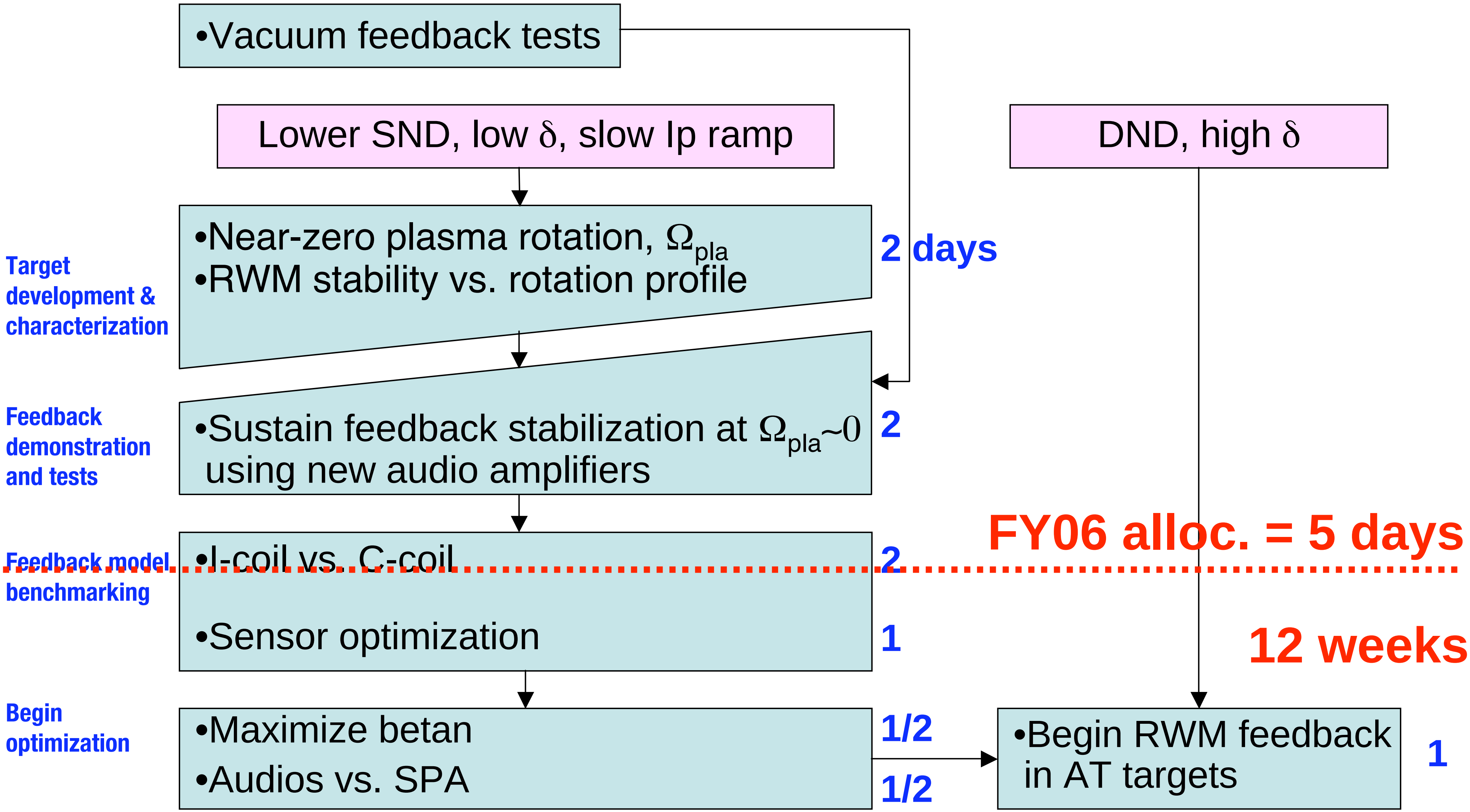
Key Efforts For 2006

- **Develop and characterize low-rotation target plasma**
  - Map out RWM stability limit vs. rotation with different rotation profile shapes
- **Demonstrate feedback stabilization at near-zero toroidal rotation using upgraded audio amplifier system**
  - Sustain feedback stabilization for ~2 sec at $C_\beta > 30\%$
  - Test feedback response to external perturbations (MHD spectroscopy of feedback stabilized plasma)
  - Start testing of model based control schemes, ELM discrimination schemes
- **Start assessment of RWM control with external vs. internal coils**

Key Efforts For 2007

- **Test RWM feedback performance with I-coils vs. C-coils**
  - Compare with models
- **Optimize feedback performance vs. sensors, algorithms, amplifiers**
- **Demonstrate RWM feedback operation near ideal-wall β_N limit**
  - Test n>1 RWM feedback
- **Develop and characterize low-rotation AT target (high δ, high q_{min})**
  - Map out RWM stability limit vs. rotation with different q-profiles, rotation profiles
  - Test stability of n>1 RWMs
  - Similarity experiments with NSTX and JET
- **Begin RWM feedback optimization in high-beta AT plasmas**

Roadmap For FY06



Future Plans

2006 2007 2008 2009

PHYSICS TASKS

Physics of rotational stabilization

Validate models of feedback without rotation

Validate ITER requirements

Feedback control of n>1 RWMs

Feedback control near ideal limit without rotation

Sustained AT operation with RWM feedback

EXPERIMENTAL TOOLS

12 ➔ 24 Audio amplifiers

C-coil + I-coil feedback

MHD spectroscopy

PCS upgrade for lower latency

Counter neutral beam injection (rotation control)

Advanced control algorithms

High triangularity divertor

Increased ECH power

Upgraded mode detection capability

Core mode structure diagnostic

2006 2007 2008 2009

DIII-D RWM Stabilization Program Addresses Key Issues For Advanced Scenario Burning Plasma

- **It is likely that RWM feedback control will be necessary to operate ITER advanced scenario (insufficient rotation)**
  - Essential, for ITER to establish the physics basis for an AT reactor
- **Feedback stabilization of the RWM without rotation has been demonstrated transiently above the no-wall b limits in DIII-D, but important questions remain:**
  - Can RWM feedback stabilization be sustained, for a long time, without plasma rotation?
  - Is present ITER design of external coils adequate for requirements?
  - Are internal feedback coils much more effective than external coils, as predicted by VALEN?
  - Does plasma rotation reduce the requirements on RWM feedback?
- **DIII-D is uniquely suited to validate models of stabilization with rotation and feedback, and make projections for ITER**
  - High beta operation
  - Internal and external control coils
  - Fast digital control system
  - High-bandwidth amplifiers
  - Rotation control