Physics of the Resistive Wall Mode and Feedack Stabilization in DIII–D

by

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for

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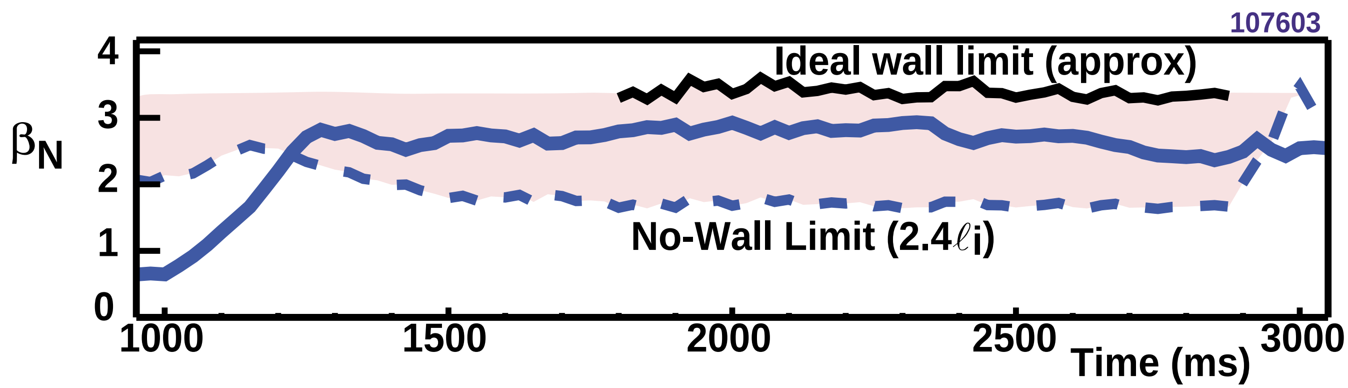
INTRODUCTION

- The n=1 ideal MHD kink mode (resistive wall mode) limits β in the Advanced Tokamak
- Theory predicts that the resistive wall mode can be stabilized by sufficient plasma rotation or active magnetic feedback
- DIII-D experiments have demonstrated sustained RWM stabilization by plasma rotation over the entire range $\beta_N^{no\ wall} \ll \beta_N < \beta_N^{ideal\ wall}$



- Understanding the stabilization mechanisms is crucial to the reactor-relevance of these results
- We have investigated the dependence of the RWM stability on several key parameters:
  - β_N
  - plasma-wall separation — H. Reimerdes QP1.083
  - plasma rotation — R.J. La Haye QP1.081, J.T. Scoville QP1.077
  - magnetic feedback — M. Okabayashi QP1.082, G.L. Jackson QP1.080
  - q-profile — R.J. Jayakumar QP1.070

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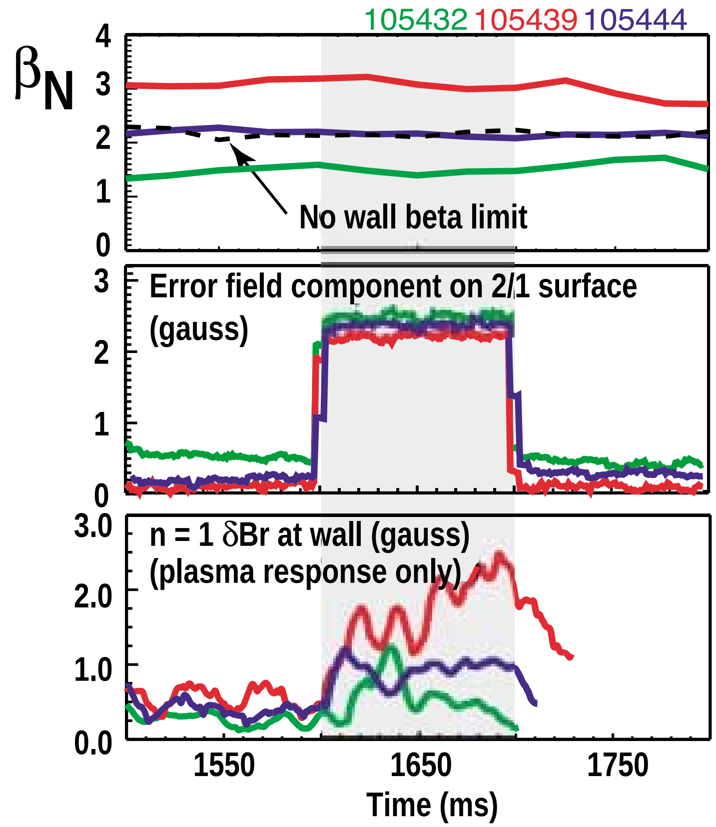
RESISTIVE WALL MODE STABILIZED BY ROTATION IS WEAKLY DAMPED - HAS STRONG RESONANT RESPONSE TO EXTERNAL PERTURBATIONS

- Use external n = 1 field pulses to probe RWM dispersion relation at $\beta_N > \beta_N^{no\text{-}wall}$.
  — Mode is rotationally stabilized

- Resonant field amplification yields three RWM measurements:
  — Growth rate (negative)
  — Toroidal phase relative to external pulse
  — Amplitude (asymptotic)



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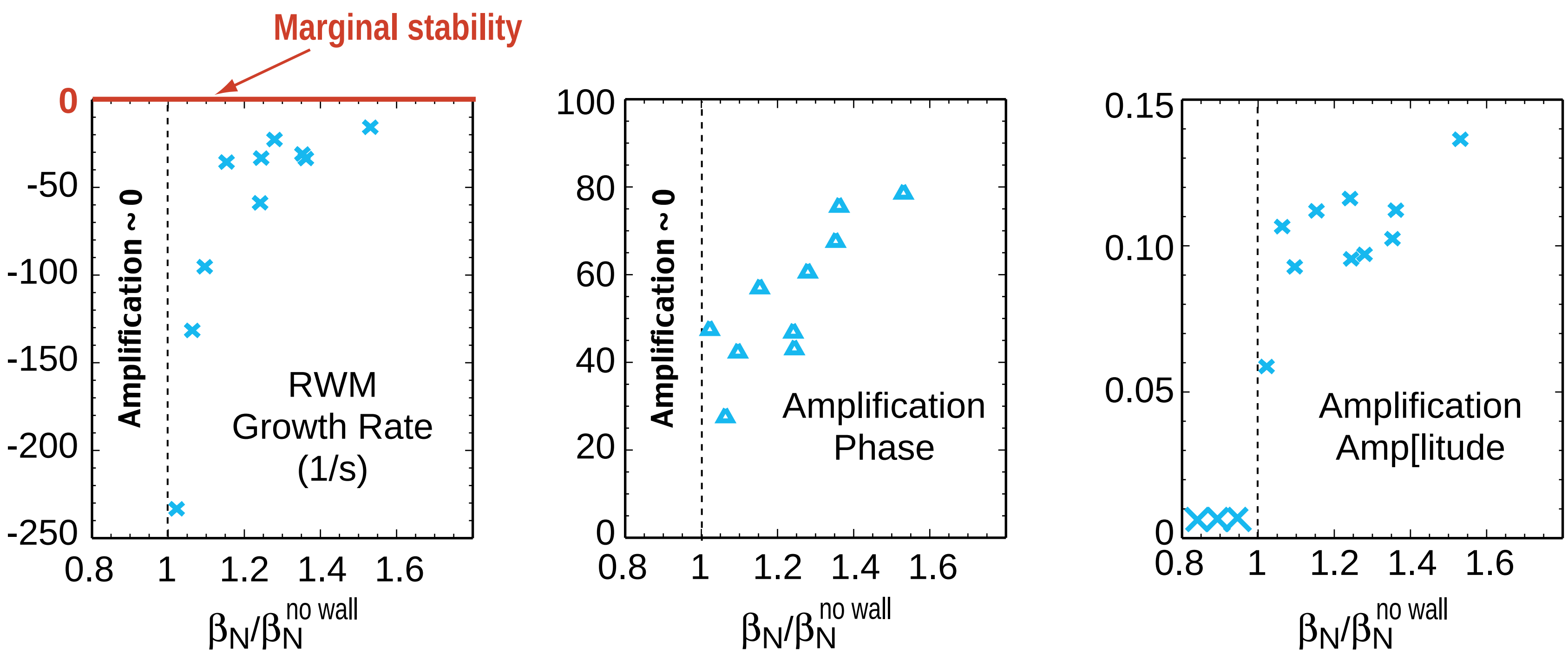
PLASMA BECOMES LESS STABLE AS β_N INCREASES

- Plasma response to pulsed n=1 field increases as β_N approaches the RWM stability boundary (γ=0)



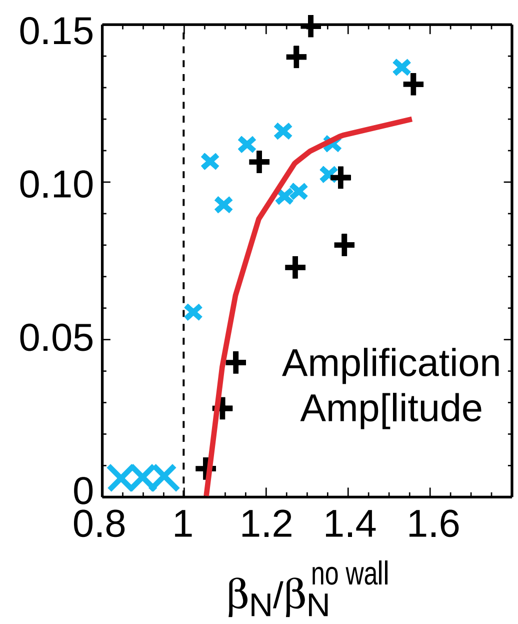
- In contrast with predictions of some RWM models, calculating a maximum resonance at the no-wall limit, not at γ=0

1-D, 1-MODE, IDEAL MHD MODEL AGREES WITH EXPERIMENTAL OBSERVATIONS

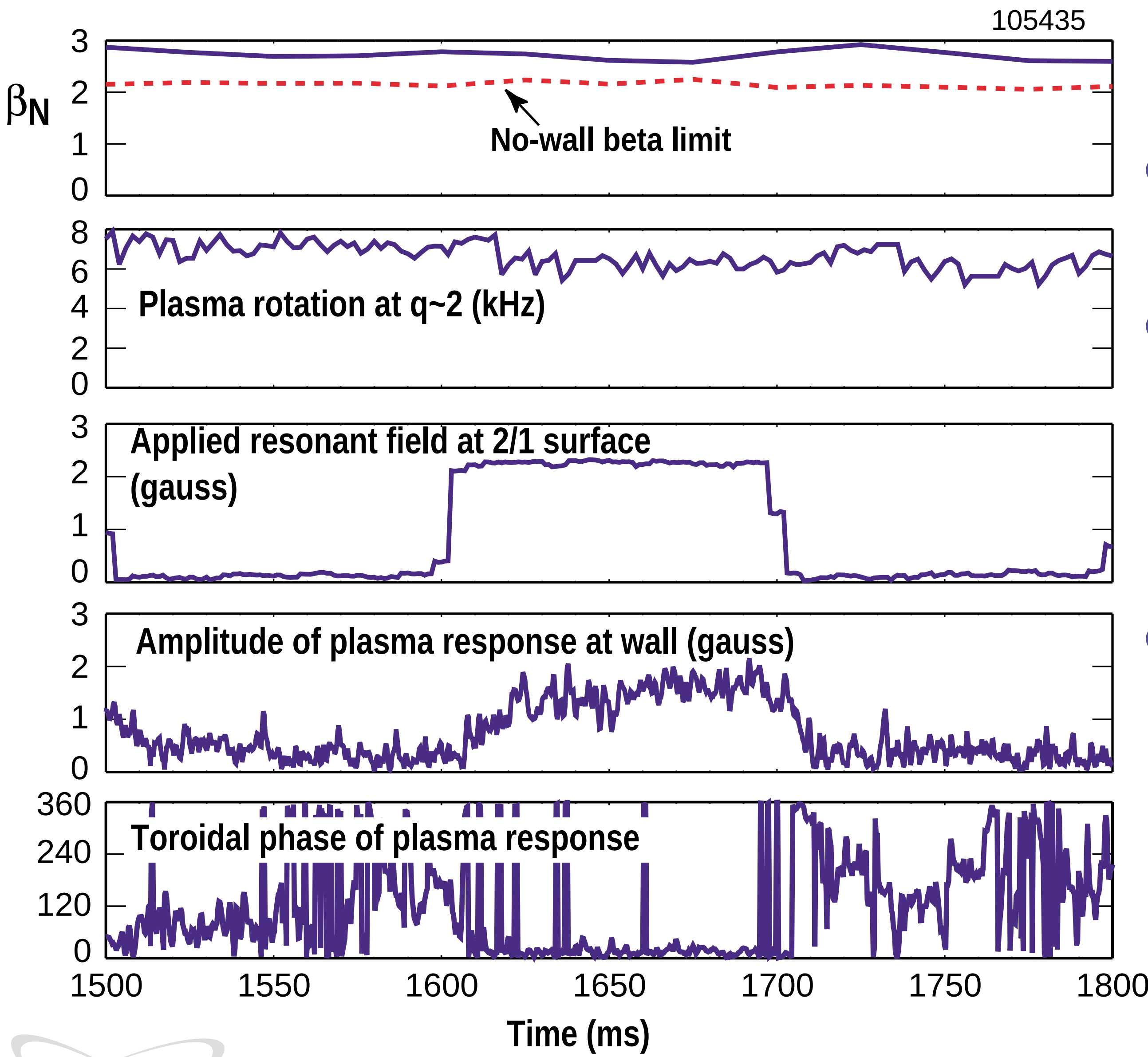
- Model gave quantitative predictions of RWM feedback dynamics **(Garofalo, Jensen, and Strait, Phys. Plasmas, 2002)**
- Model is semi-empirical: no assumption is made on nature of plasma-mode interaction, just that there is some
- Only one mode is involved => plasma response is given by only two parameters (which relate to the mode amplitude and phase)

- RWM growth rate and phase are used as input to the model
- Amplitude is predicted

× Measurements
+ Model predictions
— Fit to model



RESISTIVE WALL MODE DRIVEN BY EXTERNAL FIELD DOES NOT ROTATE (CONSTANT TOROIDAL PHASE) BUT REMAINS STABLE



- Mode rotation w.r.t. wall NOT required for stabilization
- Predicted real frequency of a stable RWM may just be a side effect of torque balance in idealized (perfectly axi-symmetric) geometry
- Dominant energy dissipation effect which stabilizes the RWM must occur solely inside rotating plasma, NOT in resistive wall

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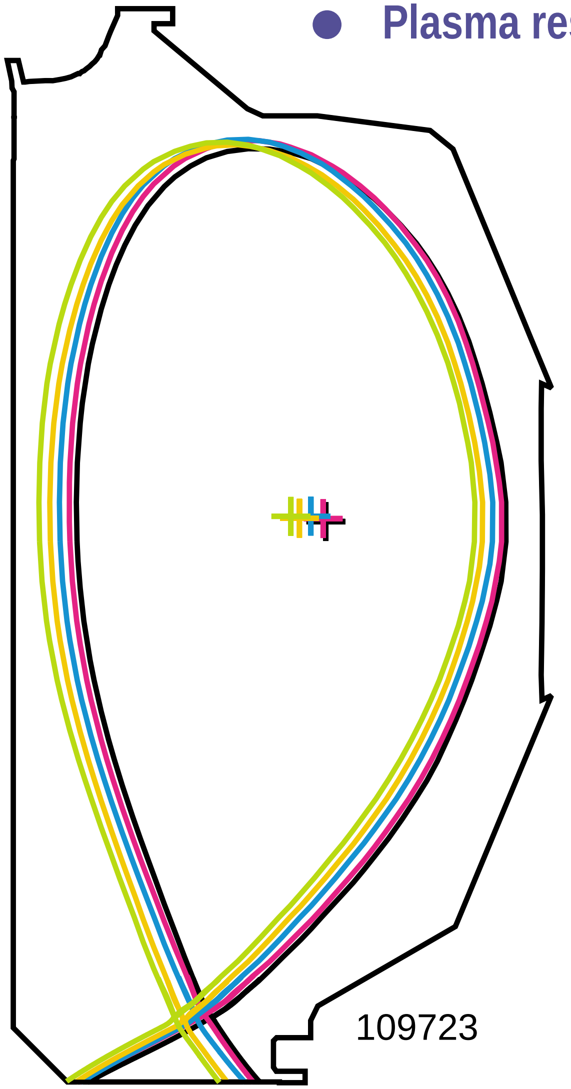
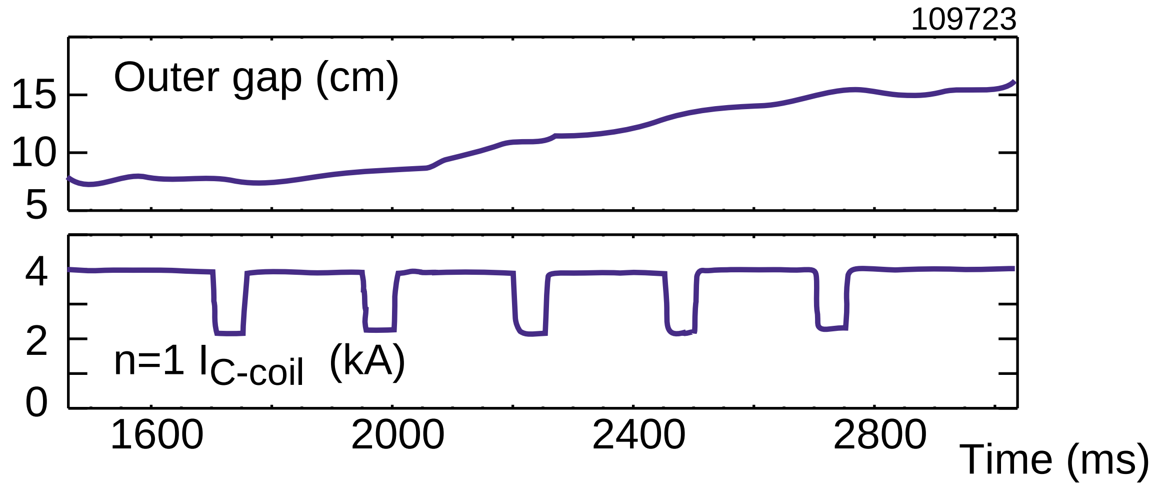
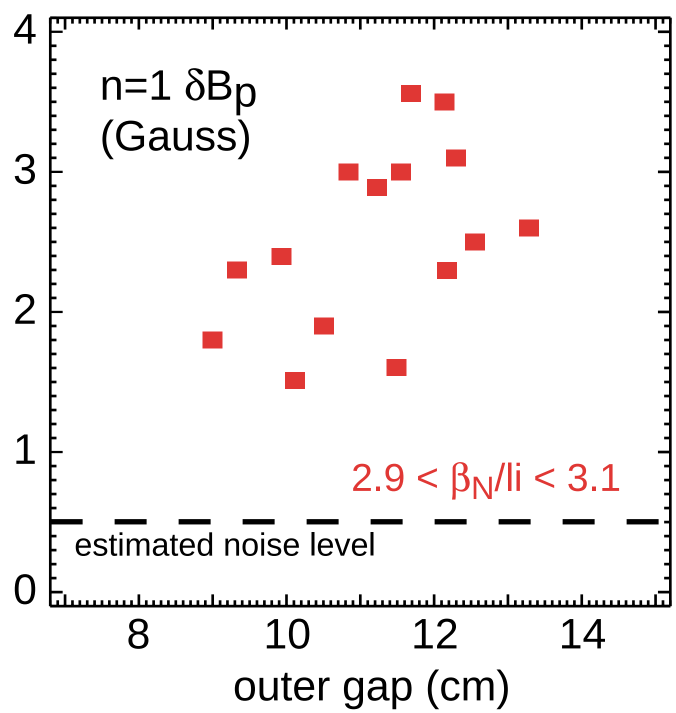
PLASMA-WALL SEPARATION SCAN SUGGESTS RESISTIVE WALL MODE MORE UNSTABLE WITH INCREASING WALL DISTANCE



- Plasma response to pulsed n=1 field increases as the outer gap increases





- In contrast with (counter-intuitive) theory predictions that the RWM becomes more stable with increasing wall distance

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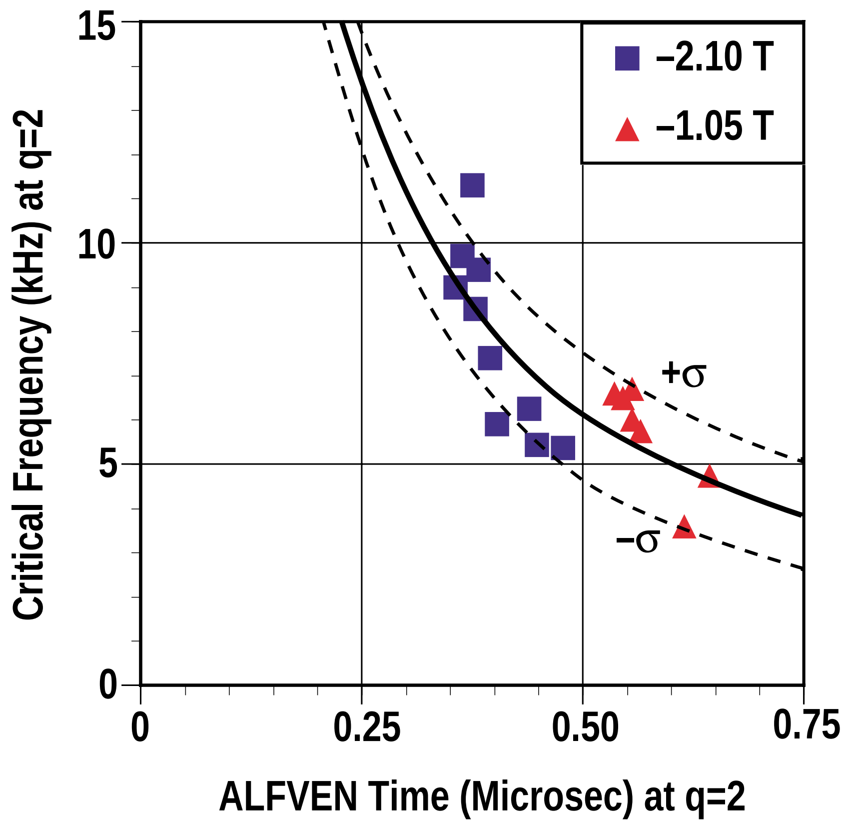
H. Reimerdes QP1.083

OBSERVED SCALING OF CRITICAL PLASMA ROTATION FOR ONSET OF RESISTIVE WALL MODE IS CONSISTENT WITH MHD THEORY

- Consistent with inverse of ALFVEN TIME: $\Omega_c \tau_A$ ~2% (Bondeson and Ward, 1994)
- Also consistent with inverse SOUND WAVE TIME: $\Omega_c \tau_S$ ~1 (Betti and Freidberg, 1995)
  - ALFVEN and SOUND times are well correlated



★ "Hidden variable" is $\beta_N / \beta_N^{no\text{-}wall}$

... $\beta_N / 2.4\ell_i = 0.9 \sim 1.9$

$f = 2.78\tau_A^{-1.14\pm0.17}$

corr = –0.79

$\sigma = \pm 1.3$ kHz

R.J. La Haye QP1.081

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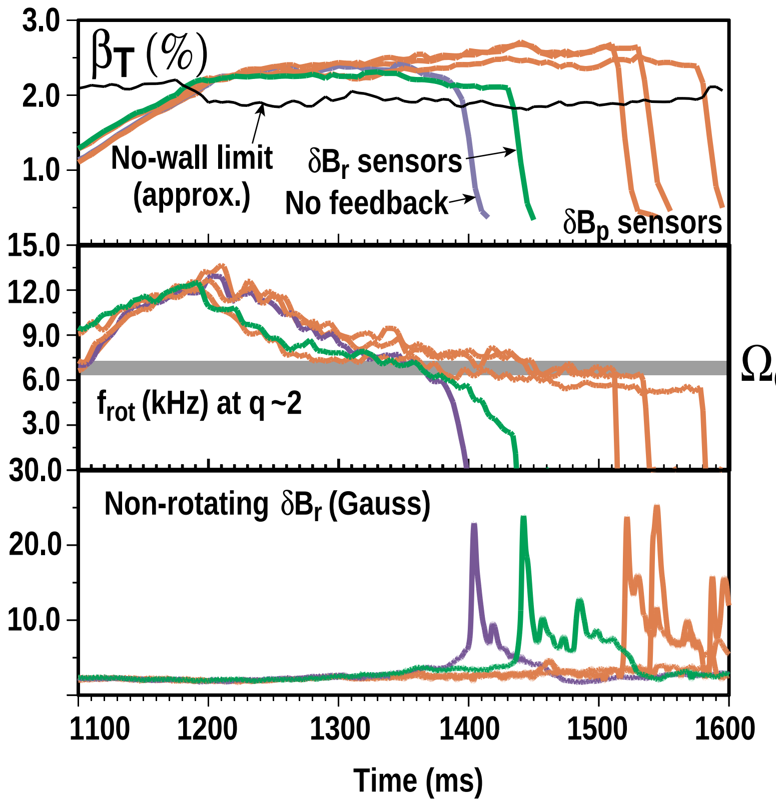
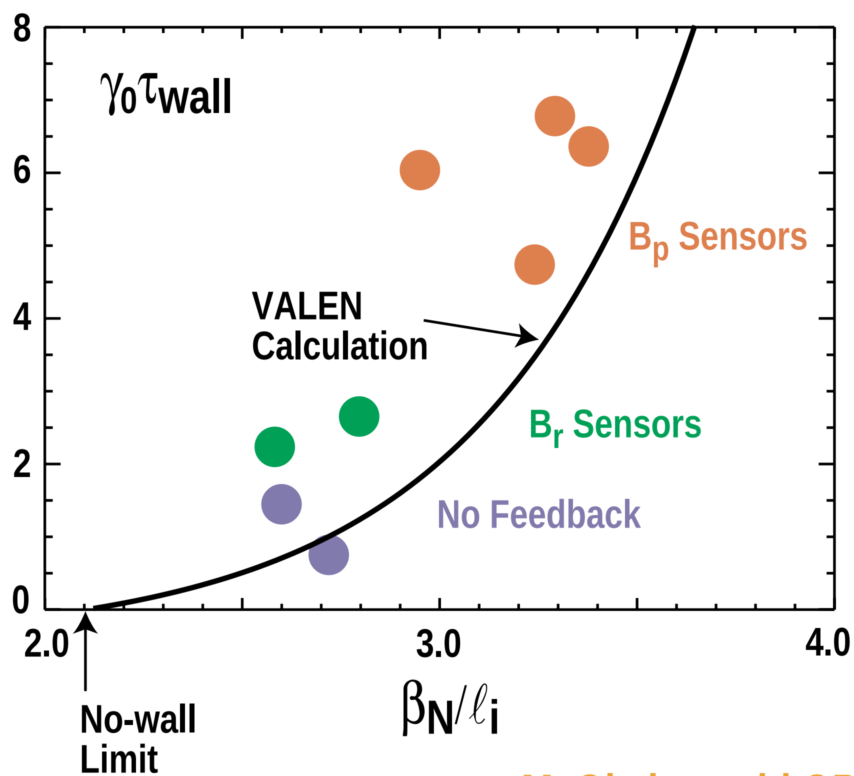
INTERNAL B_P SENSORS IMPROVE FEEDBACK CONTROL OF THE RWM, CONSISTENT WITH MODELING

- Stable duration and $\beta_N/\beta_N^{no\text{-}wall}$ increase with internal Bp sensors
- Internal Bp sensors stabilize RWM with larger open-loop growth rate γ_0
- Measured open-loop growth rate is consistent with VALEN prediction with no rotation
  - RWM feedback extends stability at plasma rotation < Ω_c





M. Okabayashi QP1.082
J.T. Scoville QP1.077

SUMMARY

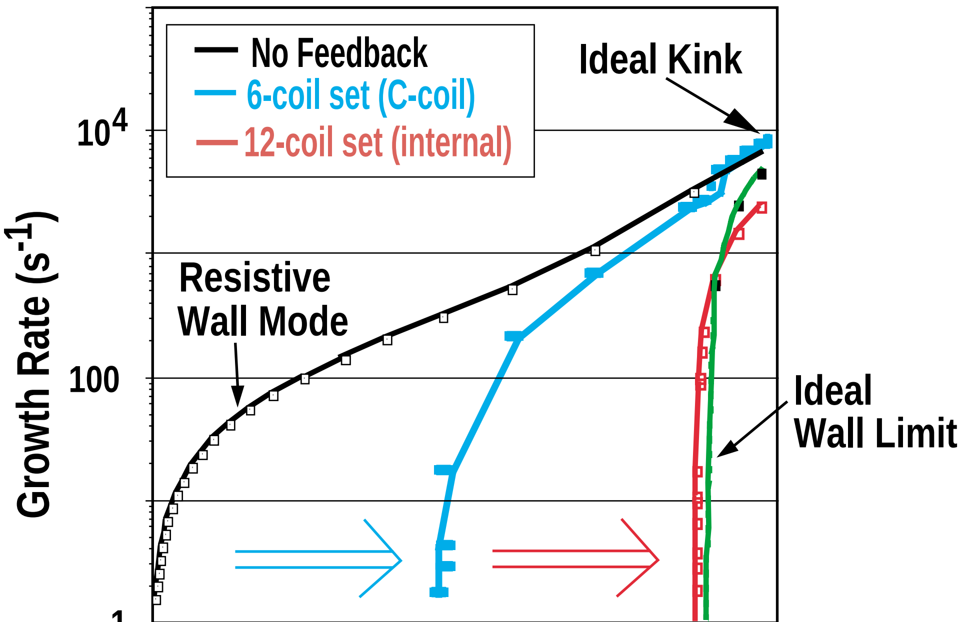
- New, attractive regimes of operation above the no-wall β–limit are possible
- Scaling of critical plasma rotation consistent with ideal MHD theory with dissipation
- RWM feedback using poloidal field sensors improves stabilization
- Resonant field amplification peaks near the RWM stability boundary, away from no-wall β–limit, in agreement with simple MHD model
- RWM rotation w.r.t. wall NOT required for stabilization
  - RWM energy dissipation which stabilizes the RWM may only occur in plasma
  - Predicted real frequency of a stable RWM may be only a side effect of torque balance in idealized geometry (perfectly axi-symmetric)
- RWM stability decreases with increasing wall distance
- Can we correctly model combined effect of plasma rotation and active feedback on RWM stability?
- Can we develop low-rotation, high-β plasmas to benchmark existing feedback models (which do not include plasma rotation)?

INTERNAL CONTROL COILS WILL BE AN EFFECTIVE TOOL FOR PURSUING BOTH ACTIVE AND PASSIVE STABILIZATION OF THE RWM

- Off-midplane coils allow better matching to poloidal spectrum of error field or RWM
- Feedback stabilization is calculated to open high beta wall-stabilized regime to plasma without rotation (may be important for burning plasma)

12-coil internal set available for experiments 2003

(VALEN 3-D)



$$\frac{\beta_N - \beta_N^{no\text{-}wall}}{\beta_N^{ideal\text{-}wall} - \beta_N^{no\text{-}wall}}$$

G.L. Jackson QP1.080

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