REACHING THE IDEAL WALL LIMIT IN DIII-D

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in collaboration with
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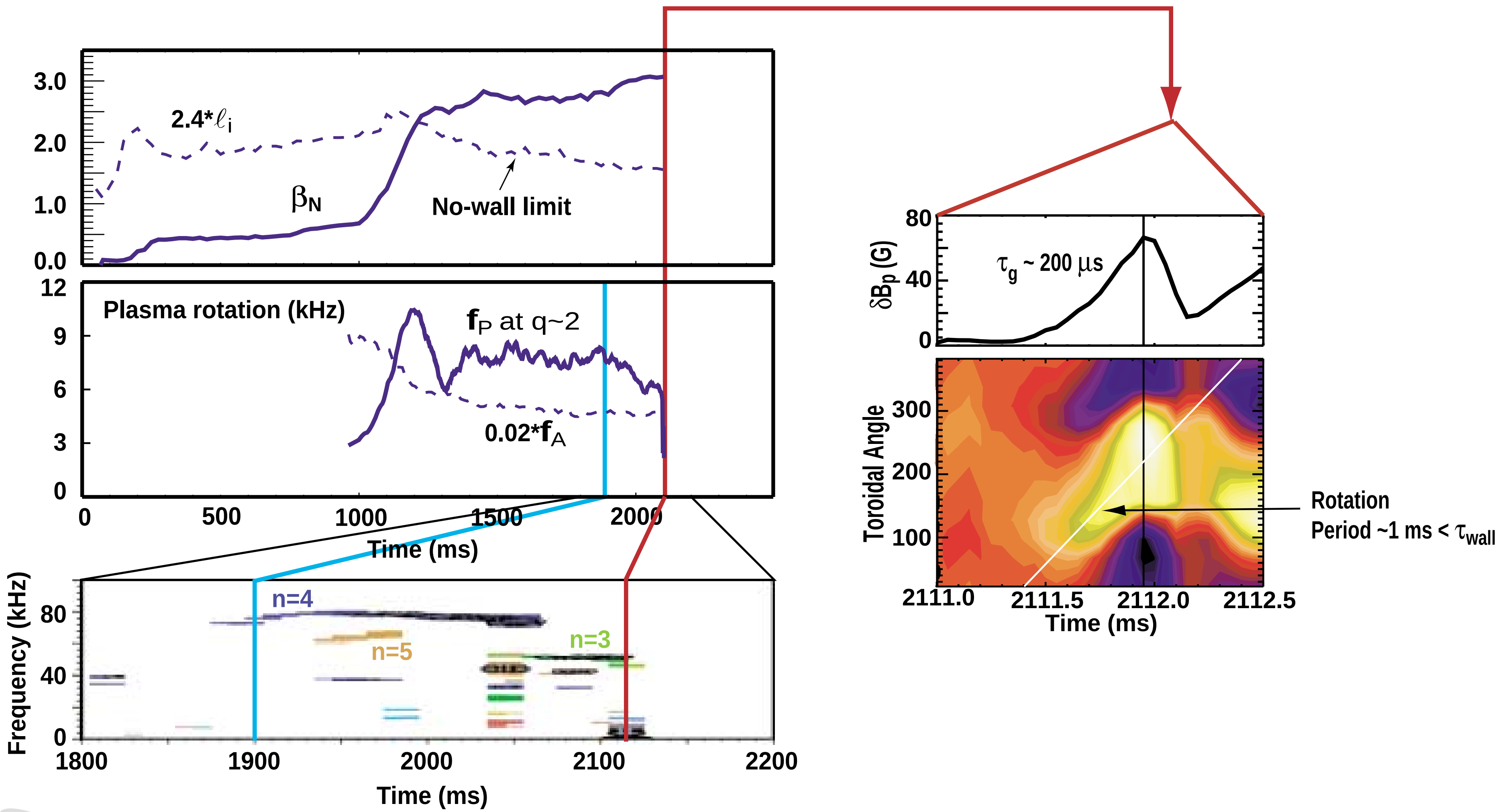
SOME KEY QUESTIONS

- Has DIII-D observed the ideal-wall limit (at $\beta >> \beta^{no\text{-}wall}$)?
- What are the observed characteristics that prove this?
- How did DIII-D achieve these results?
- Can RWM stabilization be sustained near the ideal-wall limit?
- How do we extrapolate these results to a reactor?

IDEAL n=1 KINK OBSERVED AT TWICE THE NO-WALL β_N LIMIT

- Rapid growth rate and rotation suggest little or no effect from resistive wall
- Very reproducible disruption



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CALCULATIONS INDICATE INSTABILITY OCCURS AT IDEAL-WALL β LIMIT

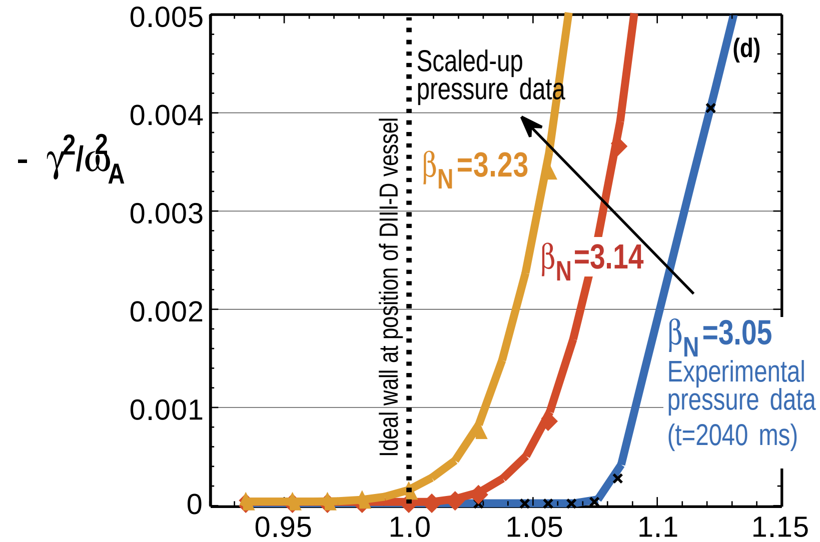
- Ideal MHD calculations find the equilibrium <10% away from $\beta_N^{\text{ideal wall}}$
- Growth rate is consistent with ideal-wall stability limit

  Ideal MHD mode driven slowly ($\tau_h >> \tau_{MHD}$) through stability limit:

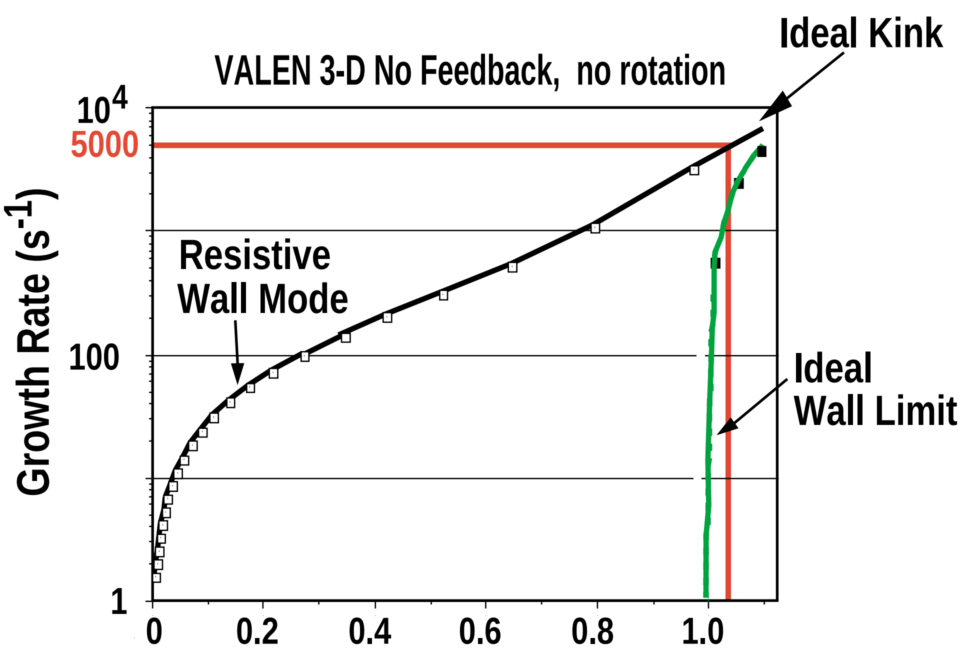
  $\tau_g = \tau_{MHD}^{2/3}\,\tau_h^{1/3} \Rightarrow \tau_{MHD} = 4\mu s$ (J. Callen, et al., *Phys. Plasmas*, 1999)

  Resistive wall mode destabilized at ideal-wall stability limit

n=1 ideal MHD stability (GATO)



VALEN 3-D No Feedback, no rotation



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

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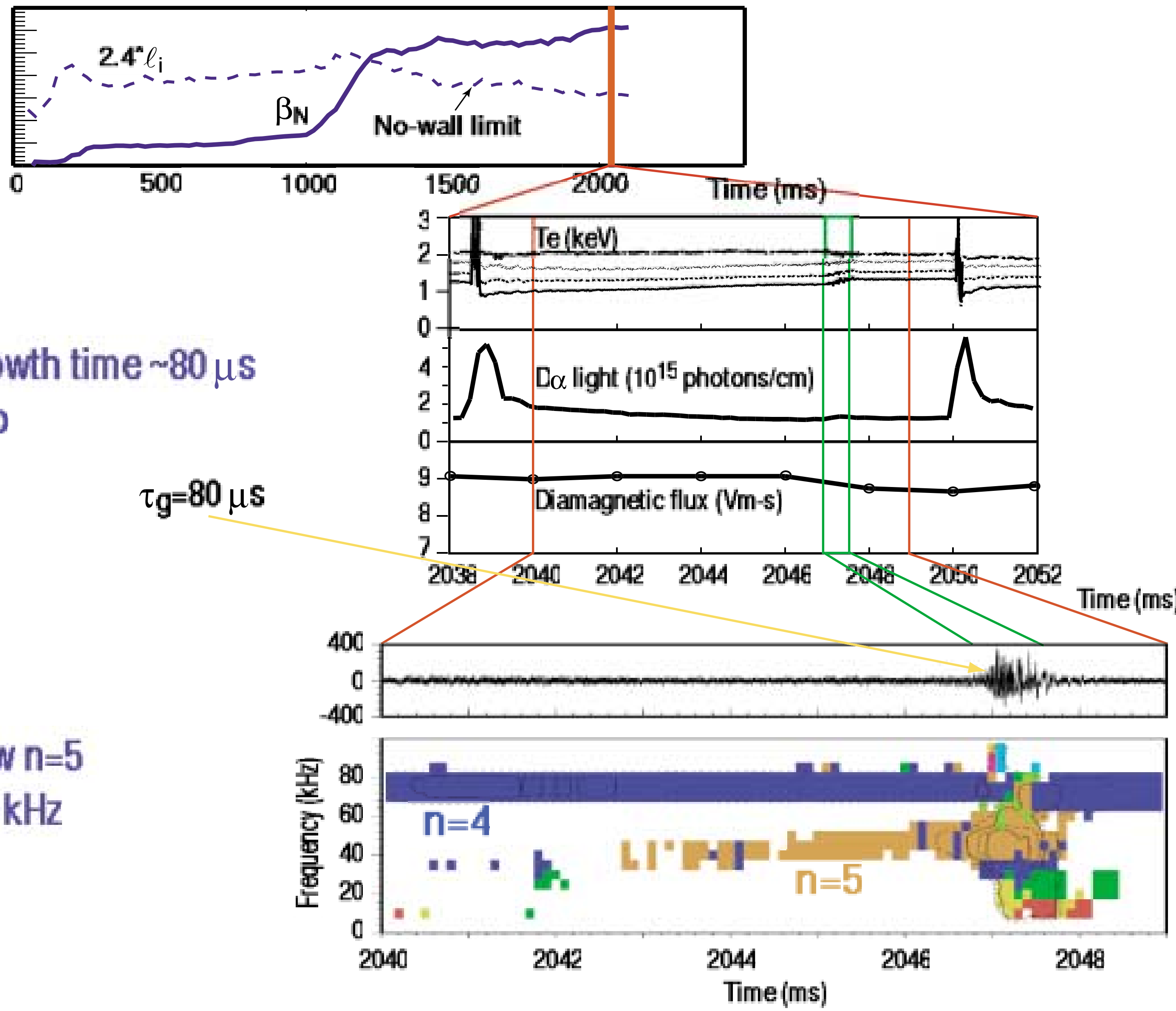
IDEAL n=5 KINK OBSERVED NEAR PREDICTED n=1 IDEAL-WALL β LIMIT

- Mode burst with growth time ~80 μs causes small β-drop

- Mirnov signals show n=5 mode rotating at ~9 kHz



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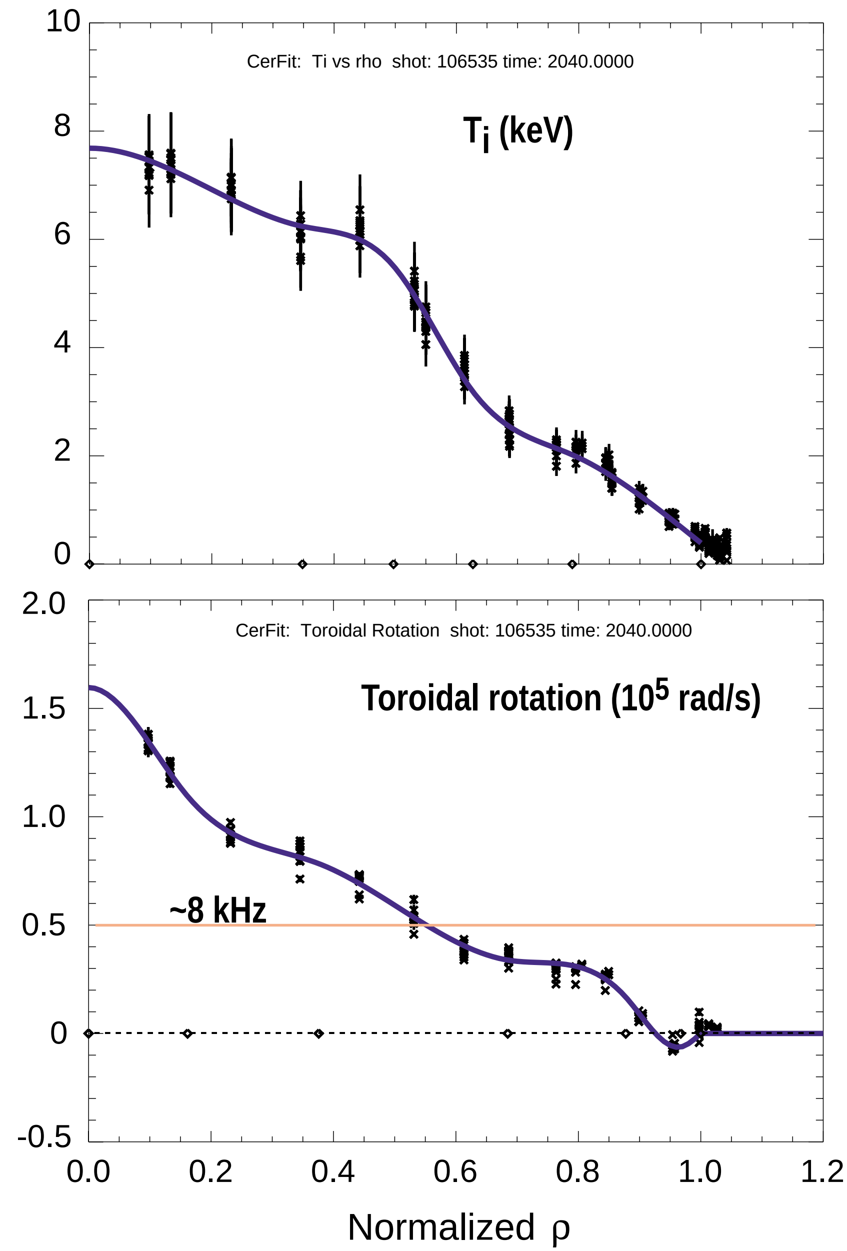
IDEAL n=5 KINK LOCALIZED NEAR THE FOOT OF AN INTERNAL TRANSPORT BARRIER

- Ion temperature and rotation data show n=5 mode is NOT an edge mode



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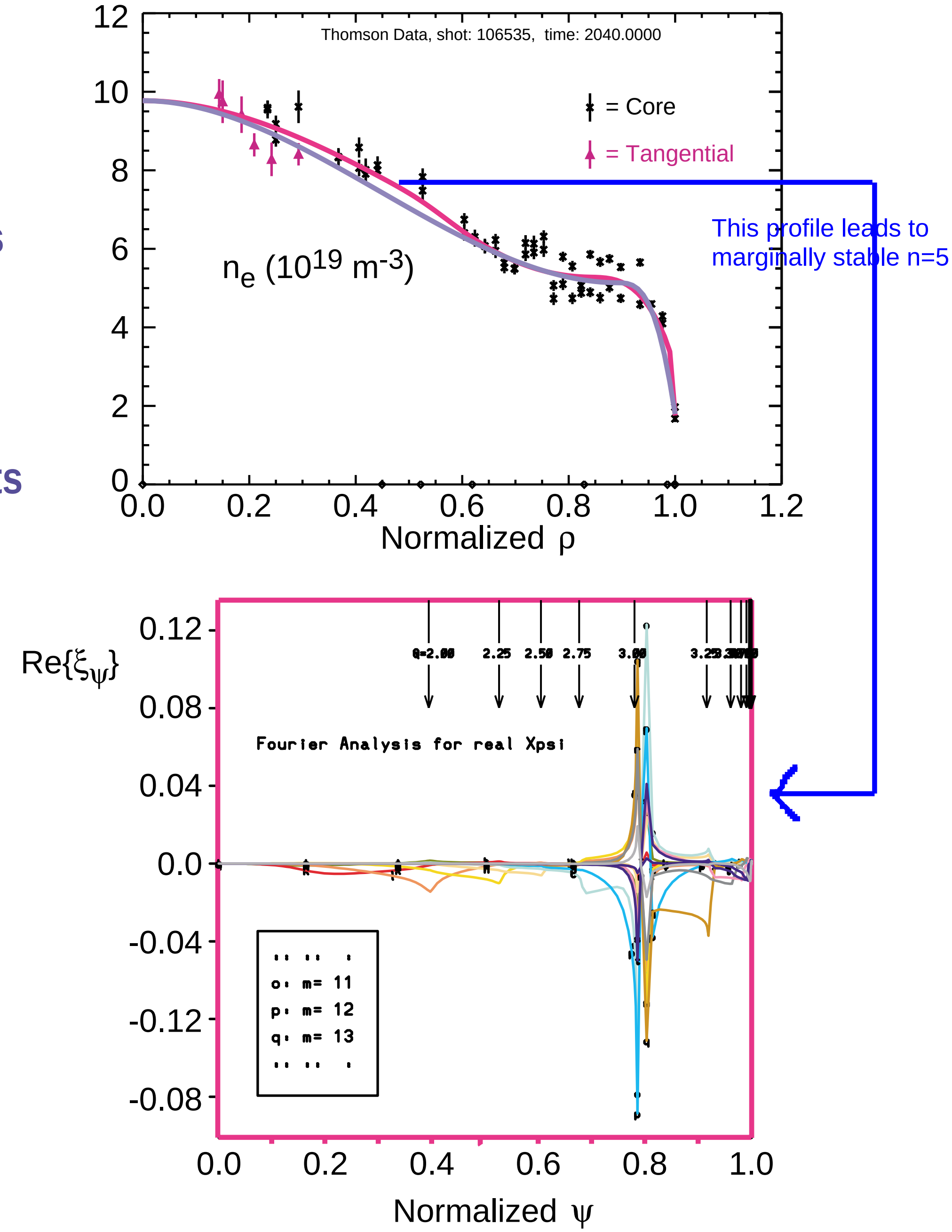
OBSERVATION OF n=5 KINK PROVIDES USEFUL HINTS TOWARDS NUMERICAL RECONSTRUCTION OF EQUILIBRIUM

- Spline fitting of profile data is normally carried out using smallest number of knots
  Stability of n=1 kink is not affected by small scale features of internal profiles

- Presence of an ITB justifies additional knots for the core profiles

- New equilibrium reconstruction is marginally stable to n=5 mode, localized near the ITB



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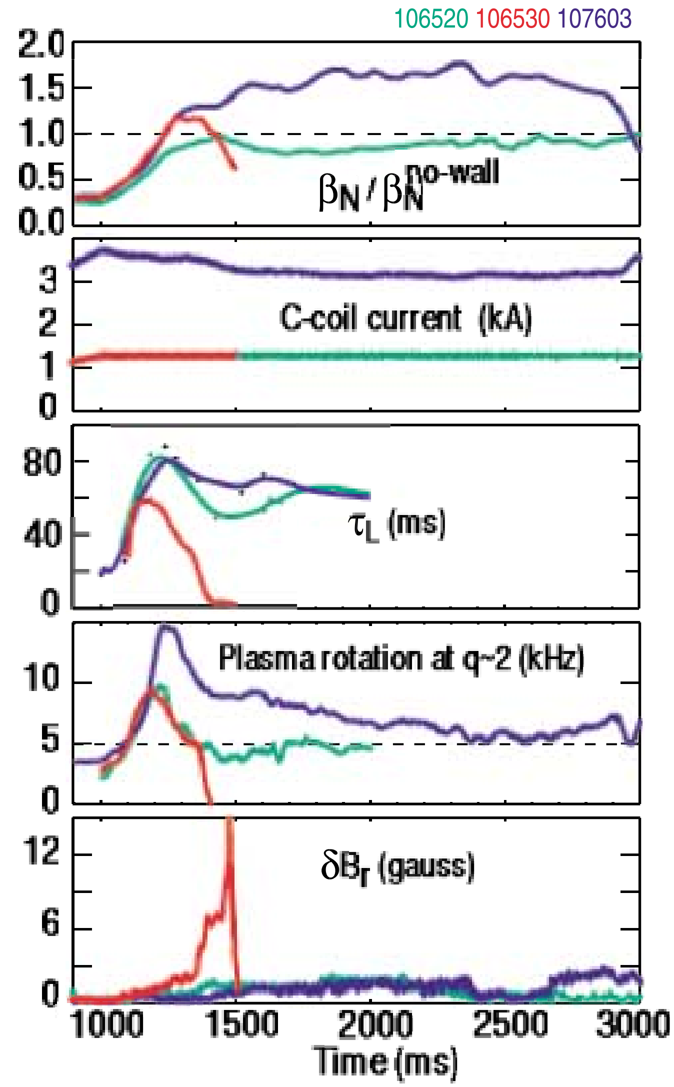
RWM STABILIZATION SUSTAINED FOR >1.5 s WITH OPTIMIZED ERROR FIELD CORRECTION

- Optimal EFC (blue) removes the decay of τ_L observed when β_N exceeds $\beta_N^{no\text{-}wall}$



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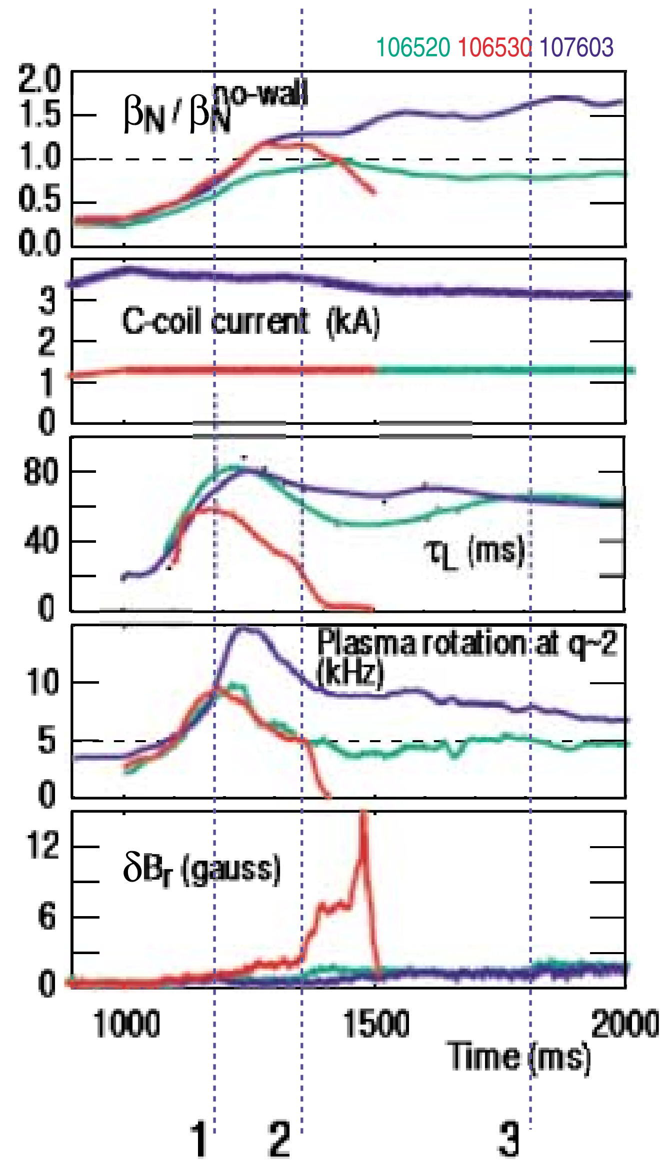
OPTIMAL ERROR FIELD CORRECTION (BLUE) REMOVES THE DECAY OF τ_L OBSERVED WHEN β_N EXCEEDS $\beta_N^{NO\text{-}WALL}$

(1) In plasmas with different EFC (red vs. blue), the evolution of τ_L starts to differ when $\beta_N \sim \beta_N^{no\text{-}wall}$.

(2) In plasmas with non-optimal error field correction (red & green), low plasma rotation leads to RWM-induced β collapse when $\beta_N > \beta_N^{no\text{-}wall}$.

(3) In plasmas with different EFC (blue vs. green), non-optimal EFC and $\beta_N < \beta_N^{no\text{-}wall}$ yield same τ_L as case with optimal EFC and $\beta_N > \beta_N^{no\text{-}wall}$.

(Garofalo, et al., Phys. Rev. Lett., 2002)



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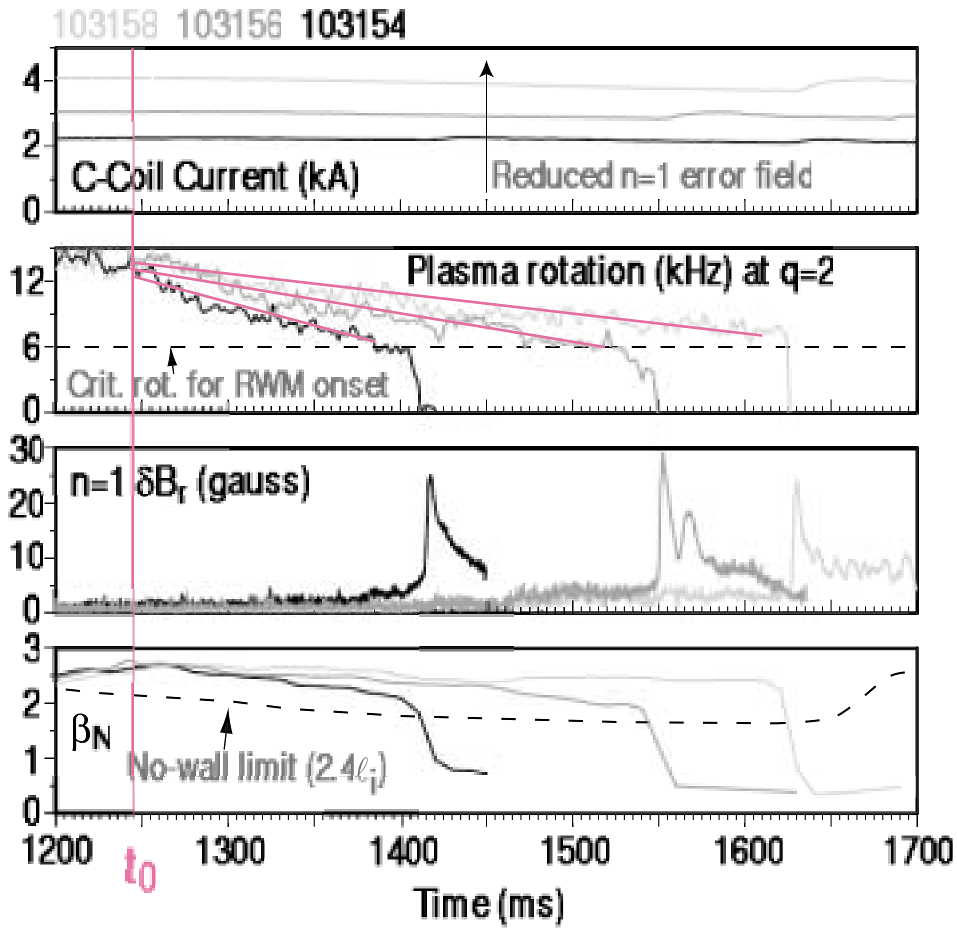
SHOT-TO-SHOT SCAN OF APPLIED n=1 FIELD YIELDS CORRECTION FIELD WHICH MINIMIZES PLASMA ROTATION DECAY RATE

- Optimal correction ~2x standard correction determined for lower-β plasmas



- Assume a REFERENCE, INTRINSIC ERROR FIELD, amplitude=B_0, phase=ϕ_0
  - RESULTING error field= REFERENCE + C-COIL field
  - Associate rotation decay rate at t=t_0 with RESULTING error field

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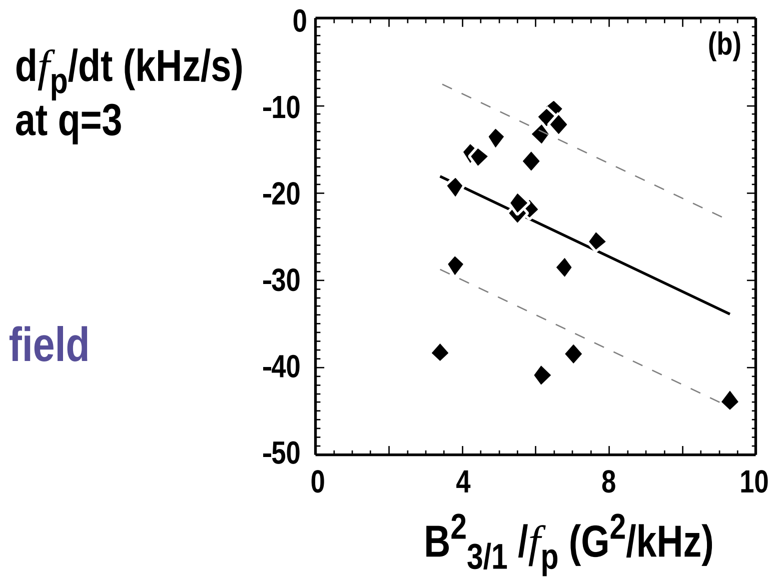
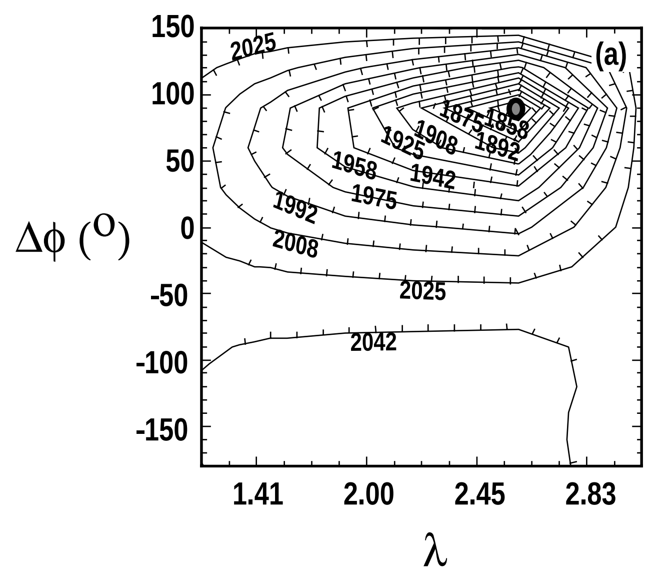
PLASMA ROTATION DECAY RATES DO NOT CORRELATE WITH ANY m/n=3/1 INTRINSIC ERROR FIELD

- Induction motor model of the plasma rotation predicts a linear relationship between the rotation decay rate and the RESULTING error field



- Varying the assumed amplitude and phase of the REFERENCE, INTRINSIC error field yields a contour plot of χ^2 with a very shallow minimum for a 3/1 field



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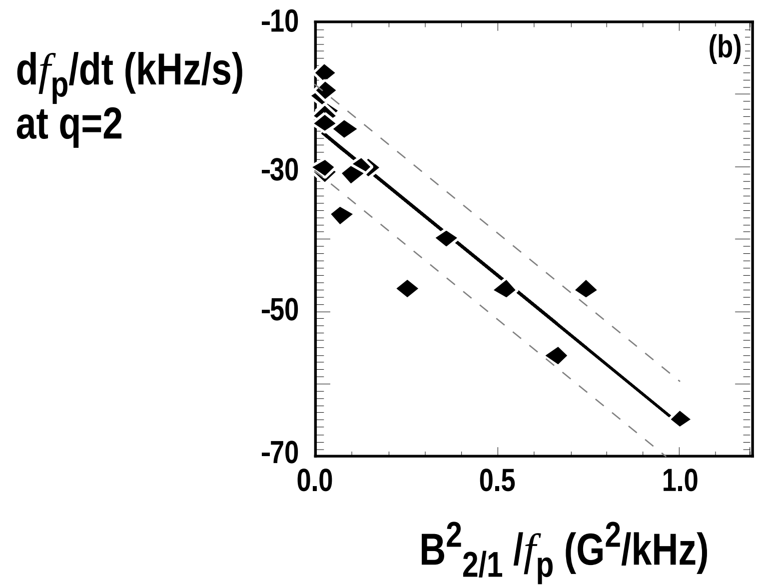
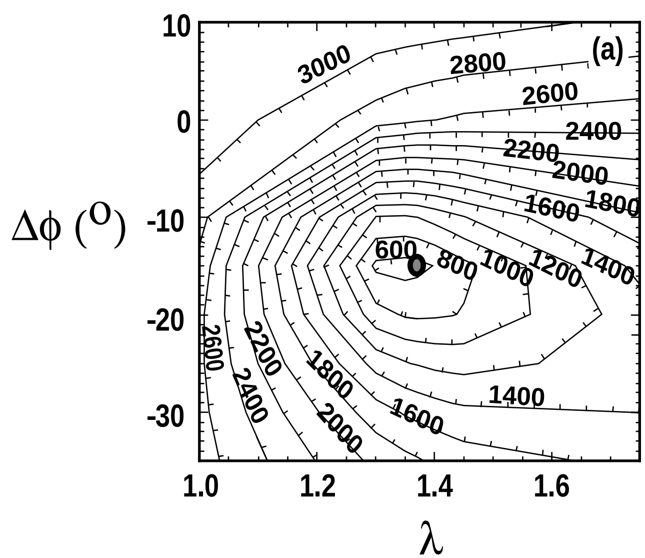
PLASMA ROTATION DECAY RATES CORRELATE WITH A ~7 gauss m/n=2/1 INTRINSIC ERROR FIELD



- Varying the assumed amplitude and phase of the REFERENCE, INTRINSIC error field yields a contour plot of χ^2 with a very deep minimum for a 2/1 field

- Best fit to model suggests relevant intrinsic error field is m/n=2/1, with $B_{2/1}$ ~ 7 gauss
  (Garofalo, La Haye, and Scoville, Nucl. Fusion, 2002)



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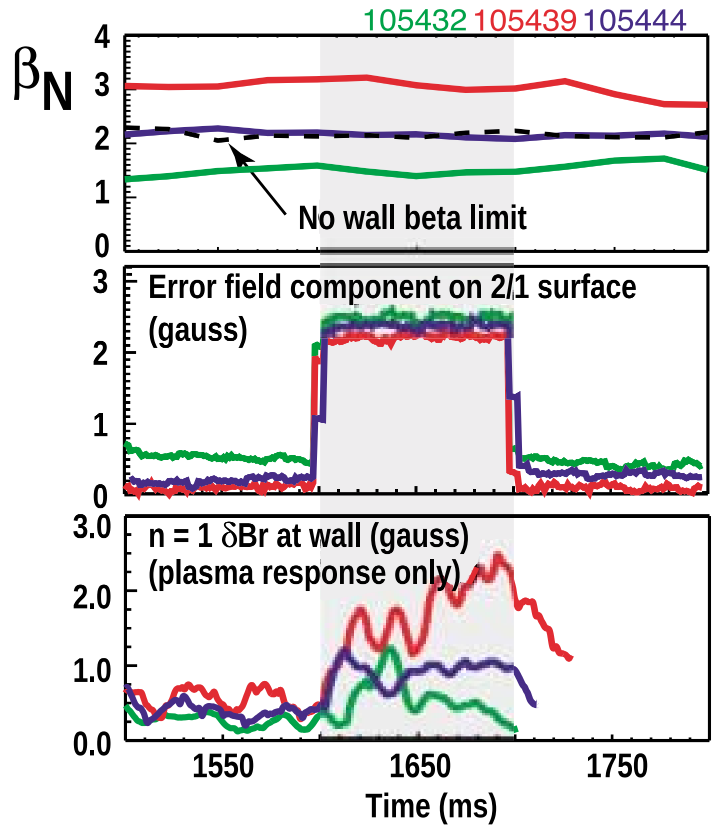
RESISTIVE WALL MODE STABILIZED BY ROTATION IS WEAKLY DAMPED - HAS STRONG RESPONSE TO RESONANT PERTURBATIONS

- RWM is nearly stationary n = 1 mode
  ⇒ can resonate with n = 1 INTRINSIC error field

- RWM is closer to marginal stability at higher β_N ⇒ resonant response increases as β_N increases above the no-wall limit

- "Error field amplification" clearly demonstrated using external n=1 field pulses

  (A. Garofalo, et al., Phys. Plasmas, 2002)



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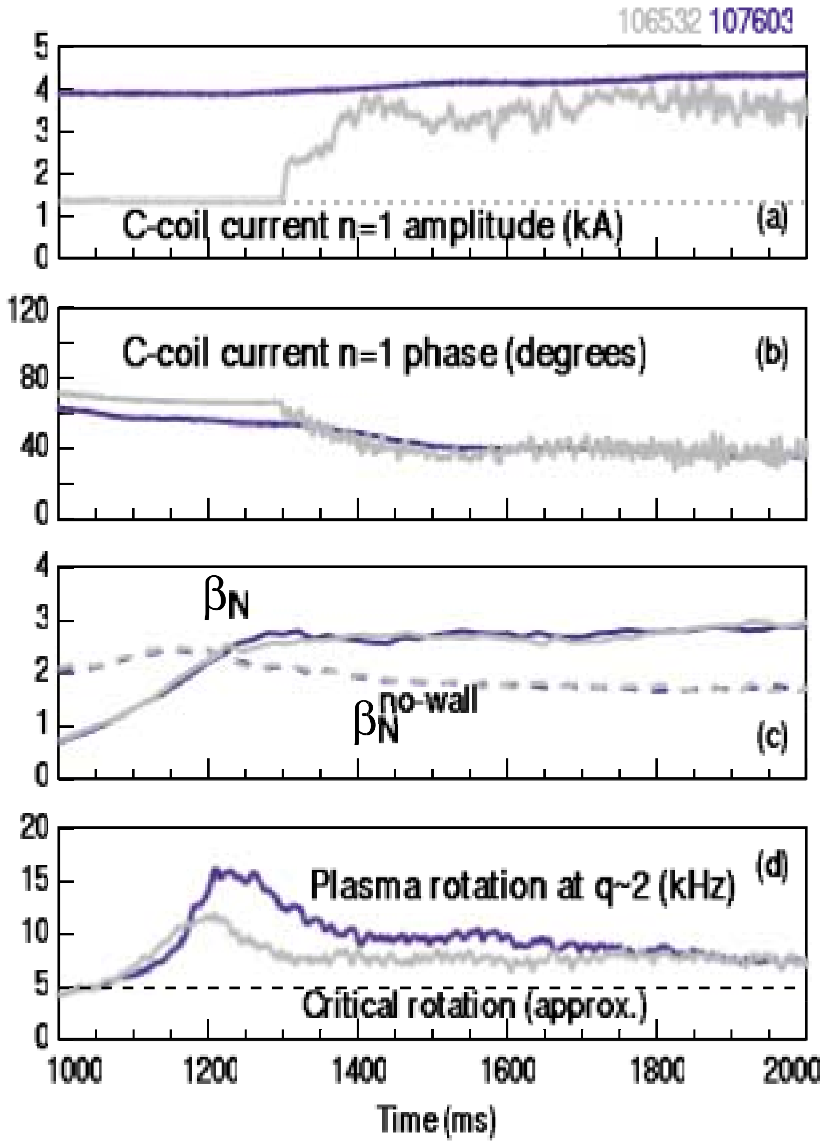
RWM FEEDBACK CAN WORK AS DYNAMIC ERROR FIELD CORRECTION SYSTEM



- The change in plasma response to the INTRINSIC error field, as $\beta_N/\beta_N^{no\text{-}wall}$ increases, is used as input for the feedback system
- With high enough value of proportional gain, the feedback can find same optimal EFC currents obtained through rotation decay-rate minimization
  - Sensors decoupled from the control coils are essential for stability of the feedback system at high gain

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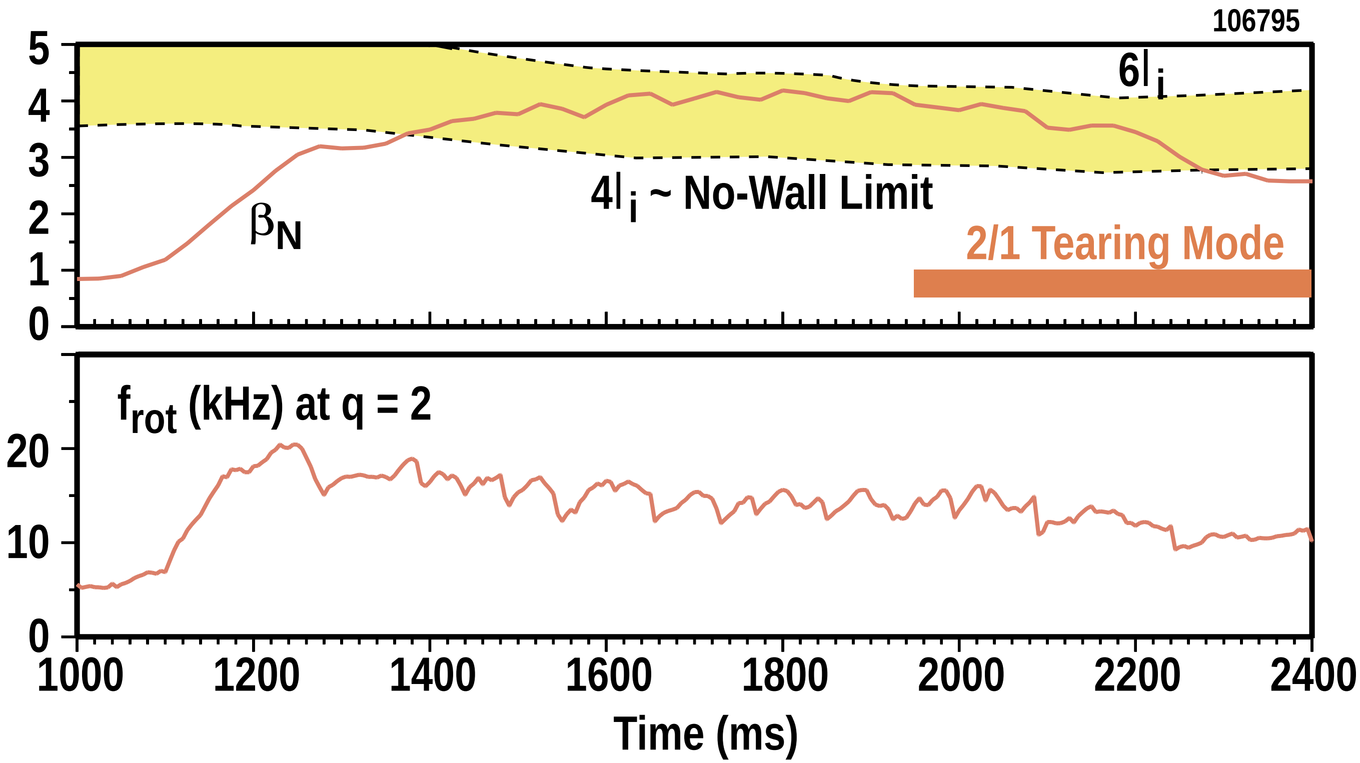
PHYSICS OF RWM AND PLASMA ROTATION TRANSLATES WELL TO ADVANCED TOKAMAK PLASMAS

- RWM feedback finds same error field correction obtained by rotation optimization
  - Dominant error field is m/n=2/1 field
- Sustained plasma rotation allows $\beta_N >> 4l_i$ in negative central shear plasma with 85% noninductive current (65% bootstrap current), and $\beta_T > 4\%$
- Large (2,1) tearing mode limits duration of high performance phase



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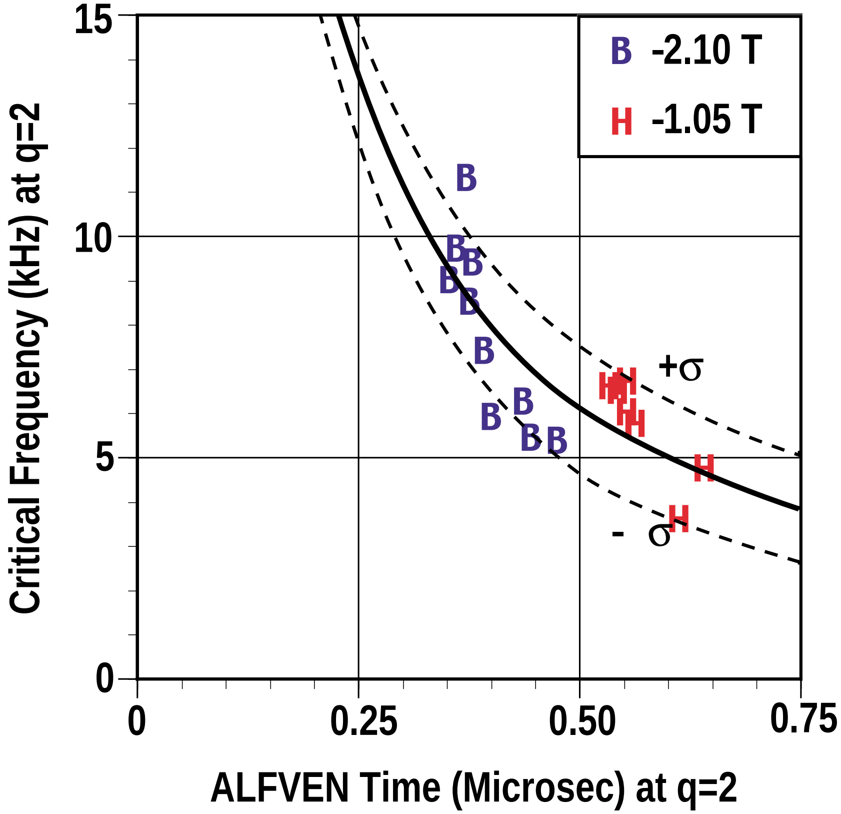
OBSERVED SCALING OF CRITICAL PLASMA ROTATION FOR ONSET OF RESISTIVE WALL MODE IS CONSISTENT WITH MHD THEORY

- Consistent with inverse of ALFVEN TIME: $\Omega_c \tau_A$ ~2% (Bondeson and Ward, 1994)



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

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

$f = 2.78\tau_A^{-1.14-0.17}$

corr = -0.79

σ = -1.3 kHz

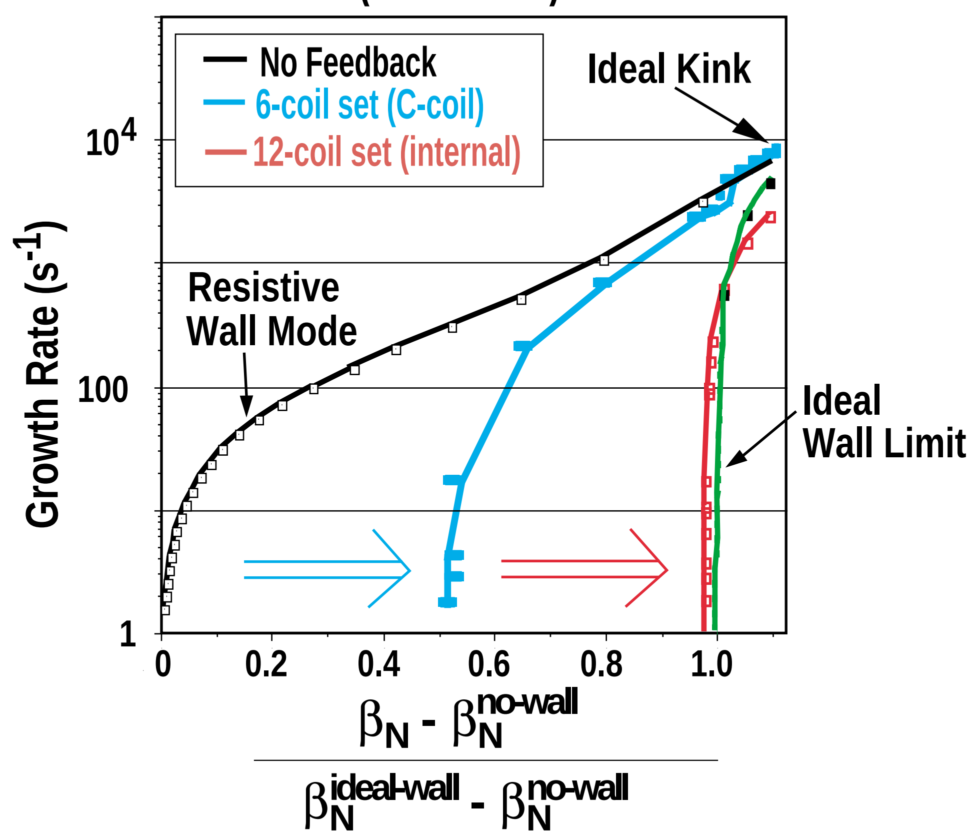
- MARS (Bondeson , Liu, Chu) calculations for ITER predict plasma rotation would be marginal for RWM stabilization

RWM STABILIZATION UP TO THE IDEAL-WALL LIMIT PREDICTED WITH NEW INTERNAL CONTROL COILS, WITHOUT PLASMA ROTATION

- 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

12-coil internal set available for experiments 2003

(VALEN 3-D)



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SUMMARY

- Ideal-wall β_N limit observed at $\beta_N = 2x\beta_N^{no\text{-}wall}$ in DIII-D
- Sustained operation at β_N just below the ideal-wall limit is possible by correction of intrinsic m/n=2/1 error field
- Projected plasma rotation in ITER may not be sufficient for RWM stabilization
- New internal control coils and poloidal field sensors in DIII-D should allow RWM stabilization near the ideal-wall β_N limit in absence of plasma rotation