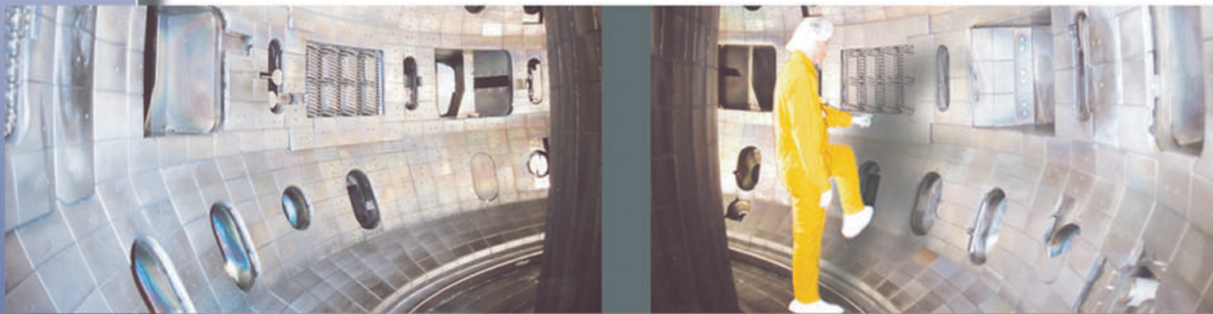

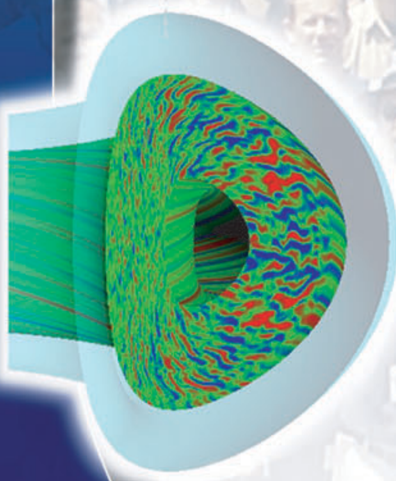

Onset and Suppression of 2/1 NTM in DIII–D

by
C.C. Petty
in collaboration with

D.P. Brennan,[1] T.C. Luce, R.J. La Haye, D.A. Humphreys, J.R. Ferron, L.A. Gorelov, A.W. Hyatt, K. Kajiwara,[2] S.E. Kruger,[3] L.L. Lao, J. Lohr, F.W. Perkins,[4] P.A. Politzer, R. Prater, D.D. Schnack,[5] E.J. Strait, A.D. Turnbull, M.R. Wade,[6] and A.S. Welander

[1]Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[2]Oak Ridge Institute for Science Education, Oak Ridge, Tennessee, USA
[3]Tex-X, Boulder, Colorado, USA
[4]Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
[5]SAIC, San Diego, California, USA
[6]Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

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GENERAL ATOMICS

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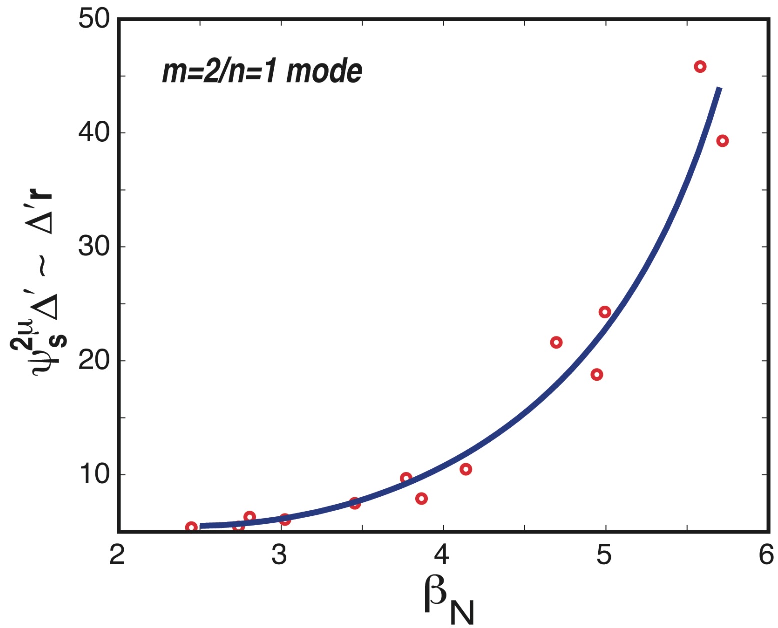
TEARING MODES REPRESENT THE PRESSURE LIMIT FOR BURNING PLASMA EXPERIMENTS

- The "spontaneous" 2/1 tearing modes considered here are classically-destabilized as the ideal MHD stability limit is approached
  - These tearing modes become indistinguishable from (island seeded) neoclassical tearing modes after the initial linear growth phase
- Onset phase of spontaneous 2/1 tearing modes can be explained by modified Rutherford equation when the evolution of the linear drive is modelled correctly
  - NIMROD simulations confirm the importance of the linear drive
- Suppression of an existing 2/1 tearing mode has been achieved in DIII–D using electron cyclotron current drive to replace the "missing" bootstrap current in the island

PART I: THEORY OF "SPONTANEOUS" TEARING MODE ONSET IS CONFIRMED BY EXPERIMENTAL DATA

$$\frac{\tau_R}{r}\frac{dw}{dt} = \underbrace{\Delta'\left[\beta_N(t)\right] r}_{\text{Classical Drive}} + a_2 \frac{J_{BS}}{J_{||}} L_q \left(\underbrace{\frac{w}{w_d^2 + w^2}}_{\text{Neoclassical Drive}} + \underbrace{\frac{w w_{pol}^2}{w_b^4 + w^4}}_{\text{Polarization Stabilization}} \right)$$

Model uses β_N(t) and $\Delta'(\beta_N)$ from PEST-III in island evolution equation



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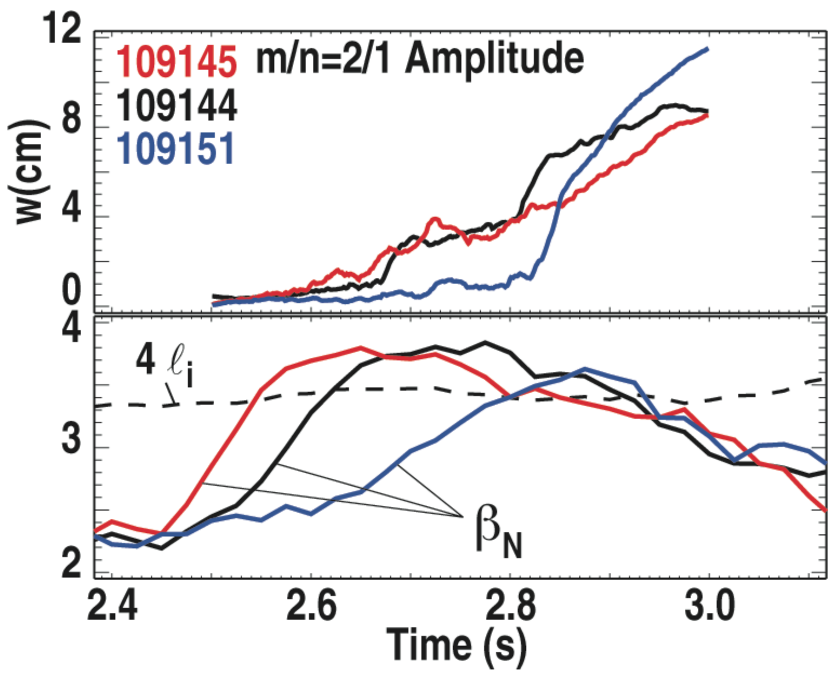
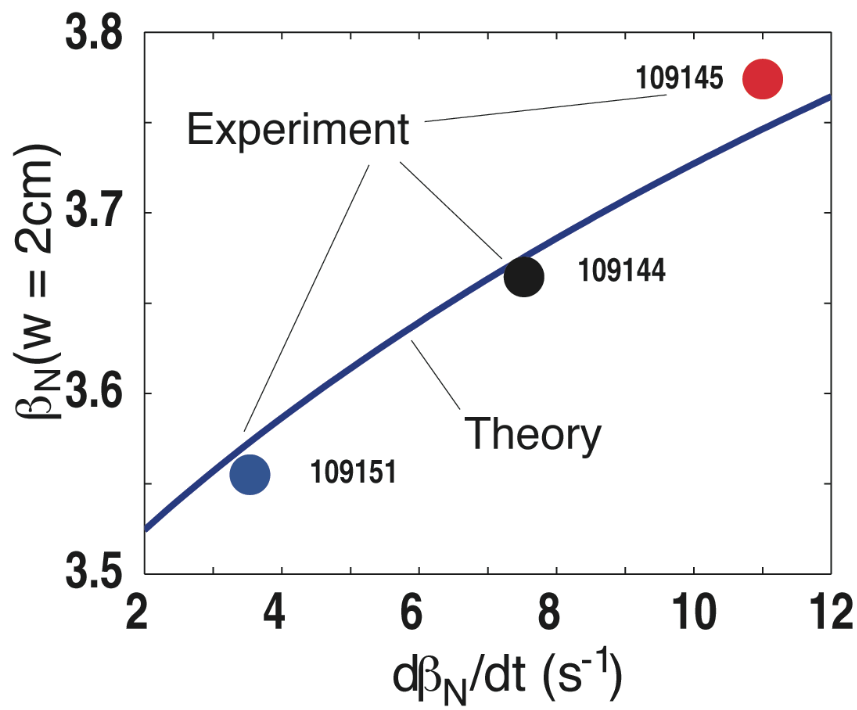
THEORY AND EXPERIMENT AGREE β_N AT FIXED ISLAND WIDTH INCREASES WITH $d\beta_N/dt$

Results support hypothesis that Δ' is increasing with β in time, consistent with theoretical model

Polarization parameter is fitted to find β_N vs. $d\beta_N/dt$ at mode onset





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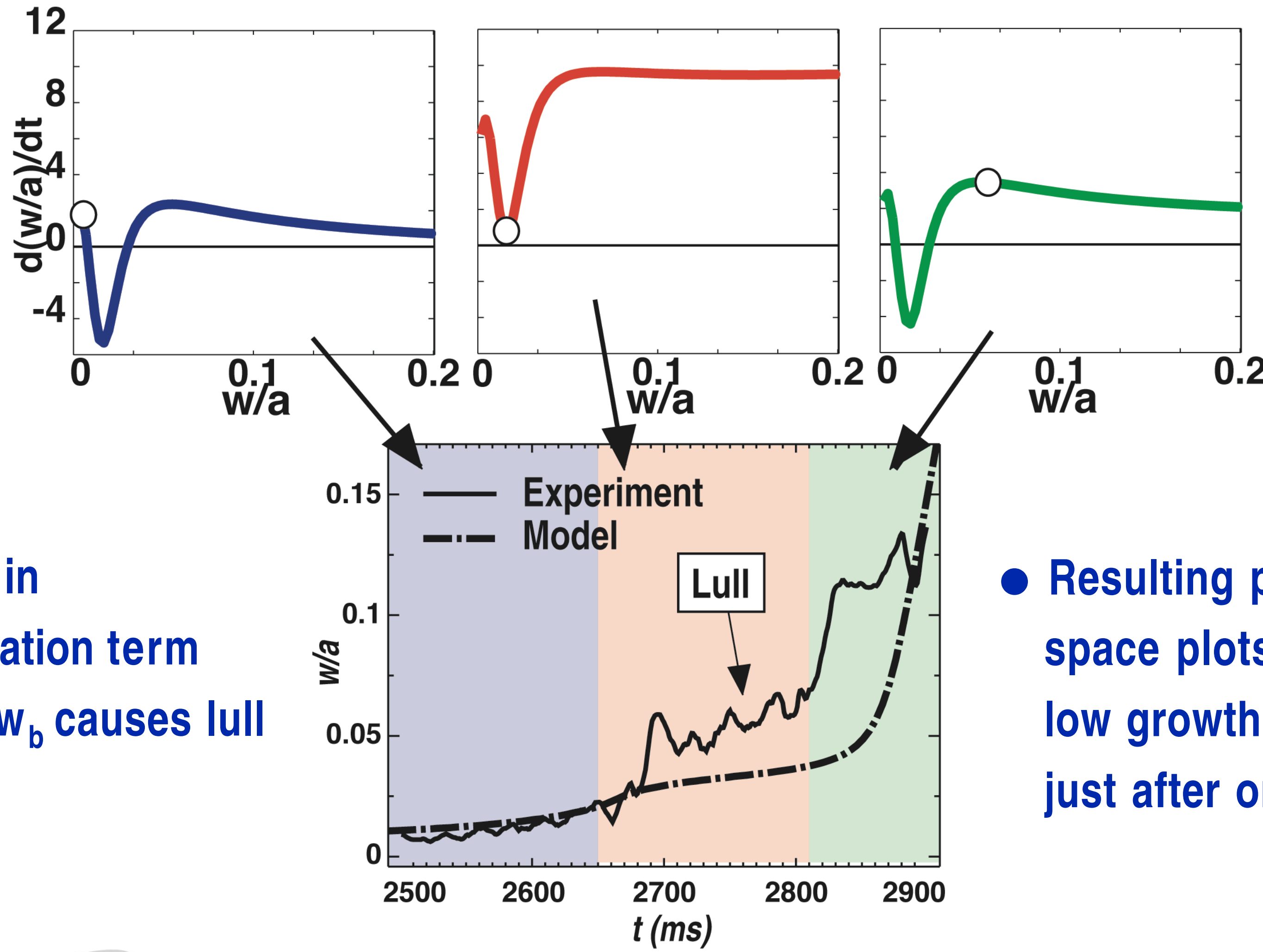
MODEL REPRODUCES LULL IN ISLAND GROWTH RATES OBSERVED IN EXPERIMENT

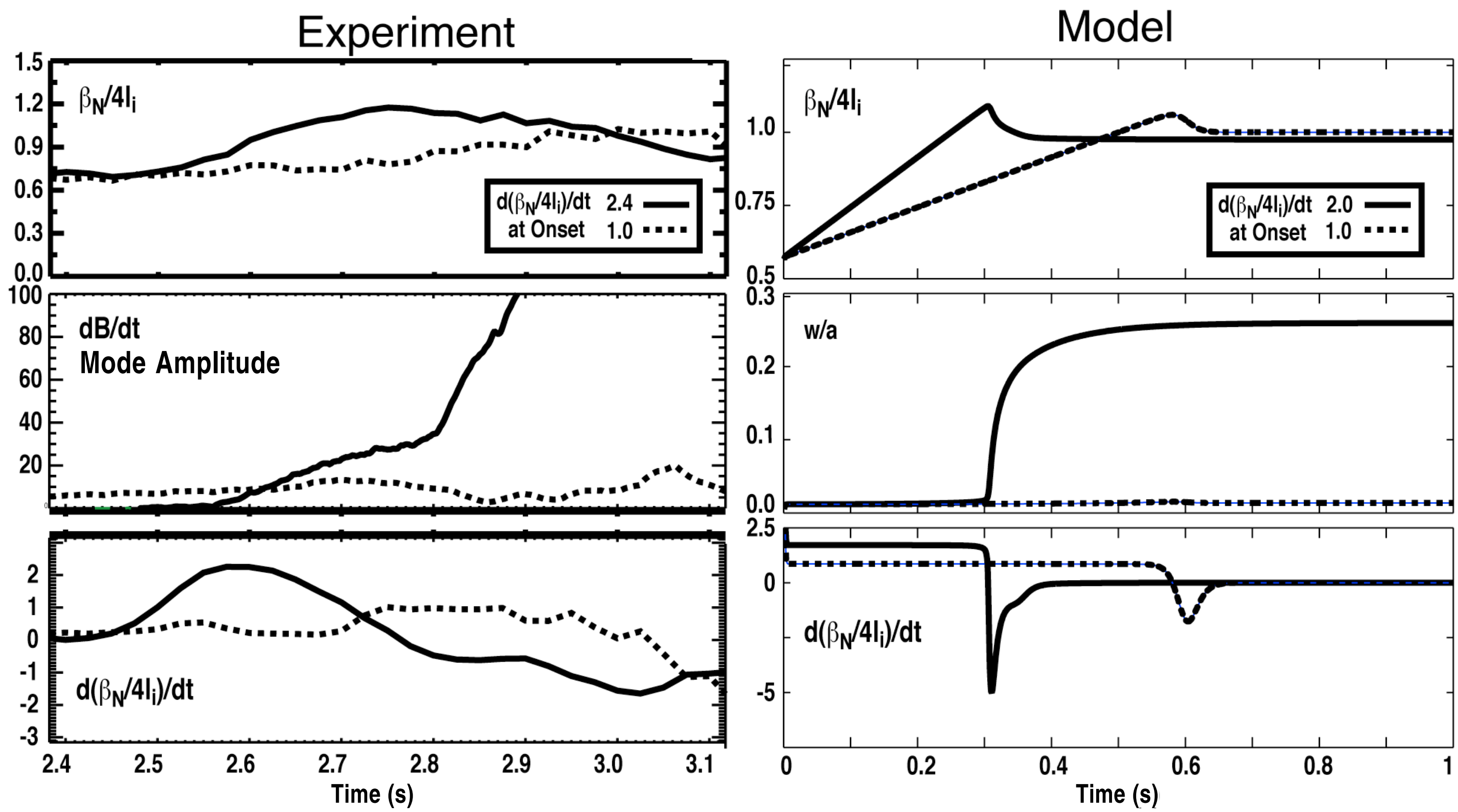


- Cutoff in polarization term for $w<w_b$ causes lull

- Resulting phase space plots have low growth rates just after onset

MINIMUM RATE OF HEATING FOR TEARING MODE ONSET QUALITATIVELY AGREES WITH EXPERIMENT

- Island causes transport, reducing β and Δ', resulting in a lower limit in $d\beta/dt$



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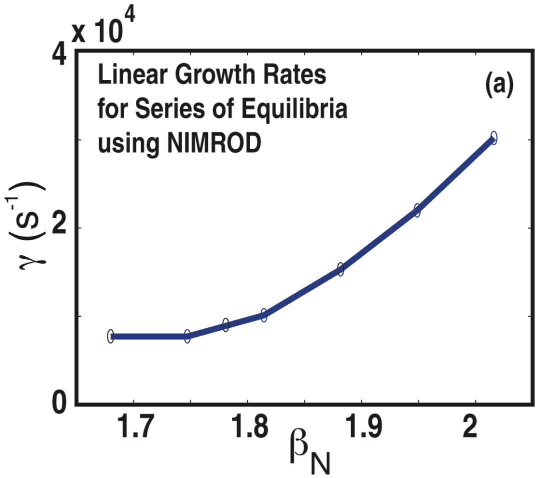
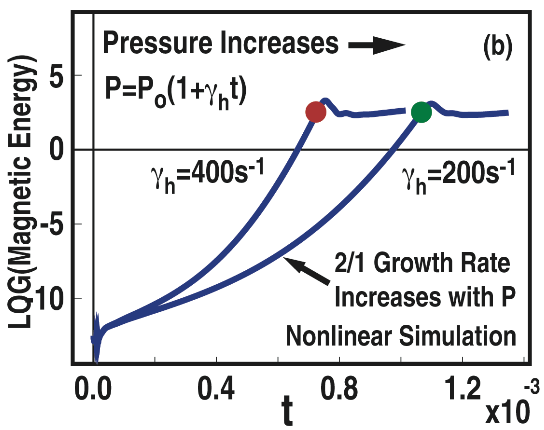
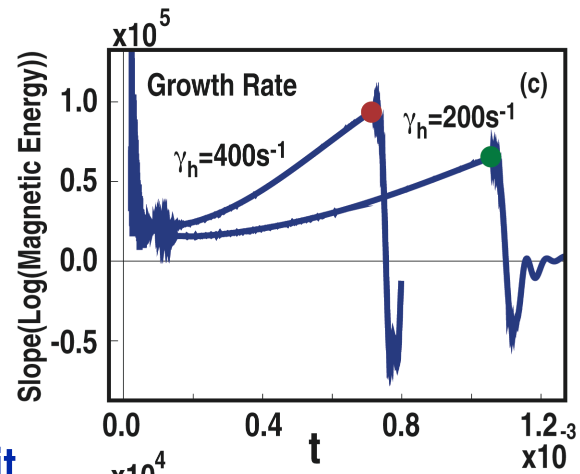
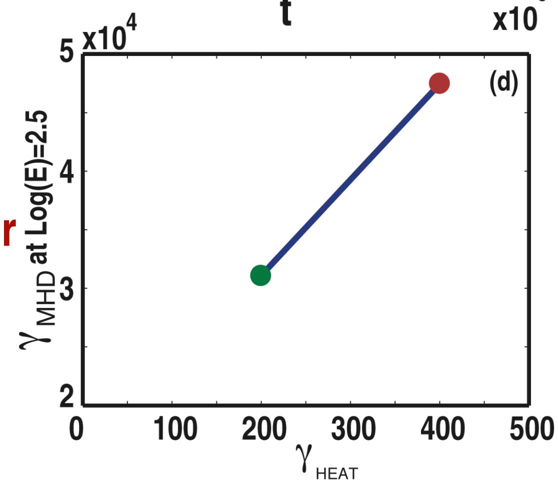
DEPENDENCE OF $\beta(w)$ AND $\gamma(w)$ ON HEATING RATE CAPTURED BY NIMROD EXTENDED MHD SIMULATIONS



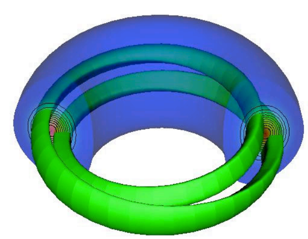


- Timescales: $\tau_R >> \tau_H > \tau_{MHD}$
- Thermal anisotropy: temperature flattening, fast parallel transport included
- Neoclassical and Polarization Effects necessary for NTM threshold and low heating rate limit
- For low heating rates, the island growth rate decreases at minimum detected size, reducing ECCD power requirements for stabilization





See poster for additional details



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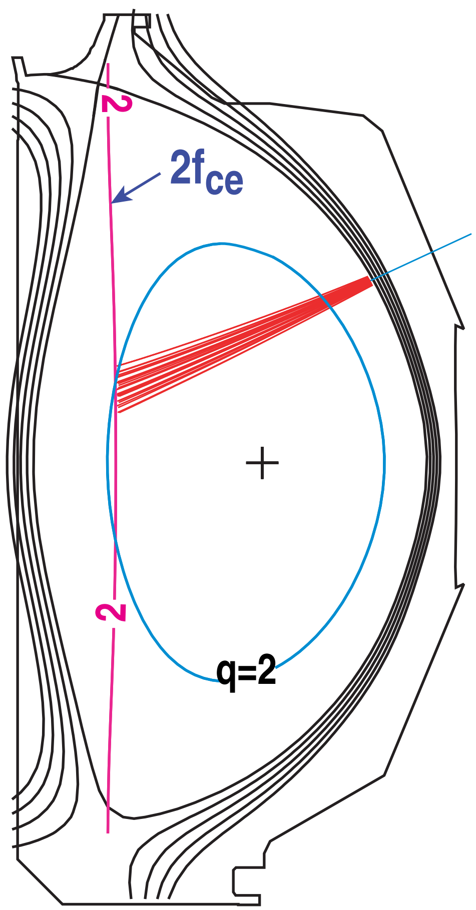
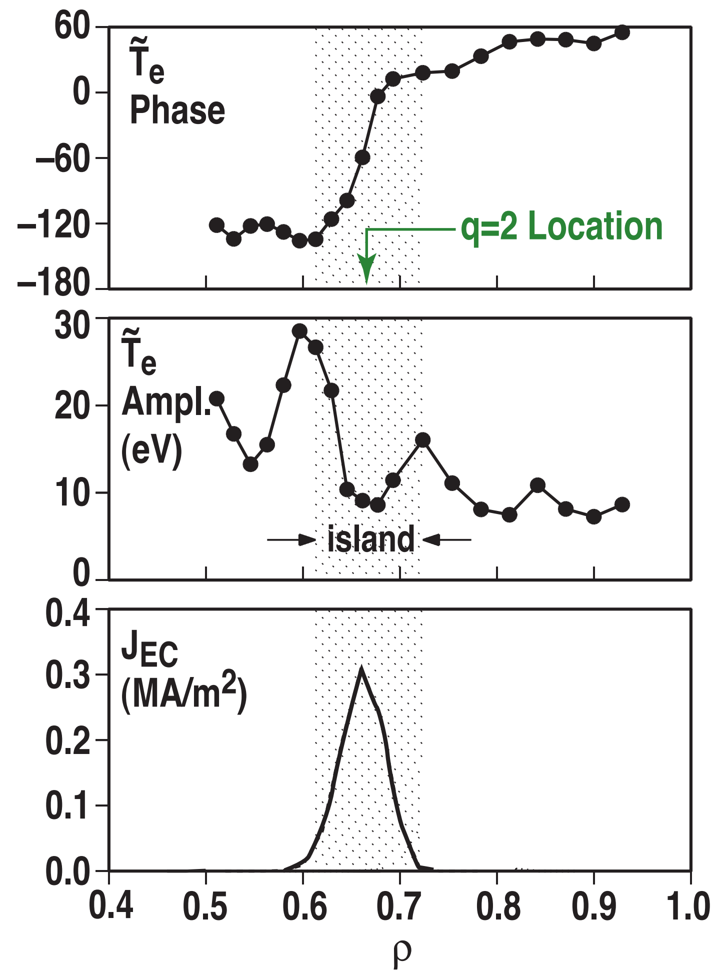
PART II: SUPPRESSION OF 2/1 TEARING MODE USING ECCD TO REPLACE "MISSING" BOOTSTRAP CURRENT

ECCD aimed at q = 2 surface



Island shrinkage optimized when ECCD is centered on 2/1 island



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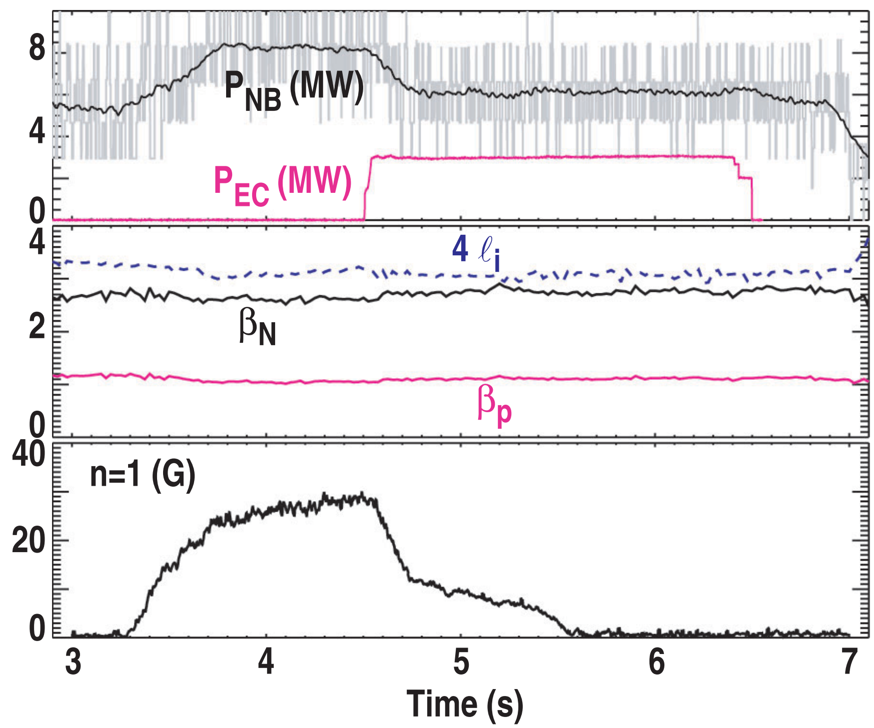
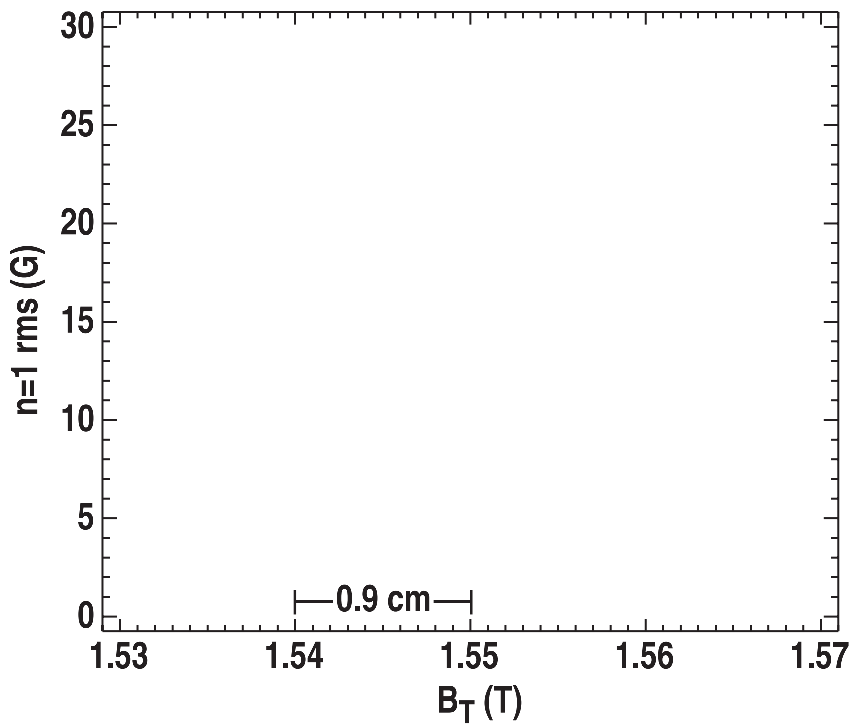
2/1 TEARING MODE IS COMPLETELY SUPPRESSED AT β = 3.5% USING CLOSED-LOOP FEEDBACK TO OPTIMIZE ECCD LOCATION

2/1 mode suppressed in hybrid discharge with β_N well above ITER baseline scenario



"Target lock" algorithm uses small, rapid variations in B_T to optimize suppression



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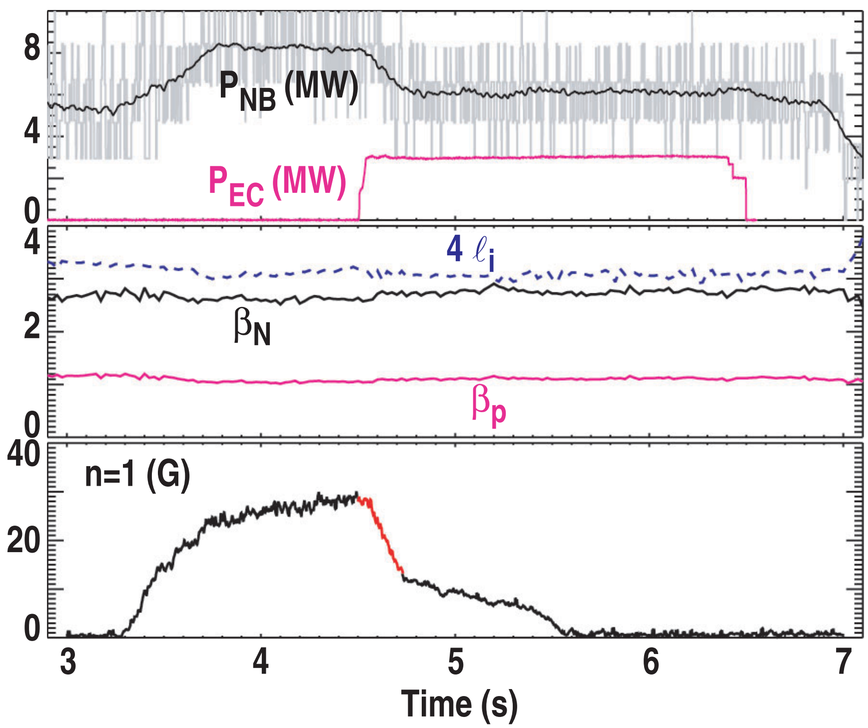

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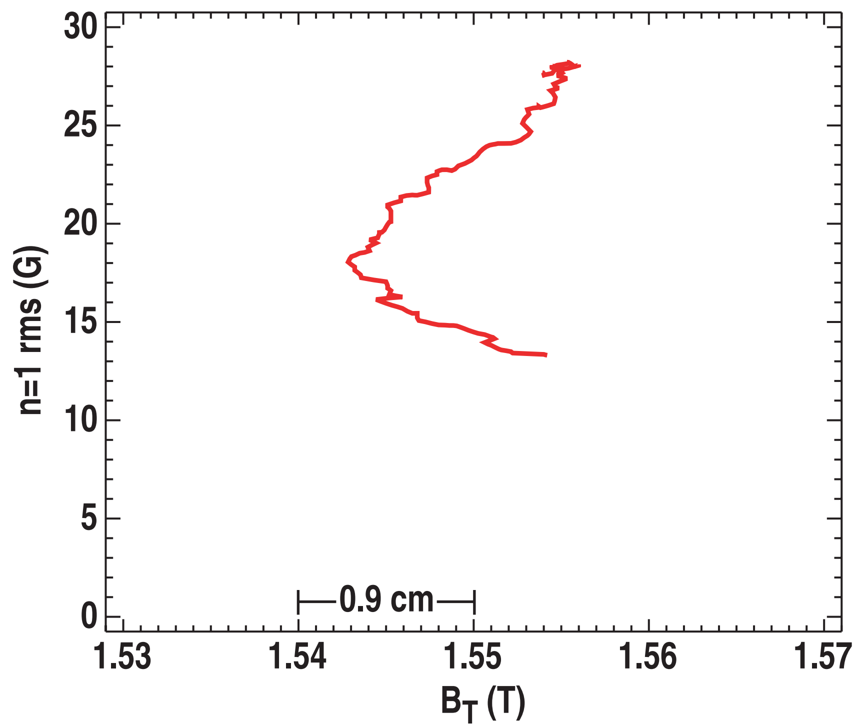

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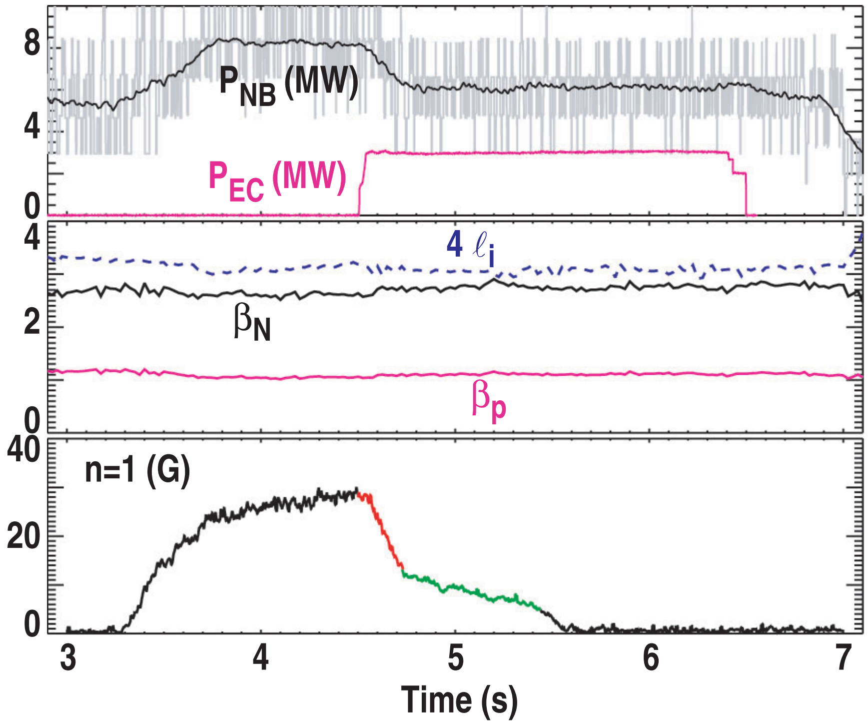

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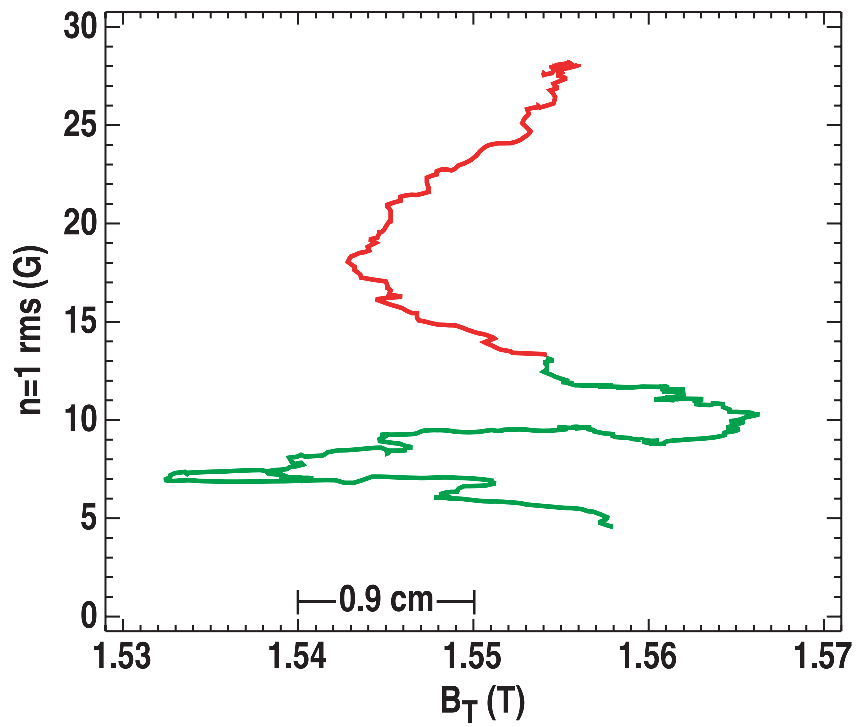

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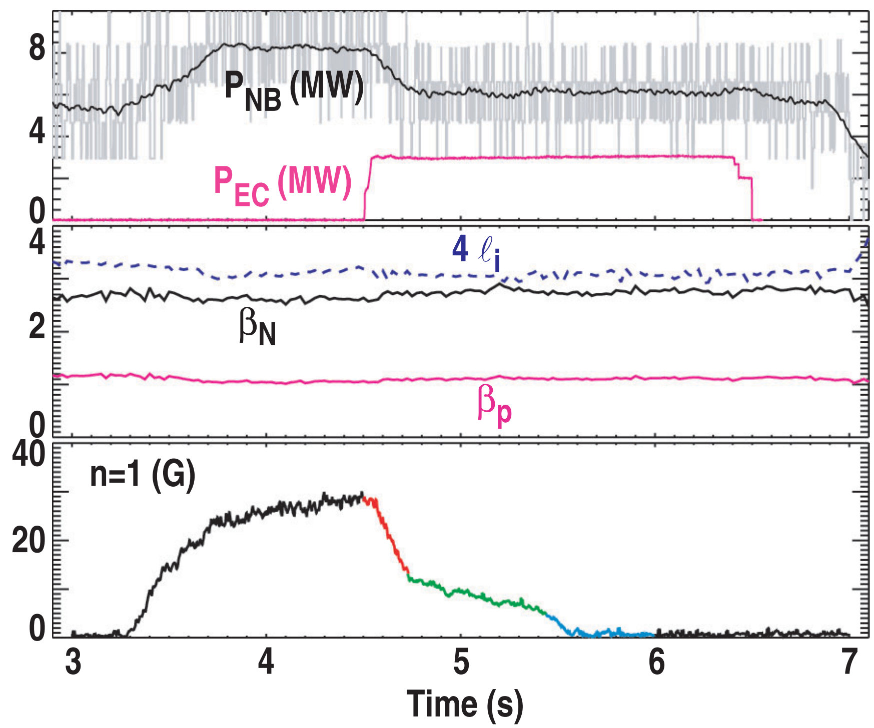

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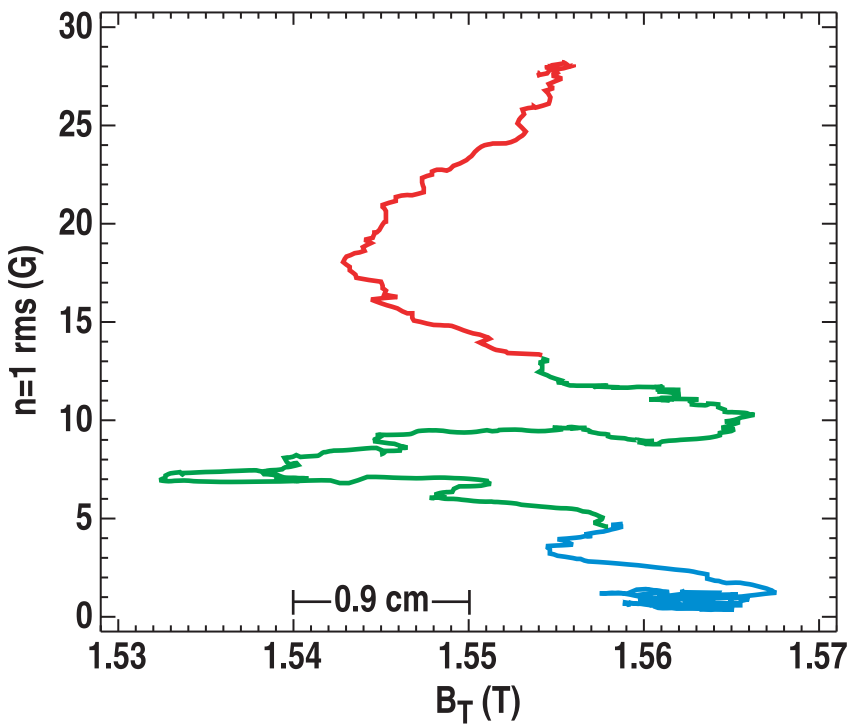

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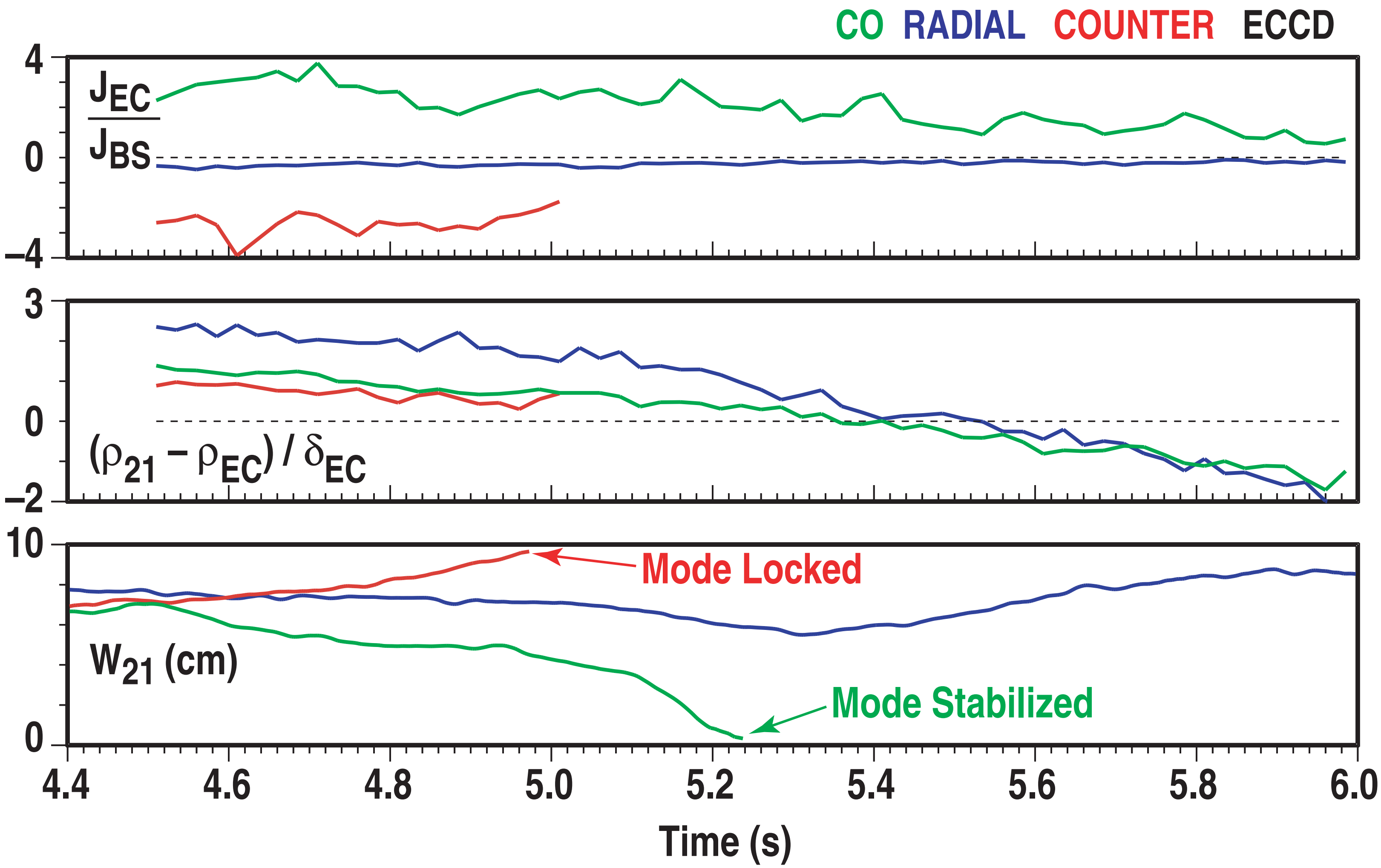
CO-CURRENT DRIVE IS NECESSARY TO STABILIZE 2/1 MODE

- Slow B_T scan sweeps 3.0 MW of ECCD past q=2 surface



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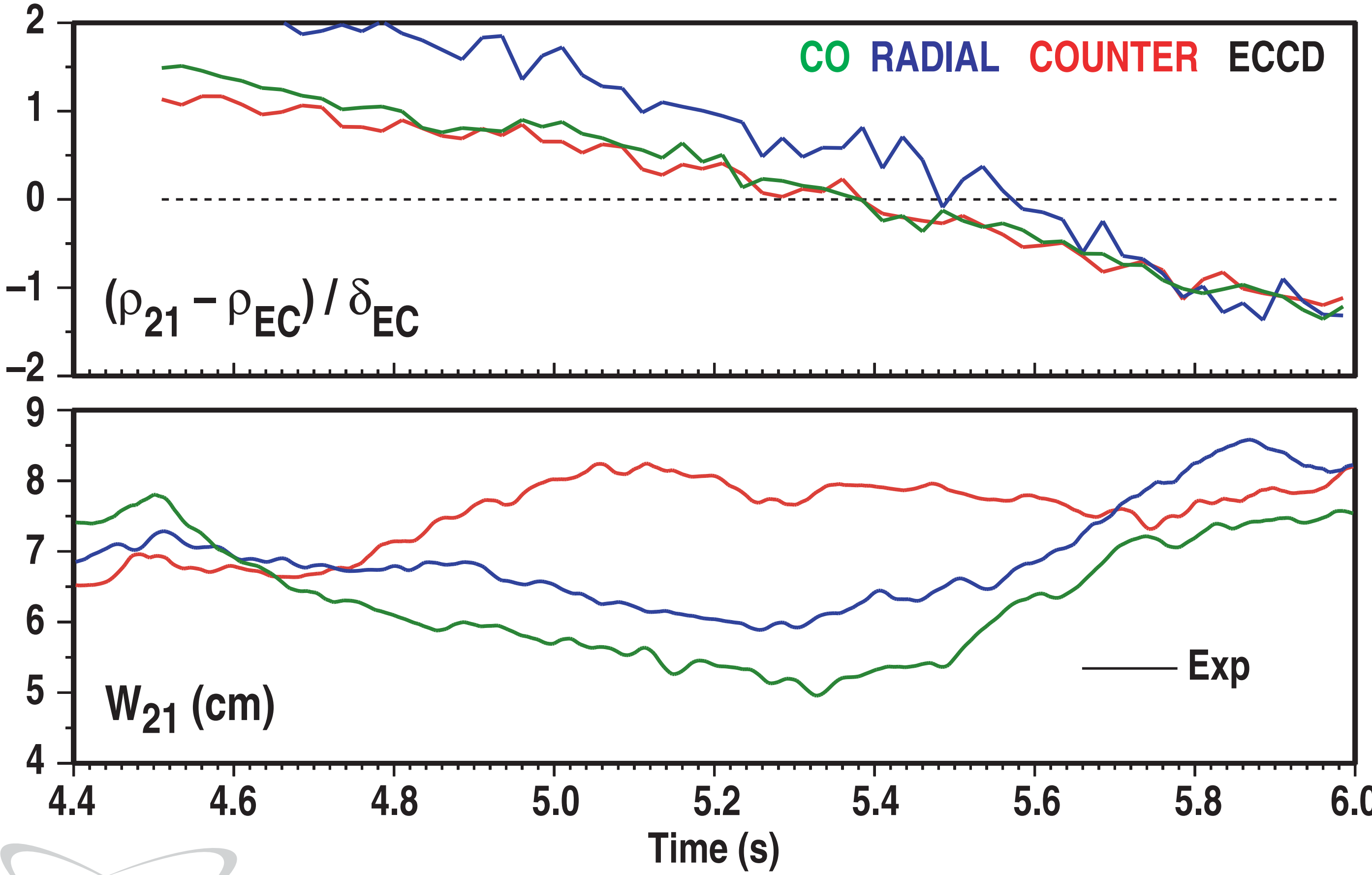
MODELLED ISLAND WIDTH FOR CO/RADIAL/COUNTER INJECTION SEPARATES EFFECTS OF ECCD AND Δ´ MODIFICATION

$$\frac{\tau_R}{r}\frac{dw}{dt} = \underbrace{\Delta' r}_{\text{Classical Drive}} + a_2 \frac{J_{BS}}{J_{||}} \frac{L_q}{w} \left[\underbrace{1}_{\text{Neoclassical Drive}} - \underbrace{\frac{w_{pol}^2}{w^2}}_{\text{Polarization Stabilization}} - \underbrace{K_1 \frac{J_{EC}}{J_{BS}}}_{\text{ECCD Stabilization}} \right]$$



- K_1 is effectiveness parameter that depends on alignment and ECCD width
- Reduced ECCD power (2.0 MW) results in partial mode suppression

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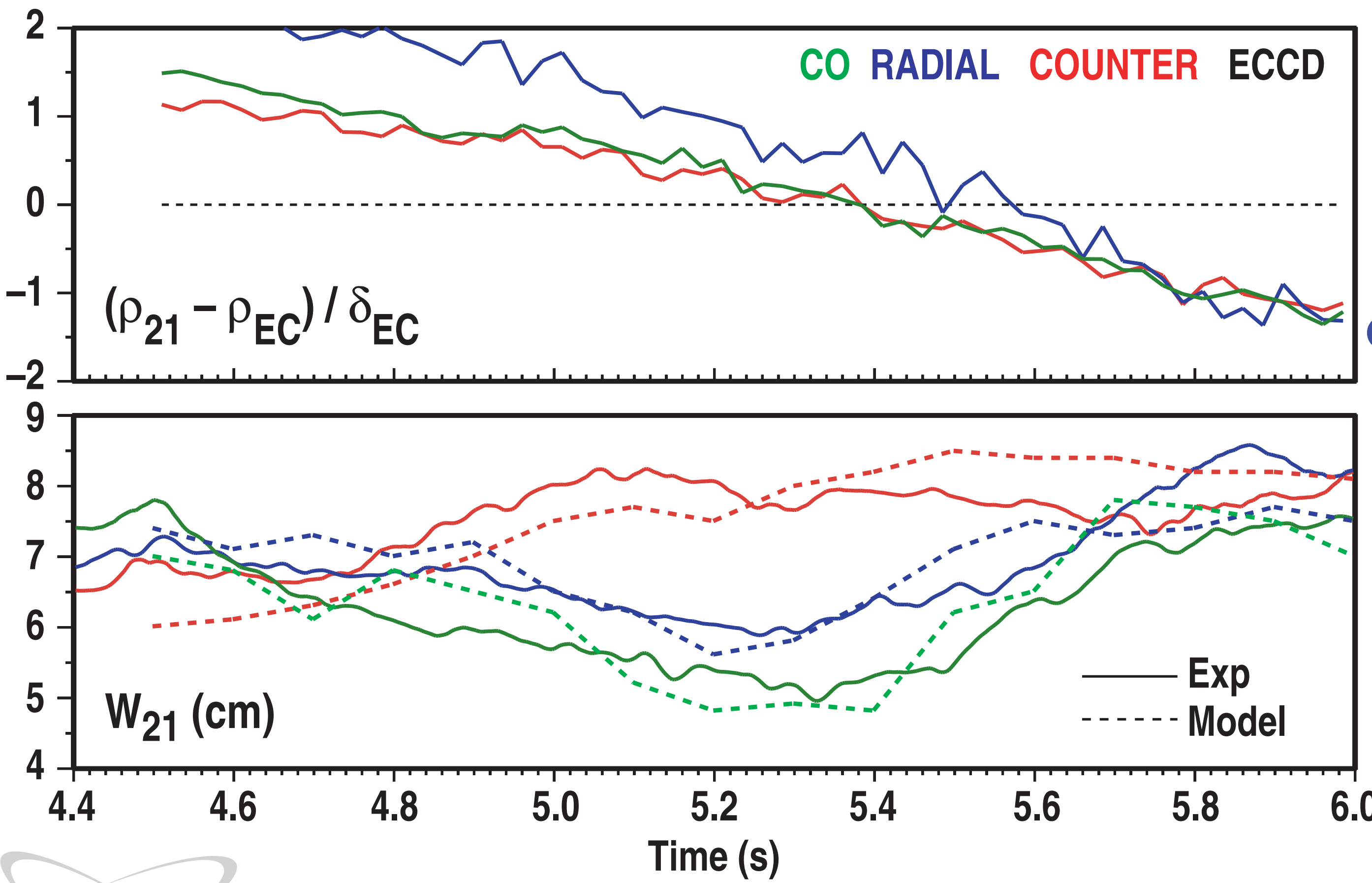

- Changes in island widths are well reproduced by including co/radial/counter ECCD in modified Rutherford equation

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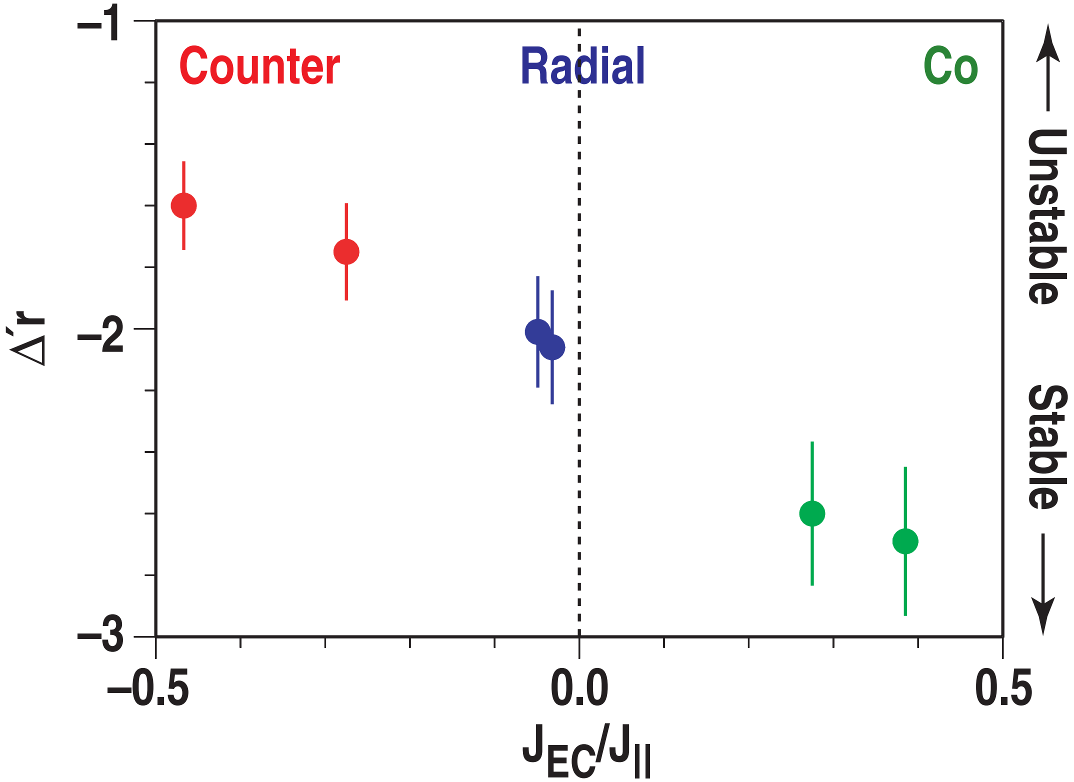
CO-ECCD MAKES Δ´ MORE NEGATIVE, WHILE COUNTER-ECCD HAS OPPOSITE EFFECT

Best fit value of Δ´during co/radial/counter ECCD at fixed deposition location



- Although Δ´ modification is significant, direct current drive in island is main reason for 2/1 tearing mode suppression

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SUMMARY

- Time evolution of linear drive is the key to understanding the growth phase of the 2/1 tearing mode
- Three physics predictions about the onset phase of the 2/1 tearing mode have been experimentally verified
  - Increase in growth rate with higher β
  - Early lull in island growth
  - Minimum heating rate for onset of 2/1 mode
- Complete suppression of 2/1 NTM has been achieved using ECCD at the q=2 surface for $\beta_N = 2.8$ ($\beta = 3.5\%$) at 90% of the ideal no-wall stability limit
- ECCD also appears to modify Δ' significantly in a direction that complements the direct current drive effect
- Future experiments will apply early ECCD to avoid 2/1 mode onset