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Development of Low Rotation Target Discharges for RWM Feedback Stabilization Using Non-Resonant Magnetic Fields,*

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Advanced Tokamak scenarios in burning plasma devices with $\beta_N > \beta_{N,NoWall}$ requires resistive wall mode (RWM) stabilization either by high toroidal rotation or feedback control using a magnetic coil set. Present modeling predicts v_ϕ in ITER is not sufficient for RWM stabilization, so a goal of the DIII-D program is to demonstrate feedback stabilization at low rotation. The DIII-D tokamak is presently configured with all neutral beam injectors in the same direction so this large momentum input must be counteracted with an externally applied torque to achieve low v_ϕ. Both n=2 and n=3 magnetic braking (non-resonant with the n=1 RWM) have been used to produce low rotation target plasmas. We will discuss the use of both external (C-coil) and internal (I-coil) picture frame coils to reduce the toroidal rotation at the m/n=2/1 flux surface to values below ω_{crit} ($\omega_{crit} \sim 0.02\ \omega_{Alfven}$) and, in particular, the dependencies of coil current, q_{95} and n_e in obtaining low rotation with β_N above the no-wall limit. The non-resonant fields also reduce ELM amplitude and we will present these observations.

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TWO TECHNIQUES HAVE STABILIZED RESISTIVE WALL MODES (RWMs) ABOVE THE NO-WALL β LIMIT IN DIII-D

- Rotational stabilization with uni-directional neutral beams
- Active feedback stabilization with n=1 coil sets
  - 6 coil external compensating set (C-coils)
  - 12 coil internal set (I-coils)

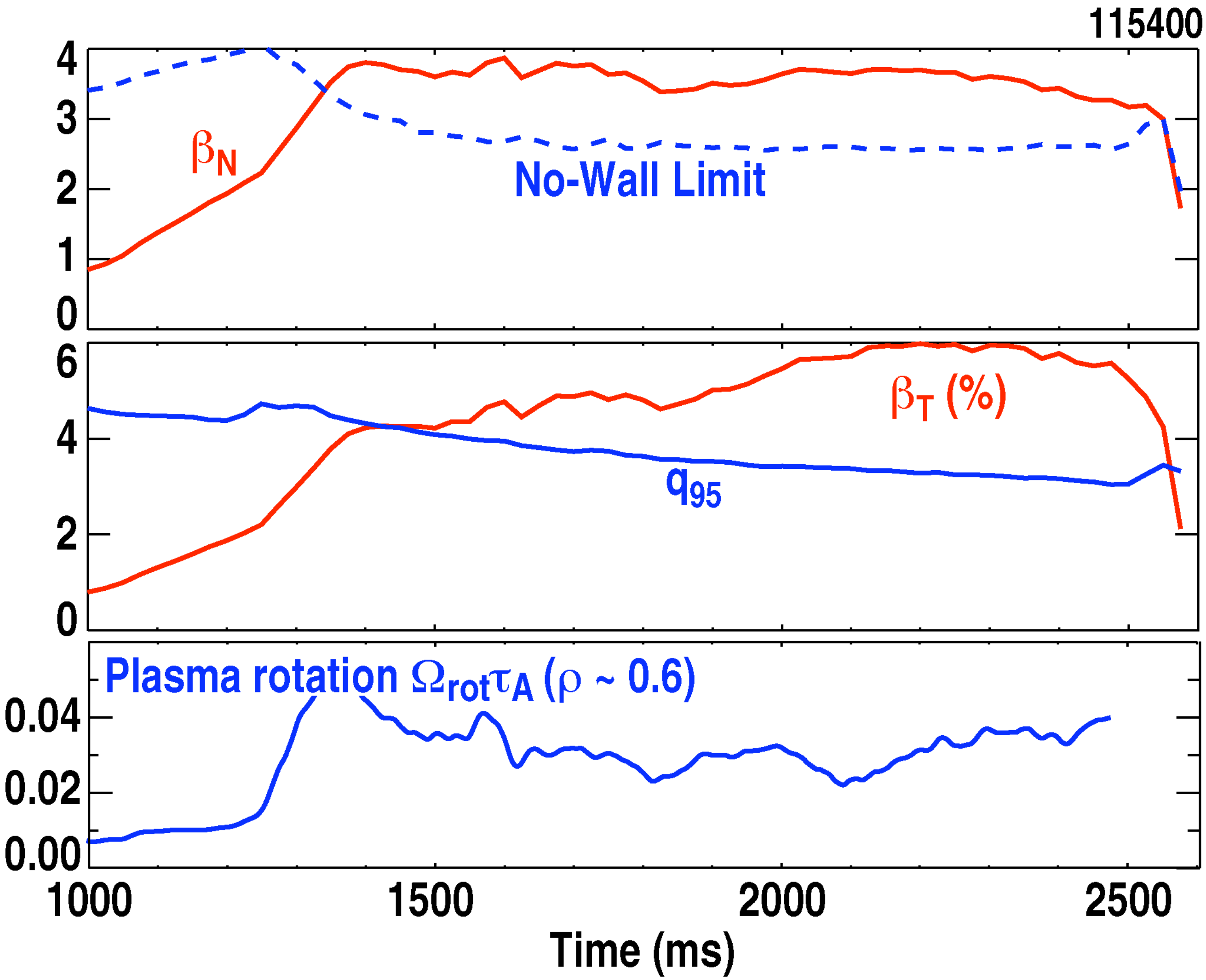
ADVANCED TOKAMAK SCENARIOS FOR ITER PREDICT TOROIDAL ROTATION WILL BE TOO LOW FOR EFFECTIVE ROTATIONAL STABILIIZATION

- Additional coil set for RWM stabilization is being considered for ITER

DIII-D CAN EXPLORE LOW ROTATION SCENARIOS WITH RWM FEEDBACK STABILIZATION

- Effective means of counteracting NB torque is required
  - n=1 braking is effective but interferes with n=1 RWM stabilization
  - Either coil set can be configured as n=2 or n=3 to provide non-resonant drag while the other coil set is used for n=1 RWM feedback stabilization

ROTATIONAL STABILIZATION OF THE RWM CAN EXTEND THE OPERATING REGIME FROM $\beta_{no\text{-}wall}$ UP TO THE IDEAL WALL β LIMIT

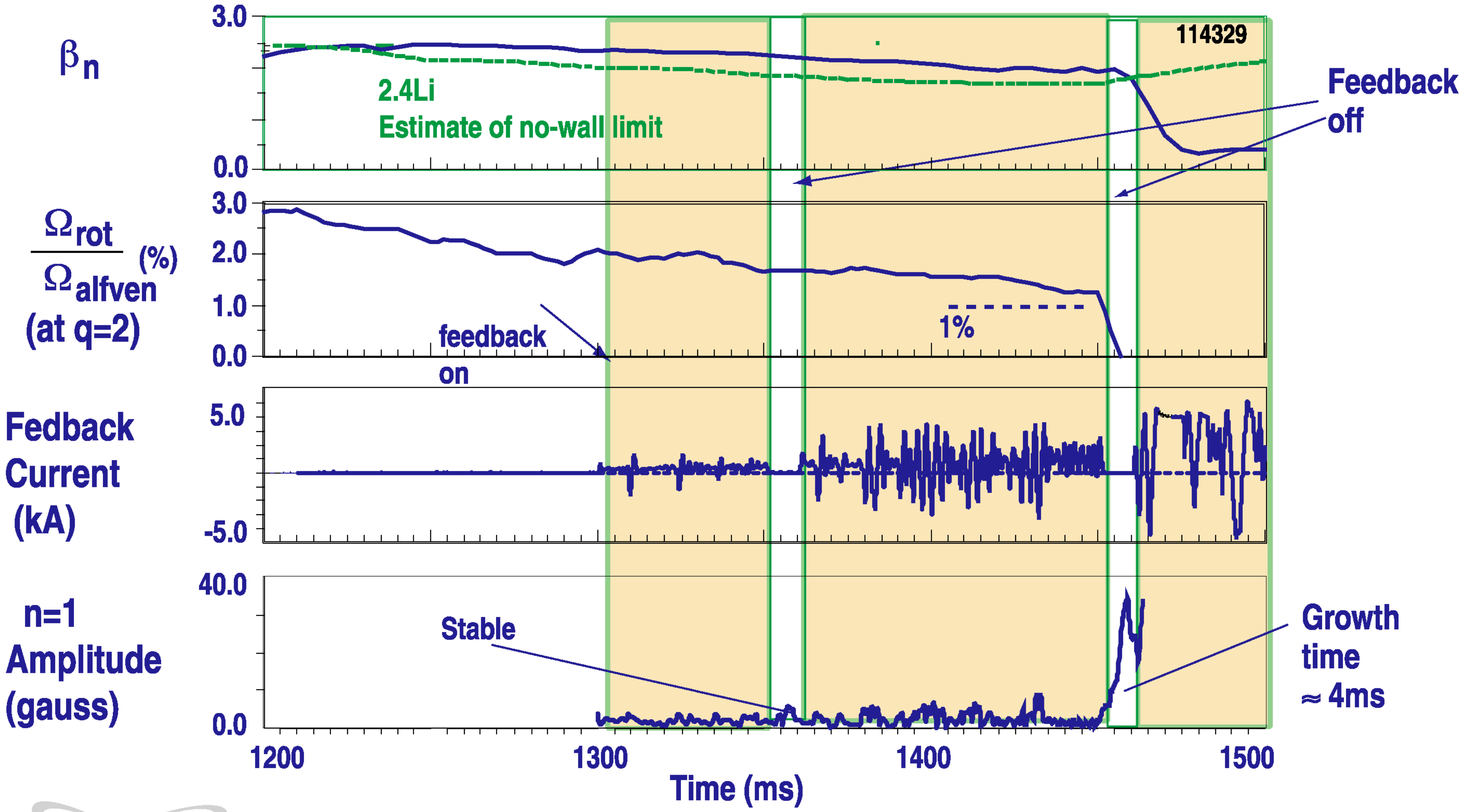


- Operation above the no-wall limit is particularly important for advanced tokamak (AT) scenarios
  - ATs rely on a large fraction of bootstrap current
  - Broad current profiles greatly benefit from wall stabilization

- Operation in the wall stabilized regime with $\beta_N \sim 6\, l_i$ and β_T reaching 6%

Reimerdes IAEA 2004

DIRECT MAGNETIC FEEDBACK SUSTAINS $\beta_N > \beta_{N,\text{no wall}}$ EVEN WHEN Ω_{rot}/Ω_A IS LOWERED TO 1.0-1.5% ON q=2 SURFACE



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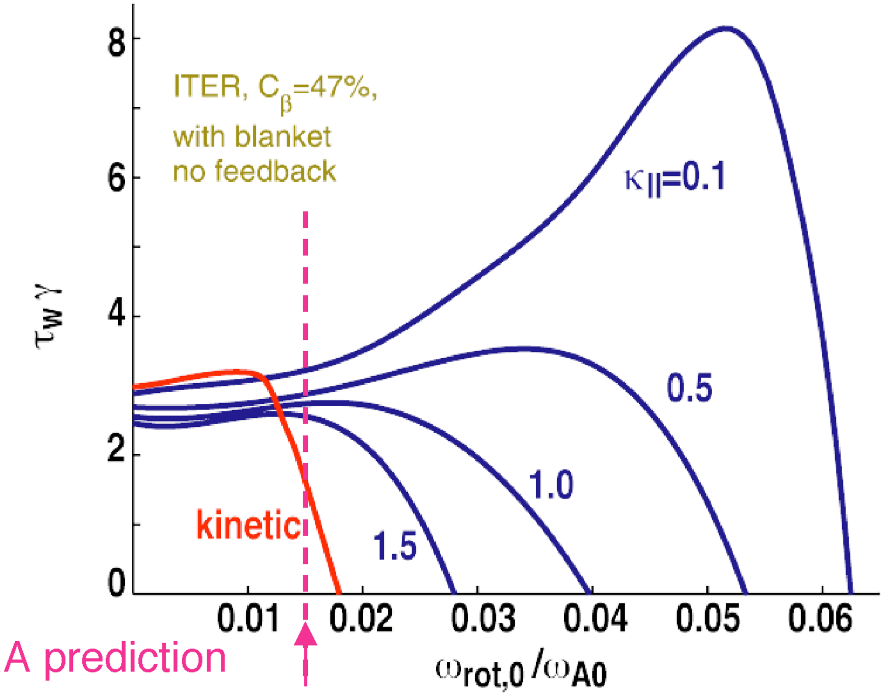
Modeling of RWM stability in ITER steady-state scenario predicts that the expected rotation is below the critical rotation required for rotational stabilization

MARS calculation

- Scenario 1 [A. Polevoi, et al, 19th IAEA conference (2002)]
- Wall modeling
  - Double wall
  - Blanket

Results

- Weak β-dependence of soundwave damping for C_β ranging from 0.2 to 0.7
- Critical rotation for kinetic damping higher at lower beta $\omega_{crit,0}/\omega_{A0} = 0.03$ at $C_\beta = 0.2$



ITER according to ASTRA prediction

Unstable

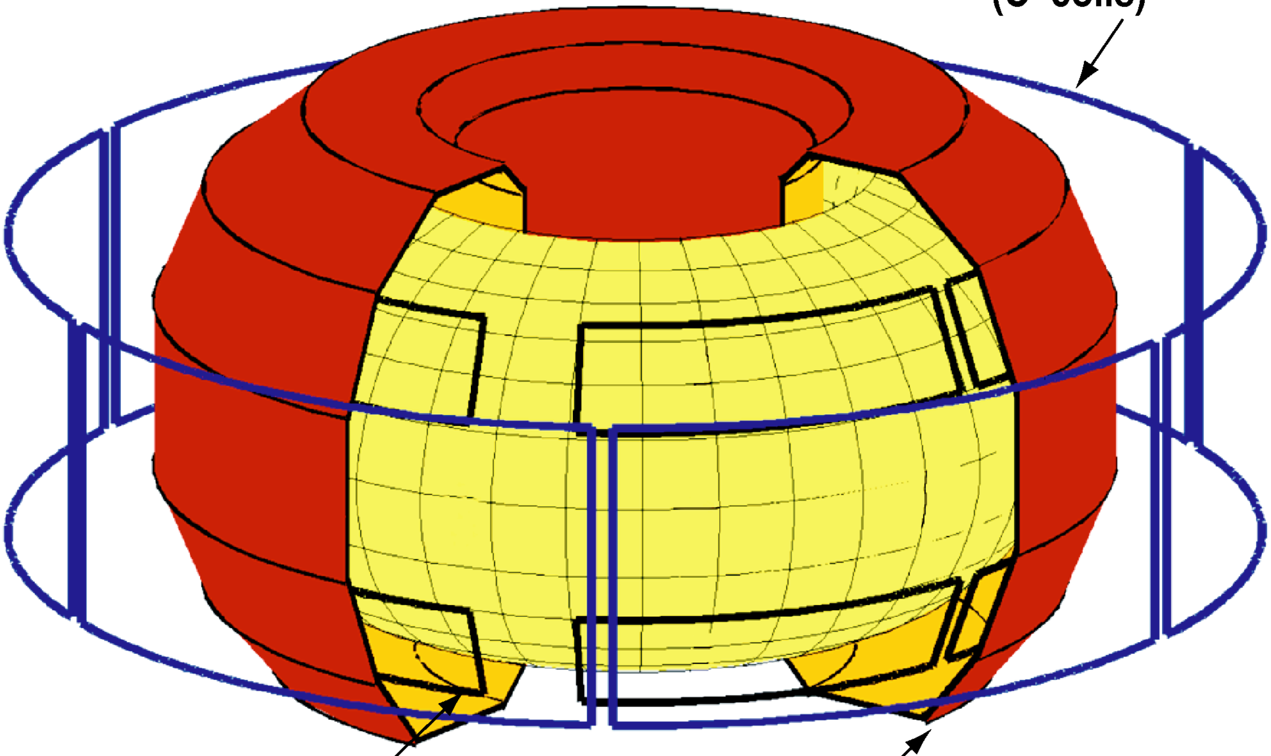
Stable

Figure 14. RWM stabilization by toroidal rotation with the profile from ITER design. Plotted is the growth rate versus the central rotation frequency normalized by the Alfven frequency at the plasma centre. An equilibrium with C_β = 47% is chosen. The different curves correspond to different damping coefficients, $\kappa_{||}$, for the fuid model as well as the kinetic model.

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

TWO COIL SETS CAN BE INDEPENDENTLY CONNECTED TO PRODUCE n=1,2,or 3 MAGNETIC FIELDS, OR COMBINATIONS

(Example: C-coil used for n=1 RWM feedback stabilization and I-coil for n=3 braking)



External Coils
(C–coils)

Internal Coils
(I–coils)

Vacuum Vessel
(Cutaway View)

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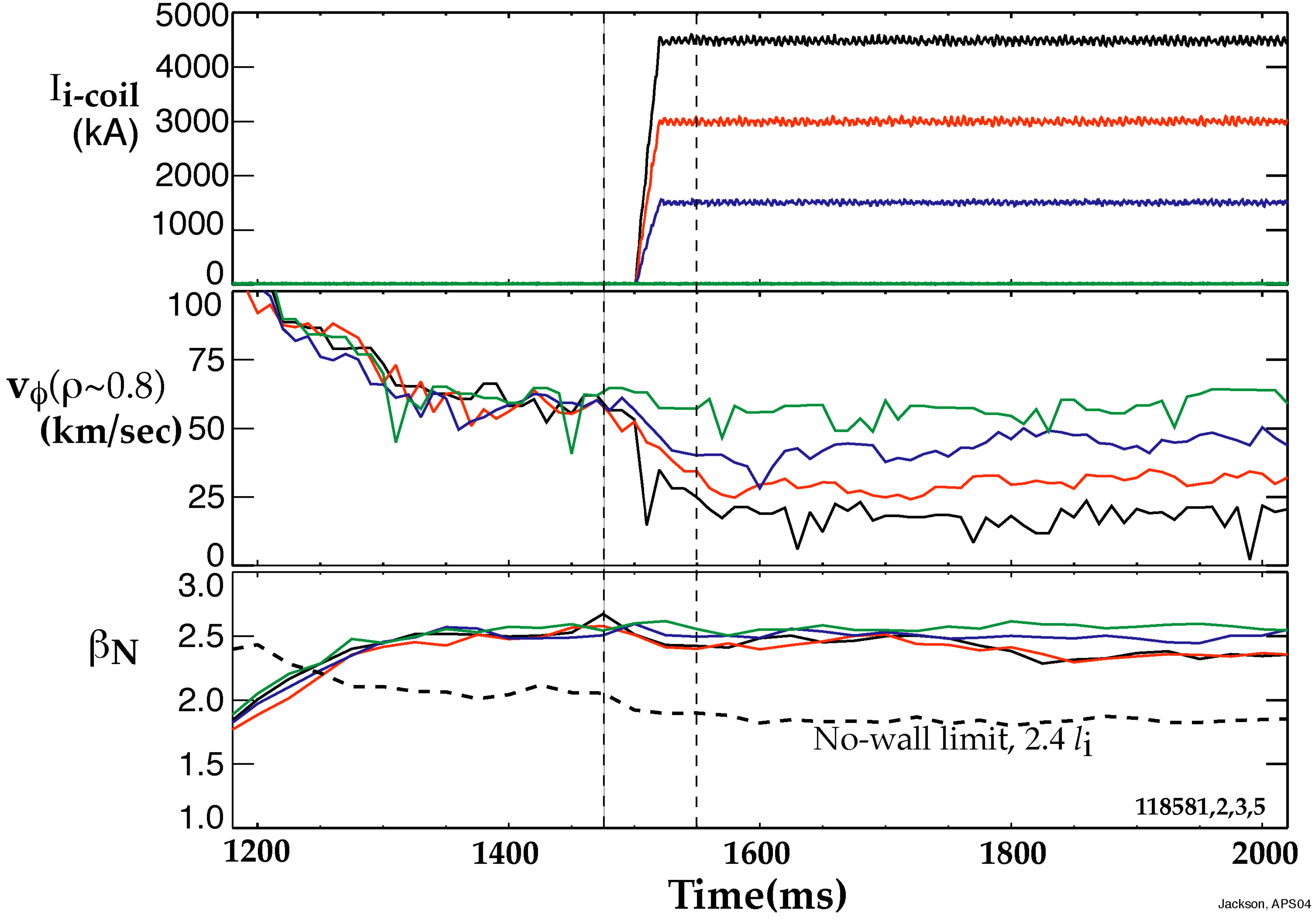
TOROIDAL ROTATION PROMPTLY DECREASES WITH THE APPLICATION OF n=3 I-COIL CURRENT



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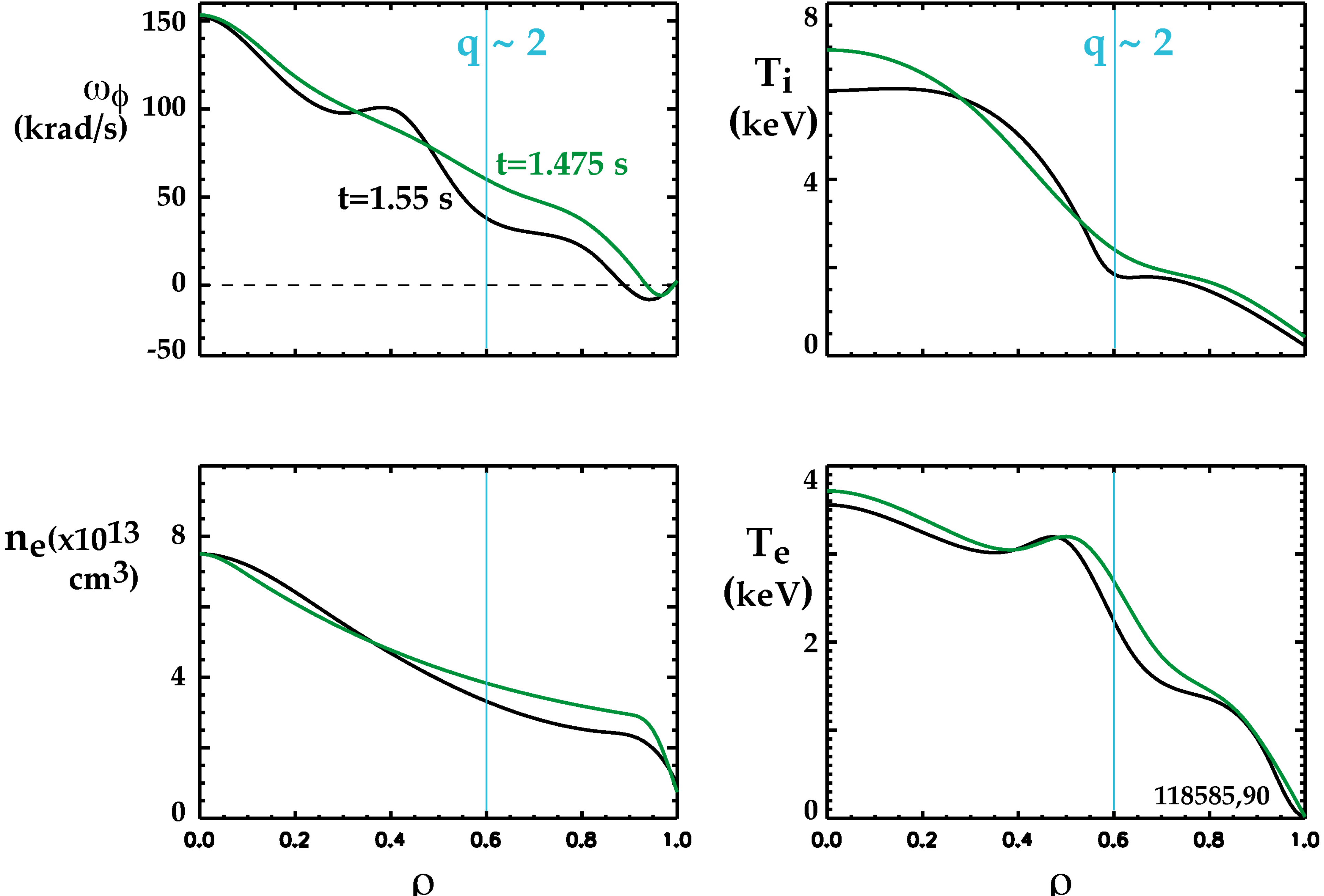
WITH n=3 BRAKING, ROTATION IS PROMPTLY REDUCED ACROSS THE OUTER PROFILE (q > 2)

Braking applied at t=1.5 s



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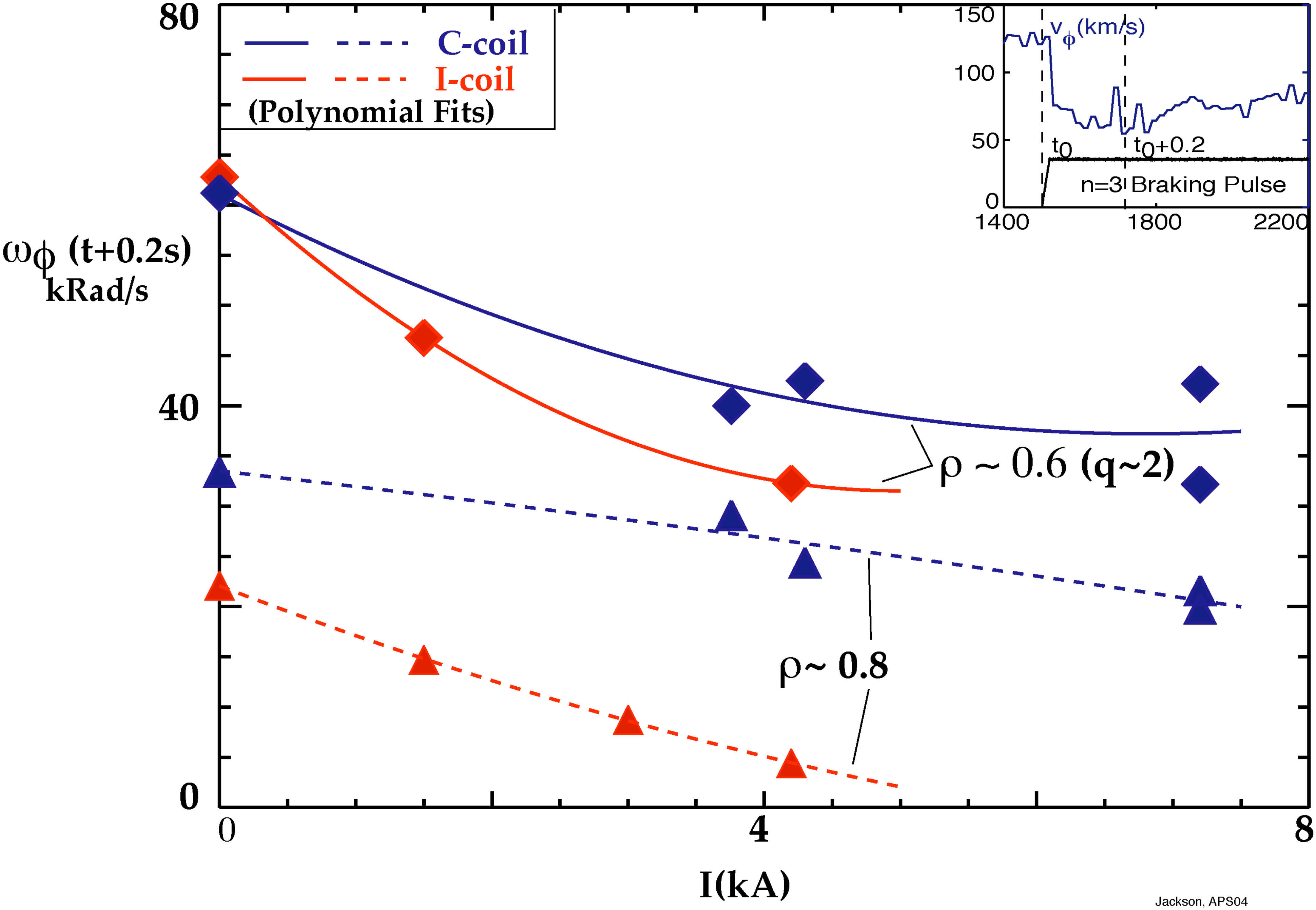
I-coil (n=3) BRAKING IS MORE EFFECTIVE THAN THE C-coil, ESPECIALLY AT LARGER NORMALIZED RADII



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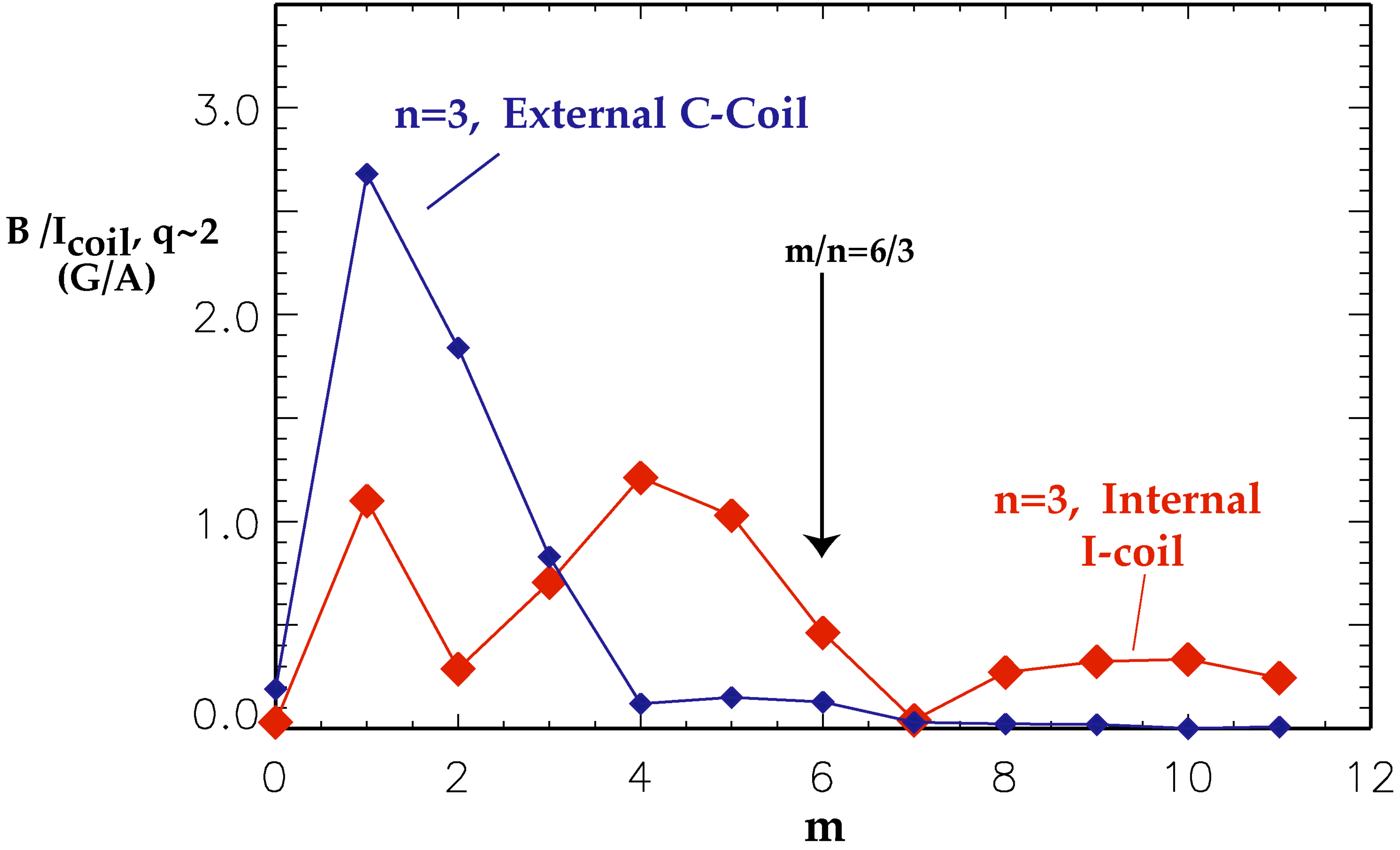
FOURIER COMPONENTS FROM I-COIL OR -C-COIL CONNECTED IN AN n=3 CONFIGURATION



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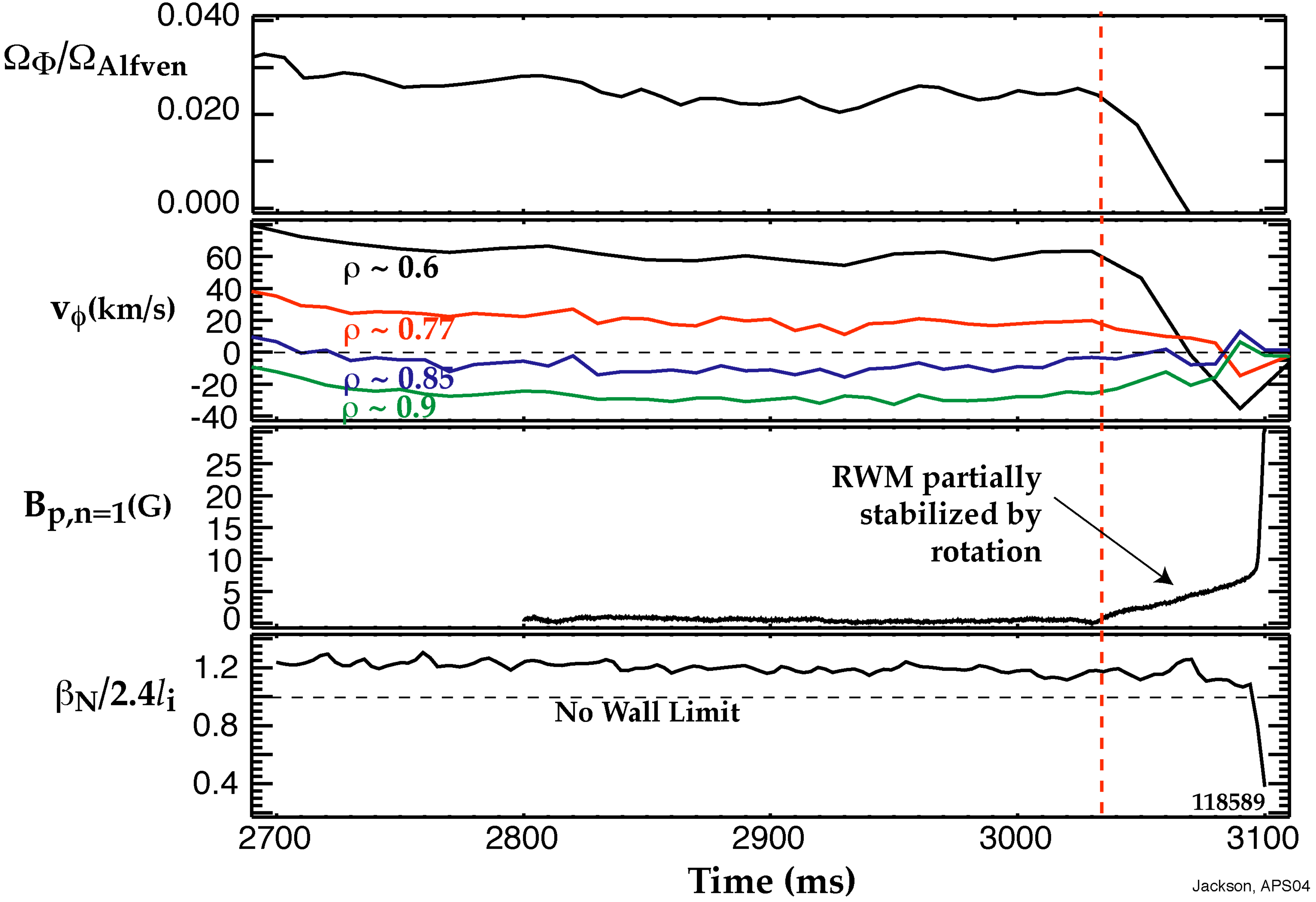
WITH NO FEEDBACK, n=3 I-COIL BRAKING CAN SLOW TOROIDAL ROTATION UNTIL $\Omega_\Phi = \Omega_{crit}$, DESTABILIZING THE RWM

- Ω_{crit} FUNCTIONAL DEPENDENCES (q_{95}, profile effects, τ_{Alfven}) ARE BEING INVESTIGATED



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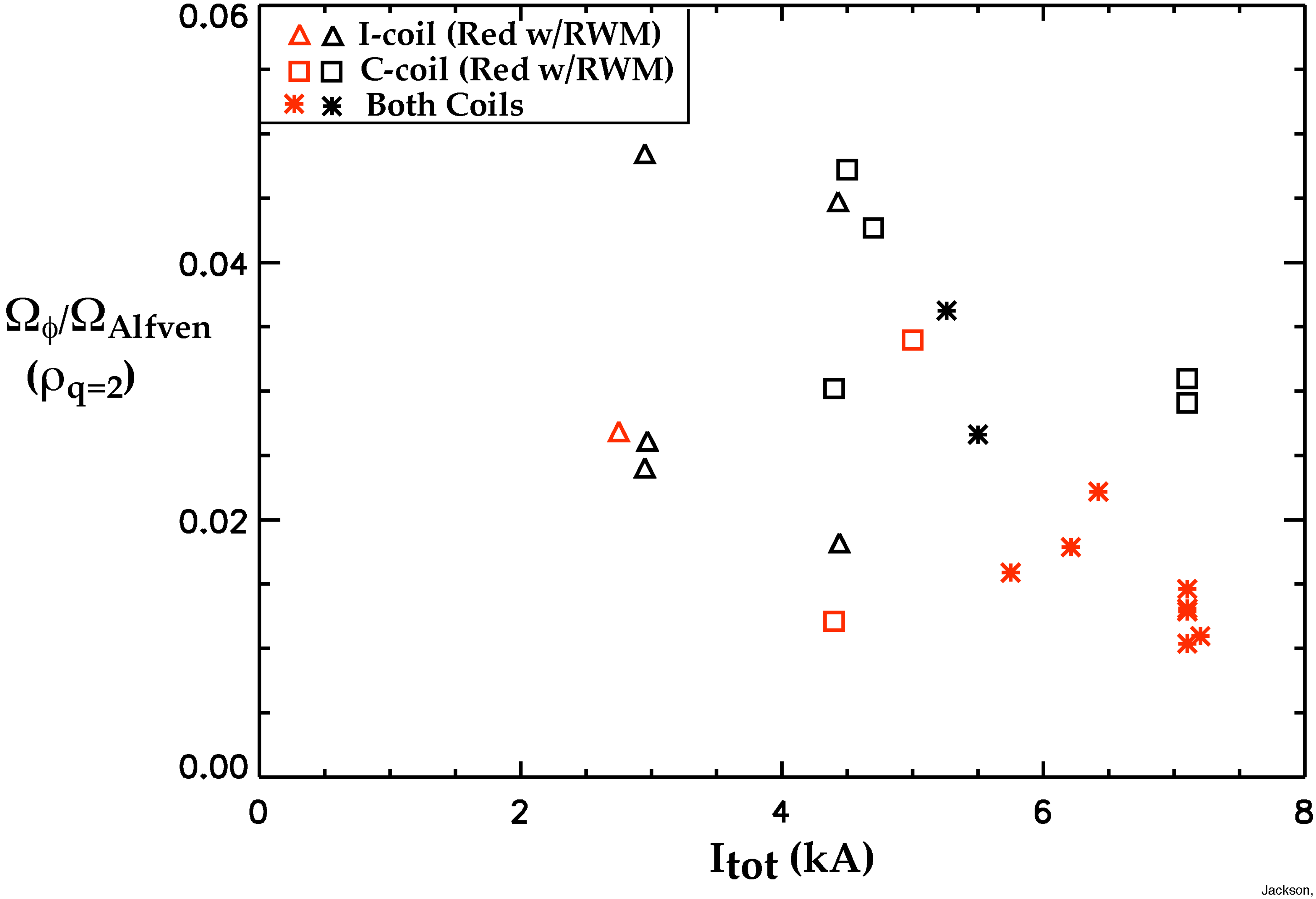
NON-RESONANT BRAKING IS PRODUCED WITH I-COIL, C-COIL, OR BOTH



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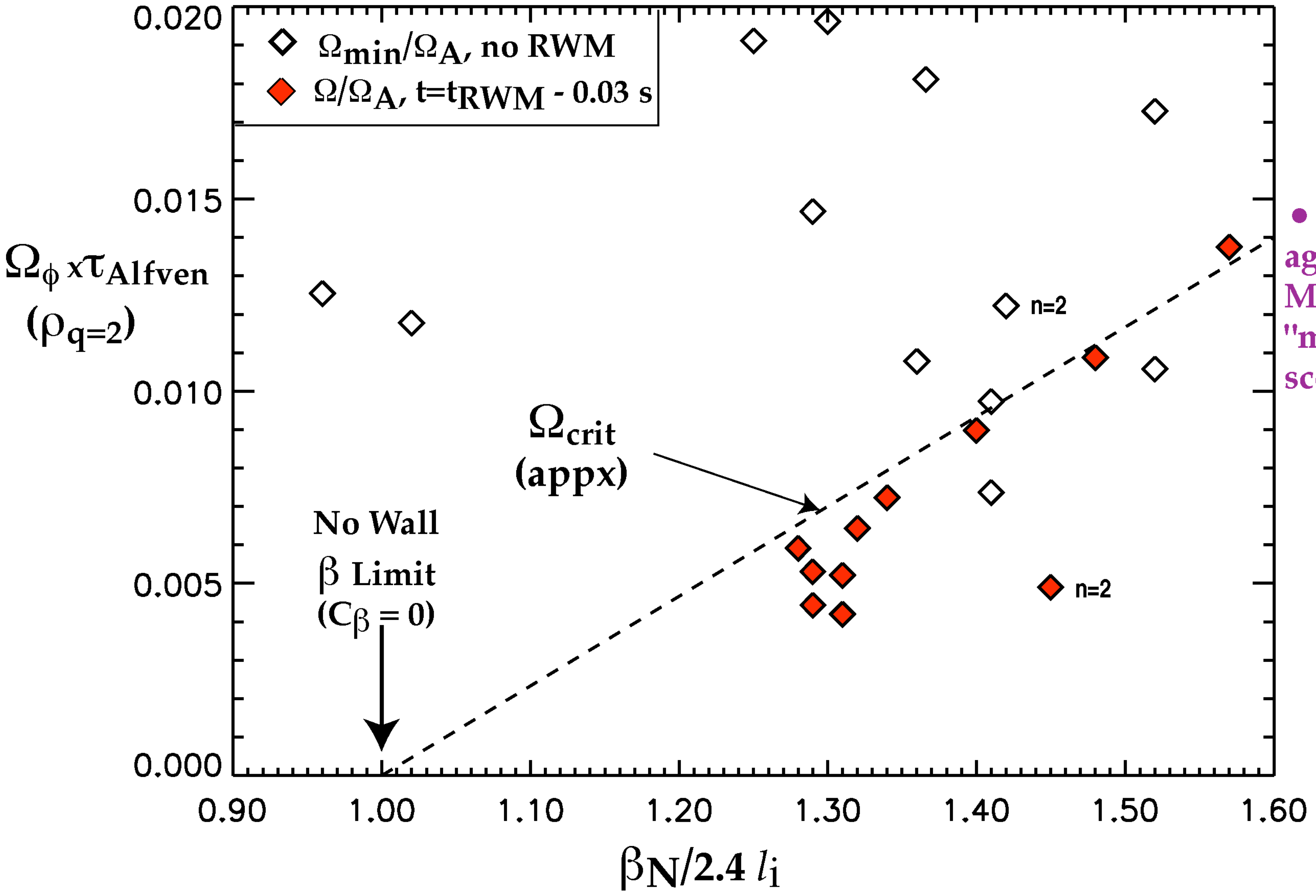
NON-RESONANT BRAKING EXPERIMENTS SUGGEST A TRESHOLD, Ω_{crit}, WHICH IS A FUNCTION OF β_N



- **Qualitative agreement with MARS-F, "moderate l_i" scenario**

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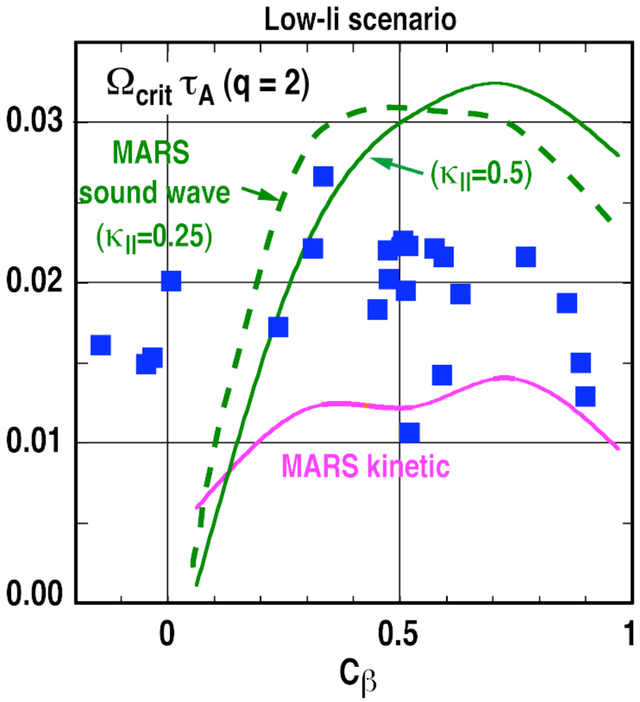
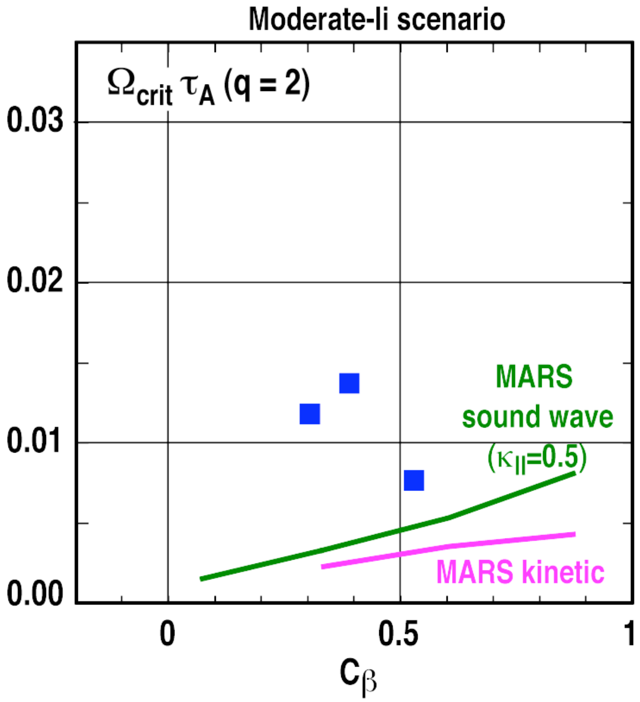
MARS predictions of Ω_{crit} in qualitative agreement with measurements


Low-li scenario


Moderate-li scenario

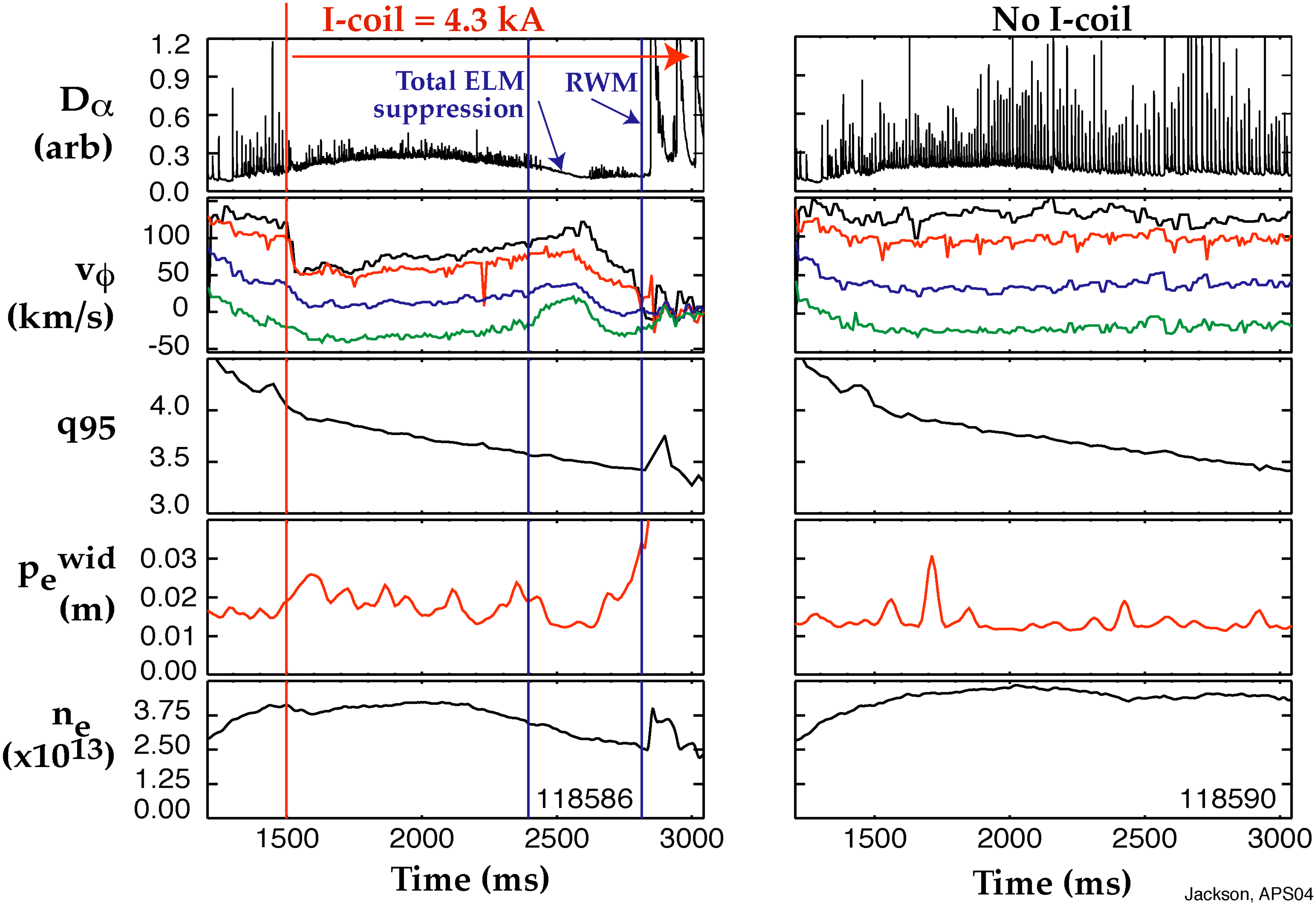
- Low-l_i scenario yields $\Omega_{crit}\,\tau_A \sim 0.02$ with weak β dependence
- Moderate-l_i scenario yields significantly lower Ω_{crit}
- Both damping models predict Ω_{crit} within a factor of 2
  - **Kinetic damping** generally underestimates Ω_{crit}
- Both models predict the trend of a lower Ω_{cri} in the moderate-l_i scenario

IS n=3 BRAKING
ACTUALLY A RESONANT EFFECT?

- Strong edge interaction observed with n=3 I-coil (but not with n=3 C-coil)
  - Changes in toroidal rotation most pronounced in the edge
  - ELM amplitude reduced with I-coil enabled and totally suppressed at $q_{95} \sim 3.5 \pm 0.05$
  - H-mode pedestal is broadened

- Physical mechanism for the n=3 edge effects has not been identified
  - Fourier spectra does <u>not</u> show strong resonant fields at $q_{95} \sim m/3$ (m=10,11,12)
  - Stochastic fields are a possible mechanism, but ELM modification occurs over a broader q_{95} range than other types of discharges (Moyer, **JI2.004**)
  - Edge harmonic oscillation (EHO) is observed on some discharges (Burrell, **BI1.002**)

I-coil (n=3) CLEARLY REDUCES ELM AMPLITUDE AND INCREASES ELECTRON PEDESTAL WIDTH. ROTATION PROFILES VARY WITH q95



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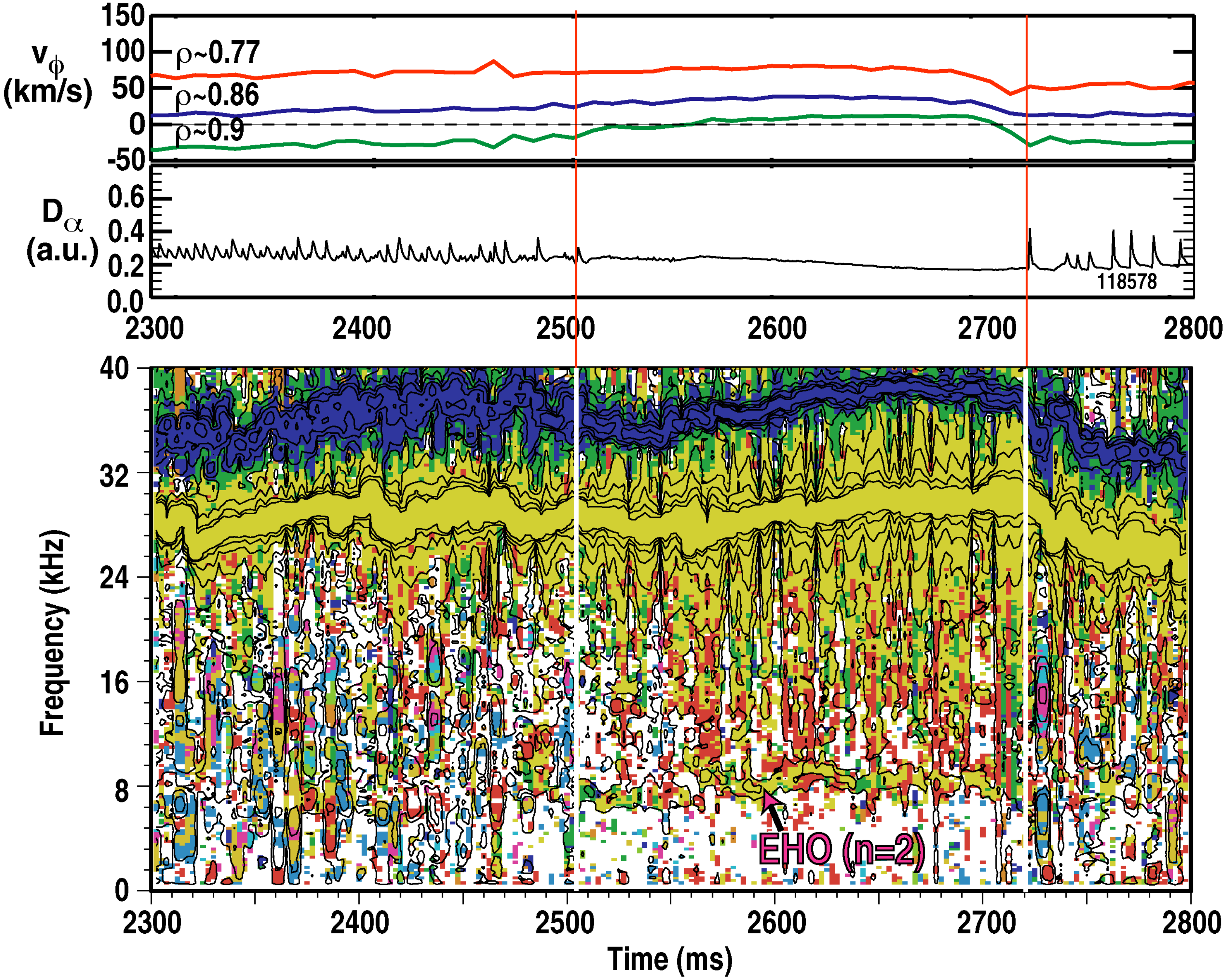
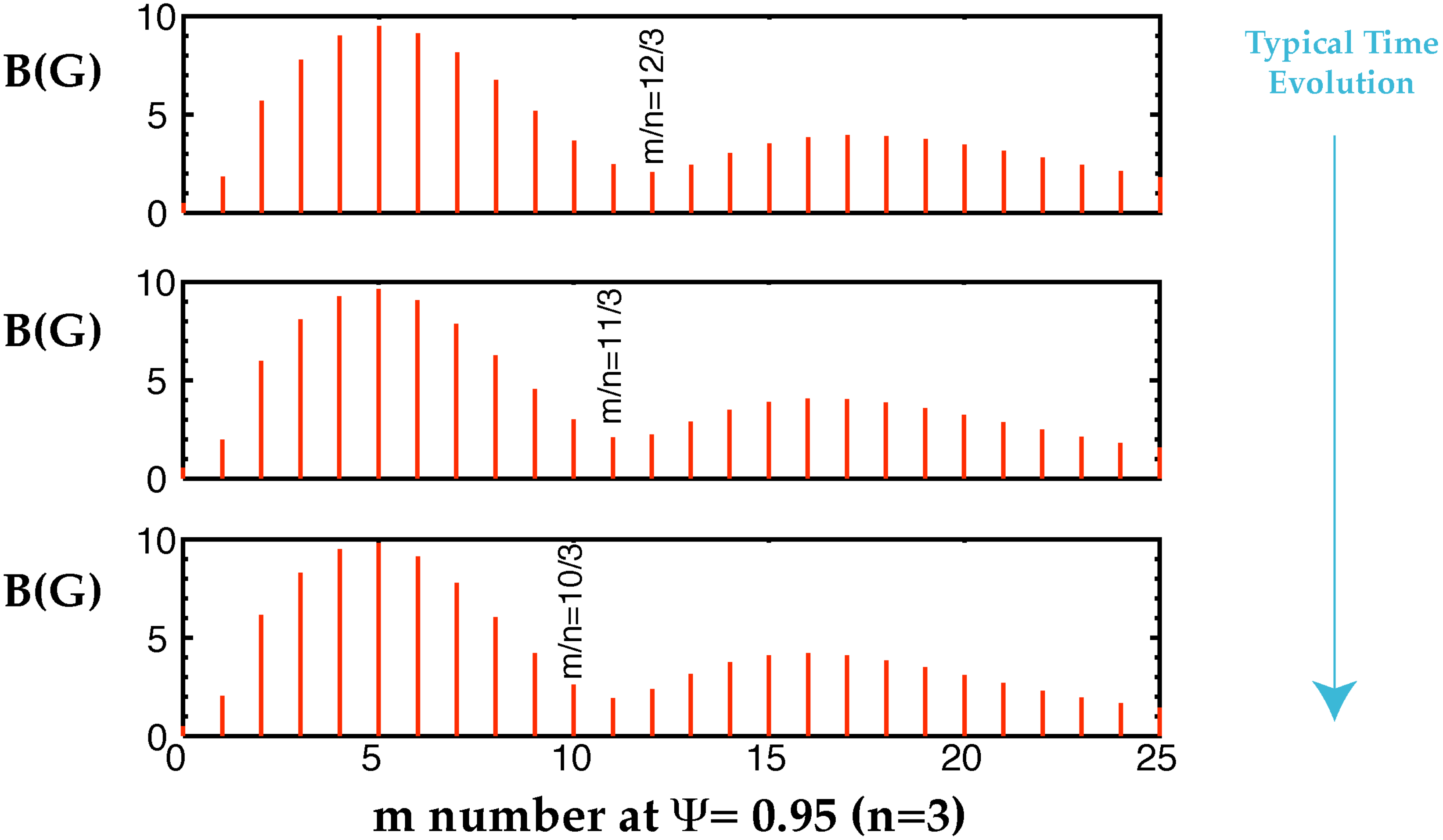
EHO IS OBSERVED IN SOME CO-injection n=3 I-coil DISCHARGES. CHANGES IN ROTATION PRECEDE CHANGES IN ELM BEHAVIOR



MODELING SHOWS NO STRONG RESONANT FIELDS AT THE PLASMA EDGE WITH n=3 I-COIL EXCITATION ("Odd Parity")



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SUMMARY

- **Both external coil sets, I-coil and C-coil, have successfully been used for rotational braking**
- **With sufficient n=3 drag, resistive wall modes are observed**
- **Critical frequency, Ω_{crit}, for onset of RWMs is a function of β_N**
- **I-coil is more effective than C-coil in braking**
  - **Effect is most pronounced near plasma edge**
  - **Higher I-coil current produces lower rotation, though not as strong as theory predicts**
  - **n=2 configurations have also successfully reduced toroidal rotation**
- **Strong reduction of ELM amplitude is observed with n=3 I-coil**
  - **Observed over a broad range of q_{95}**
  - **Physical mechanism has not been determined. May be stochastic, EHO, or resonant interactions**