Progress on understanding rotational RWM stabilization in DIII-D

by
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with
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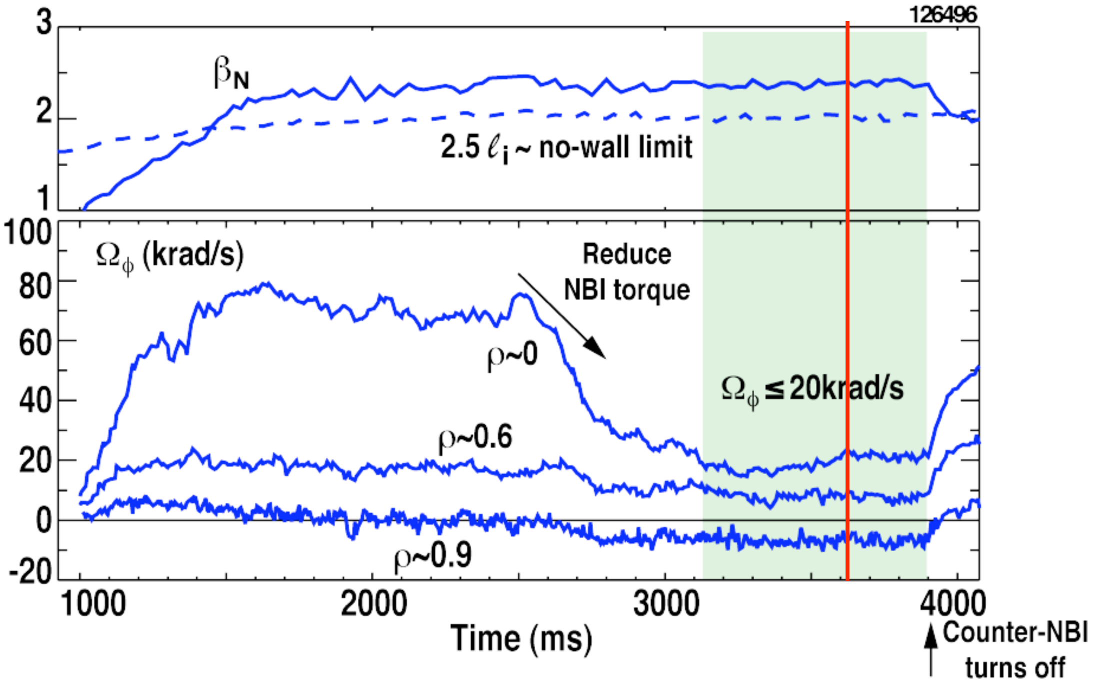
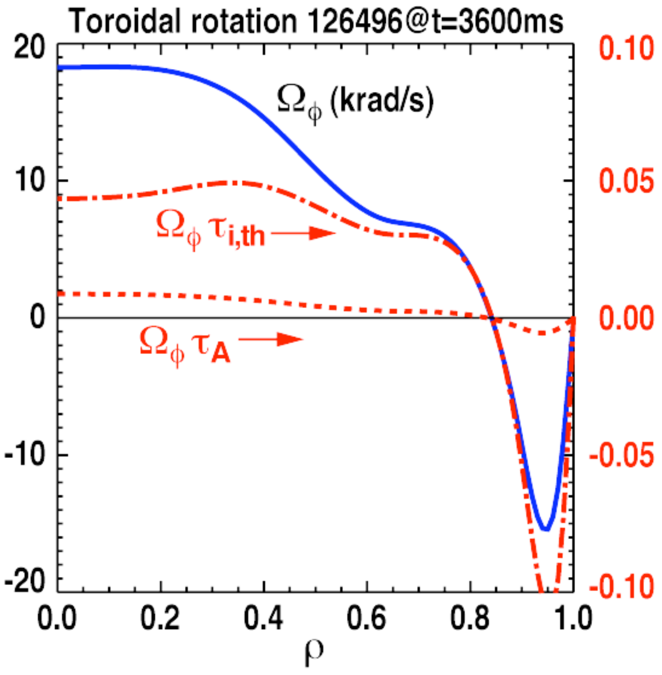
Sustained resistive wall mode (RWM) stabilization with very low plasma rotation obtained with balanced NBI

- **Toroidal rotation of less than 20 krad/s across the entire profile can be sufficient for RWM stability**
  - Corresponds to less than 10% of the ion thermal velocity or less than 1% of the Alfvén velocity
- **Correction of *n*=1 intrinsic error field is essential for stability at low rotation**





Outline

1. **Rotation thresholds in wall-stabilized discharges with good error field correction and low NBI torque**
   - Diamagnetic rotations of (measured) carbon impurities and main ions are of the order of the measured rotation threshold

2. **Comparison of observed rotation threshold with linear RWM theory**
   - Kinetic damping models with and without taking into account the precession of trapped particles predict stability even below the measured rotation

3. **Relation between RWM onset and tearing mode onset**
   - Low rotation wall-stabilized plasmas are susceptible to 2/1 tearing modes

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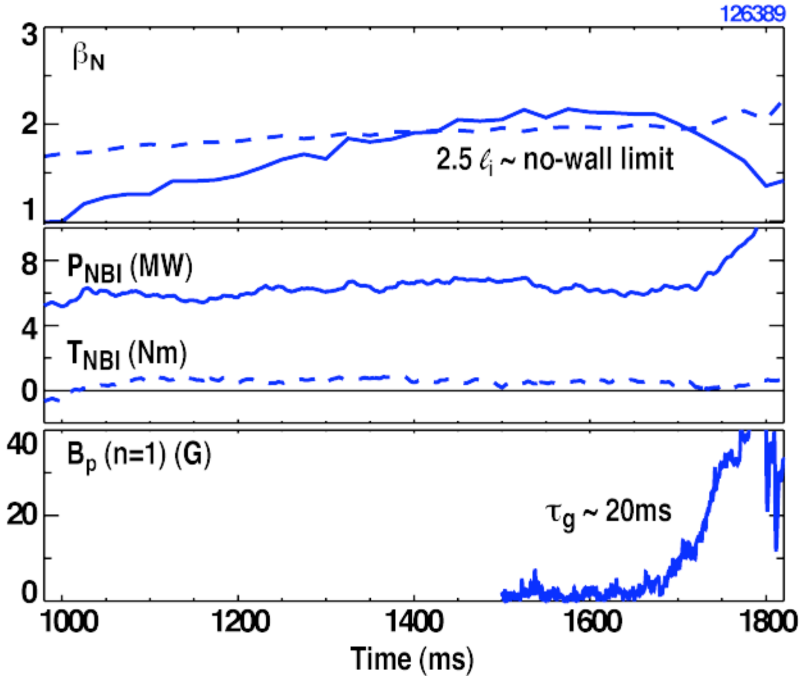
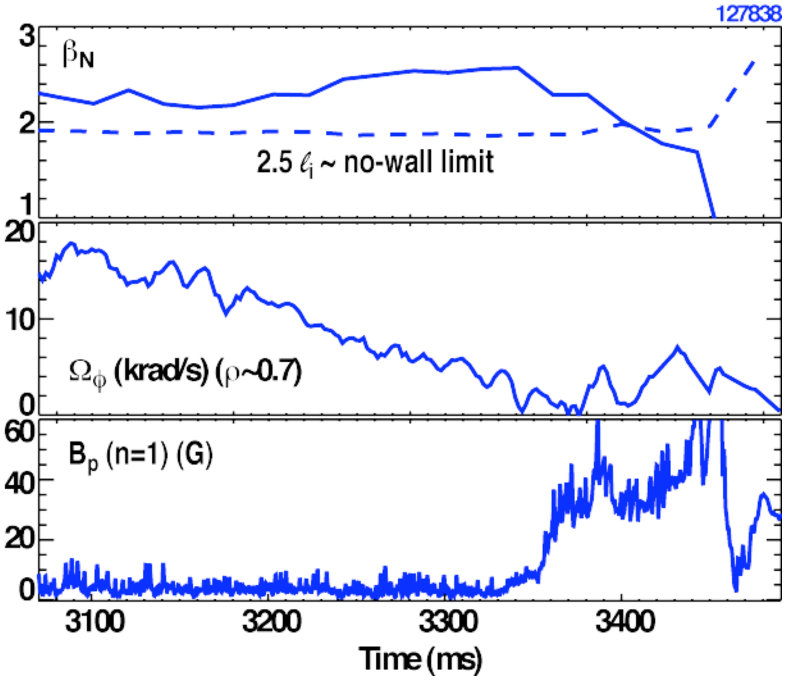
RWM observed at high β AND low rotation

β ramp-up at low torque



Ω_ϕ ramp-down at high β



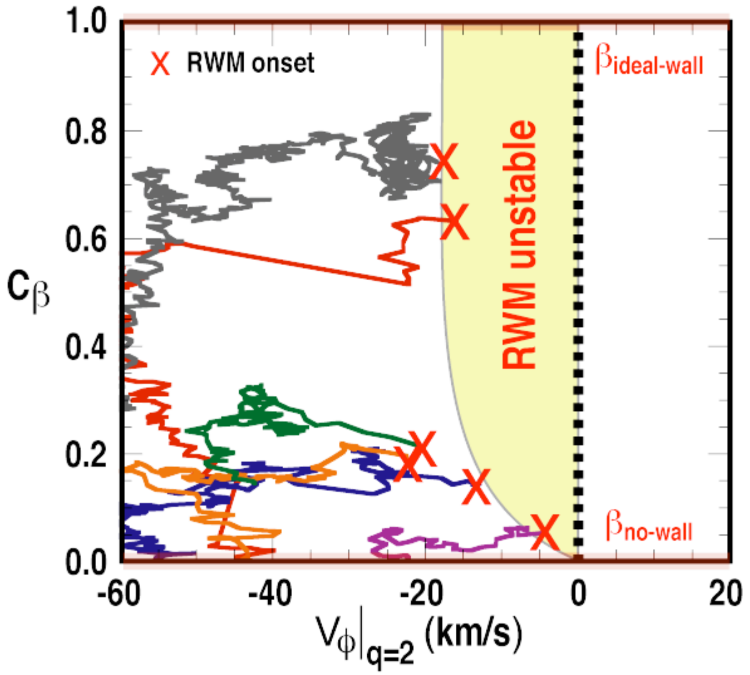
- **Various trajectories in Ω_ϕ-β space lead to instability**

Rotation thresholds in low NBI torque plasmas in DIII-D and JT-60U are in surprisingly good agreement

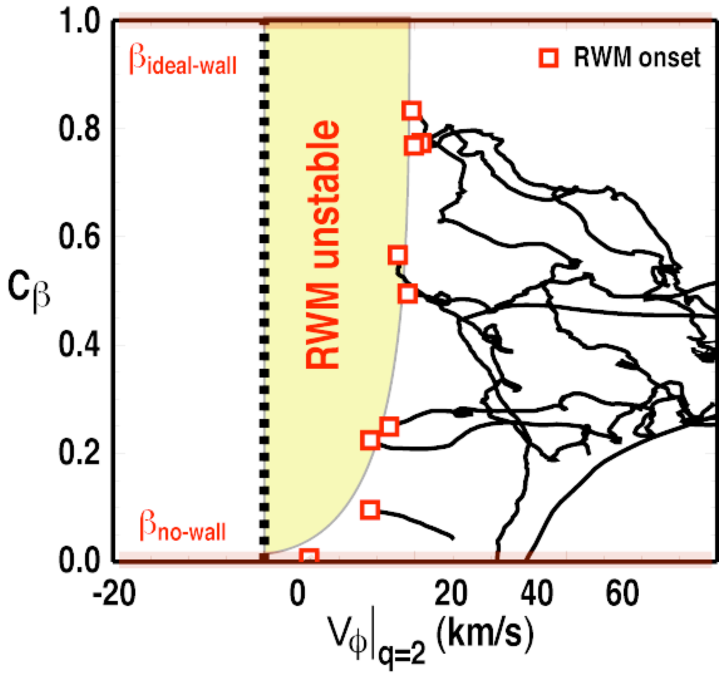
- **Reduce NBI torque until RWM becomes unstable**

Courtesy of
Dr. M. Takechi

JT-60U [M. Takechi et al, *PRL* 2007]



DIII-D [E.J. Strait et al, *PoP* 2007]



- **Evaluating the magnitude of the rotation threshold at the *q*=2 surface results in good agreement**

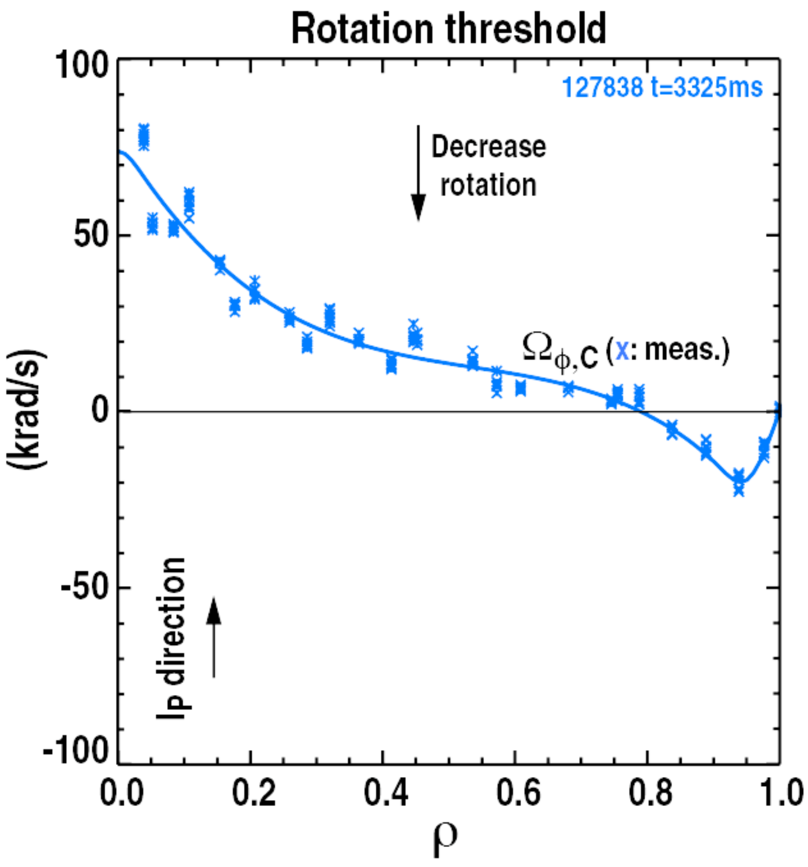
Rotation threshold too low to neglect diamagnetic rotation/difference between ion species

- **Charge exchange recombination (CER) spectroscopy measures carbon impurity rotation**
- **$\Omega_\phi = V_\phi / R$ is not a flux function**
  - Assume $\nabla \cdot \mathbf{V} = 0$, $V_r = 0$ and force balance

$$\mathbf{V} = k(\psi)\mathbf{B} + R\Omega(\psi)\mathbf{e}_\phi$$

  - Poloidal flow leads to $k \neq 0$
- **Radial force balance links species *j* via the radial electric field E_r**

$$\Omega_j = \underset{\overset{\uparrow}{\omega_E}}{\frac{E_r}{RB_\theta}} - \underset{\overset{\uparrow}{\omega_{*i,j}}}{(Z_j n_j e)^{-1}\frac{dP_j}{d\psi}}$$



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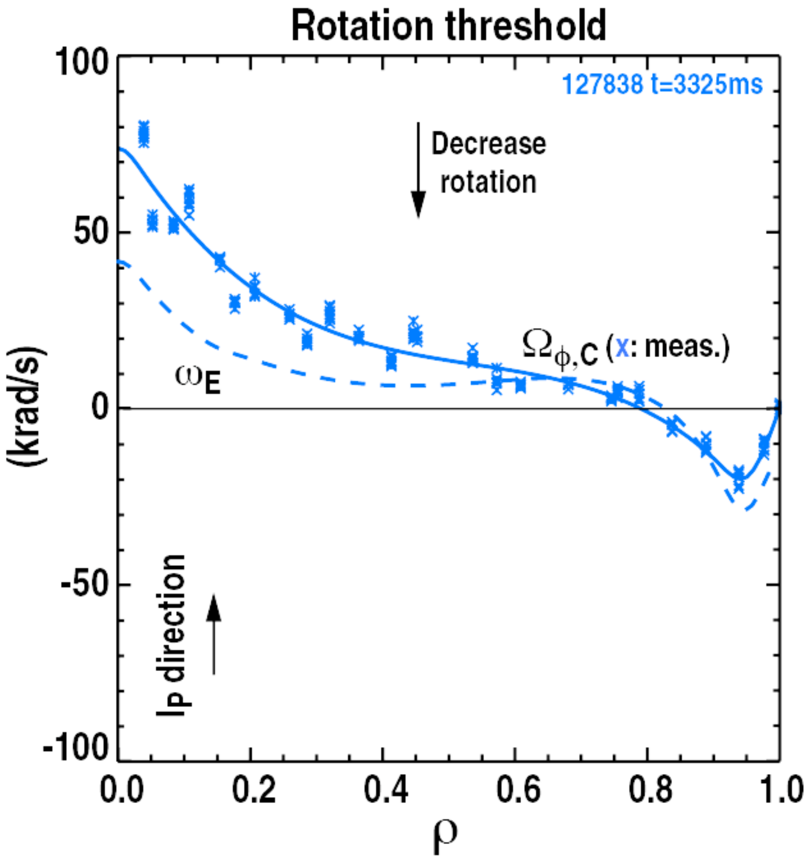

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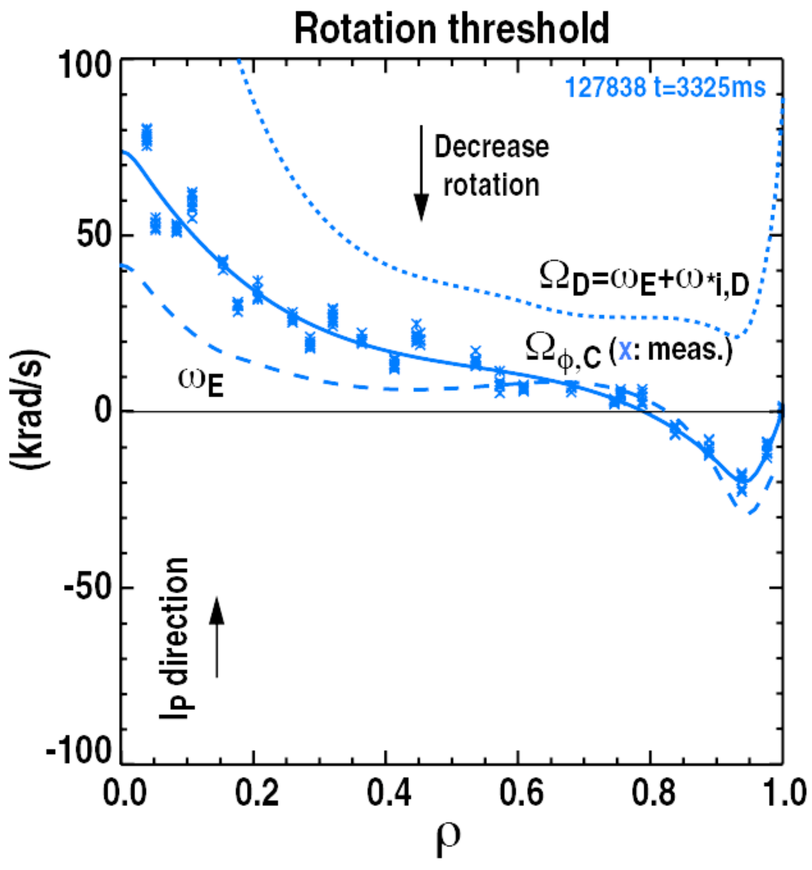
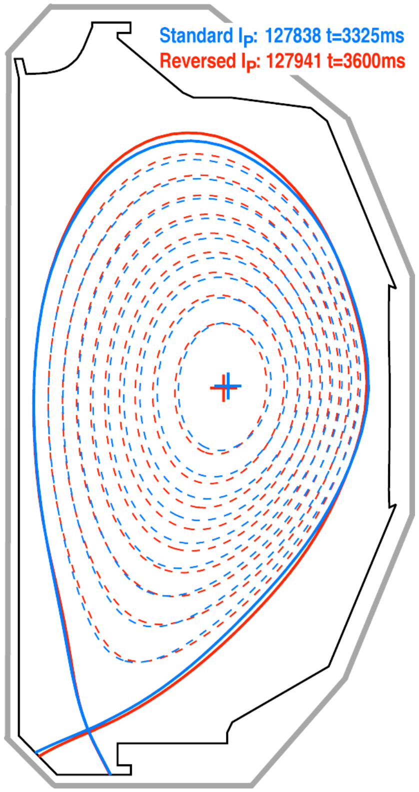
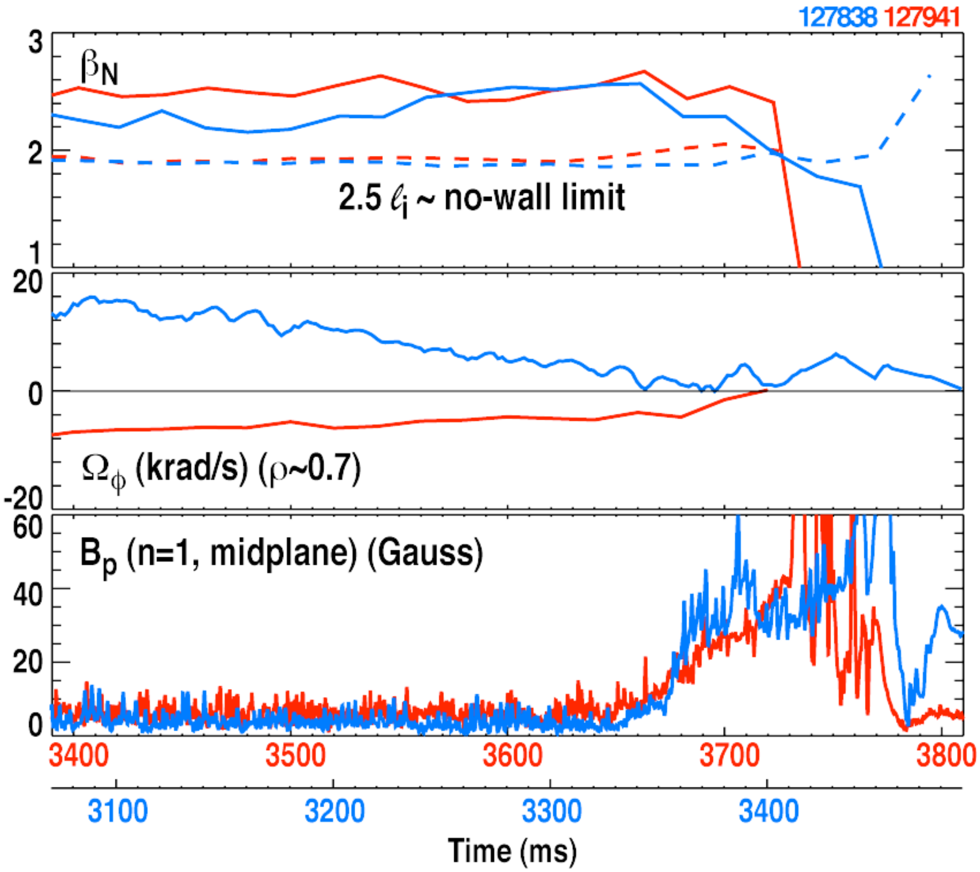


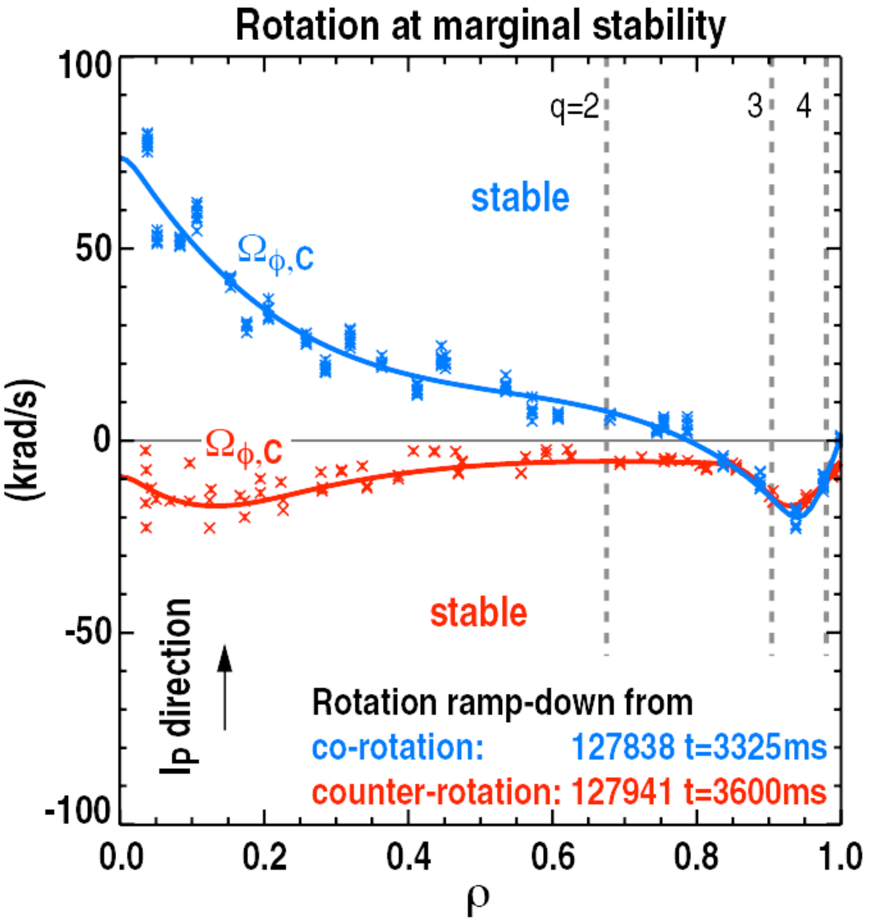
Role of rotation components studied by comparing thresholds in co- and counter-rotating plasmas





- **NBI torque ramp-downs in similar co-rotating (with respect to I_P) and counter-rotating plasmas lead to RWM onsets**

Comparison of profiles in co- and counter-rotating plasmas indicates importance of ω_E for RWM stabilization



- **Compare profiles before mode onset in co- and counter-rotating plasmas**

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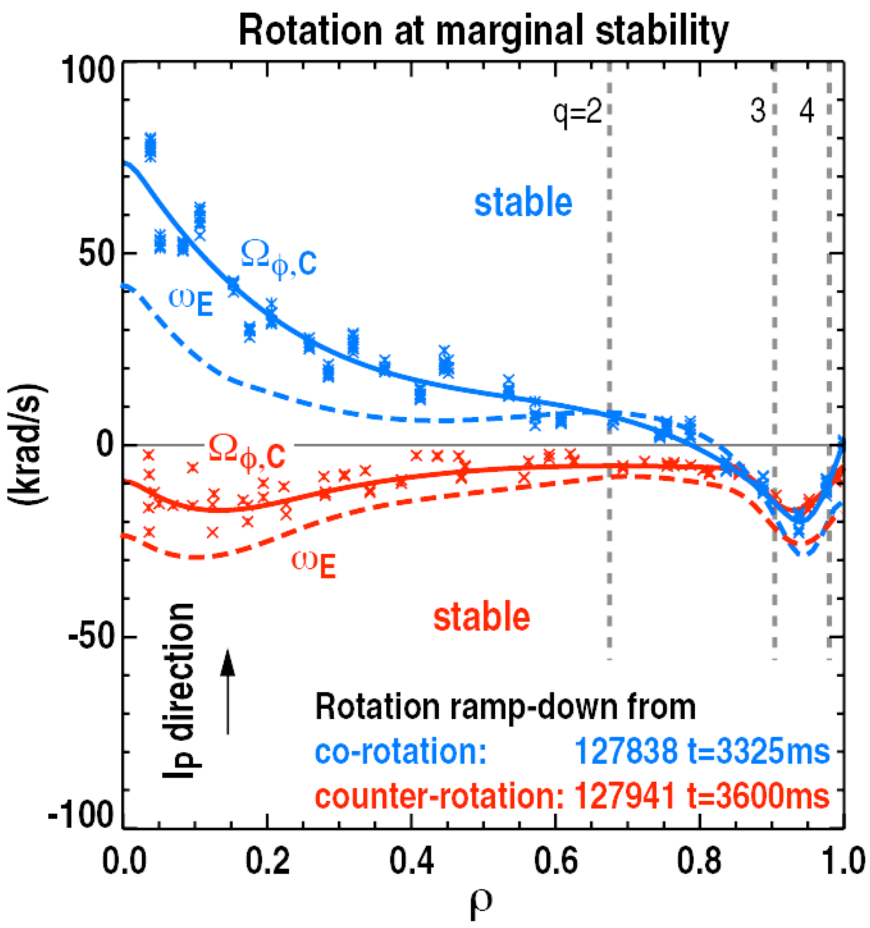

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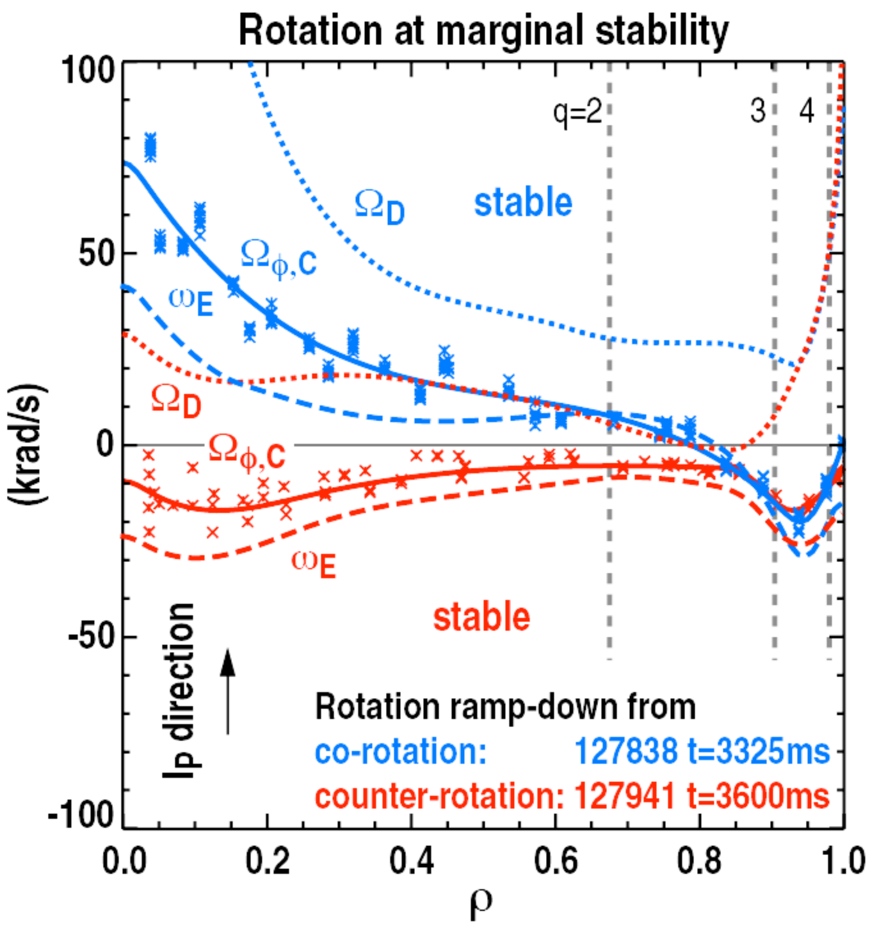

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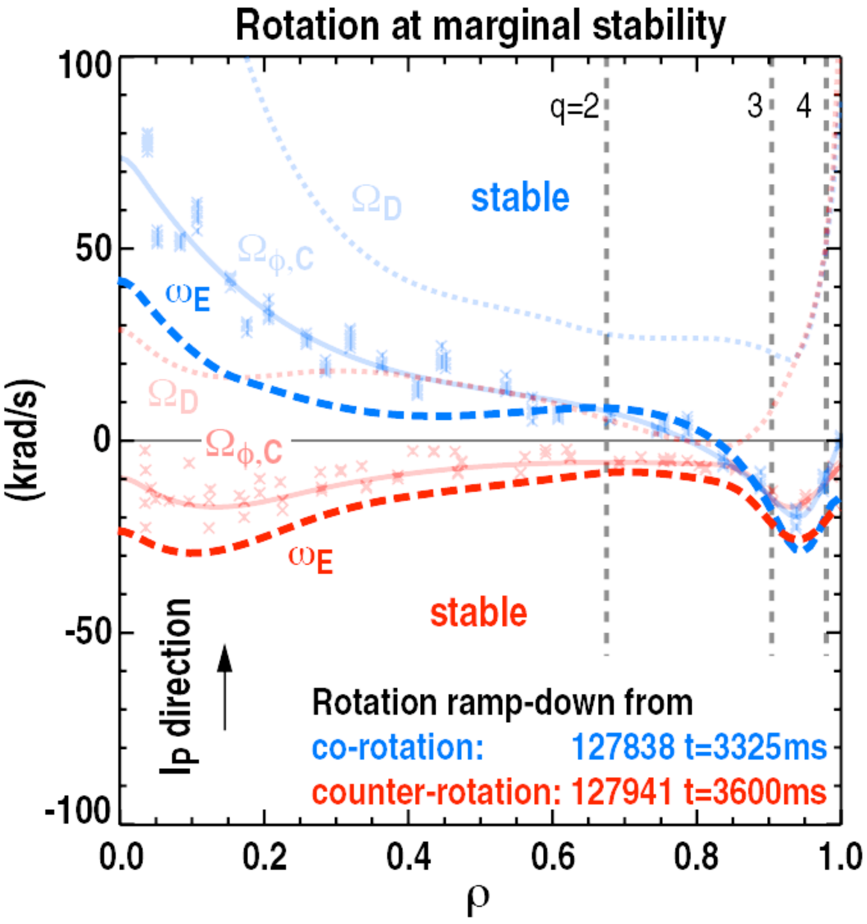
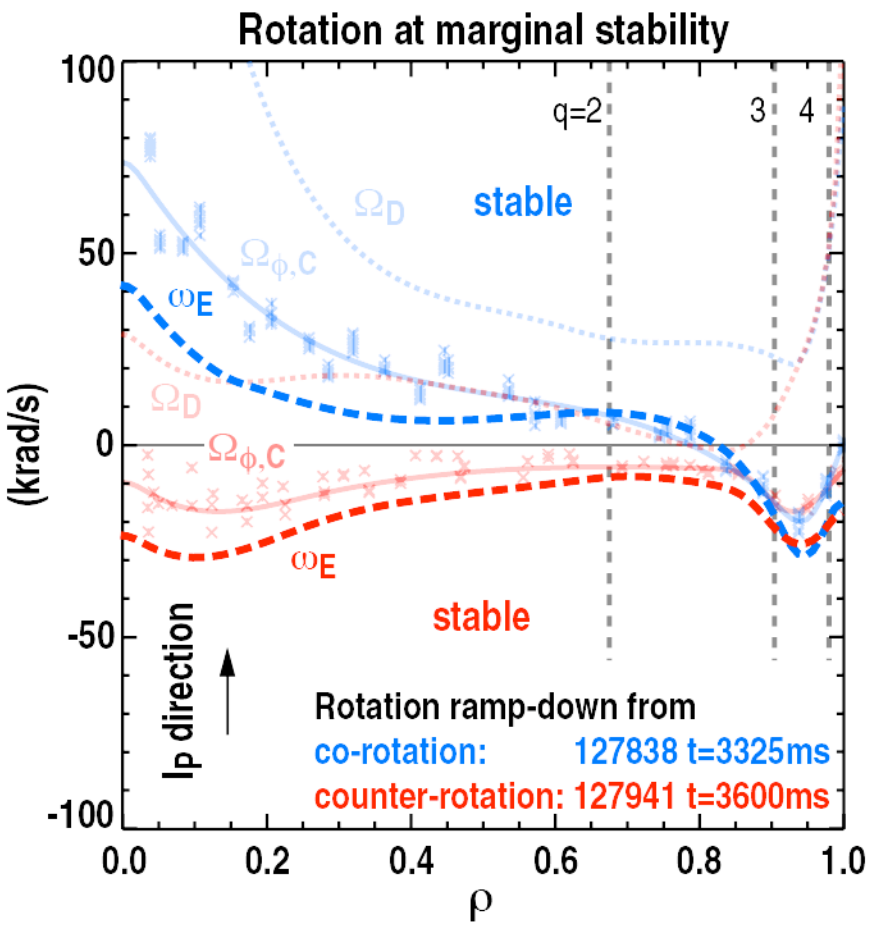


- **Compare profiles before mode onset in co- and counter-rotating plasmas**
- **Best agreement in magnitude of ω_E**
  - Similar magnitude at all resonant surfaces

Comparison of profiles in co- and counter-rotating plasmas indicates importance of ω_E for RWM stabilization



- **Compare profiles before mode onset in co- and counter-rotating plasmas**
- **Best agreement in magnitude of ω_E**
  - Similar magnitude at all resonant surfaces
- **Caveats:**
  - Neglect poloidal rotation
  - Assumes no symmetry-breaking mechanism
  - Rotation profiles do not vary for $\rho>0.9$

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4. **Summary/Conclusions**

Slow growth makes RWM susceptible to various stabilization mechanisms

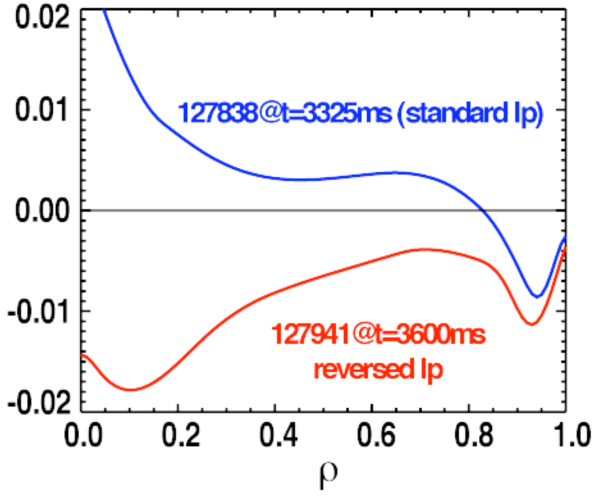
- **Soundwaves**
  - Finite parallel viscosity [Bondeson & Ward, *PRL* 1994]
- **Kinetic effects (wave-particle resonances)**
  - Transit frequency of passing particles [Bondeson & Chu, *PoP* 1996] $\omega_t \sim v_{i,th}/R$
  - Bounce frequency of trapped particles [Bondeson & Chu, *PoP* 1996] $\omega_b \sim (r/R)^{1/2}\, v_{i,th}/R$
  - Precession frequency of trapped particles [Hu & Betti, *PRL* 2004] $\omega_D \sim (\rho_L/r)^{1/2}\, v_{i,th}/R$
- **MHD effects**
  - Shear Alfvén resonance [Zheng et al, *PRL* 2005]

- **Compare experimental rotation threshold to linear RWM stability predictions**
  - MARS-F code [Liu et al, *PoP* 2000]
  - Kinetic post-processor to PEST code [Hu et al, *PoP* 2005]

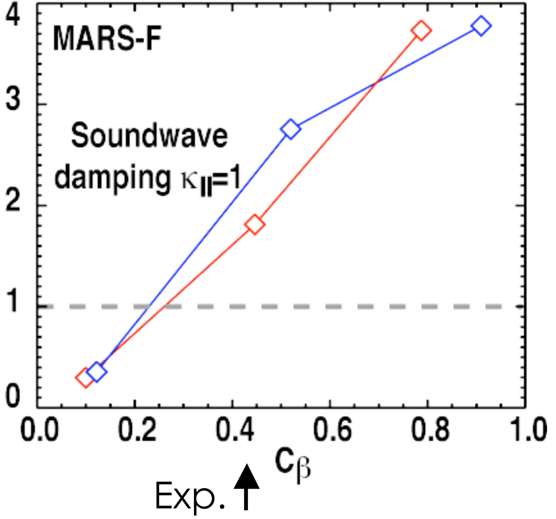
Semi-kinetic damping model in MARS-F predicts stability even below the “low” experimental threshold

- **MARS-F assumes $\Omega >> \omega_{*i}, \omega_D$ (finite ω_{*i}, ω_D are being included** [Chu, Liu, APS 2007]**)**
  ➔ use ω_E rotation

Experimental rotation threshold $\omega_E \tau_A$



Scaling factor of experimental ω_E at marginal stability



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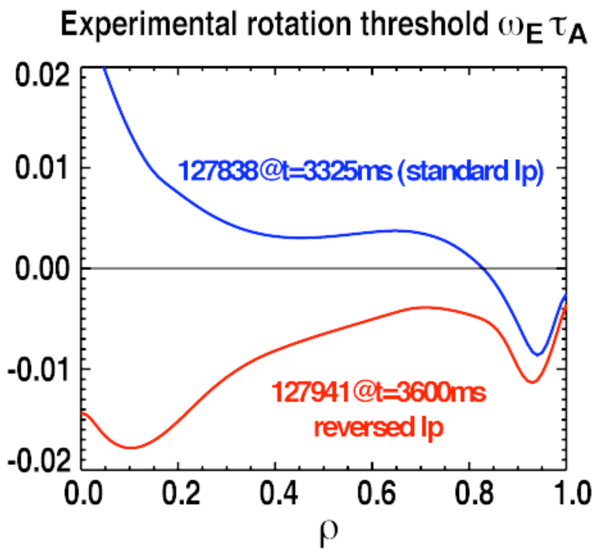
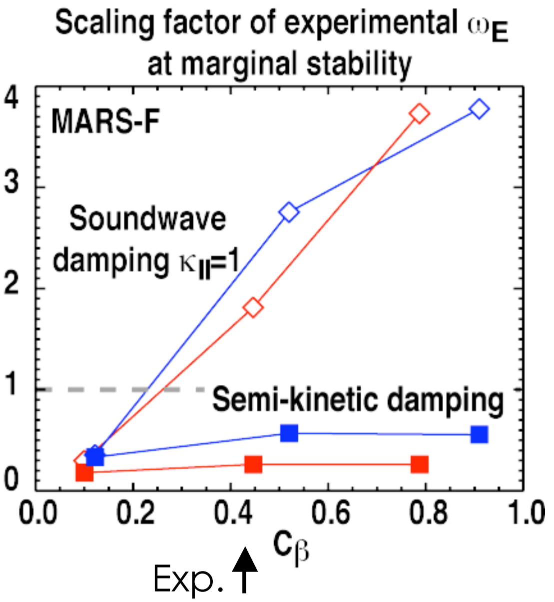
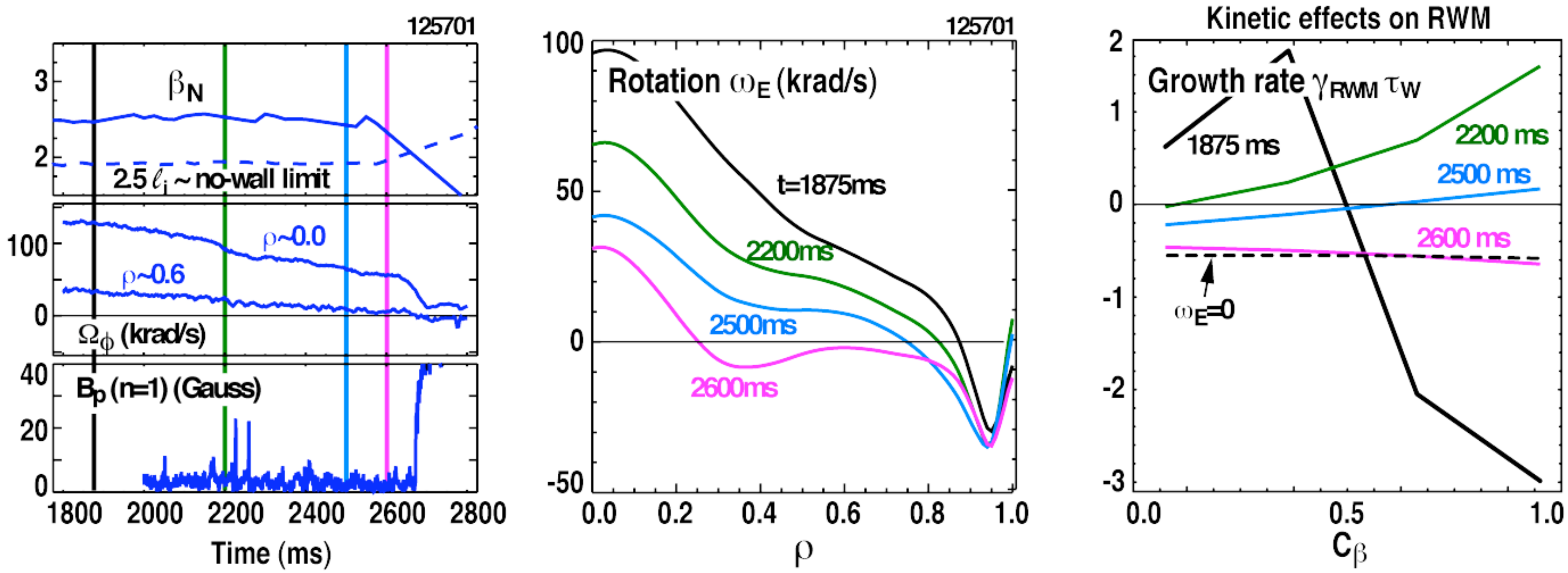




- **Sound-wave damping predicts strong β-dependence, overestimates rotation threshold at high β ➔ inconsistent with the experiment**
- **Semi-kinetic damping underestimates rotation threshold**
  - Requires additional physics to explain mode onset in DIII-D

Resonance with precession drift of trapped particles predicts stability at low or no rotation

- **Kinetic post-processor to PEST code takes into account finite ω_{*i}, ω_D**



[Bo Hu et al, Sherwood 2007]

- **Kinetic theory predicts low rotation threshold/no rotation to be stable**
  - Requires additional physics to explain mode onset in DIII-D
- **Shear Alfvén damping provides stability at high rotation**
  - Need for stabilization mechanism at intermediate rotation values

Both kinetic models predict stability below the rotation threshold in DIII-D discharges with balanced NBI

	No rotation ($\Omega=0$)	Low rotation ($\Omega<\Omega_{crit}$)	Intermediate rotation ($\Omega>\Omega_{crit}$)	High rotation ($\Omega>>\Omega_{crit}$)
DIII-D	?	unstable	stable	stable
MARS-F soundwave	unstable	unstable	unstable	stable
MARS-F semi-kinetic	unstable	stable	stable	stable
PEST kinetic postprocessor	stable	stable	stable	unstable

- **Kinetic theory can explain the stability of low rotation, wall stabilized DIII-D discharges**
- **A satisfactory picture of the stability threshold at low rotation requires:**
  - Additional physics to explain the mode onset and beta collapse (e.g. penetration of residual resonant error fields)
  - Resolution of discrepancies between the kinetic models

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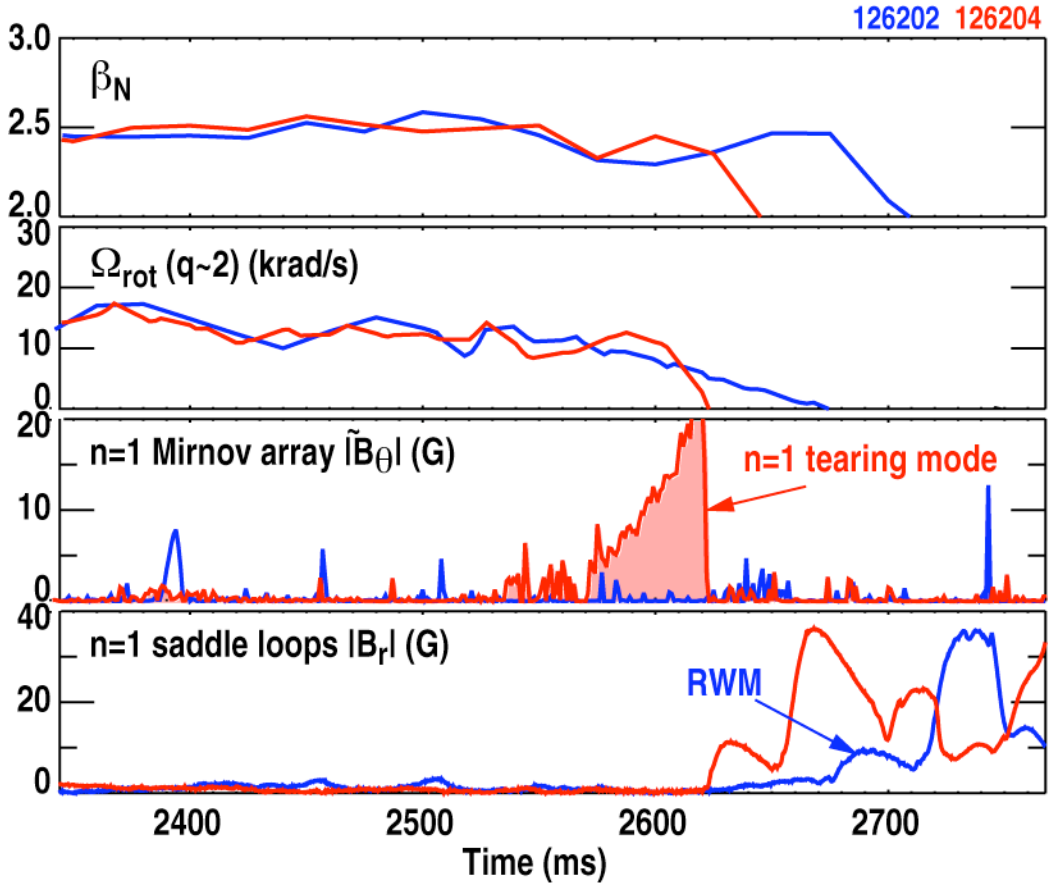
4. **Summary/Conclusions**

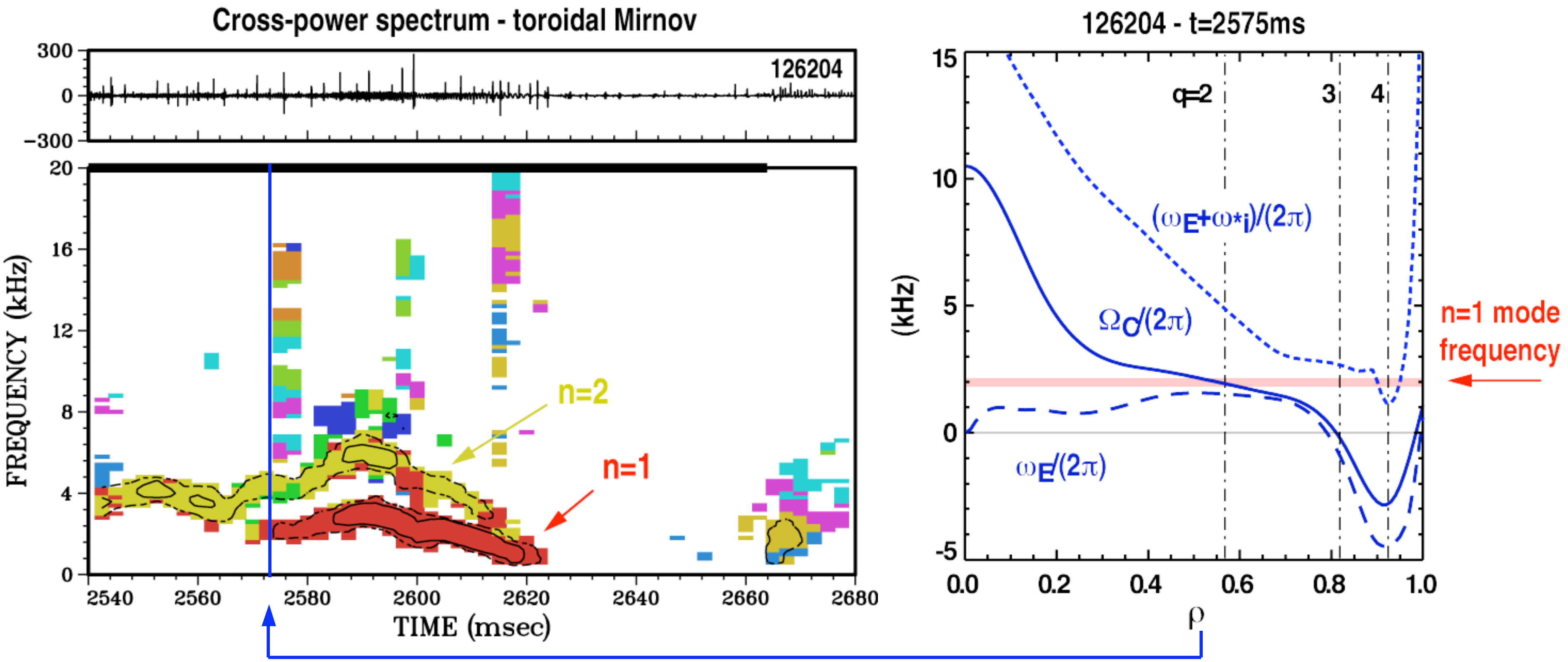
Low rotation, high beta plasmas are also susceptible to *n*=1 rotating modes

- **Mode is born rotating, but quickly (in the order of 10-100ms) locks to the vessel**
  - Mode is thought to be a 2/1 (neoclassical) tearing mode



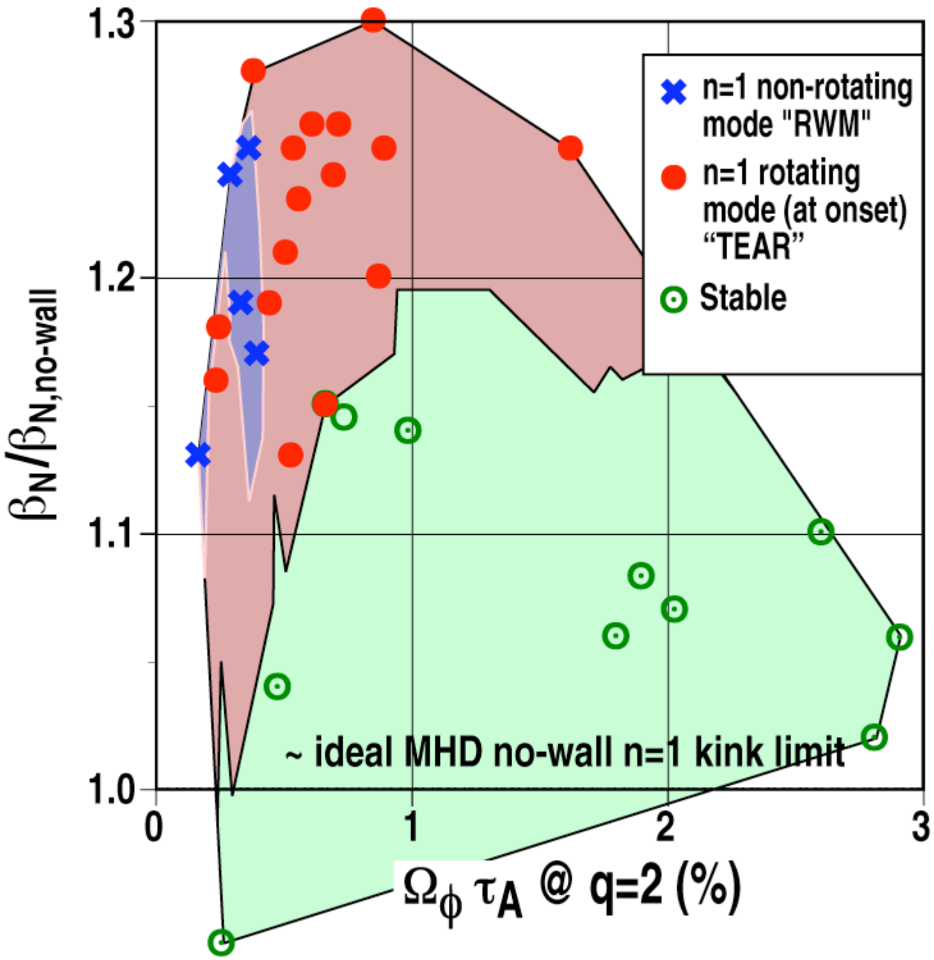
Rotation frequency of the *n*=1 rotating mode is consistent with a 2/1 tearing mode

- **Rotation frequency of *n*=1 mode matches impurity and ω_E rotation in the vicinity of the *q*=2 surface**
  - For $\omega_{rot}/(2\pi)$ ~ 2.2 kHz ($\omega_{rot}\tau_w$~50) wall behaves like an ideal conductor



Before observing the RWM the discharge has to pass through a region which is susceptible to tearing

- **Onset of 2/1 tearing mode frequently observed at rotation values just above the RWM rotation threshold**
  - Decrease of NTM beta threshold with decreasing rotation has been observed in sawtoothing plasmas [Buttery, APS invited 2007]



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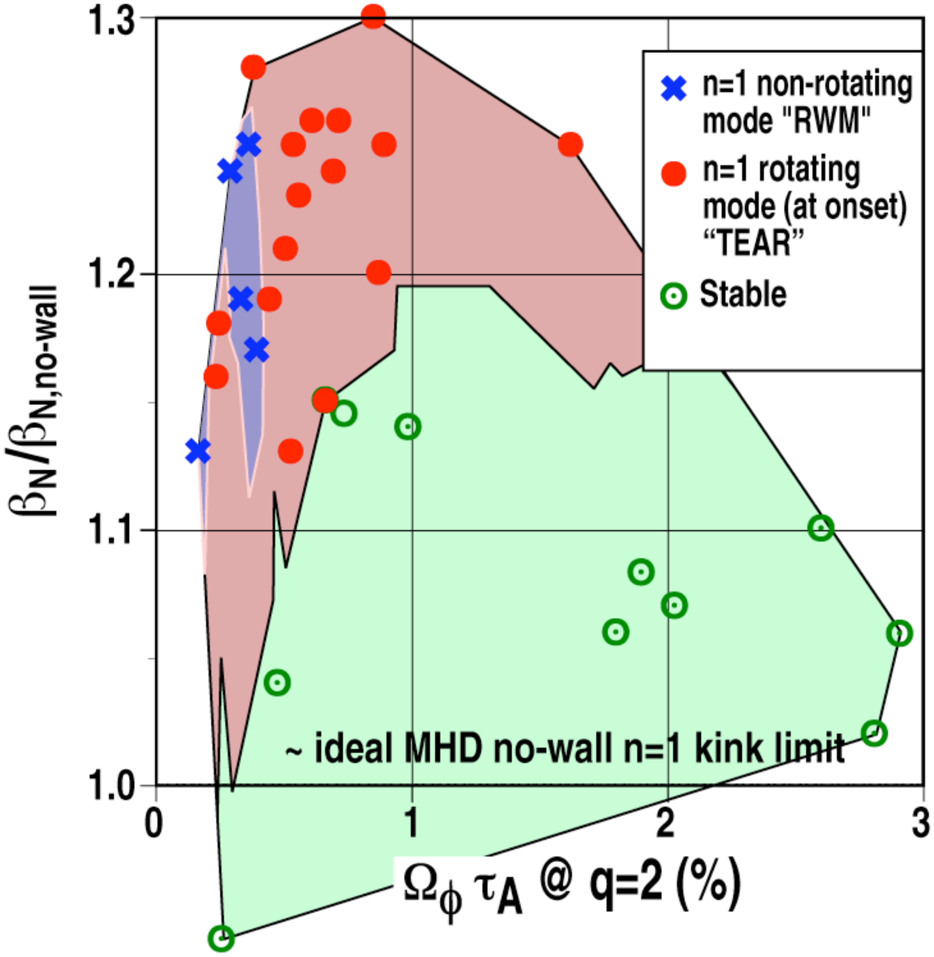
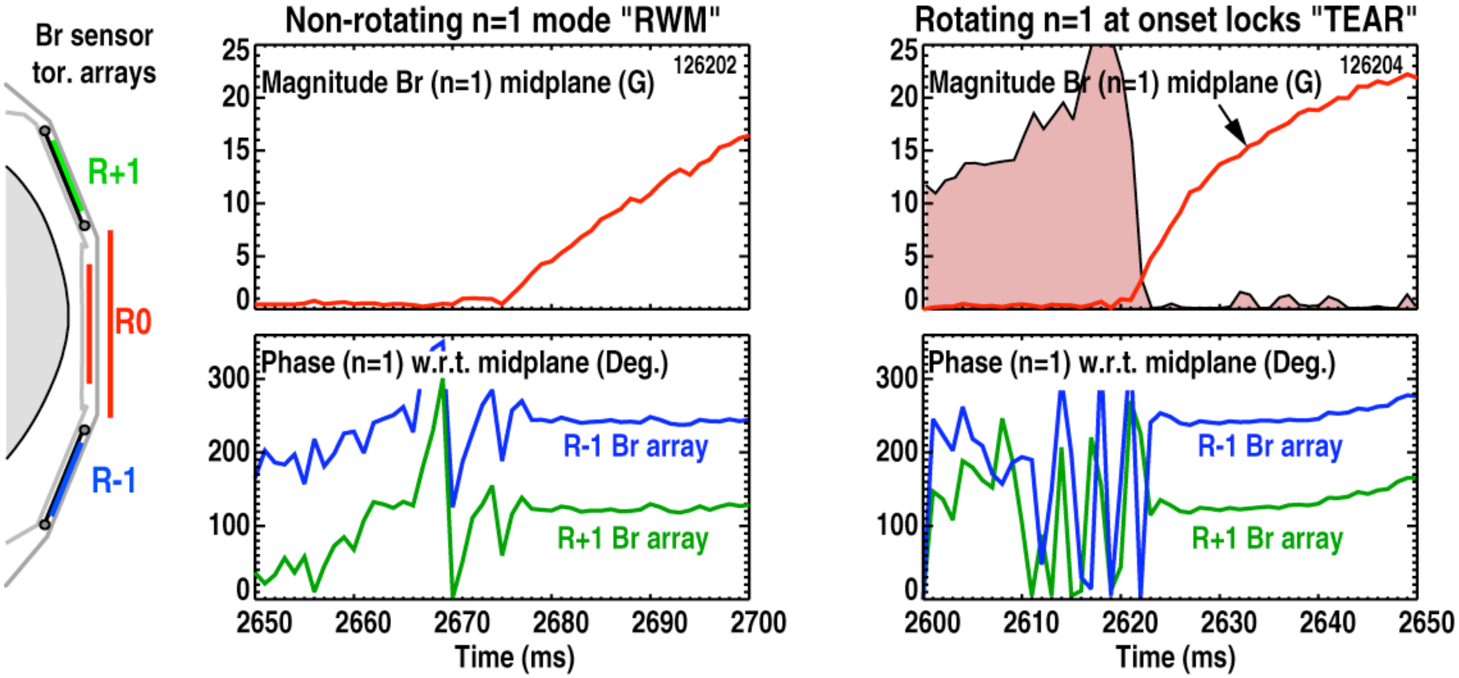
- **Is the non-rotating mode (“RWM”) the same tearing mode that grows locked from the start?**



Once the rotating mode locks it's structure at the wall is identical to the structure of the non-rotating mode



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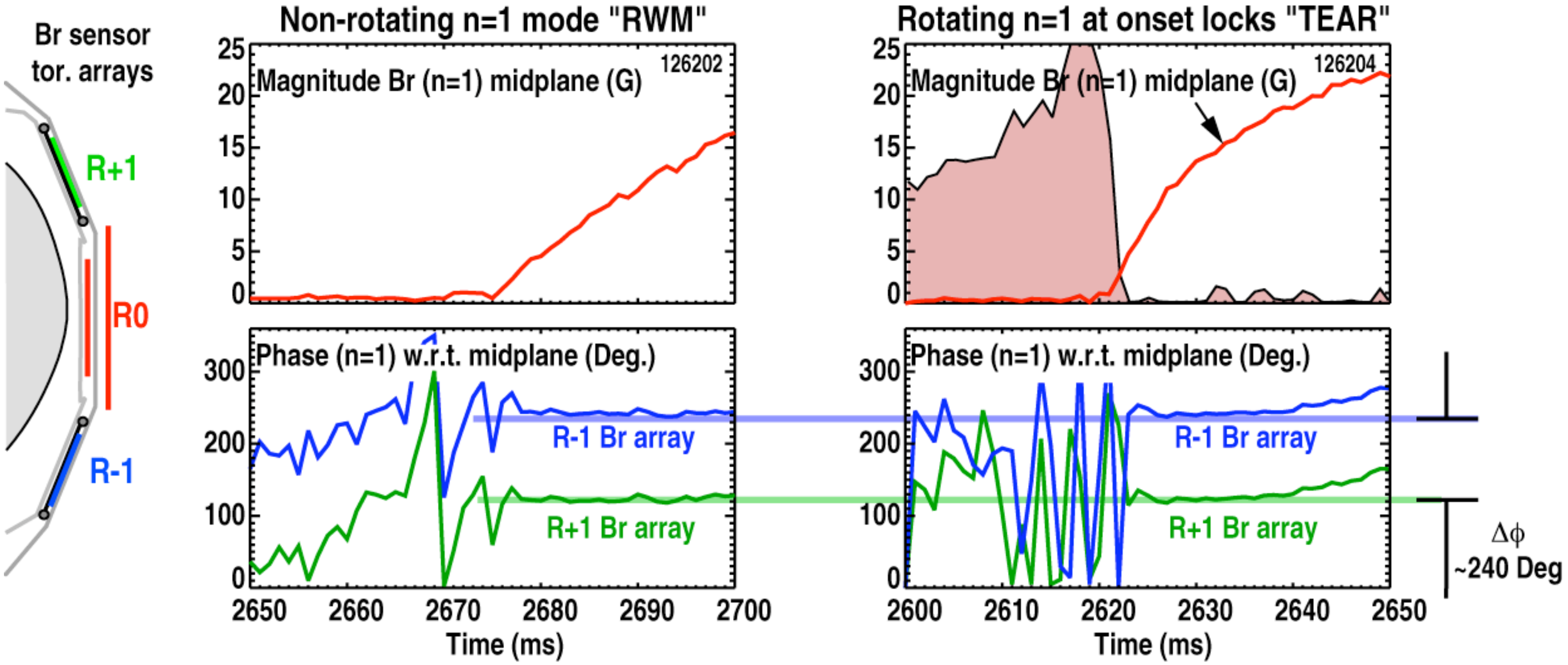

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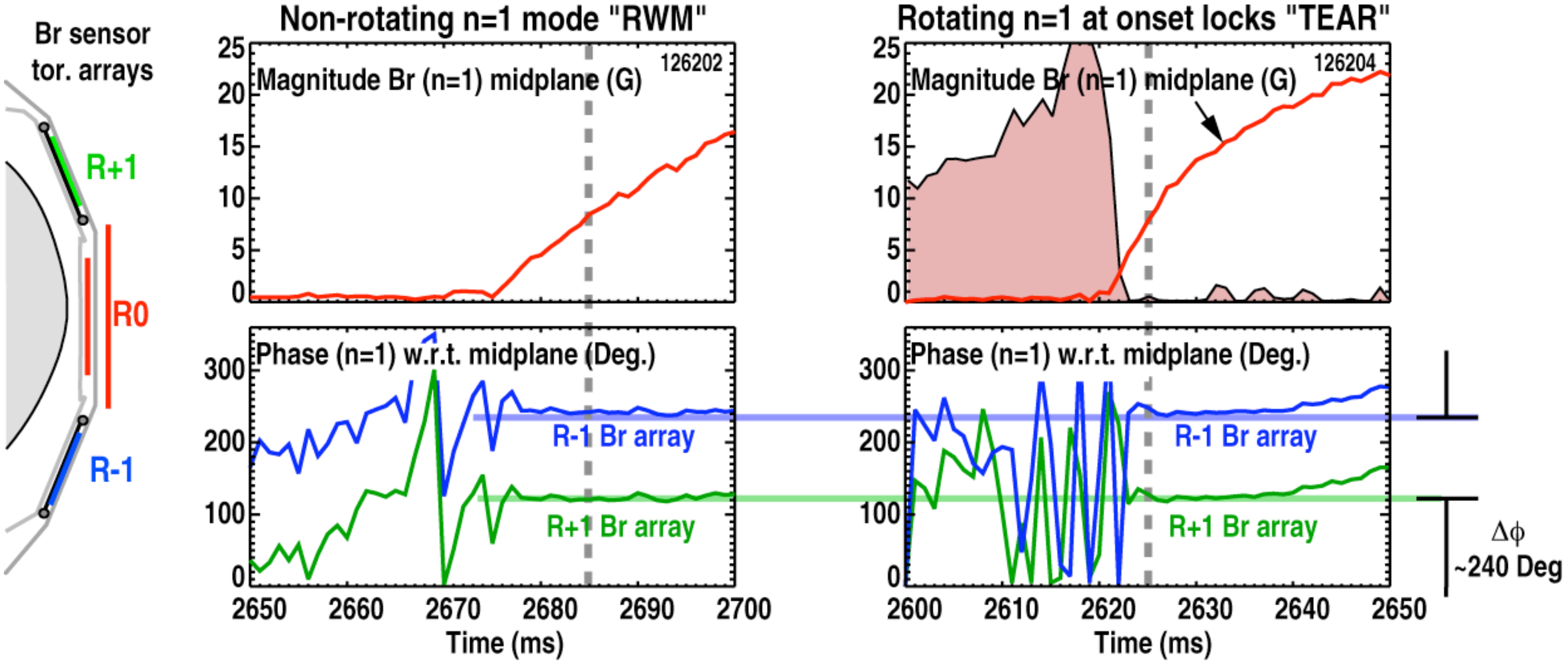

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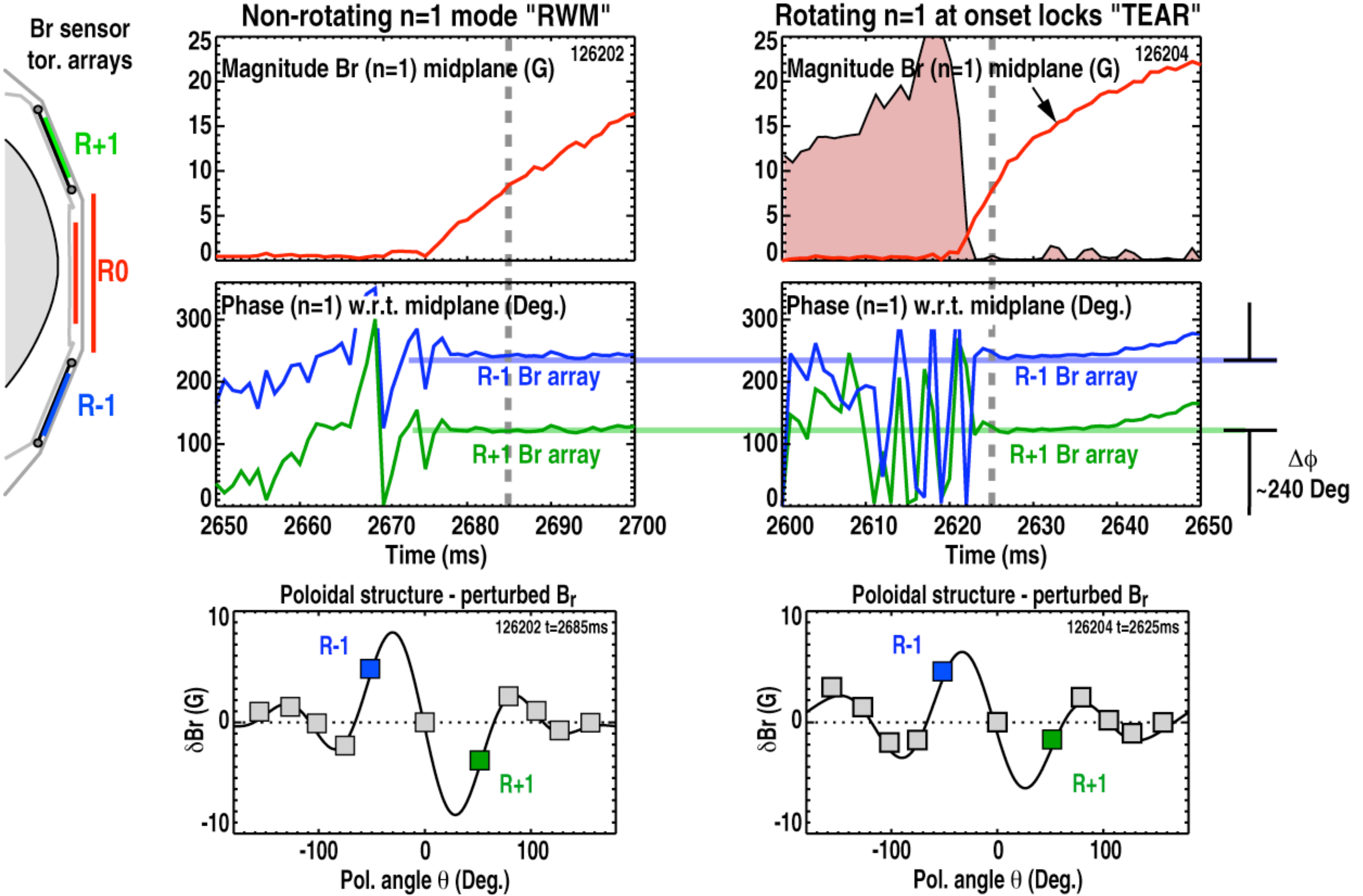
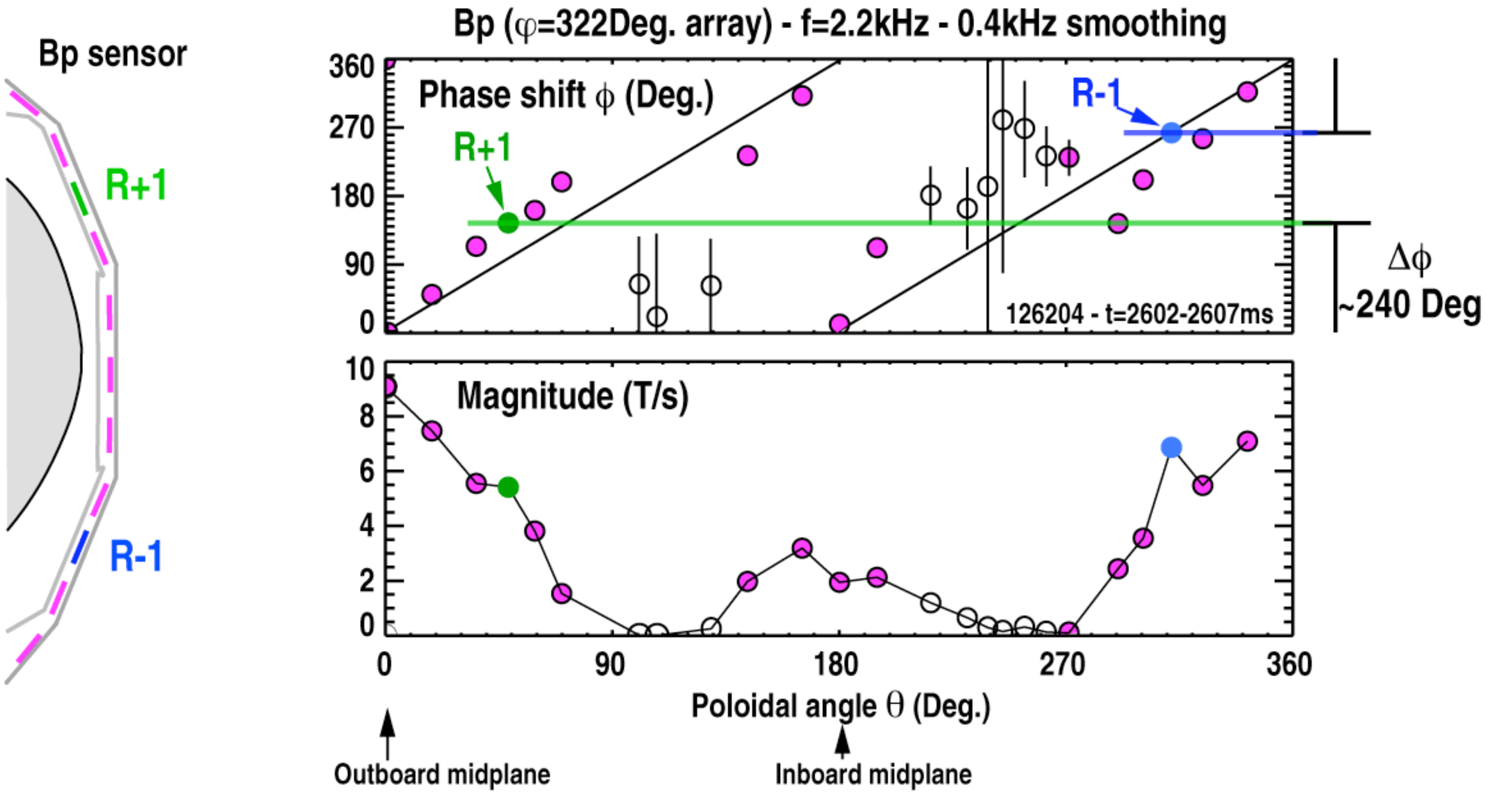
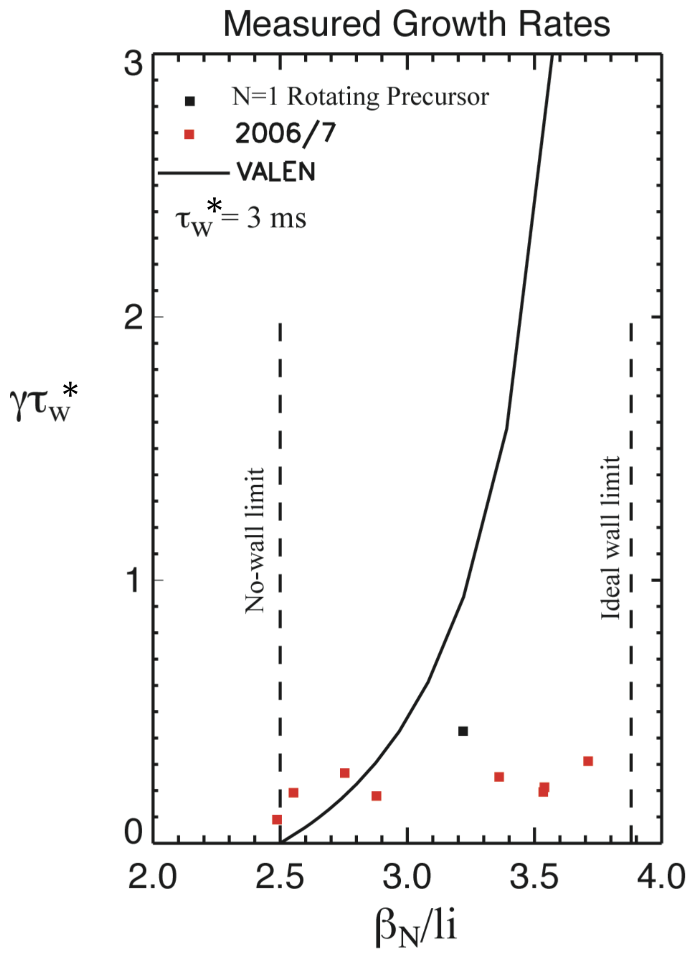


The rotating *n*=1 mode has similar outboard pitch and ballooning structure as either mode in the locked phase

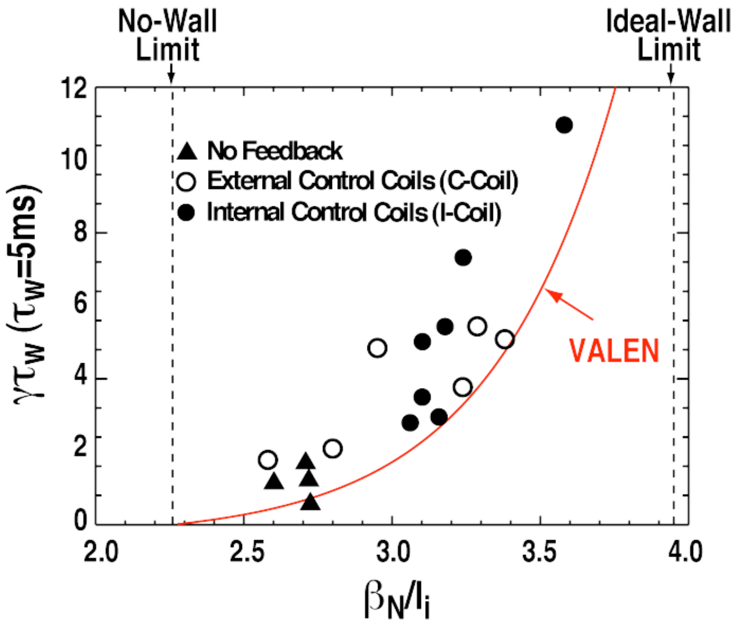


- **Rotating and non-rotating modes have same 240Deg phase shift between R+1 and R-1**
- **Rotating and non-rotating modes have a similar ballooning character**

Growth rates of non-rotating *n*=1 modes in low-torque plasmas do not agree with linear RWM theory



- **Beta dependence of γ's with balanced NBI differ from γ's with magnetic braking**
  - Why does magnetic braking yield γ's consistent with ideal MHD RWM predictions?



[Strait et al. *PoP* (2004)]

Summary/Conclusions

- **RWM is stabilized despite a low NBI torque and low rotation**
  - Reduction of error field is critical in obtaining stability at low rotation
- **Even with error field correction a non-rotating *n*=1 mode becomes unstable when β exceeds the no-wall limit and the rotation drops below a threshold**
  - At the threshold diamagnetic frequencies and the difference between impurity and main ion rotation are of the order of the measured rotation
- **Linear kinetic models can predict stability at and below the low rotation threshold**
  - Description of the mode onset would require additional physics
  - Kinetic models require benchmarking/resolution of discrepancies

Summary/Conclusions (cont.)

- **Plasmas close to the rotation threshold are susceptible to *n*=1 tearing**
  - Perturbation structures at the wall of rotating (“tearing”) and non-rotating (“RWM”) *n*=1 modes at high beta and low rotation are similar
  - Growth rates of non-rotating modes do not agree with the linear ideal MHD RWM model

- **What is the relation between the ideal MHD RWM and resistive MHD in plasmas with rotation in the order of the diamagnetic drift frequency?**
  - Do amplified residual error fields create an NTM seed at low rotation?
  - Does a Δ' unstable island precede the ideal MHD RWM when it’s stability boundary (including kinetic effects) is approached sufficiently slowly (in analogy to Brennan et al, *PoP* 2002)?
  - Do we simply observe a lowering of the NTM beta threshold with lower rotation independent of ideal MHD stability limits?