Rotation profile modifications by RWMs and rotation control with RWM feedback

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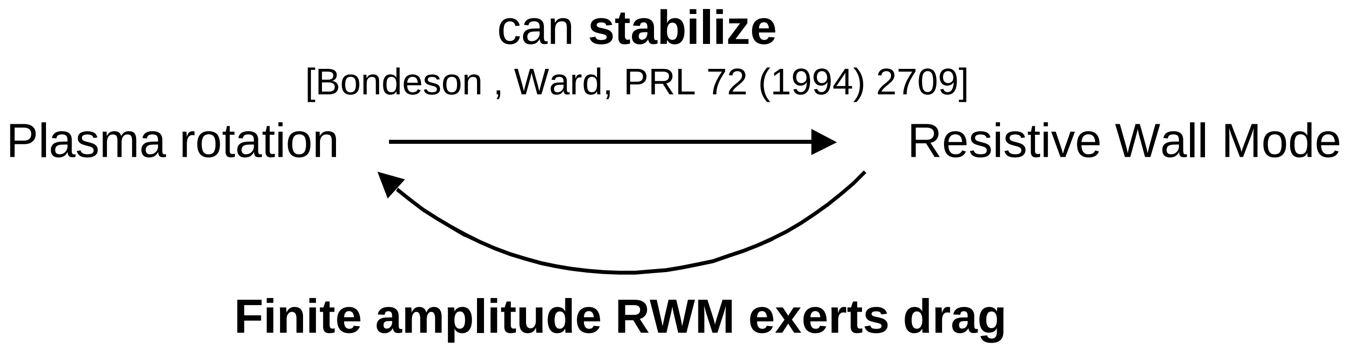
Motivation



can **stabilize**

[Bondeson , Ward, PRL 72 (1994) 2709]

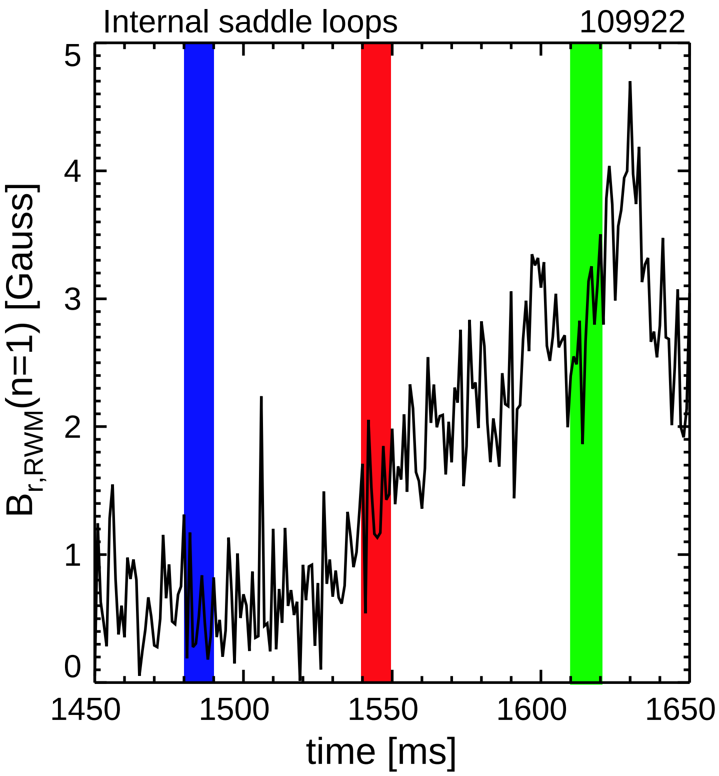
Plasma rotation → Resistive Wall Mode

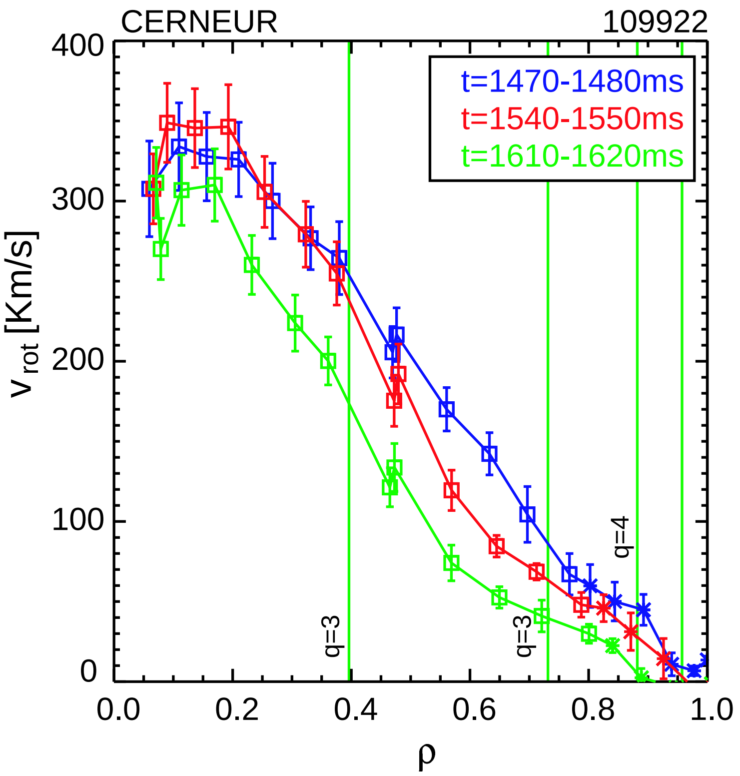
Finite amplitude RWM exerts drag

- Minimizing the drag essential for sustained rotational stabilization of the RWM. Key discovery: ‘Error field amplification’ [Boozer, PRL 86 (2001) 5059]
  - Effect of finite amplitude RWM on rotation profile.
  - Compare rotation decay with ‘transit time magnetic pumping’.
- Use additional drag to access a low-rotational regime for feedback control of the RWM without the stabilizing effect of plasma rotation.
  - Combine RWM braking with RWM feedback control.

Finite amplitude RWM slows plasma across entire profile

- Use external n=1 field to excite marginally stable RWM (resonant field amplification - RFA).





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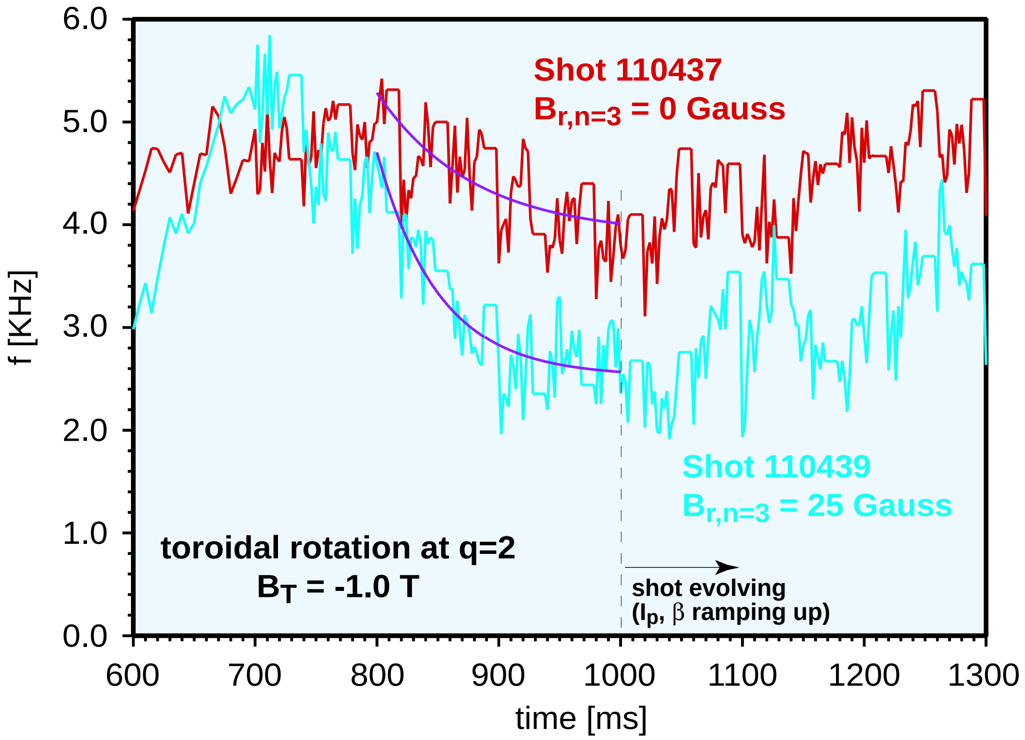
Drag of external non-resonant field described by “Transit Time Magnetic Pumping”

Apply m/n=1/3 external field
(**no resonant interaction with RWM**)



[T. Scoville et al, APS, Orlando 2002]

Rotation decay for “**transit time magnetic pumping**”

$$\frac{df}{dt} = \frac{f_0 - f}{\tau_L} - C_{\mathrm{ttmp}}\left(\frac{B_r}{B_T}\right)^2 f$$

Fit results:

f_0 = 3.9KHz

$\boldsymbol{C_{\mathrm{ttmp}} = 8.7 \bullet 10^5\ \mathrm{s}^{-1}}$

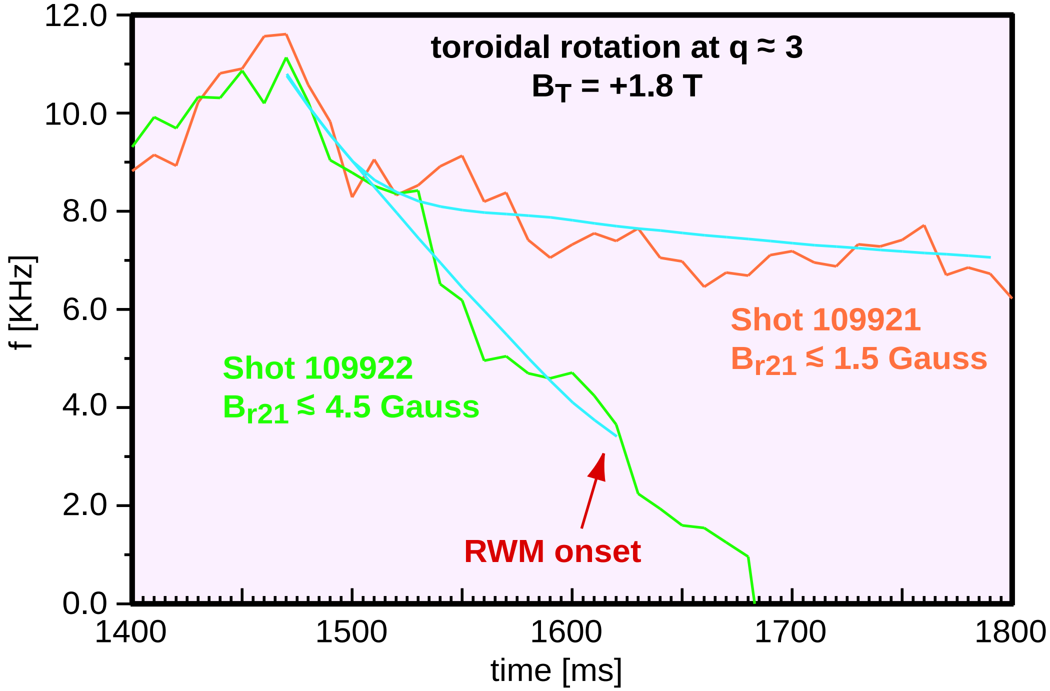
Calculate C_{ttmp} from profiles
[La Haye et al, PP 9 (2002) 2051]:

$\boldsymbol{C_{\mathrm{ttmp}} = 3.1 \bullet 10^5\ \mathrm{s}^{-1}}$

Predicted value **just** three times smaller.

Drag of finite amplitude RWM too large to be explained by TTMP

Apply n=1 external field (resonant interaction with RWM, but no q=2 surface)



[T. Scoville et al, APS, Orlando 2002]

Rotation decay for "**transit time magnetic pumping**"

$$\frac{df}{dt} = \frac{f_0 - f}{\tau_L} - C_{\text{ttmp}}\left(\frac{B_r}{B_T}\right)^2 f$$

Fit results:

f_0 = 15.5KHz

C_{ttmp} = 1.0 •10^9 s^{-1}

Calculate C_{ttmp} from profiles

[La Haye et al, PP 9 (2002) 2051]:

C_{ttmp} = 5.1 •10^5 s^{-1}

The braking field has to be at least 25 times larger than the applied external field. Observed is an order of 1.

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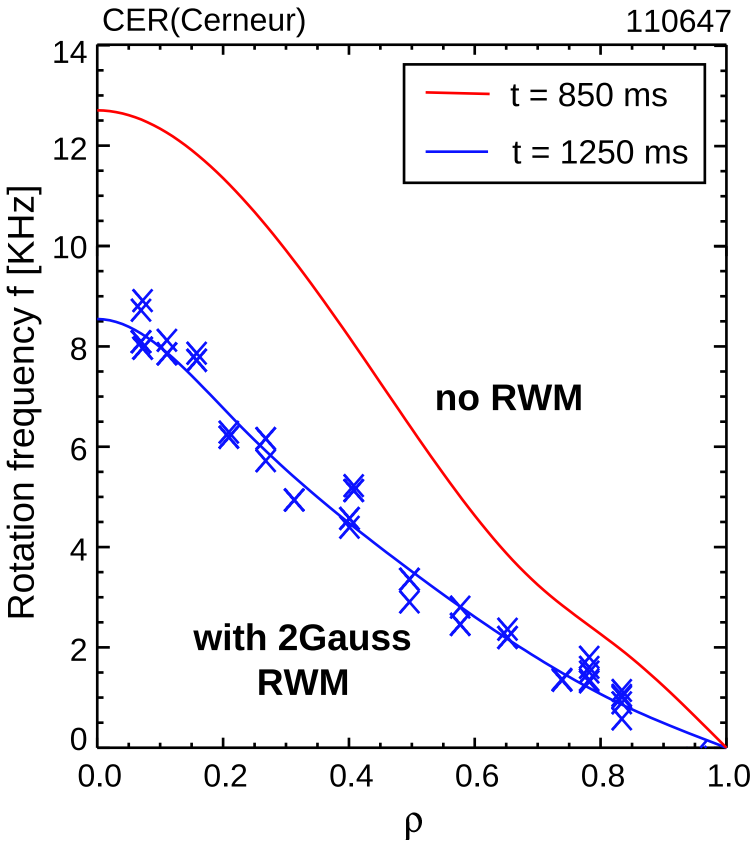
Can we use a finite amplitude RWM to access a low rotational regime for direct feedback control?



RWM (B_r(wall)=2 Gauss) in a 1T plasma:

- Uniform braking.
- Reduction of momentum confinement τ_L by 70%.
- Reduction of energy confinement τ_E by 30%.

→ **RWM is an efficient brake.**

Idea: Combine n=1 braking with RWM feedback.

→ Control the RWM at a finite amplitude (rather than 0).

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Feedback control on a finite amplitude RWM

Apply C-coil field B_{ext}, if detected error B_{err} is not equal to a requested B_{offset}.

$$B_{\mathrm{ext}} = -PID\left(B_{\mathrm{err}} - B_{\mathrm{offset}}\right)$$

PCS (choose proportional gain G_{P} and a pre-programmed C-coil offset I_{offset}, neglect derivative and integral gain):

$$B_{\mathrm{ext}} = M_{\mathrm{c}} I_{\mathrm{offset}} - G_{\mathrm{P}} B_{\mathrm{err}}$$

Plasma response described by resonant field amplification of a marginally stable RWM (phenomenological):

$$B_{\mathrm{RWM}} = A_{\mathrm{RFA}} B_{\mathrm{ext}}$$

Using “mode-control” (B_{err}=B_{RWM}) the resulting equilibrium RWM amplitude is:

$$B_{\mathrm{RWM}} = \frac{A_{\mathrm{RFA}}}{1 + A_{\mathrm{RFA}} G_{\mathrm{P}}} \cdot M_{\mathrm{c}} I_{\mathrm{offset}}{}^{*}$$

*I_{offset} defined with respect to the optimum correction currents of the intrinsic error field.

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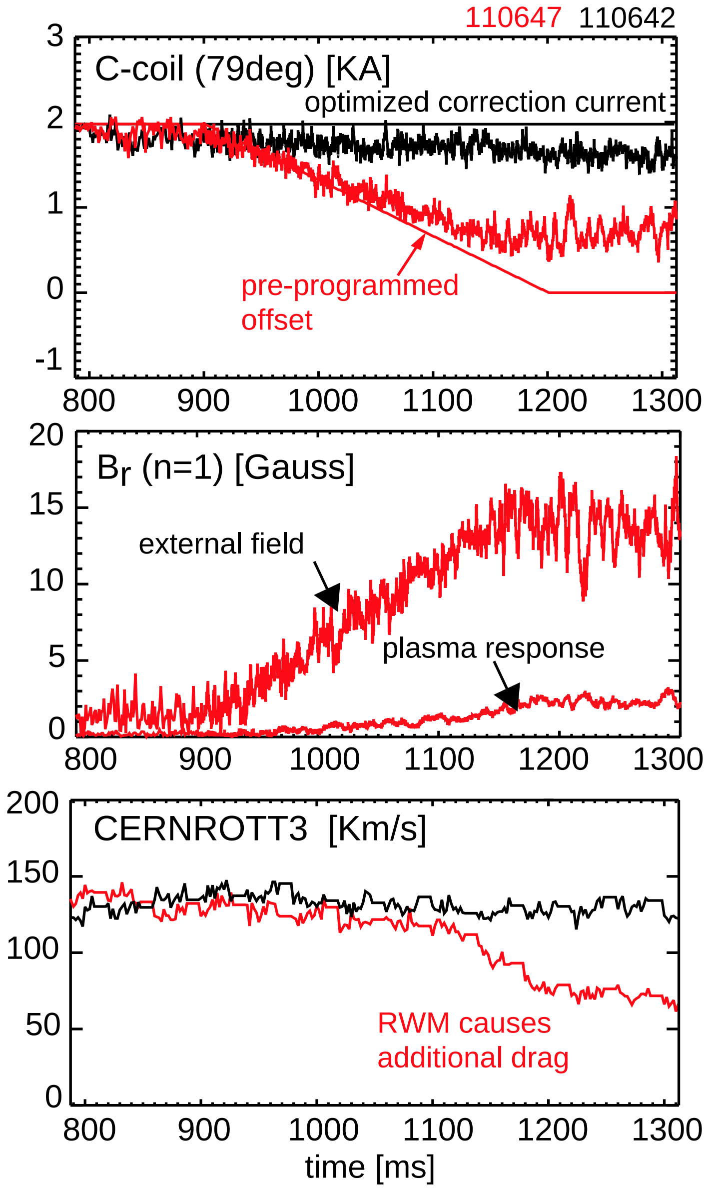
Feedback with a pre-programmed current offset excites marginally stable RWM

In the presence of RFA the feedback system will partially compensate I_{offset},

$$I_{\mathrm{C}} = \frac{1}{1+A_{\mathrm{RFA}}G_{\mathrm{P}}} \cdot I_{\mathrm{offset}}$$

Experiment: Apply a pre-programmed offset to the optimum C-coil currents at $\beta > \beta_{\mathrm{no\text{-}wall}}$:

- Partial correction of the C-coil offset corresponds to A_{RFA}~0.15.
- Consistent with an observed A_{RFA}~0.17 measured by magnetic probes.



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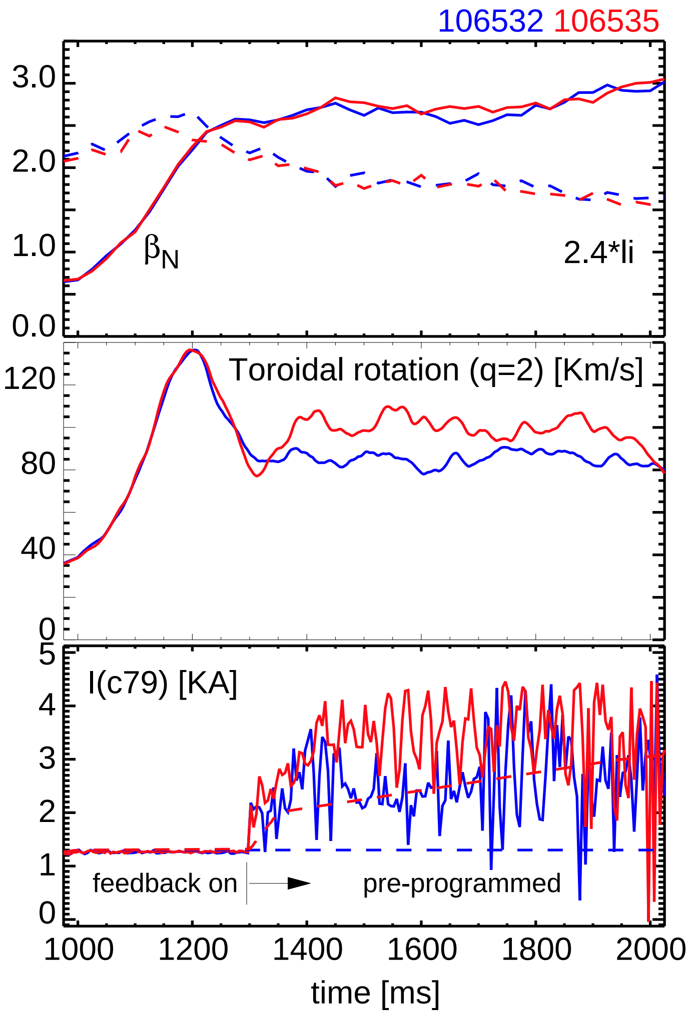
RWM feedback finds optimum correction current

Optimize C-coil currents to minimize the RFA amplitude and, hence, drag.

- Feedback reduces the difference between pre-programmed and optimum correction currents,

$$I_C = \frac{1}{1+A_{RFA}G_P} \cdot I_{offset}$$

- The improvement is typically ~50% (G_P~5, A_{RFA}~0.2)
- Several iterations improve the correction currents.



[Garofalo et al,NF 42 (2002) 1335]

Extension of feedback model to an unstable RWM shows that an applied offset does not change the condition for stability

Assume,

$$\delta W_{\mathrm{RWM}} \propto B_{\mathrm{RWM}}^2$$

and

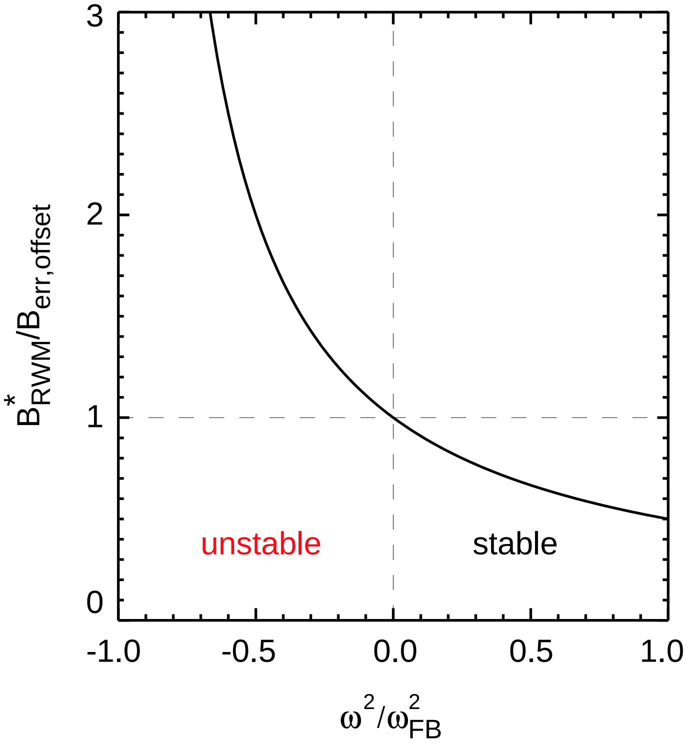
$$F_{\mathrm{ext}} \propto B_{\mathrm{ext}}$$

Then, the condition for stability,

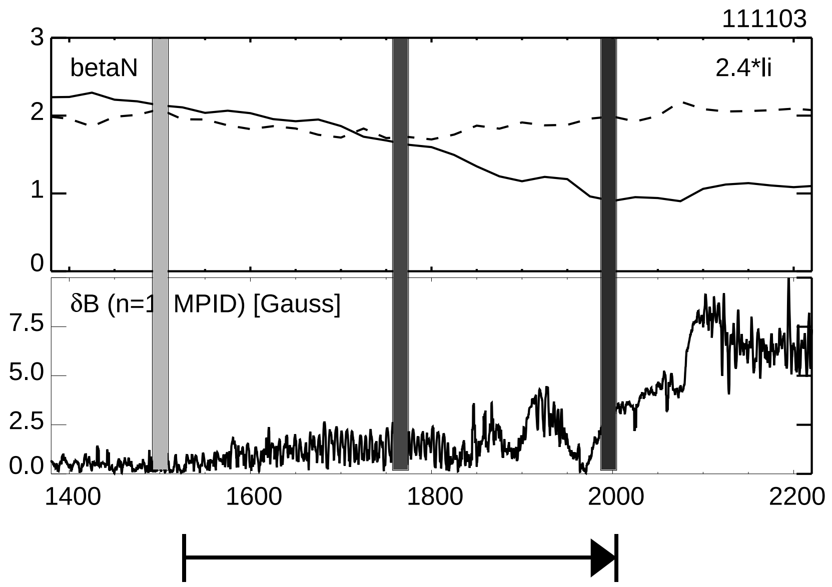
$$\omega^{*2} = \omega^2 + \frac{G_{\mathrm{P}}\alpha}{\kappa} > 0$$

is independent of the offset.

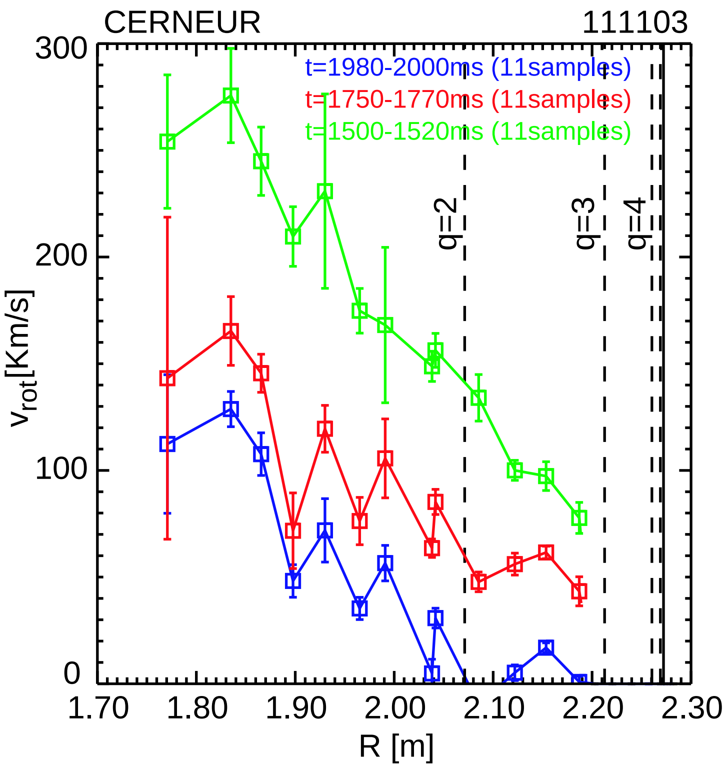
B_{RWM}, however, increases continuously with decreasing RWM stability → **non-linear** effects more likely to become important.



RWM braking at low rotation can generate magnetic islands



Ramp I_{offset} up to 7 KA.



- RFA of marginally stable RWM → **global braking**.
- Large external n=1 field at low rotation creates magnetic islands → local braking and bad confinement.

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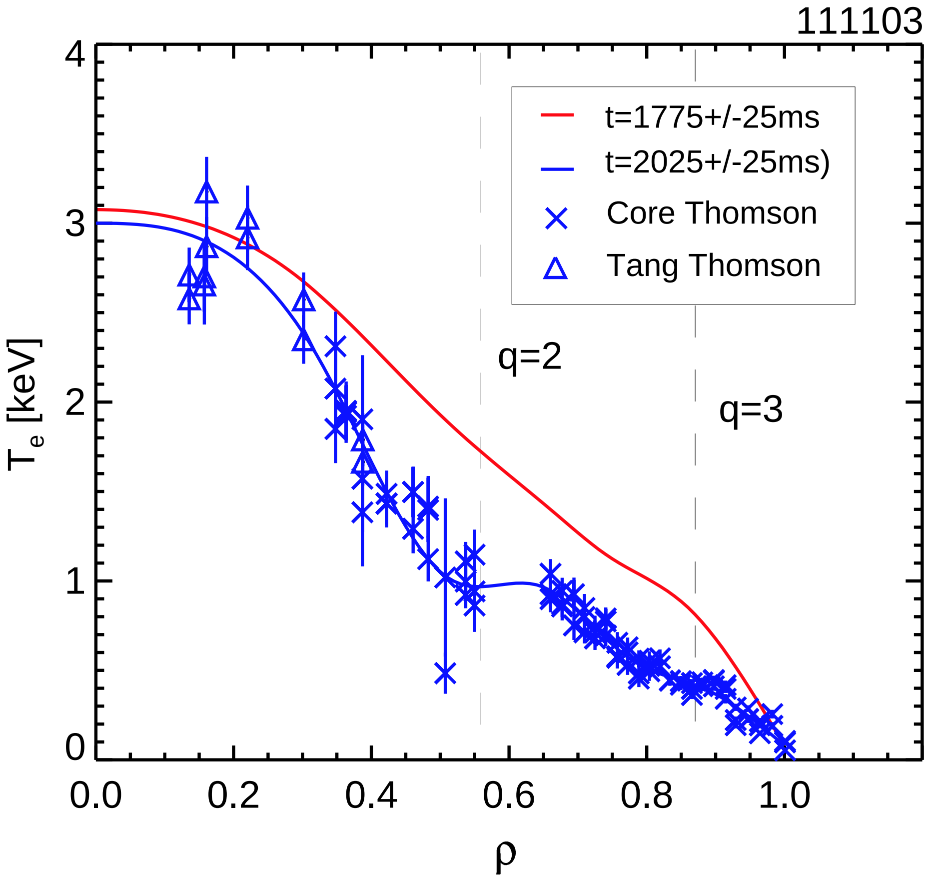
Avoid large external field at low rotation with a rotation dependent $I_{C,offset}$.

External field at low rotation causes magnetic islands

- RWM braking →T_e profile shows no islands.
- Large external n=1 field at low rotation →T_e profile shows signature of 2/1 and 3/1 islands.



Summary

Effect of RWM on rotation profile

- The RWM causes a rotation decay across the entire profile.
- The RWM drag is too large to be explained by ‘transit time magnetic pumping’ alone.

Combine RWM braking with RWM feedback

- Pre-program C-coil current offset is only partially corrected by RWM feedback and excites marginal stable RWM for additional drag.
- RWM feedback can iteratively improve correction of intrinsic error field.
- RWM braking at low rotation prone to island generation → need to maintain rotation above a critical value.