Resistive and Ferritic Wall Modes in the Rotating Wall Experiment

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for

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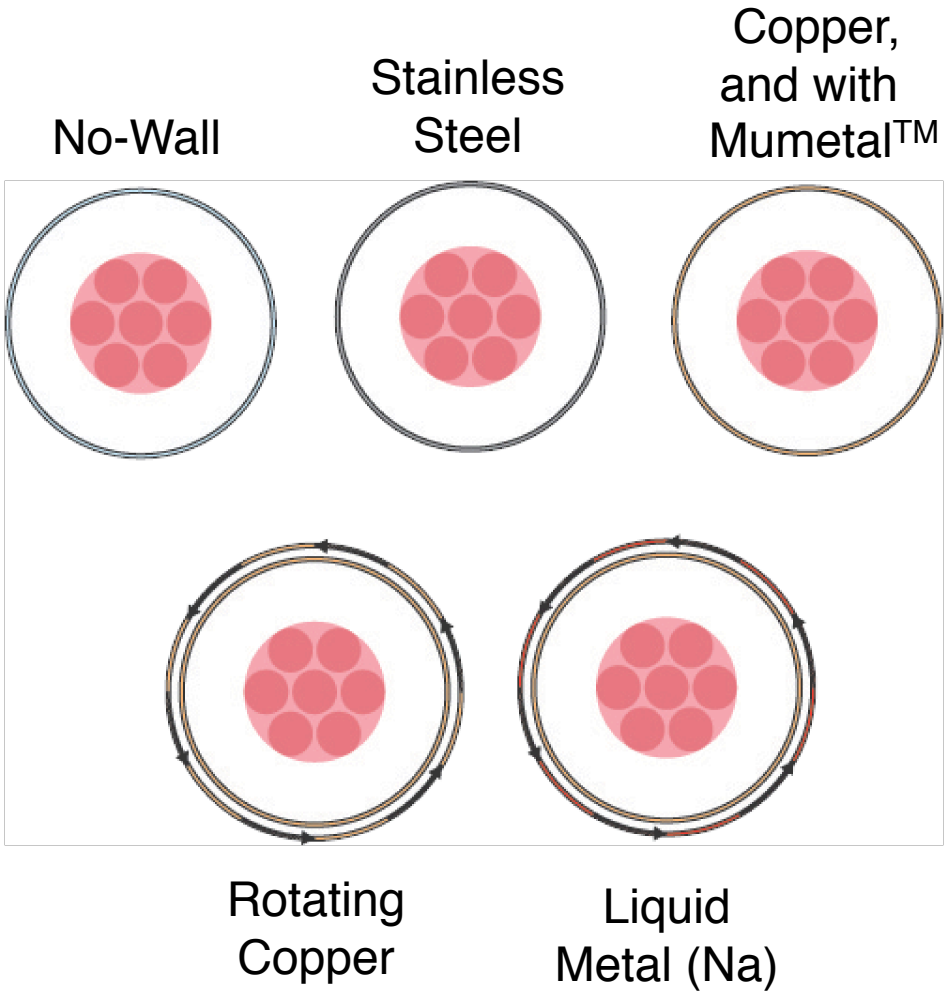
The resistive and resistive-ferritic wall modes have been identified on RWE.

RWE



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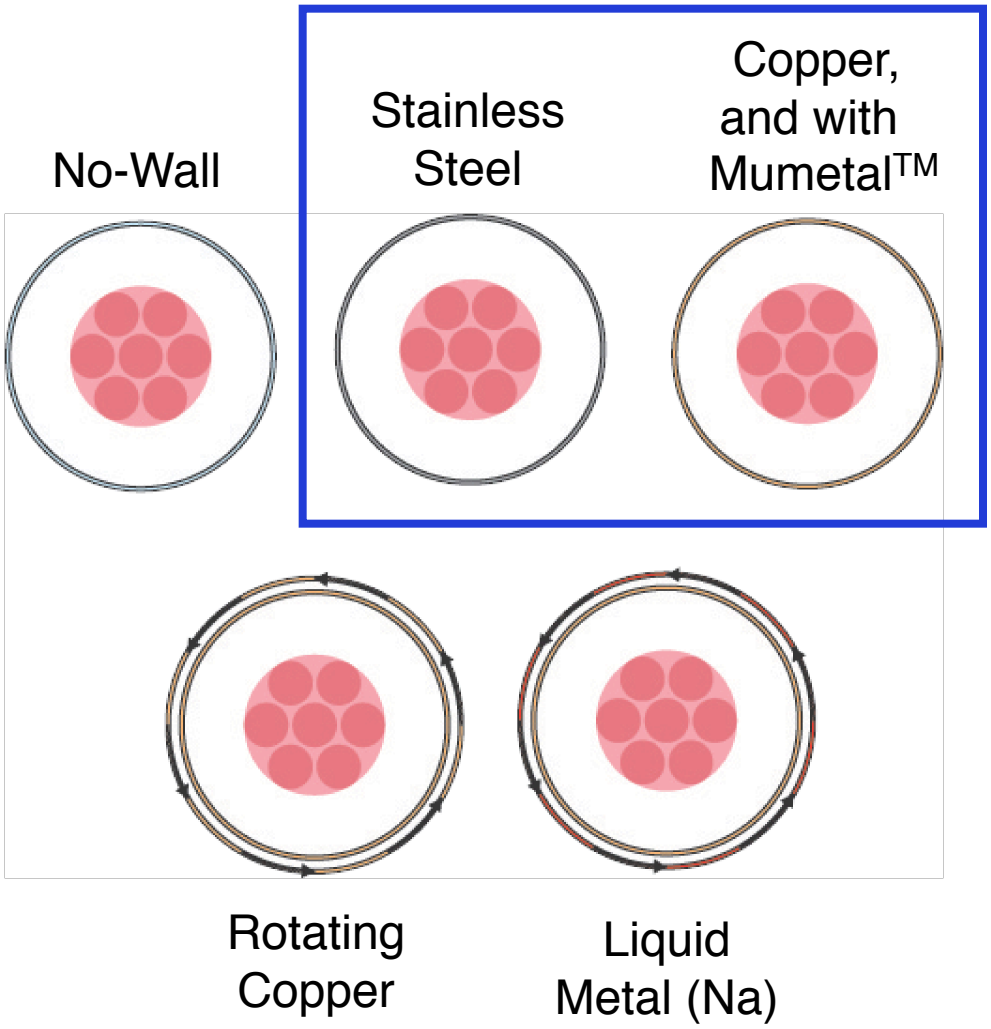
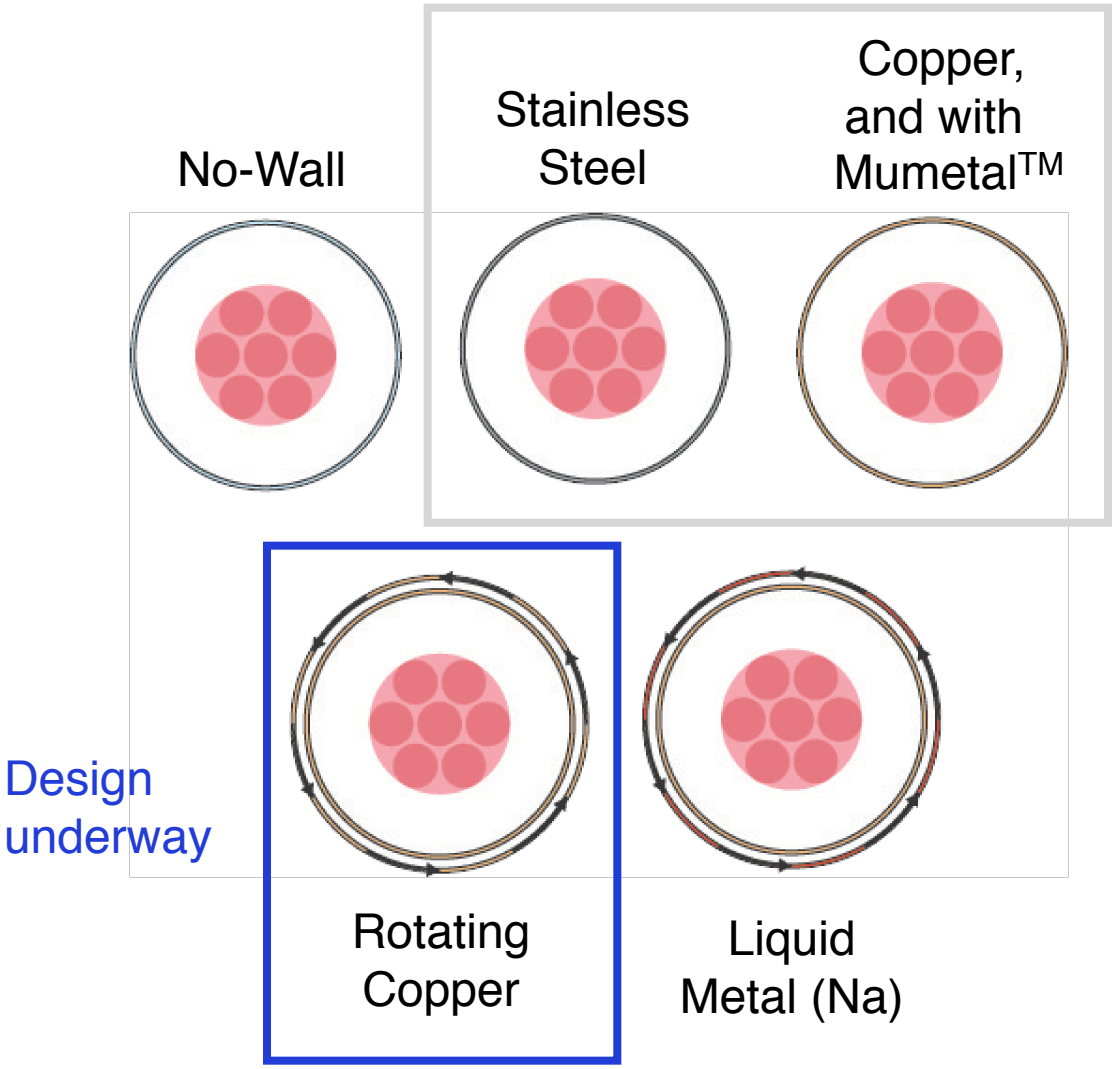


Main part of talk

The resistive and resistive-ferritic wall modes have been identified on RWE. Next step is the rotating shell.

RWE



Kink stability in a line-tied cylindrical screw pinch.

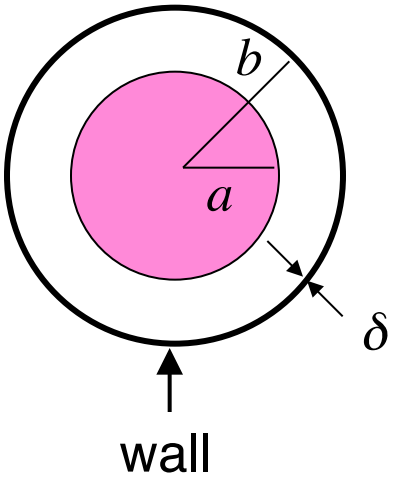
RWE

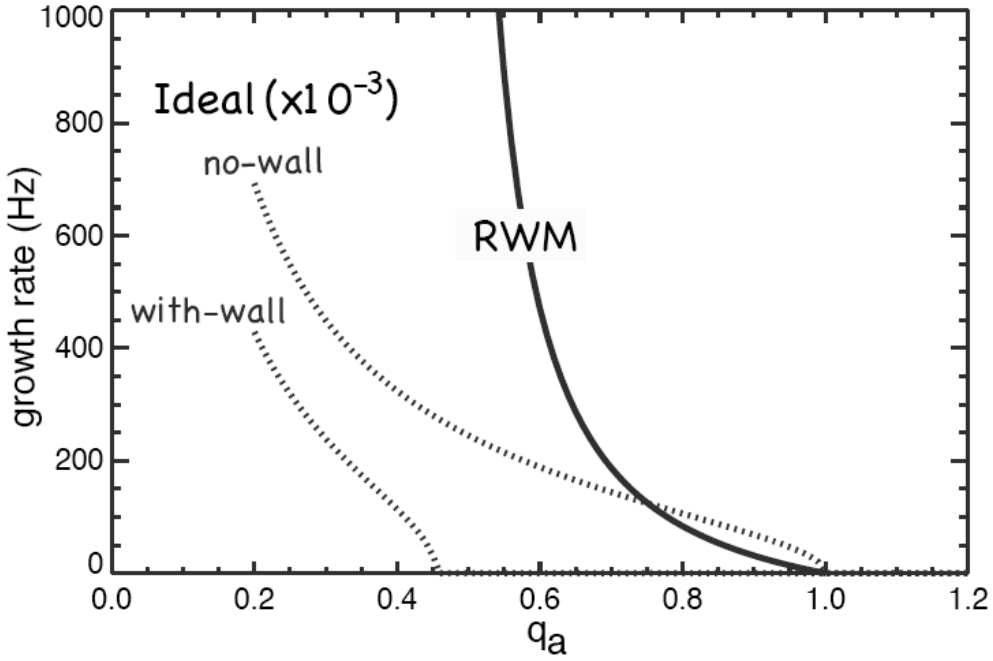
- Kruskal-Shafranov m=1 kink stability threshold, no-wall limit

$$\frac{4\pi^2 a^2}{L}\frac{B_z}{\mu_0 I_p} = q(a) > 1$$

- Perfectly conducting wall at $r=b$, with-wall limit

$$q(a) > 1 - \left(\frac{a}{b}\right)^2$$



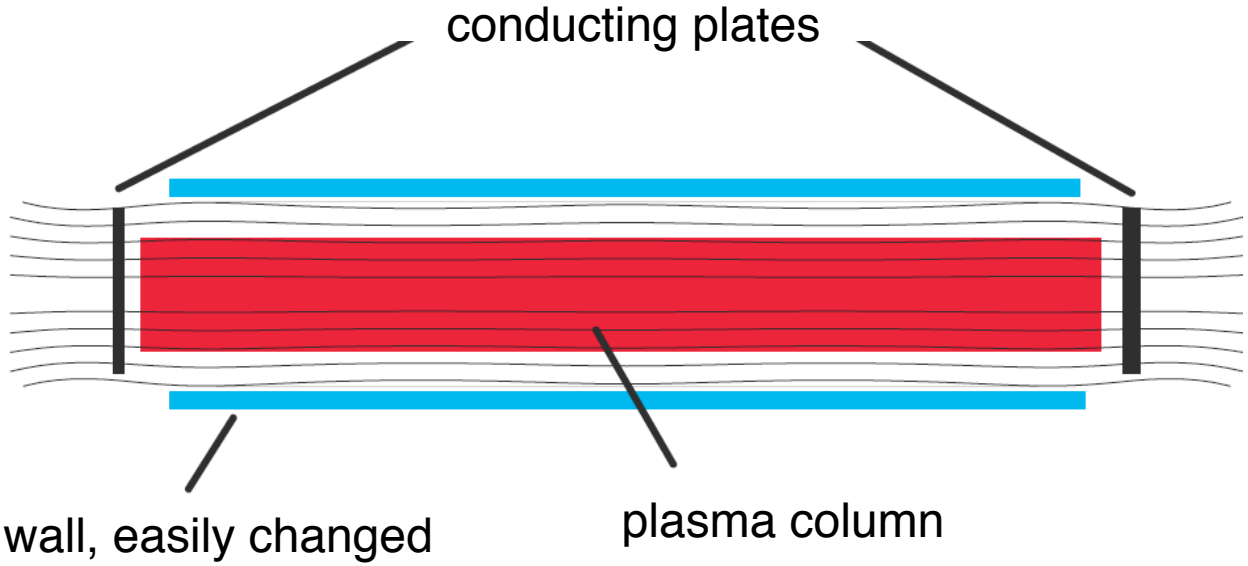


$$\gamma_{RWM}^{-1} \sim \tau_b$$

$$\tau_b = \frac{\mu_0 b \delta}{\eta}$$

RWE produces line-tied screw pinch plasmas, with walls that are easy to change.

RWE



No-wall, internal kink: Bergerson et al, PRL ’05

RWM and ferritic mode: Bergerson et al., PRL ’08 (accepted)

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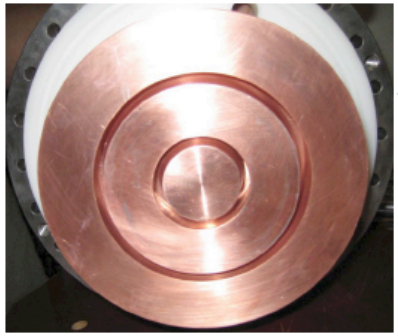
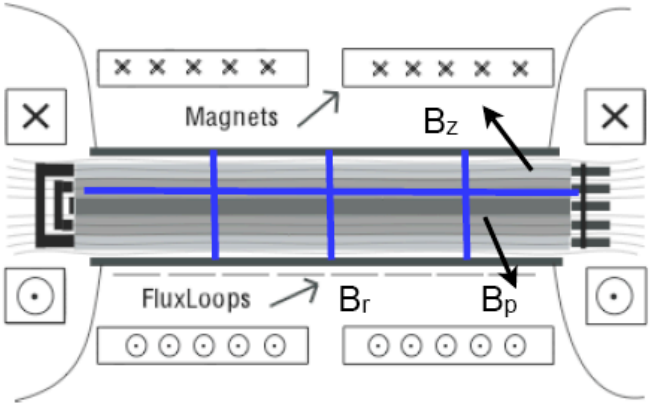
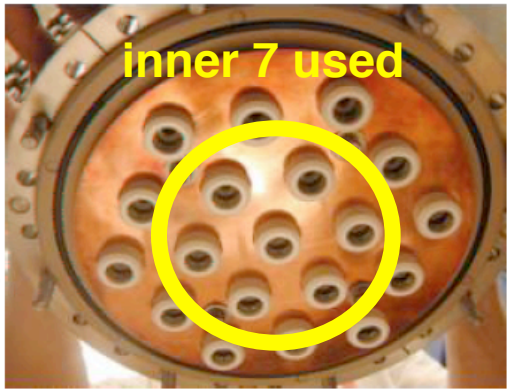
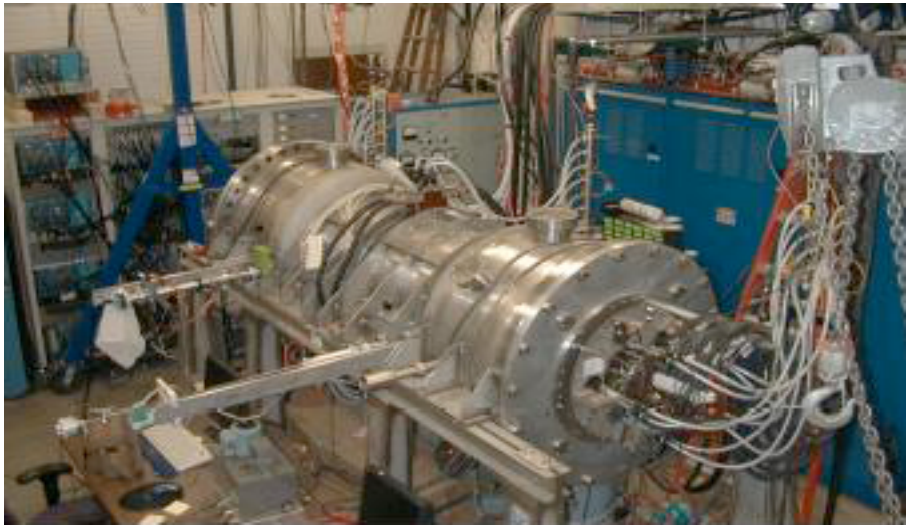
RWE







2D array of BR pickup coils on shell surface is primary diag.



Parameters:

$a \leq 10$ cm

$L = 120$ cm

$B < 1000$ G

$n \sim 4 \cdot 10^{13}$ cm^{-3}

$T_e \sim 20$ eV

$\tau_A \sim 10$ μs

$S \sim 60$

Resistive wall mode for a single wall in the line-tied screw pinch.

RWE

- Dispersion relation for m=1:

$$1-\Delta_a = \frac{2}{nq_a} \qquad \text{where} \qquad \Delta_a = \frac{1}{\tilde{B}_r(a)}\frac{d}{dr}\left(r\tilde{B}_r\right)_{r=a+}$$

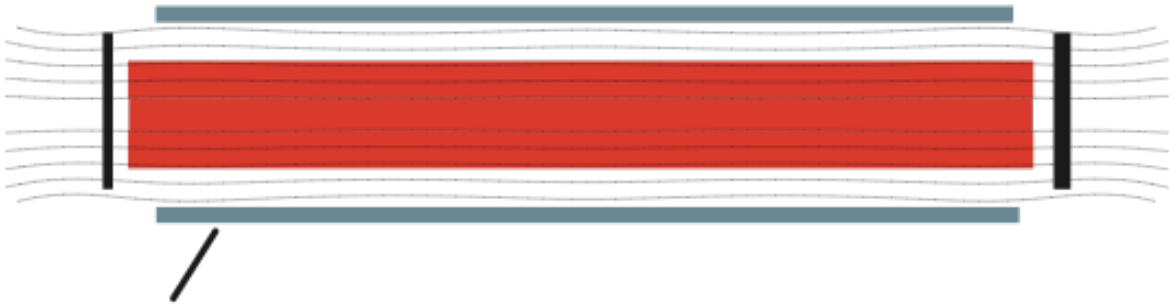
and $$\Delta_a = \frac{-1-\frac{\gamma\tau_b}{2}\left[1+\left(\frac{a}{b}\right)^2\right]}{1+\frac{\gamma\tau_b}{2}\left[1-\left(\frac{a}{b}\right)^2\right]}$$ for force-free, flat current profile equilibrium

⇨ $$\gamma = \frac{2}{\tau_b}\frac{1-q_a}{q_a-1+\left(\frac{a}{b}\right)^2}$$ for n=1 (most unstable)

C. Hegna, PoP '04

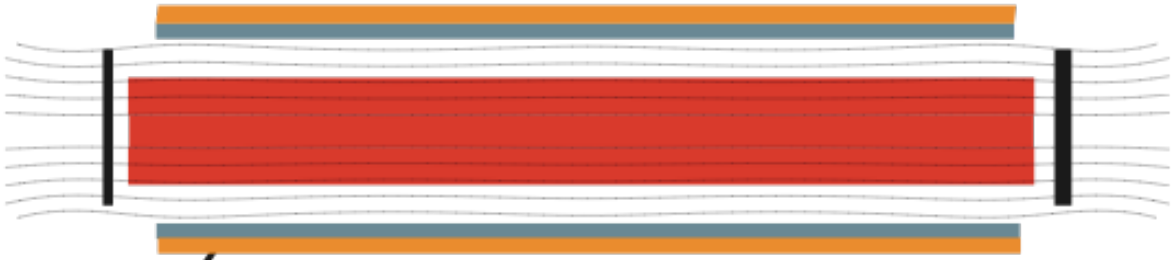
Stainless steel and copper walls used to demonstrate RWM growth rate dependence on wall resistance.

RWE



Stainless steel wall

τ_b = 0.5 ms

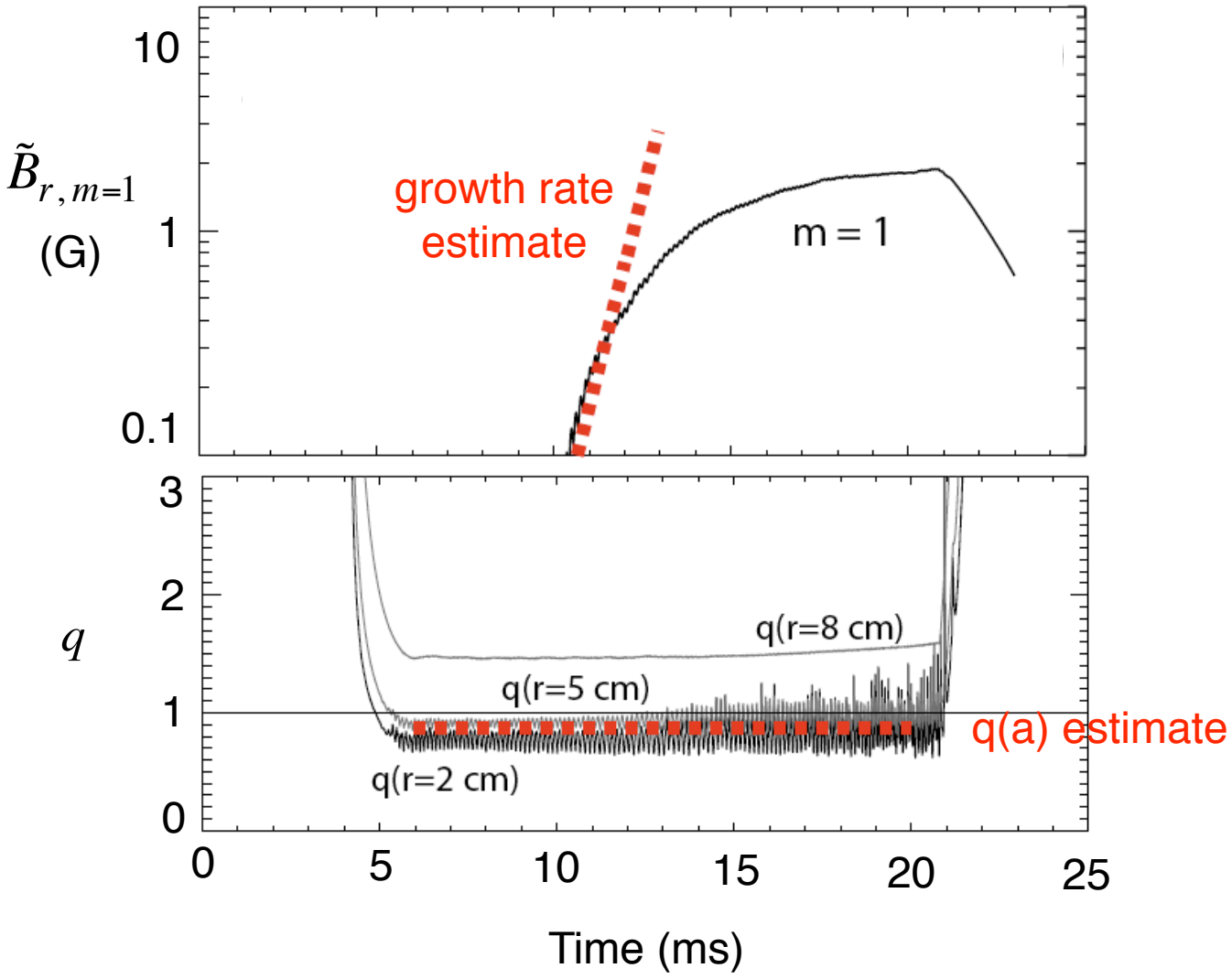


Stainless steel + copper wall

τ_b = 7 ms

Typical observation of the resistive wall mode, in this case the τ_b = 7 ms wall.

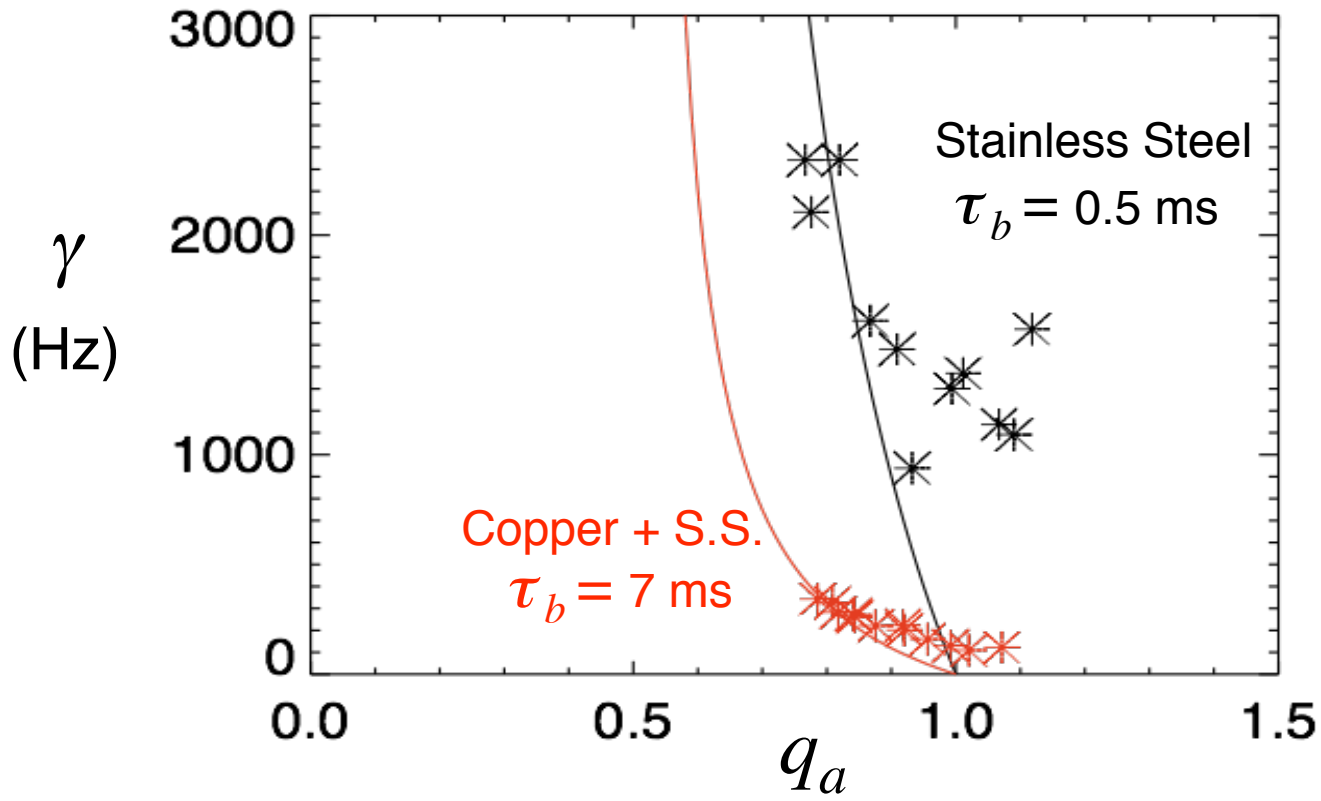
RWE



Growth rate depends on wall time, as expected.

RWE

- RWM onset occurs with $q(a)$ a little larger than 1
  - Current profile is not flat (but strong $J(r)$ sensitivity not expected)
  - Plasma column radius expands slightly from cathode to anode
  - Finite axial flow increases $q(a)$ threshold
  - Possible role of non-ideal MHD effects?

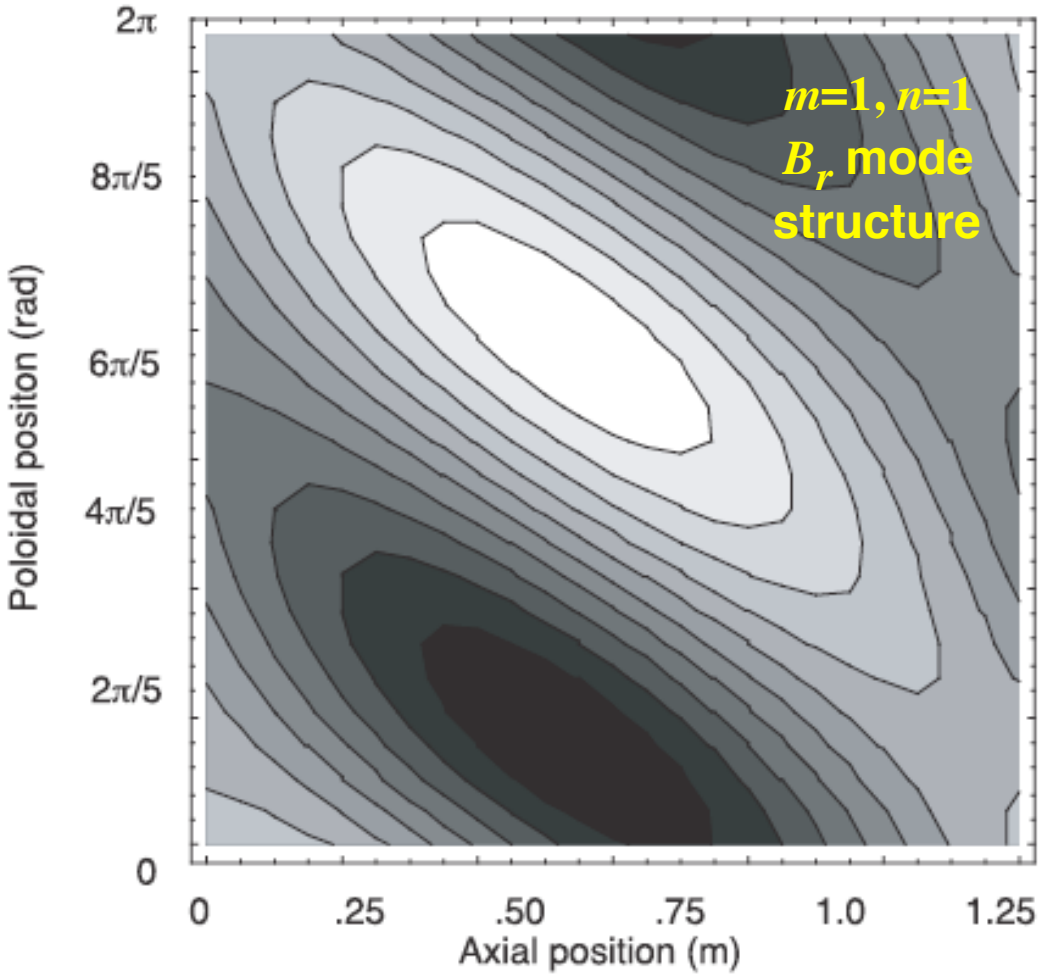


Axial mode structure more complicated for line-tied B.C. than for periodic B.C.

RWE

- For line-tied B.C., axial mode structure depends on equilibrium

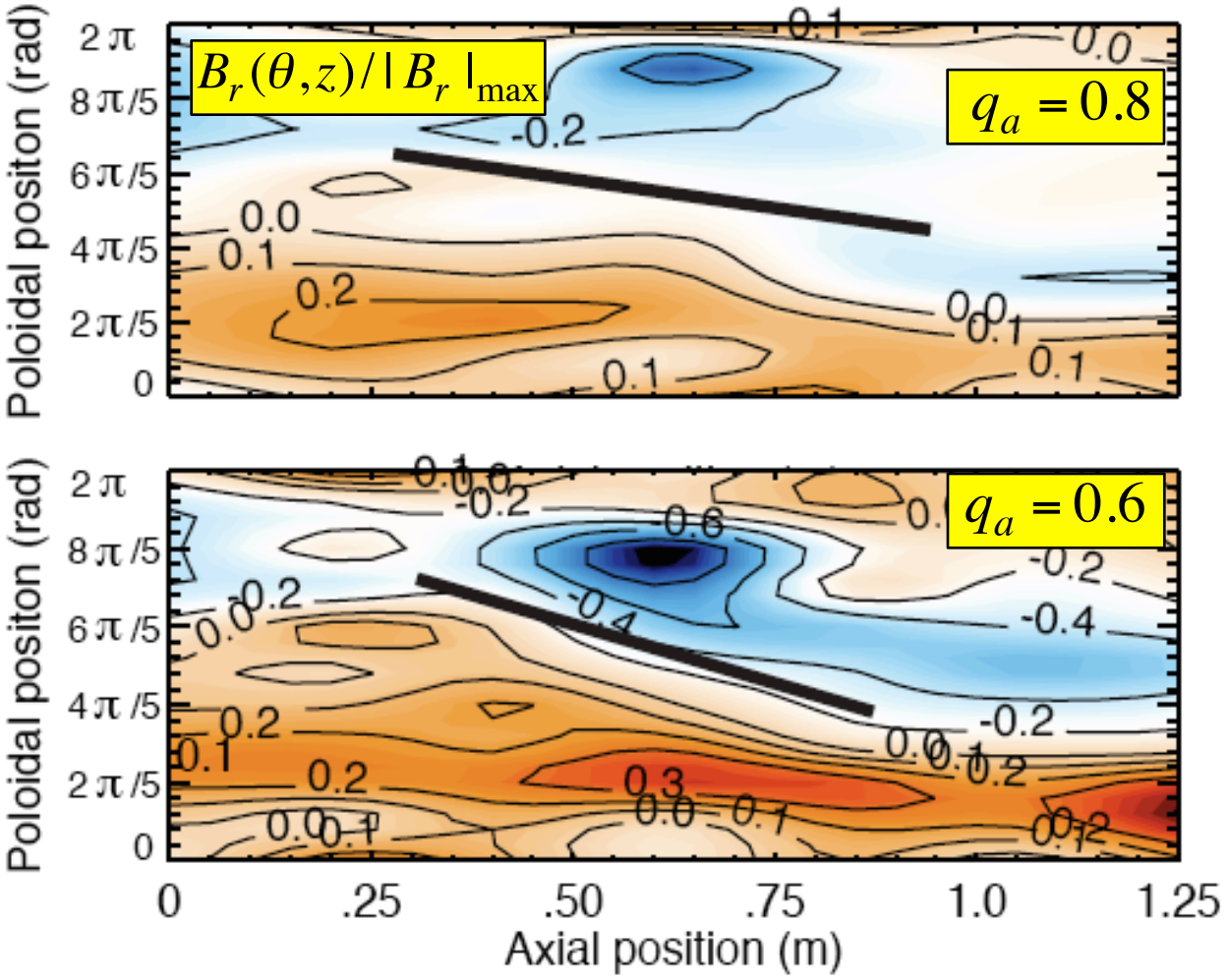
$$\xi_r(r,\theta,z) = f(r)e^{im\theta}e^{i(1-2/nq_a)n\pi z/L}\sin\left(\frac{n\pi z}{L}\right)$$

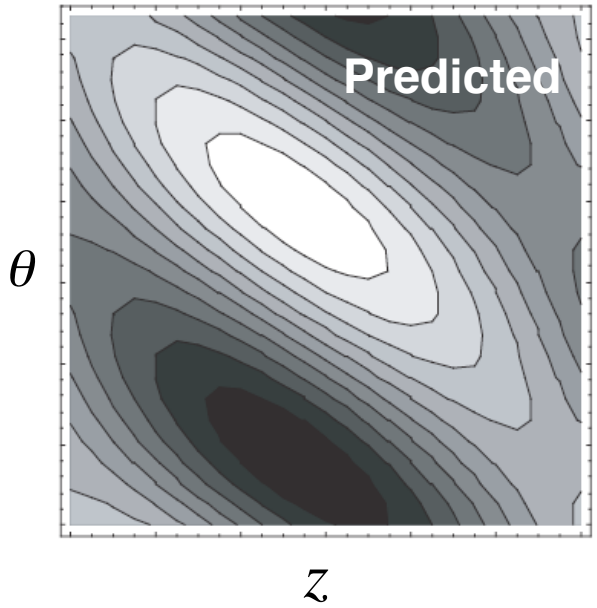


Measured RWM mode structure agrees reasonably well with analytic prediction.

RWE

$$\tilde{B}_r(\theta,z) = e^{i\theta} e^{i(1-2/q_a)\pi z/L} \sin\left(\frac{\pi z}{L}\right)$$



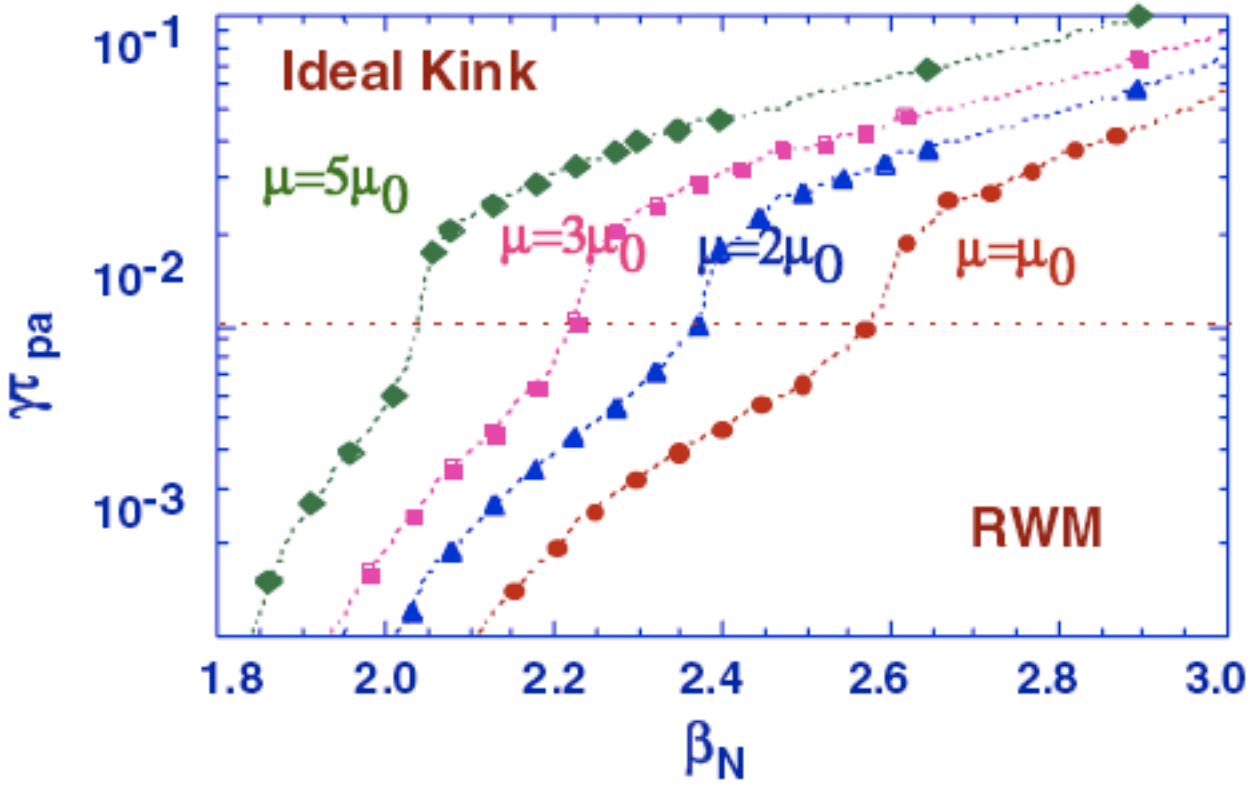


Ferromagnetic-Resistive Wall

Critical beta limit for the tokamak is predicted smaller for a ferromagnetic-resistive wall.

RWE

- Low activation ferritic steel attractive for a fusion reactor
- Relative permeability $\mu/\mu_0 \sim 2$ for wall embedded in high toroidal field



G. Kurita et al, NF '03 and '06

RWM for a single ferritic-resistive wall in the line-tied screw pinch.

RWE

- Same dispersion relation as for resistive wall:

$$1-\Delta_a = \frac{2}{nq_a}$$

but with

$$\Delta_a = \frac{-1+\left(\frac{a}{b}\right)^2\left[\frac{\delta}{2b}\left(\hat{\mu}-\hat{\mu}^{-1}\right)-\frac{\gamma\tau_b}{2}\right]\Big/\left[1+\frac{\delta}{2b}\left(\hat{\mu}+\hat{\mu}^{-1}-2\right)+\frac{\gamma\tau_b}{2}\right]}{1+\left(\frac{a}{b}\right)^2\left[\frac{\delta}{2b}\left(\hat{\mu}-\hat{\mu}^{-1}\right)-\frac{\gamma\tau_b}{2}\right]\Big/\left[1+\frac{\delta}{2b}\left(\hat{\mu}+\hat{\mu}^{-1}-2\right)+\frac{\gamma\tau_b}{2}\right]}$$

$$\Rightarrow \quad \gamma = \frac{2}{\tau_b}\left[\frac{1}{q_a-1+(a/b)^2}\right]\left[(1-q_a)+\frac{\delta}{2b}\left[(\hat{\mu}+\hat{\mu}^{-1}-2)(1-q_a)+(\hat{\mu}-\hat{\mu}^{-1})(a/b)^2\right]\right]$$

ferromagnetic response

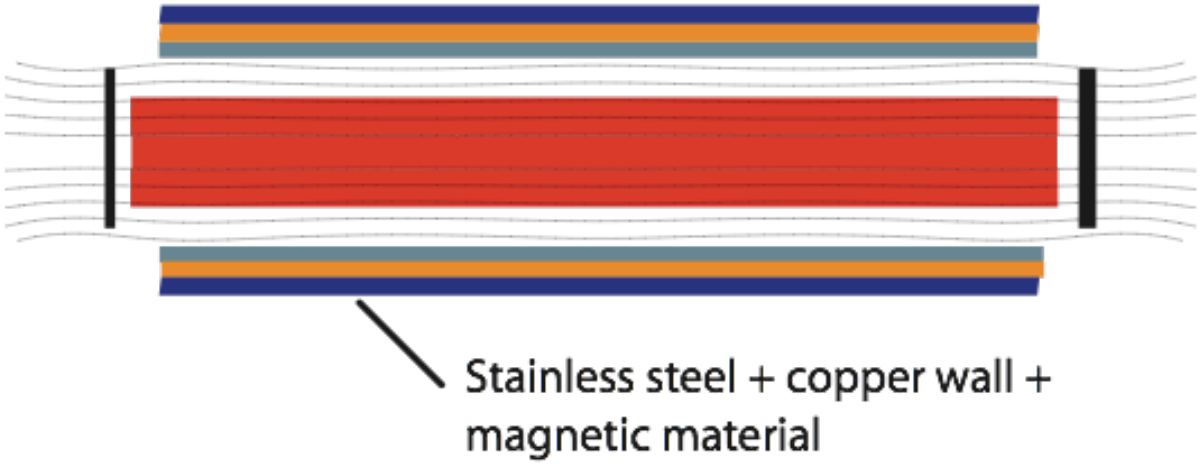
$$\hat{\mu} = \mu/\mu_0$$

$$n = 1$$

Thin Mumetal™ sheet wrapped on the outer surface of the copper wall used to explore ferromagnetic response.

RWE

- Growth rate for the 2-wall system, one resistive and one ferritic-resistive, is straightforward to derive (but ugly).



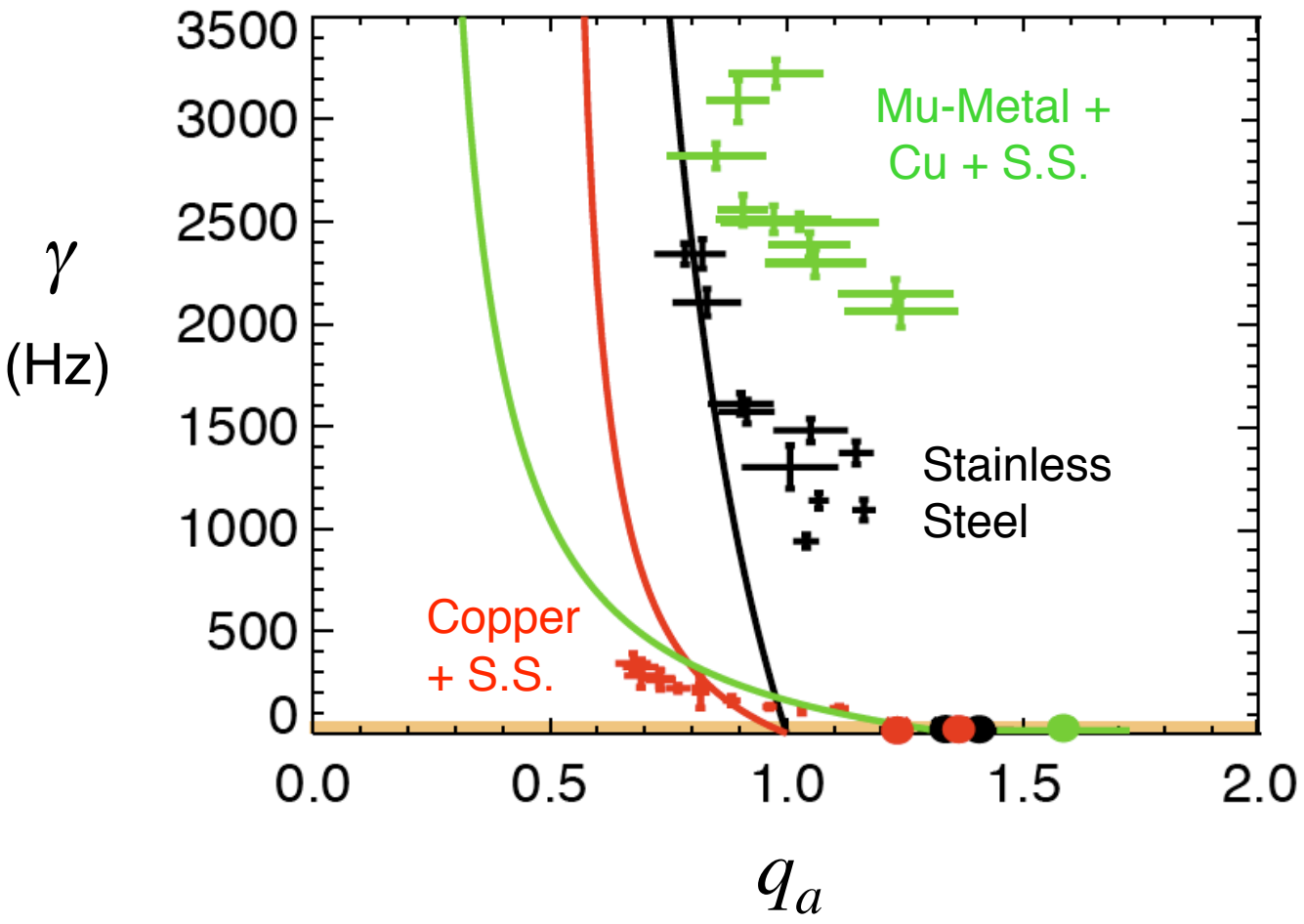
τ_b = 7 ms

$\hat{\mu} \approx 1200 \quad @\, 300$ G

The ferritic-resistive wall mode occurs at higher q(a), but with a much larger growth rate than expected!

RWE

- Expect slowest wall time will limit RWM growth, in this case the copper wall



Next step: Rotating Wall

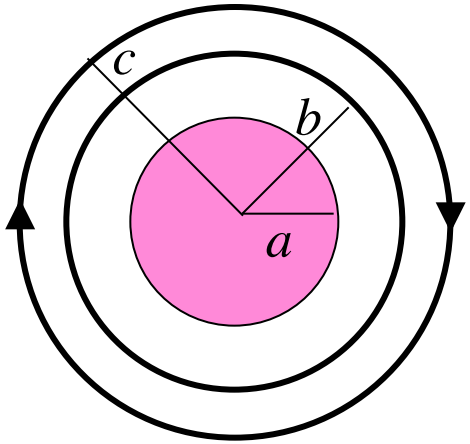
Liquid metal wall/coolants in a fusion reactor could in principle be used as an integrated RWM stabilizer.

RWE

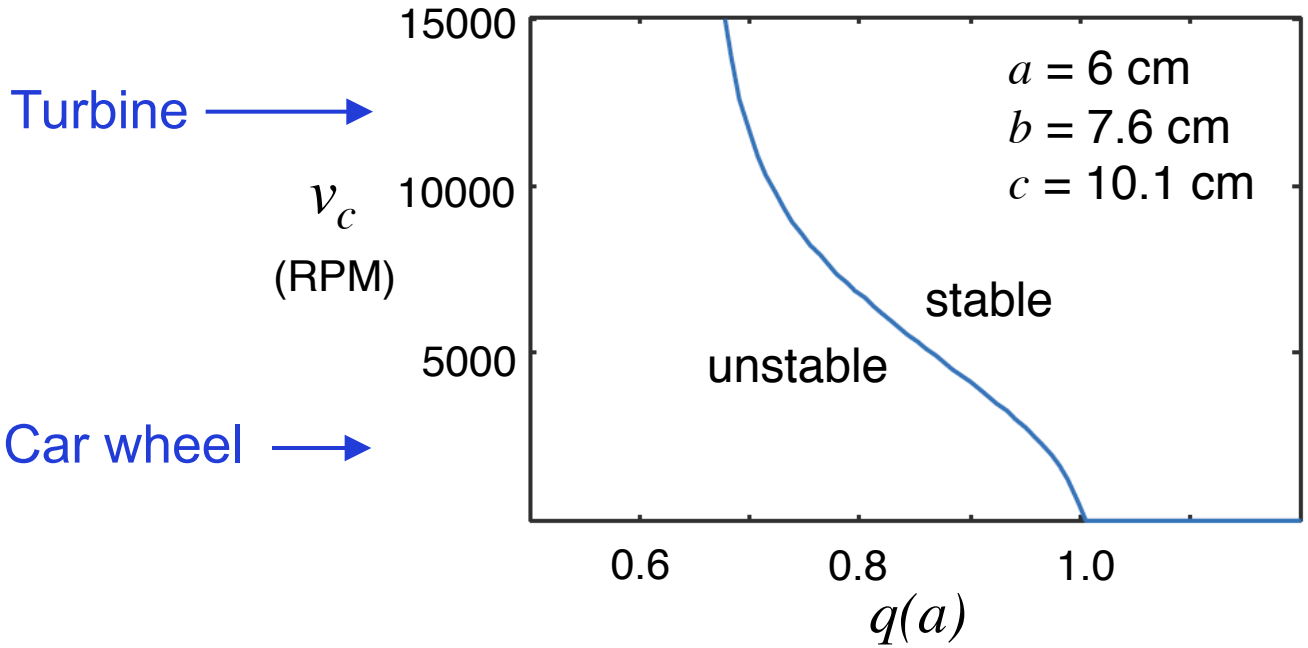
- Test with solid rotating shell (together with a stationary shell)
- Liquid shell offers more flexibility, e.g., poloidally asymmetric boundary conditions

$$\Delta_a = f\left[\gamma\tau_b, (\gamma + iv_c/c)\tau_c, \frac{a}{b}, \frac{a}{c}\right]$$

v_c = wall rotation velocity

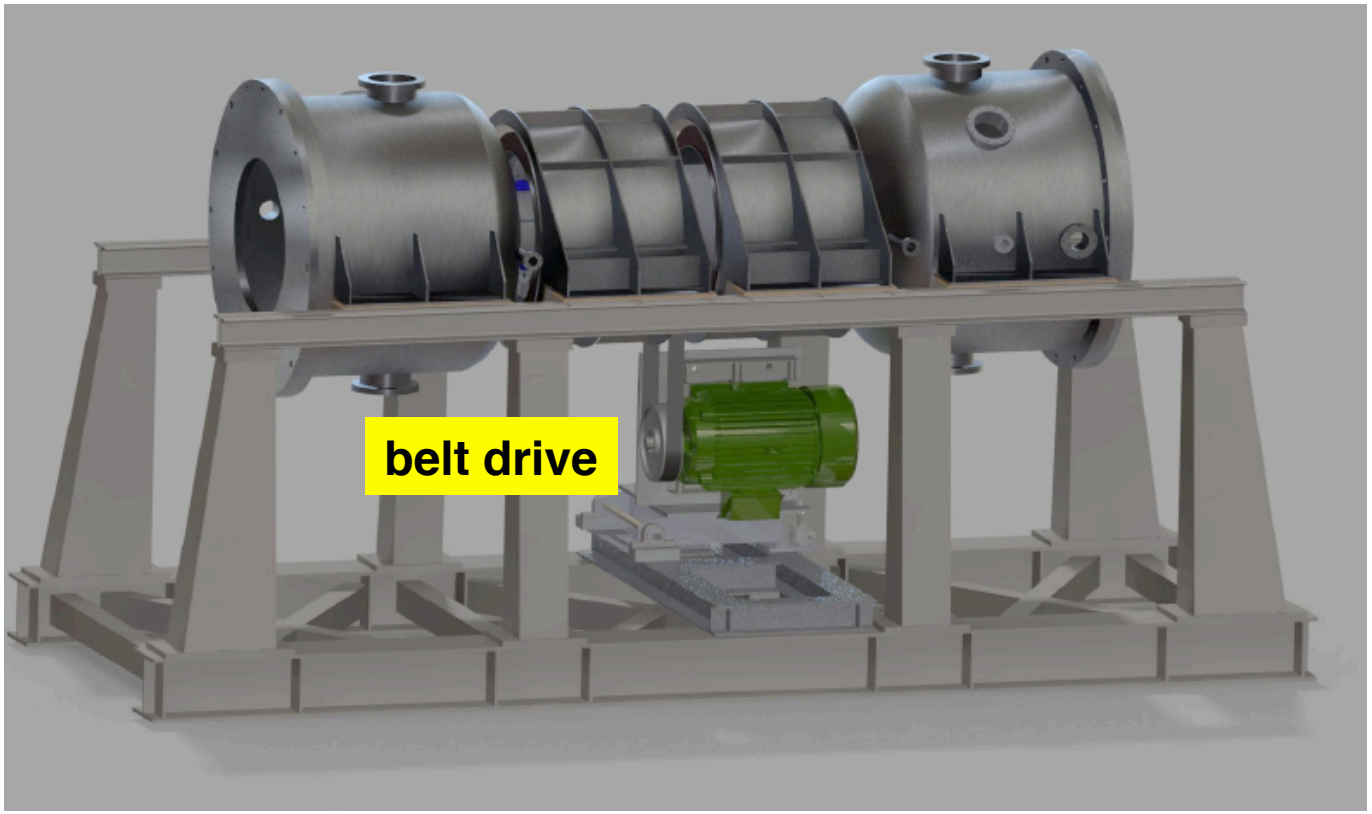


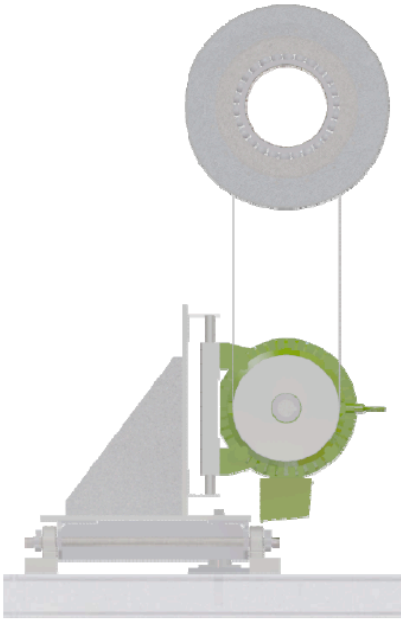
outer wall rotates



Design for adding a rotating wall has begun.

RWE



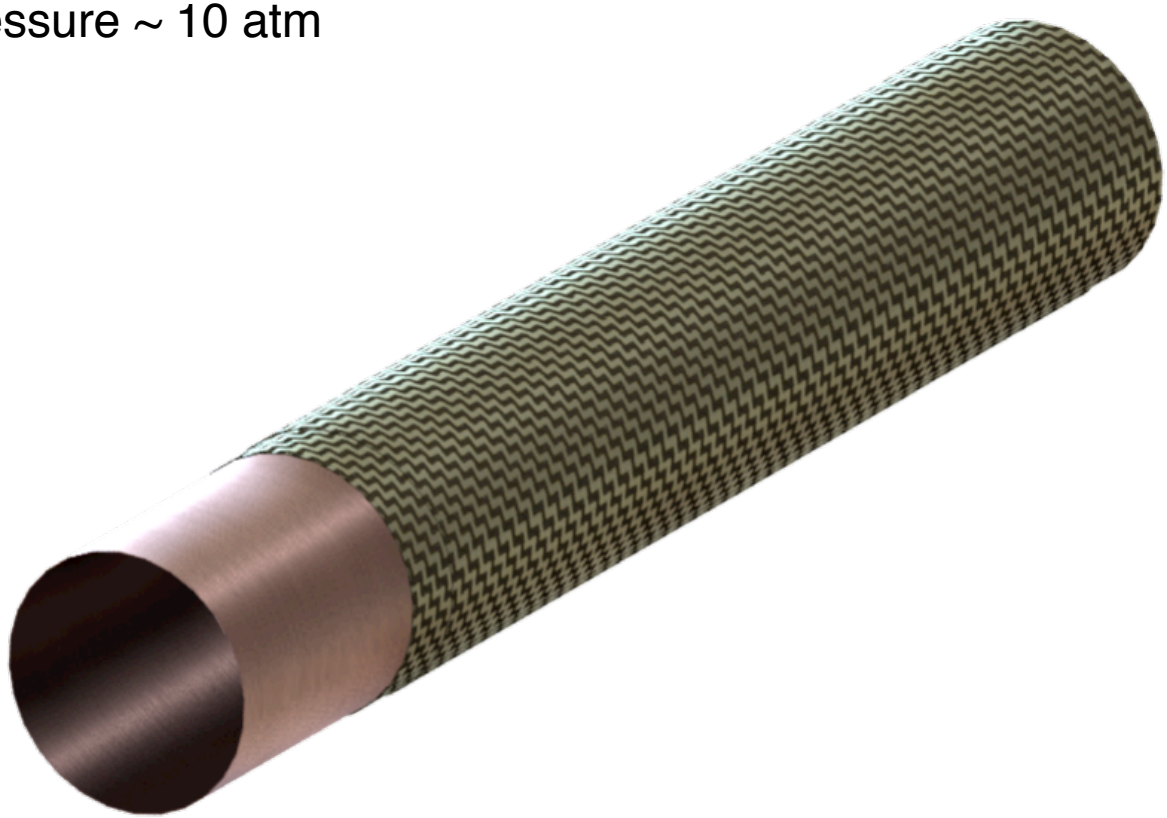


C. Paz-Soldan, R. Kendrick et al

Thin, rotating shell must withstand substantial stresses.

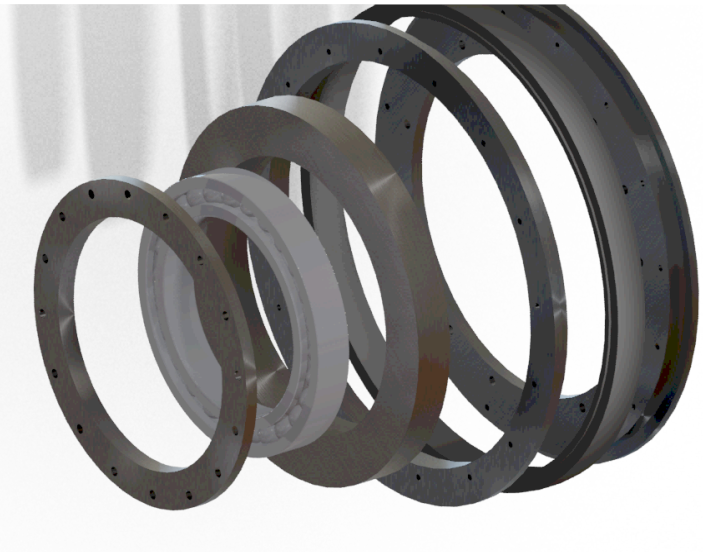
RWE

- Copper shell, 1 mm thick
- Reinforced using carbon fiber composite
- Must be very well balanced
- Expansive pressure ~ 10 atm



Ball bearing design appears feasible, though challenging.

RWE



Summary.

RWE

- The resistive and ferritic-resistive wall modes have been identified in a line-tied screw pinch.
- The resistive wall mode onset, growth rates, and mode structure are close to expectations.
- For the ferritic-resistive wall, mode onset is as expected, but the growth rate is much faster than predicted.
- The design for the rotating wall next-step experiment is underway.