The Role of a Conducting Shell on the Stability of the Line-Tied Kink in the Rotating Wall Machine

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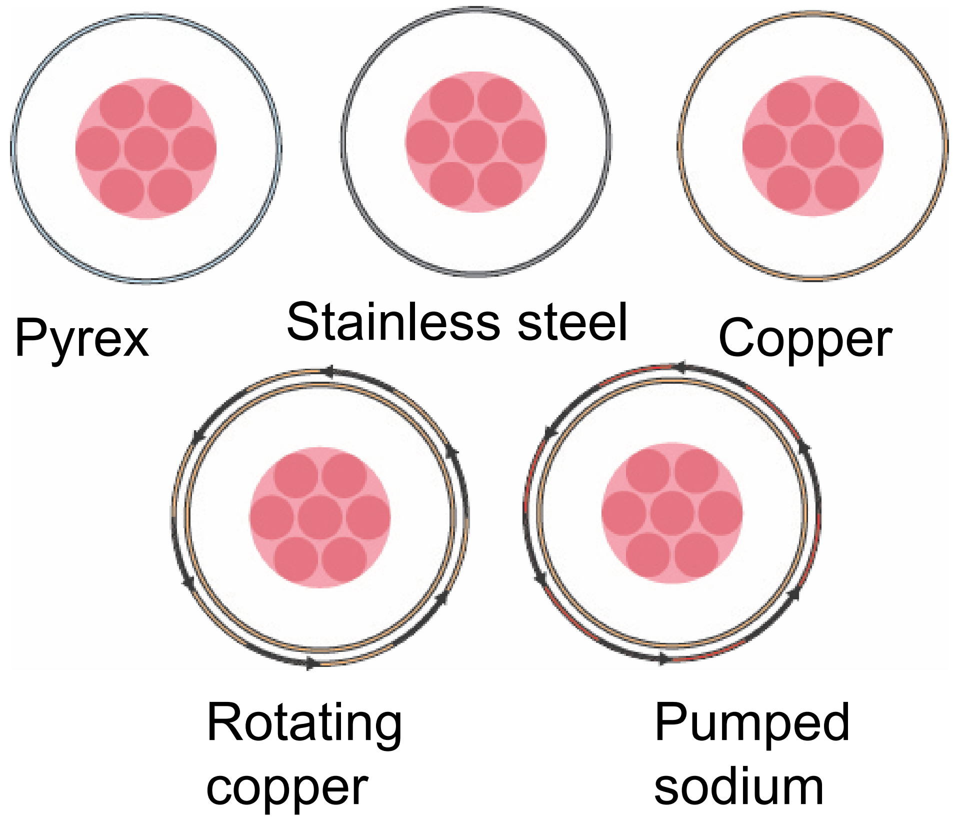
Outline

- Motivation
- Current driven kink in a line tied plasma with and without a conducting wall
- Initial results from NIMROD simulations
- Summary

Goals of the rotating wall machine

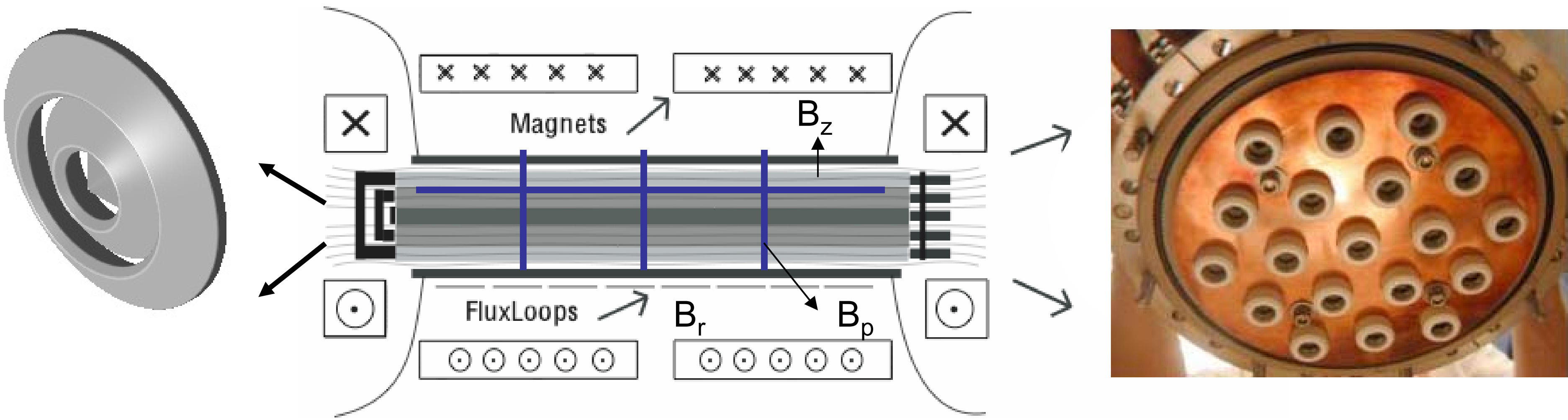
- Identify the RWM and test stabilization scheme with moving walls
- Contrast MHD in periodic and line-tied systems

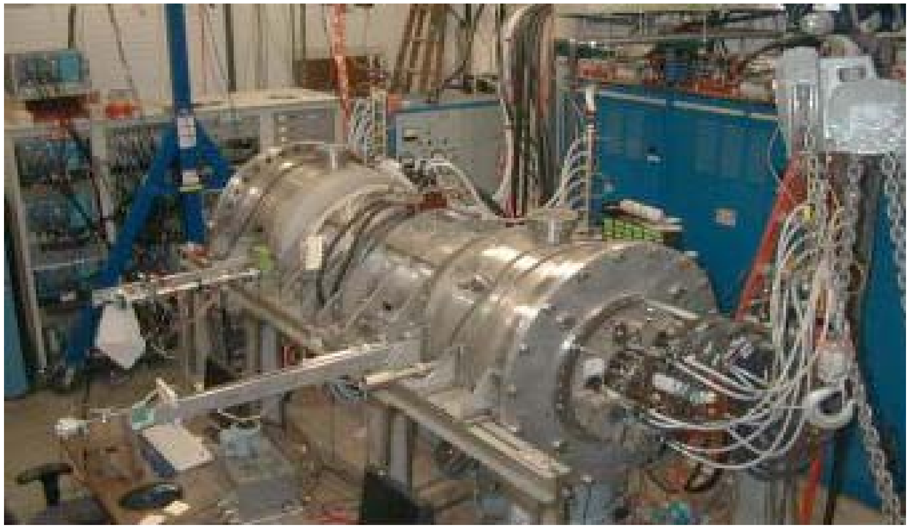


A second conducting wall, rotating with respect to first wall, can stabilize the RWM

[C.C. Gimblett, Plasma Phys. Cont. Fusion 31, p 2183 (1989).]

The rotating wall machine





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
$S \sim 60$
$\beta \sim 3\%$

MHD stability of the line-tied screw pinch

- Astrophysical community has studied ideal plasmas unstable to internal modes
  - Stability regime is very sensitive to current profile
- Fusion community has characterized the external kink
  - No-wall instability set by q_a = 1 (Kruskal Shafranov)

$$q_a \quad \frac{4 \;\; {}^2 a^2 B_z}{{}_o I_p L}$$

$$q_a \quad 1$$

  - Ideal wall instability limit depends upon proximity of shell

$$q_a \quad 1 \quad \frac{a}{b} \;\; {}^2 \quad 0$$

  - Resistive wall mode exists between no-wall and ideal wall limits

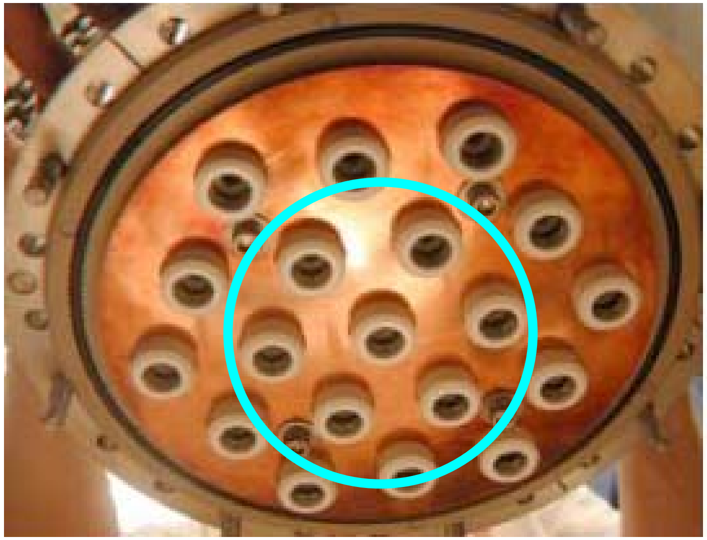
C.C. Hegna, Phys. Plasma 11, p4230 (2004)
D.D. Ryutov, et al. Plys. Plasma 11, p4740 (2004)

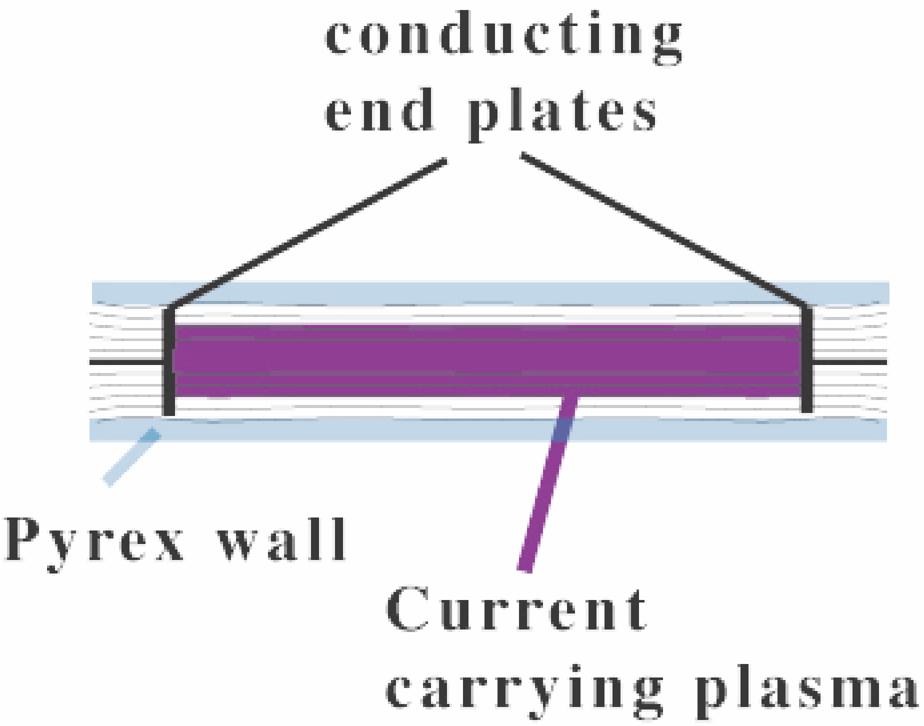
Overview of experimental results

- Explored MHD with insulating and resistive walls
- Mode initiates as an internal kink, not external kink
  - Mode onset at $q_0 = 1$, not $q_a = 1$
- B_r goes to zero with conducting shell, but mode still exists
- Two separate modes found in line-tied plasma
  - One is ideal and saturates into a rotating helical external kink
  - One is associated with current relaxation and implies magnetic reconnection

See Bergerson *et al.* (PRL ‘05) for full insulating wall results

Experimental setup





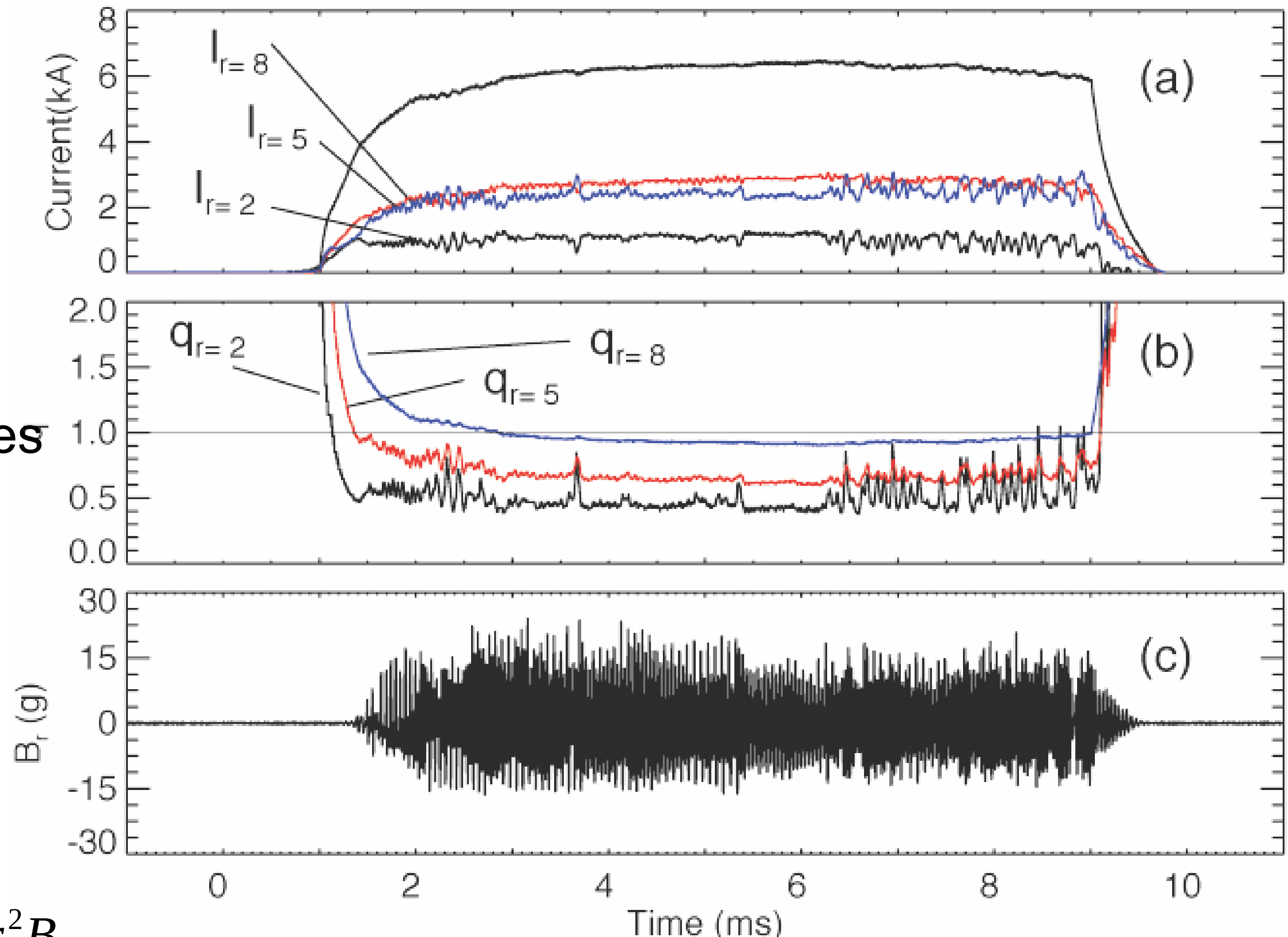
Wall is Pyrex

Central 7 guns are
pulsed and biased └ ┬

MHD activity observed when q drops below 1

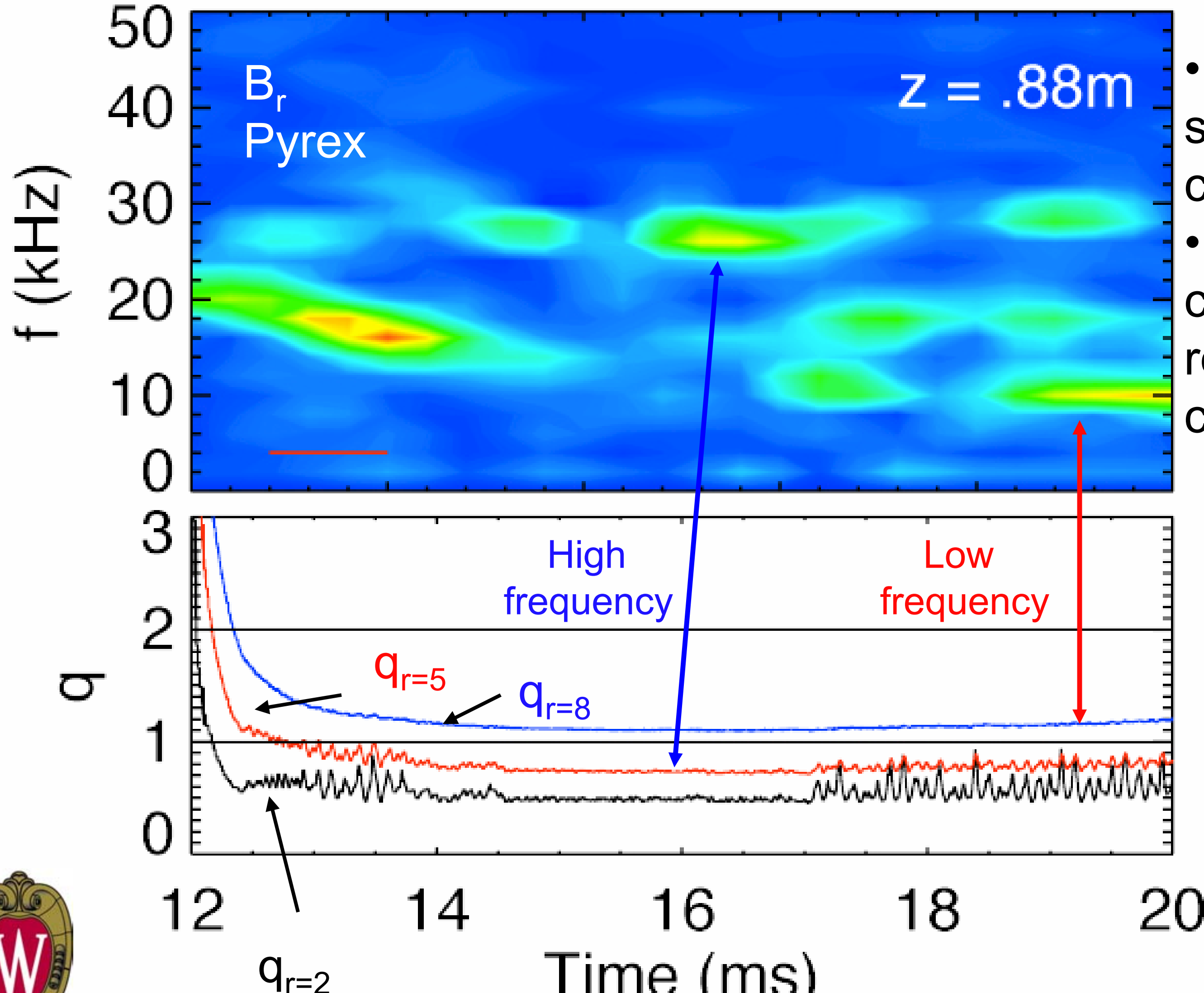
Safety factor q lowers as current increases

MHD activity present when q < 1



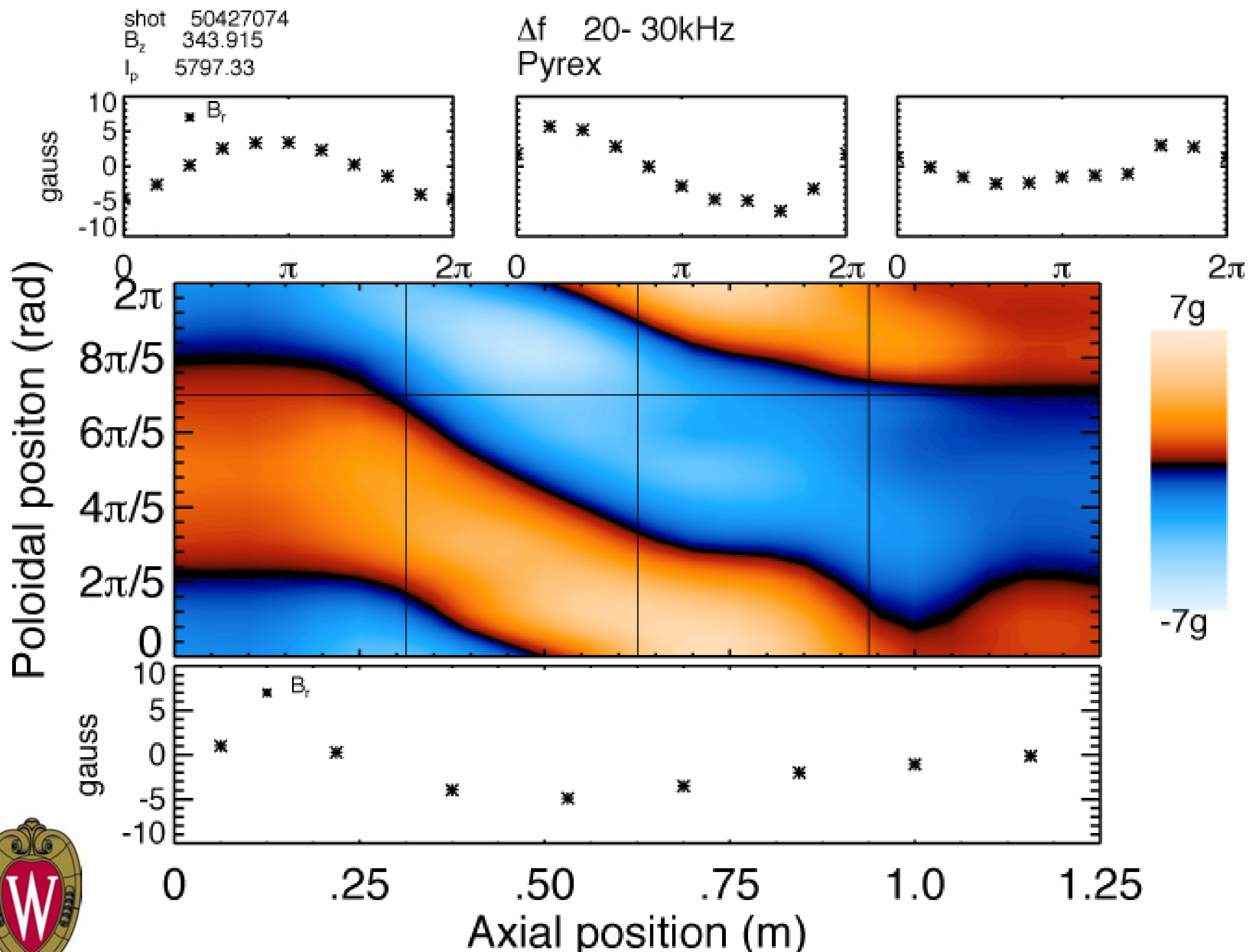
$$q_r \quad \frac{4\ \ ^2r^2B_z}{_oI_pL}$$

Two modes co-exist in plasma



- High frequency mode strongest at quiescent current profile
- Low frequency mode correlated with relaxation oscillation in current

High frequency mode is a rotating helical equilibrium with ideal characteristics



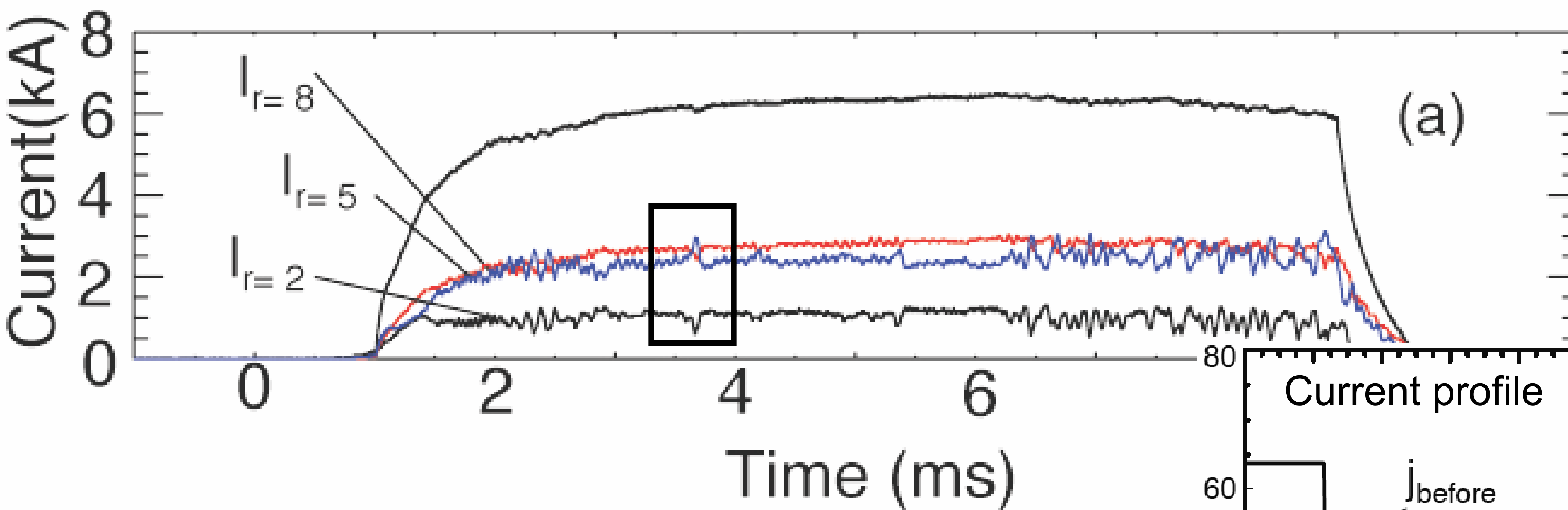
- Expect clear m =1, n =1 eigenmode in ideal plasma

Movie

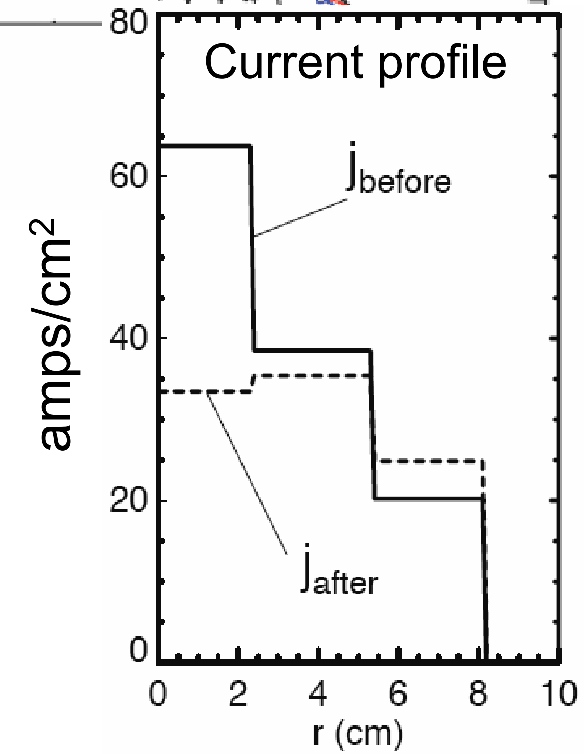
•Br(¶ ¶ ¶ t he ta) is a rotating m =1 mode

•Br(z) has clear n=1 character

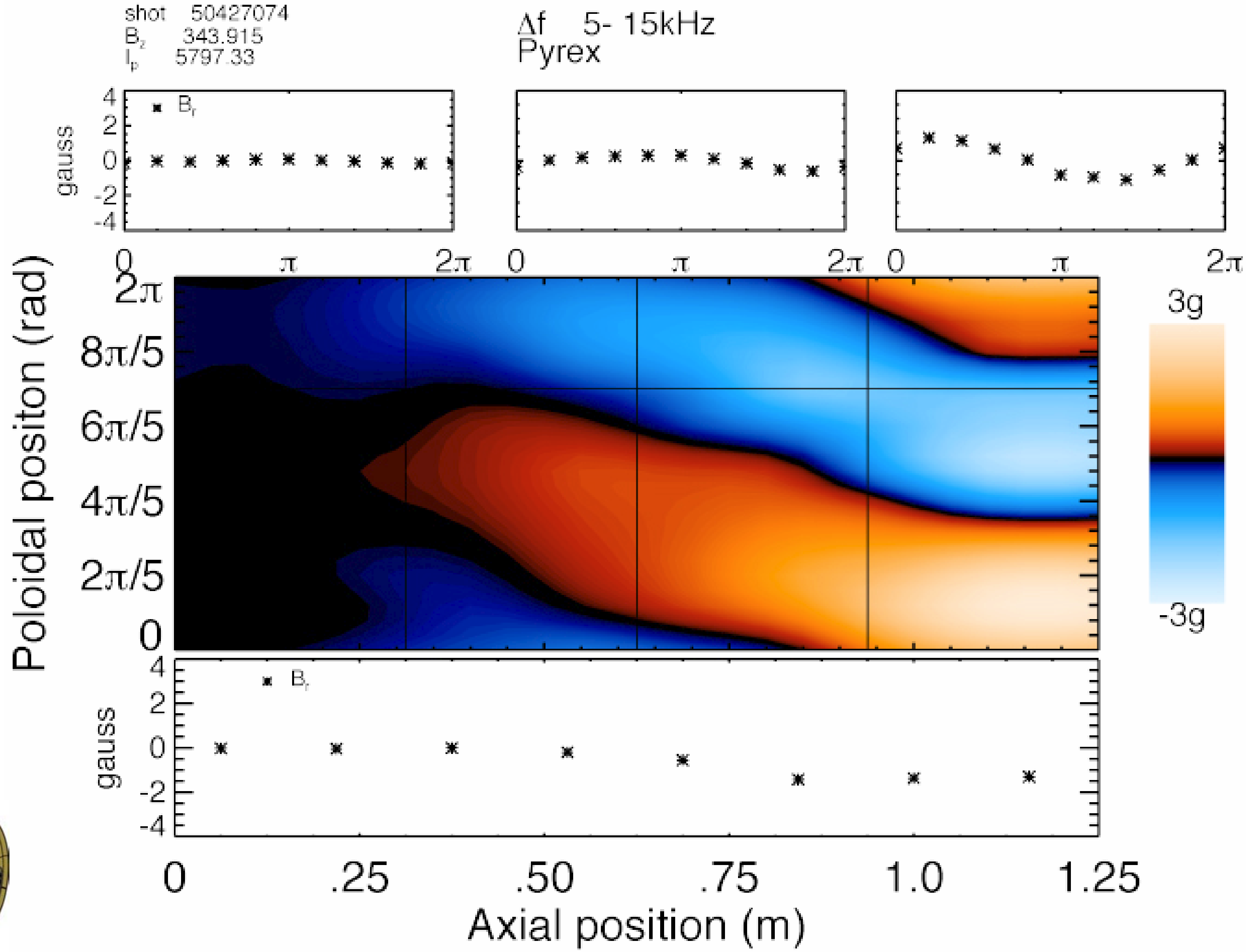
Current redistribution events imply magnetic reconnection.



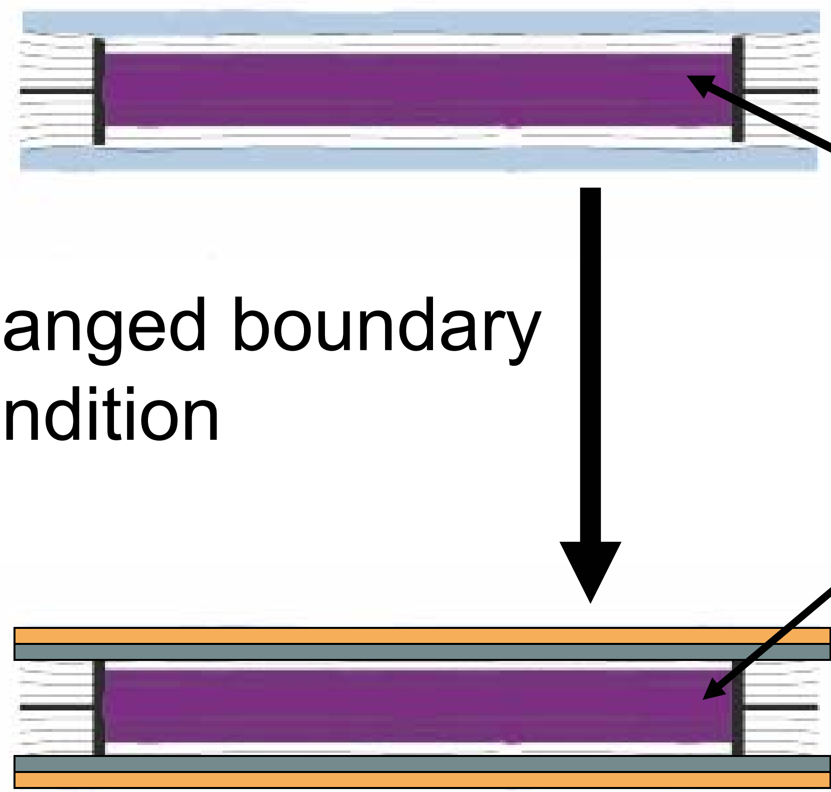
- Current is fixed at the guns because the nozzles are held in place
- Current profile broadens between the cathode and anode



Low frequency mode suggests current channel has shifted



Wall time increased by replacing pyrex with a copper + stainless steel wall



pyrex wall

Changed boundary Condition

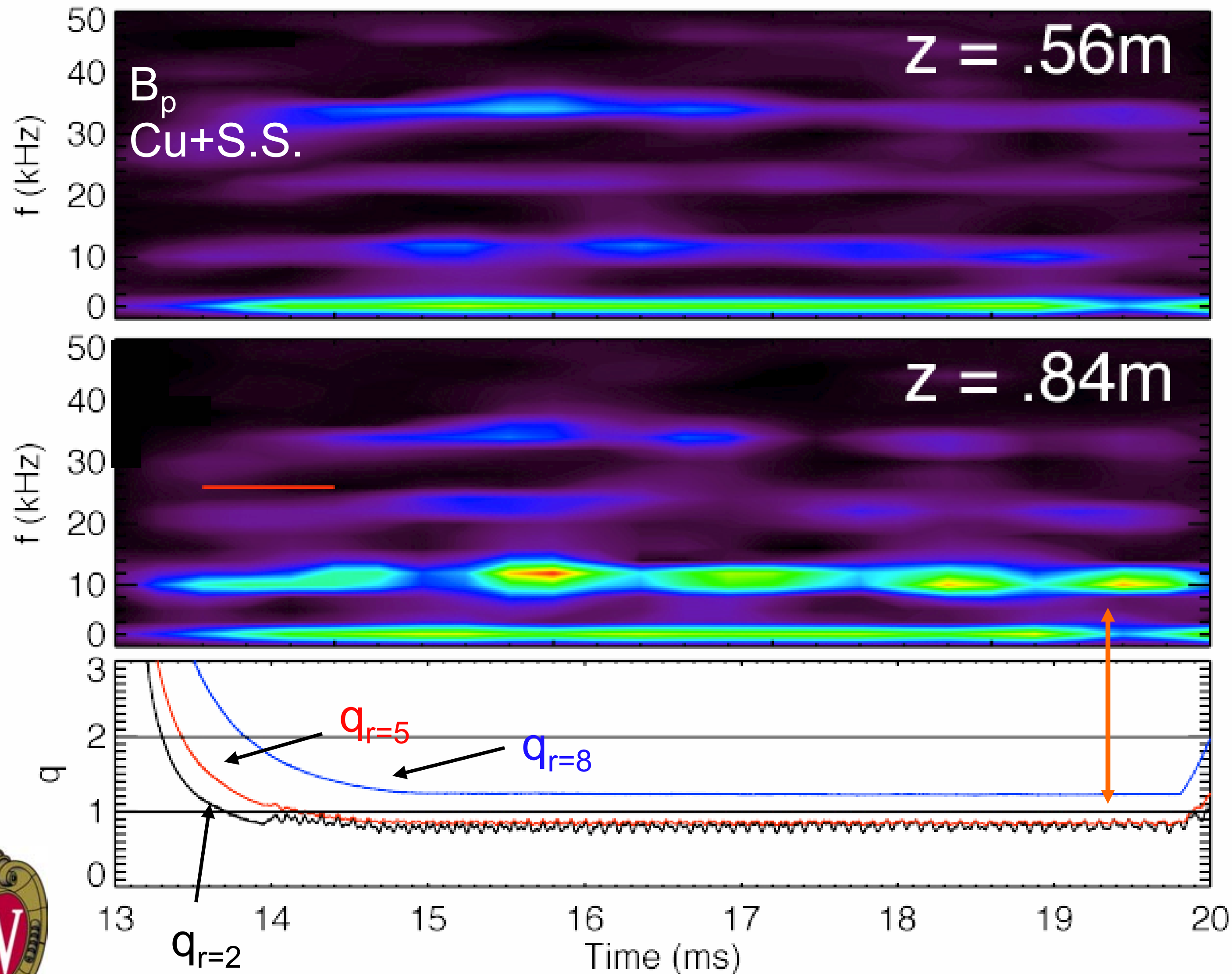
Current carrying plasma

S.S. + Cu wall Boundary condition has longer wall time

$$w \qquad {}_{o} r_{w} \quad w \quad w$$

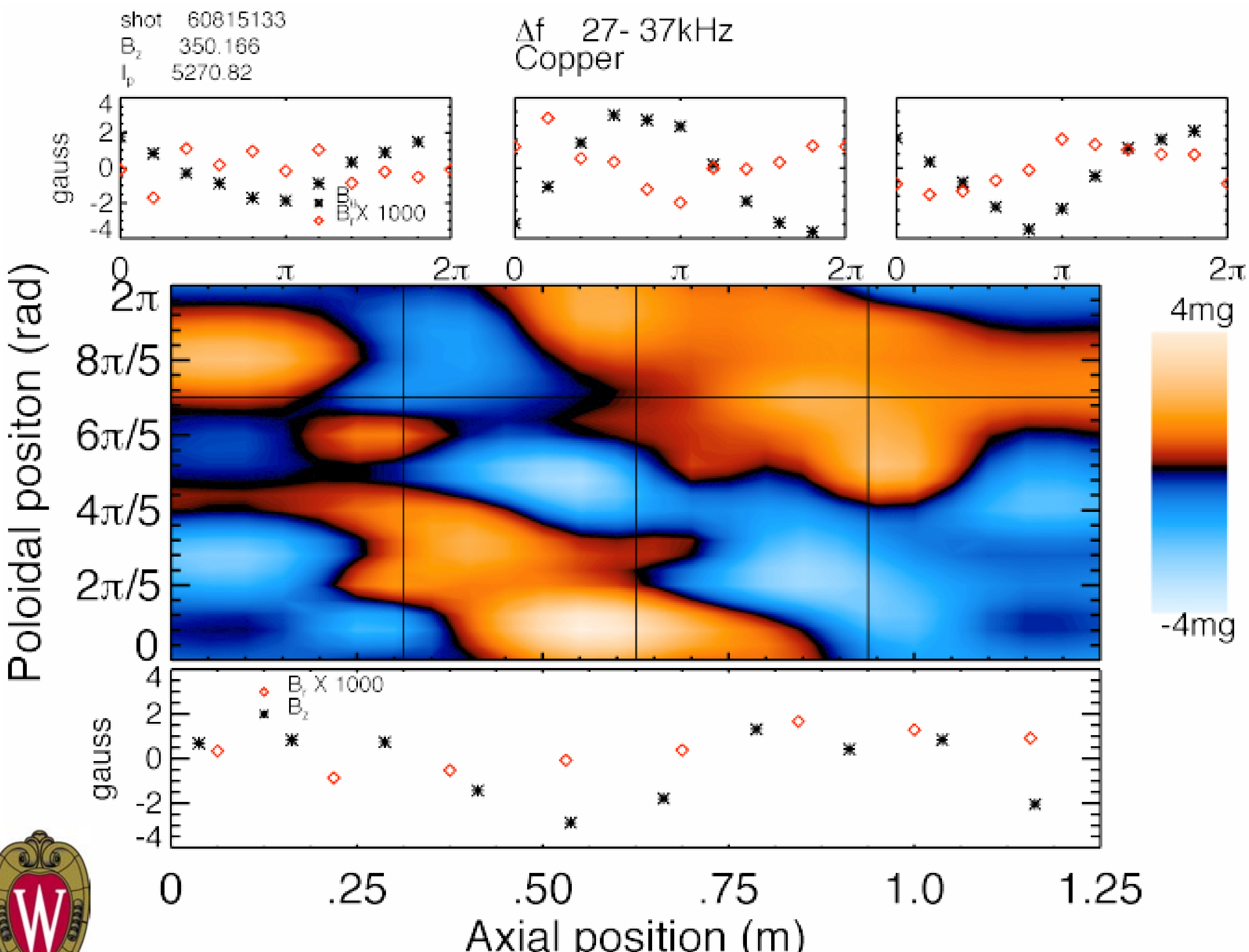
$$w \qquad 7\, ms$$

Low and high frequency modes still exist with conducting shell



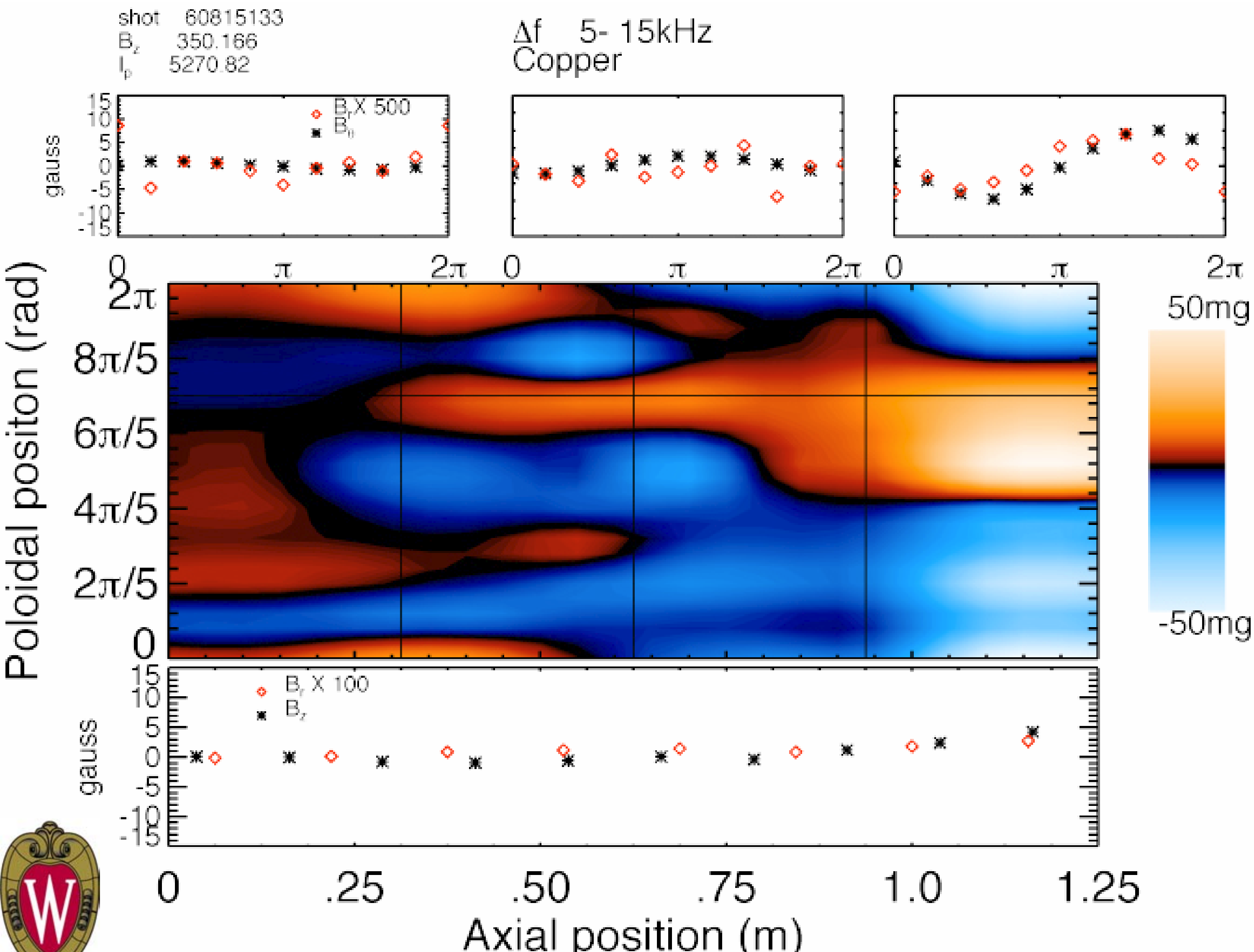
•Same mode dynamics seen

Longer wall time alters eigenmode



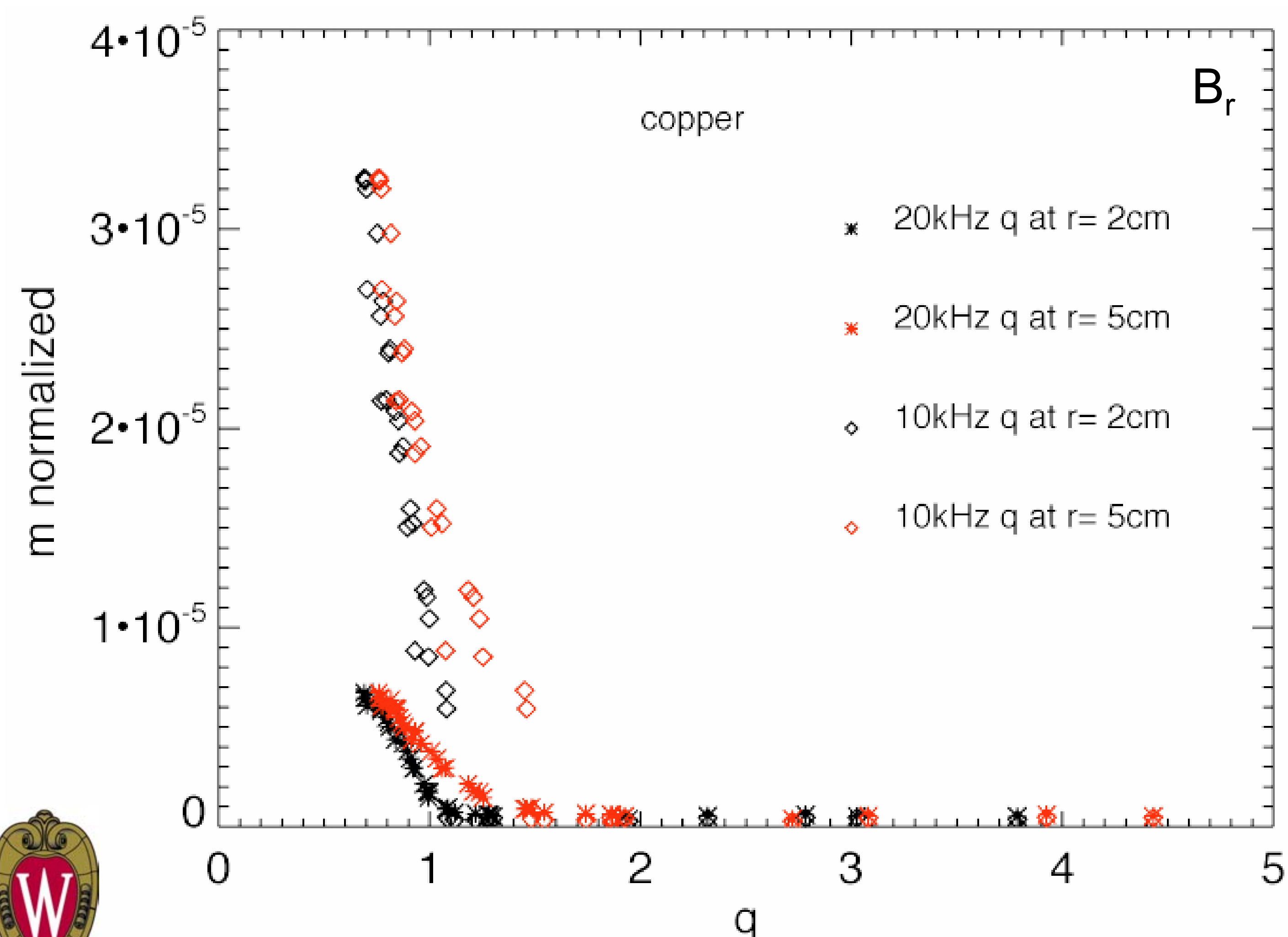
- High frequency mode satisfies ideal wall boundary condition
- B_r is 1000X smaller
- Magnitude of B_p is unchanged

Low frequency mode dominates plasma



- Low frequency mode is ~10X larger than high frequency mode

Modes onset around q_0 1



- Indicative of internal kink mode
- Onset character excludes external kink

Summary of MHD modes thus far

- Modes have same onset condition regardless of boundary condition at wall
  - B_r is ~0 with longer wall time
  - B_p unchanged with different wall times
- Modes grow faster than wall time
- High frequency mode has ideal (m = 1, n = 1) characteristics
  - Rotating helical equilibrium consistent with line-tied behavior
- Low frequency mode associated with relaxation events in current profile

The NIMROD code is used for our numerical computations of basic resistive MHD and MHD+collisional transport.

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B} - \eta \mathbf{J})$$ Faraday's/Ohm's laws

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$ low-ω Ampere's law

$$\rho\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V}\cdot\nabla\mathbf{V}\right) = \mathbf{J}\times\mathbf{B} - \nabla p + \nabla\cdot\nu\rho\nabla\mathbf{V}$$ flow evolution

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$$\frac{\partial n}{\partial t} + \nabla\cdot(n\mathbf{V}) = \nabla\cdot D\nabla n$$ particle continuity

$$\frac{n}{\gamma-1}\left(\frac{\partial T}{\partial t} + \mathbf{V}\cdot\nabla T\right) = -\frac{p}{2}\nabla\cdot\mathbf{V} + \nabla\cdot n\left[\chi_{\|}\hat{\mathbf{b}}\hat{\mathbf{b}} + \chi_{\perp}\left(\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}}\right)\right]\cdot\nabla T + \frac{\eta \mathbf{J}^2}{2}$$ (single) temperature evolution

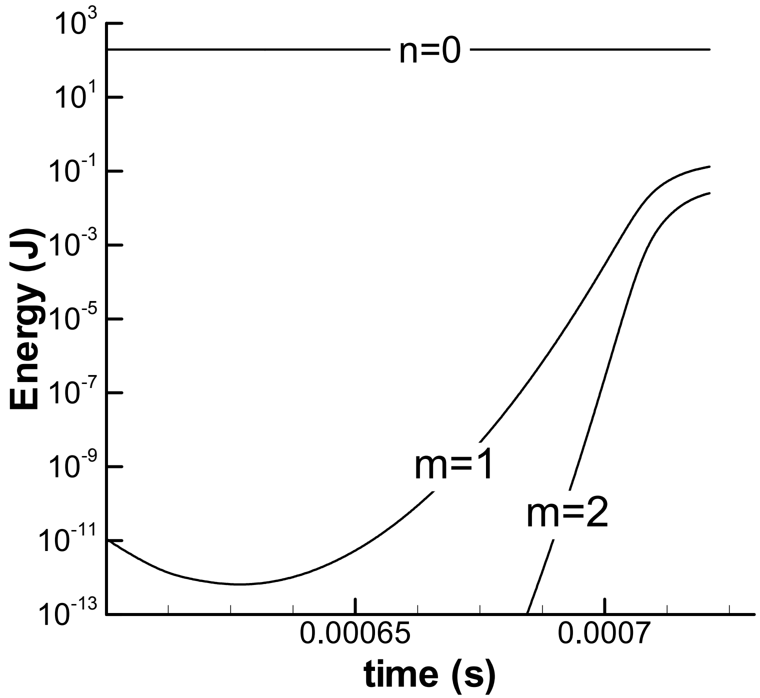
$$\hat{\mathbf{b}} \equiv \mathbf{B}/|\mathbf{B}|$$ local magnetic direction vector

- Braginskii transport coefficients are used for $\chi_{\|}$ (electron), $\chi_{\perp}$ (ion), and η.
- The NIMROD code [http://nimrodteam.org] evolves the system in 3D.
  - High-order finite elements help resolve anisotropies [JCP **195**, 355 (2004)].

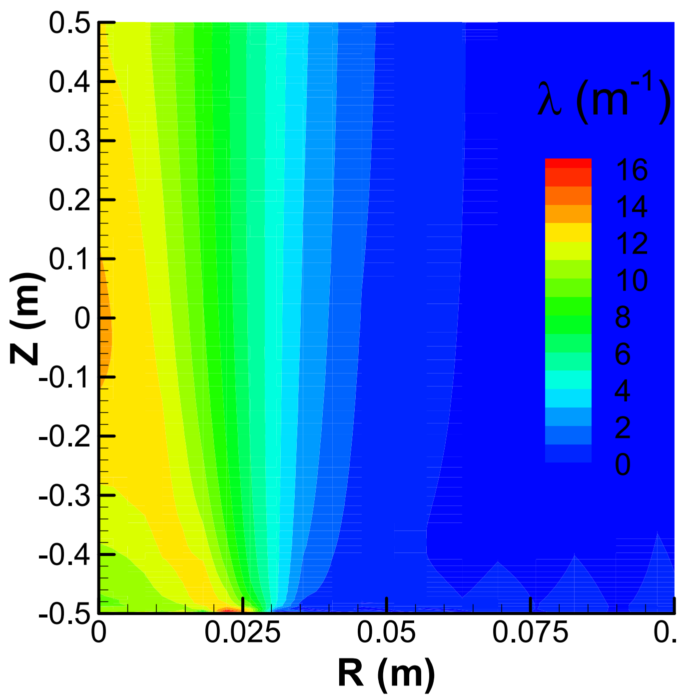
Rotating wall machine parameters used in the NIMROD code

- Recent NIMROD MHD simulations of RWM use realistic parameters:
  - $n_{column} \sim 1\times10^{19}$ m^{-3}, T~5-10 eV
  - B_{axial}=0.05 T, I_{axial}=5 kA (at end of ramp)
- Based on spheromak results, temperature-dependent resistivity is expected to be important, so the combined MHD/collisional energy transport modeling is used.
  - η/μ_0=411 $T^{-3/2}$ m^2/s (T in eV), $\chi_{\|}$=387 $T^{5/2}$ m^2/s
- An artificial D=100 m^2/s and kinematic viscosity of 100 m^2/s are used in the computation reported here.

The simulation shows the growth of the *m*=1 mode to be faster than exponential after it becomes unstable (while pinching continues).



Magnetic fluctuation energy evolution.

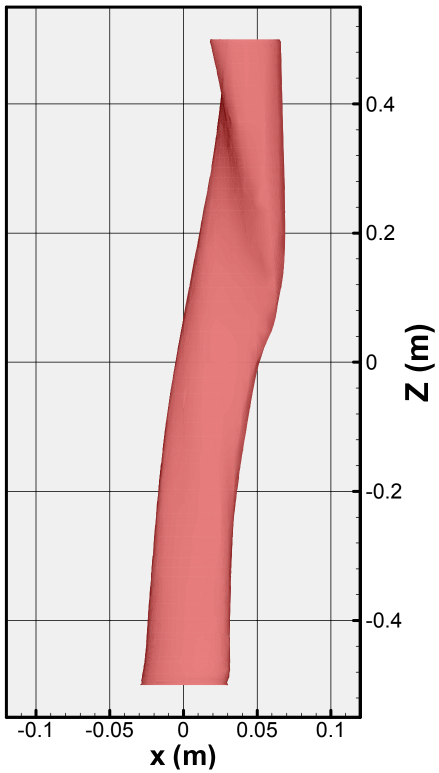


Parallel current profile at 0.63 ms.

- The plasma-gun array is modeled as a symmetric heat and particle source at the bottom of the chamber, on axis.
- The simulation shows instability at 0.63 ms, I_z=1.3 kA.
- The current channel has $q = 2\pi r B_z / L B_\phi \cong 1.4$ at this point.

The fluctuation amplitude is small at initial saturation, but there is appreciable deflection of the current channel with the large aspect ratio.

- There is also a corresponding deflection of the temperature profile (not shown)
- This suggests that magnetic reconnection has occurred, since the location of the temperature source has not changed
- Ideal instability would not be displaced at anode
- Astrophysical community has done these types of simulation and seen similar effects

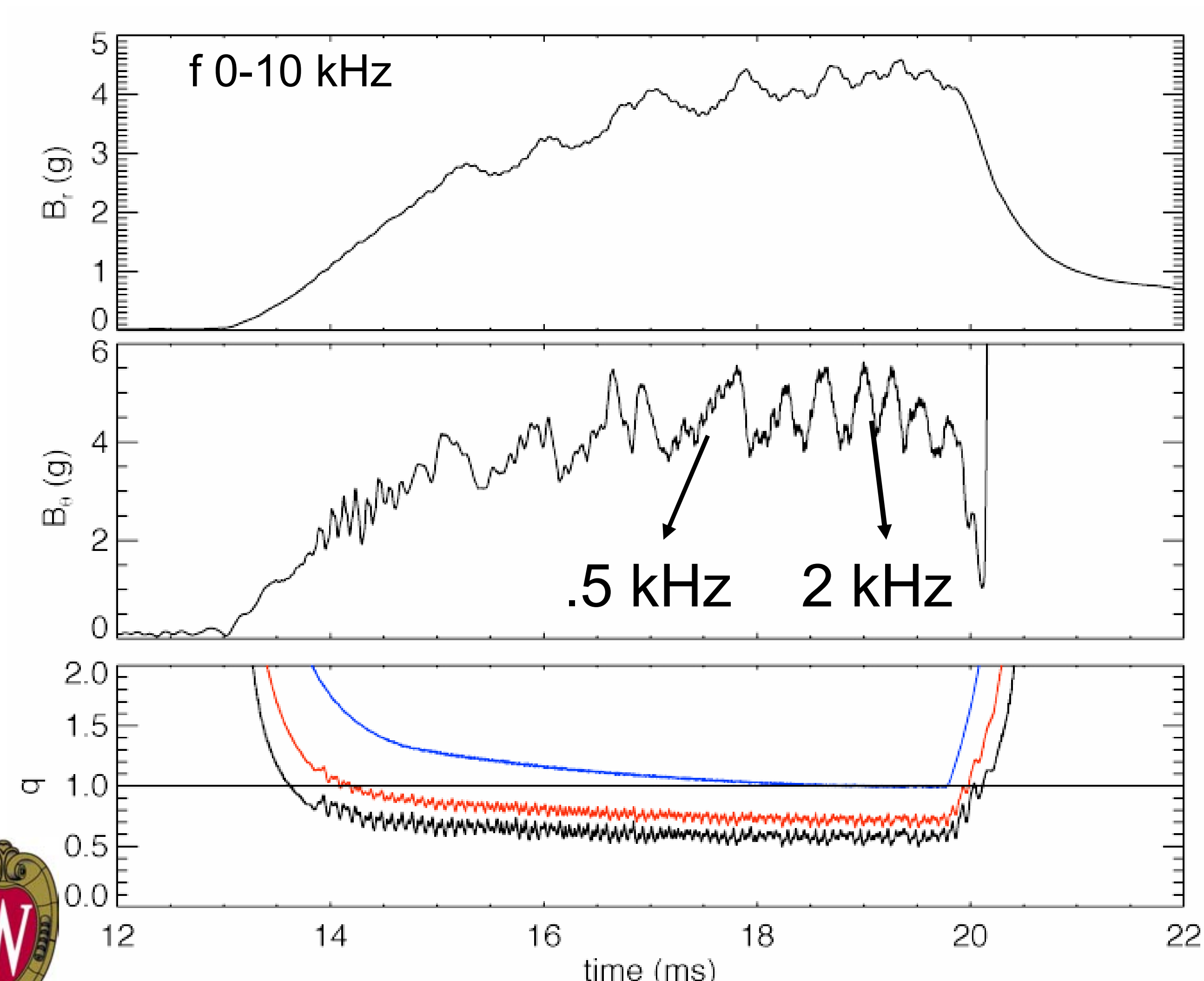


The λ=10 m^{-1} isosurface shows a deflection of approximately 3 cm over the 1 m path.

See Lionello et al, Astrophys. J.'98

Candidate for external RWM

stainless steel wall $_{wall}$ $0.5ms$



- •Events appear when q_a < 1
- •Linear growth rate close to wall time
- •Events are seen in B_r and B_p

Summary

- The plasmas are dominated by an ideal saturated line-tied kink and a lower frequency mode indicative of reconnection in the plasma
  - Both modes are internal, not external
- Modeling has identified a non-symmetric mode attributed to reconnection and analogous to the low frequency mode found in the experimental plasma
- Events consistent with the external RWM have been identified in stainless steel. Additional analysis with s.s. and copper shells is required to determine if these are in fact the external RWM

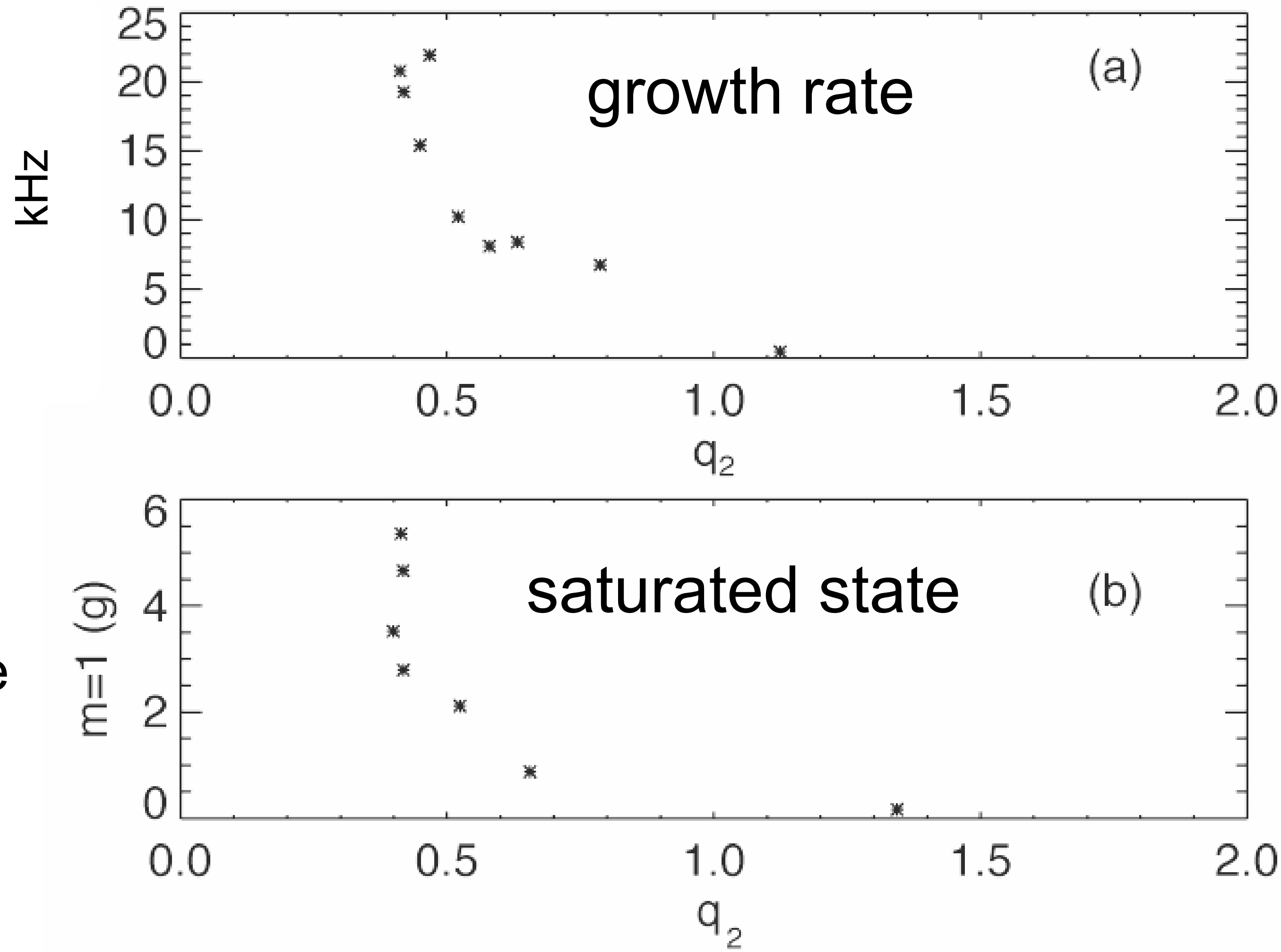
Future

- Continue search for external resistive wall mode
  - Control rotation in the plasma
  - Try different current profiles
  - Increase size of plasma column
- Look to understand role of field errors in plasma
- Change mirror ratio in magnets to increase confinement and conduction
- Continue NIMROD studies to clarify internal resistive dynamics

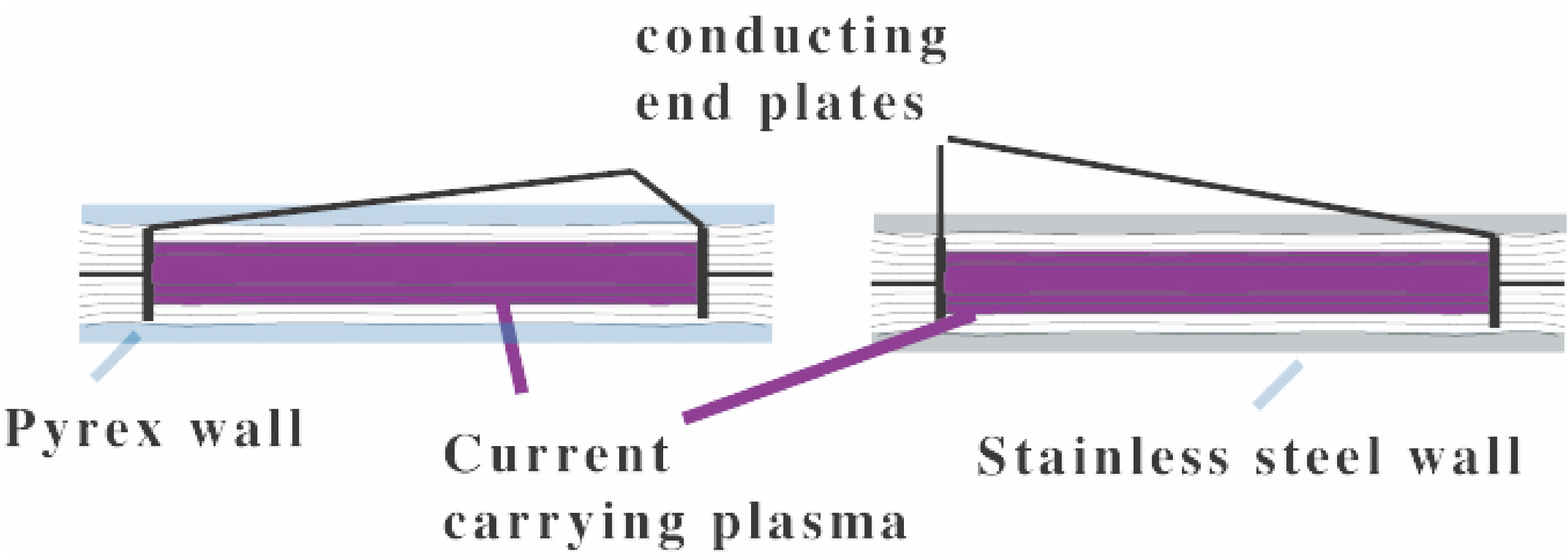
Growth rate increases as q decreases

Plasma current is adjusted to create q scan

Both growth and saturated mode amplitude increase below $q_{r=2} < 1$



Impose conducting wall boundary condition on plasma



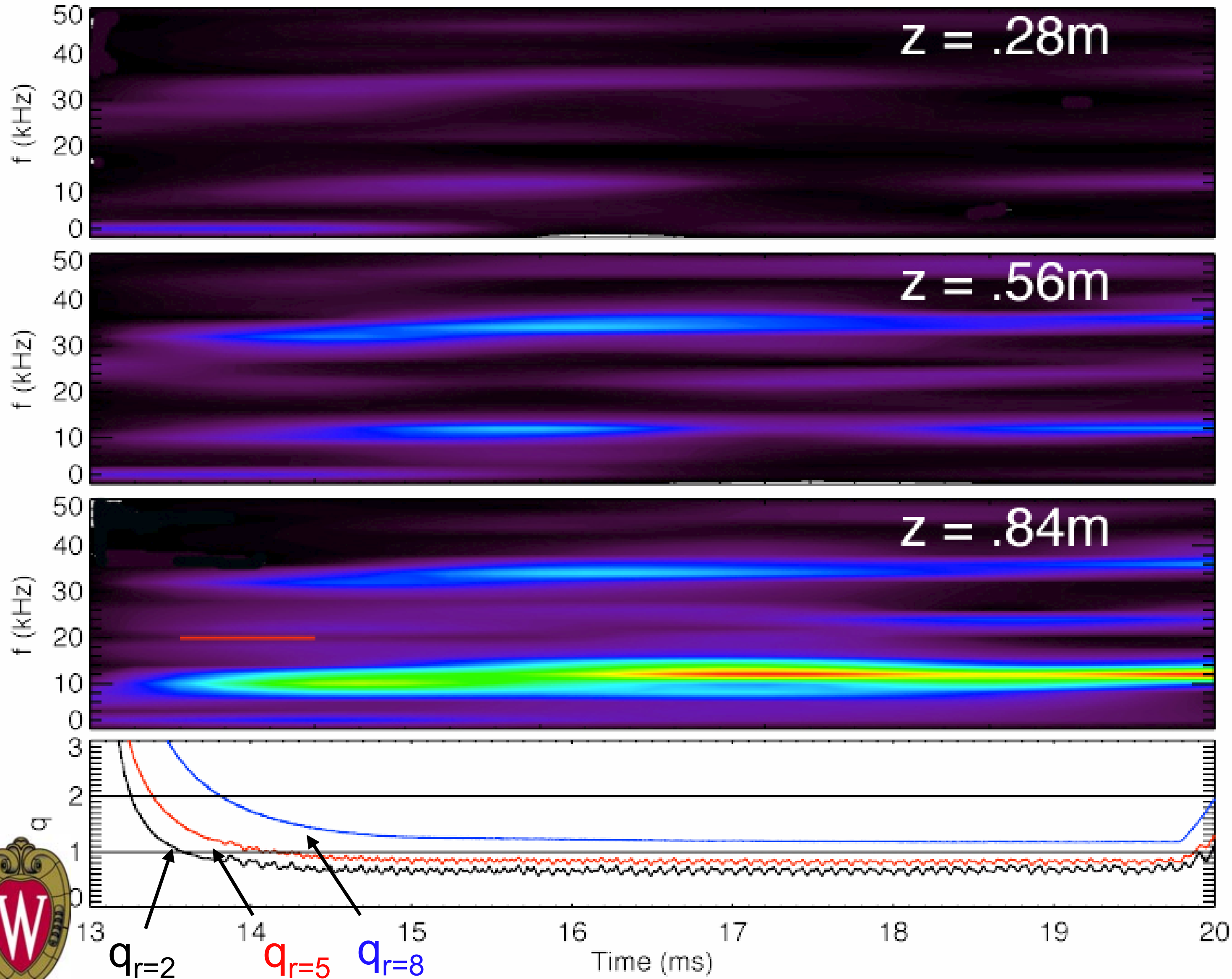
Boundary condition tests no-wall limit

Boundary condition tests resistive wall mode

$$_w \qquad {}_o r_w \;\; {}_w \quad {}_w$$

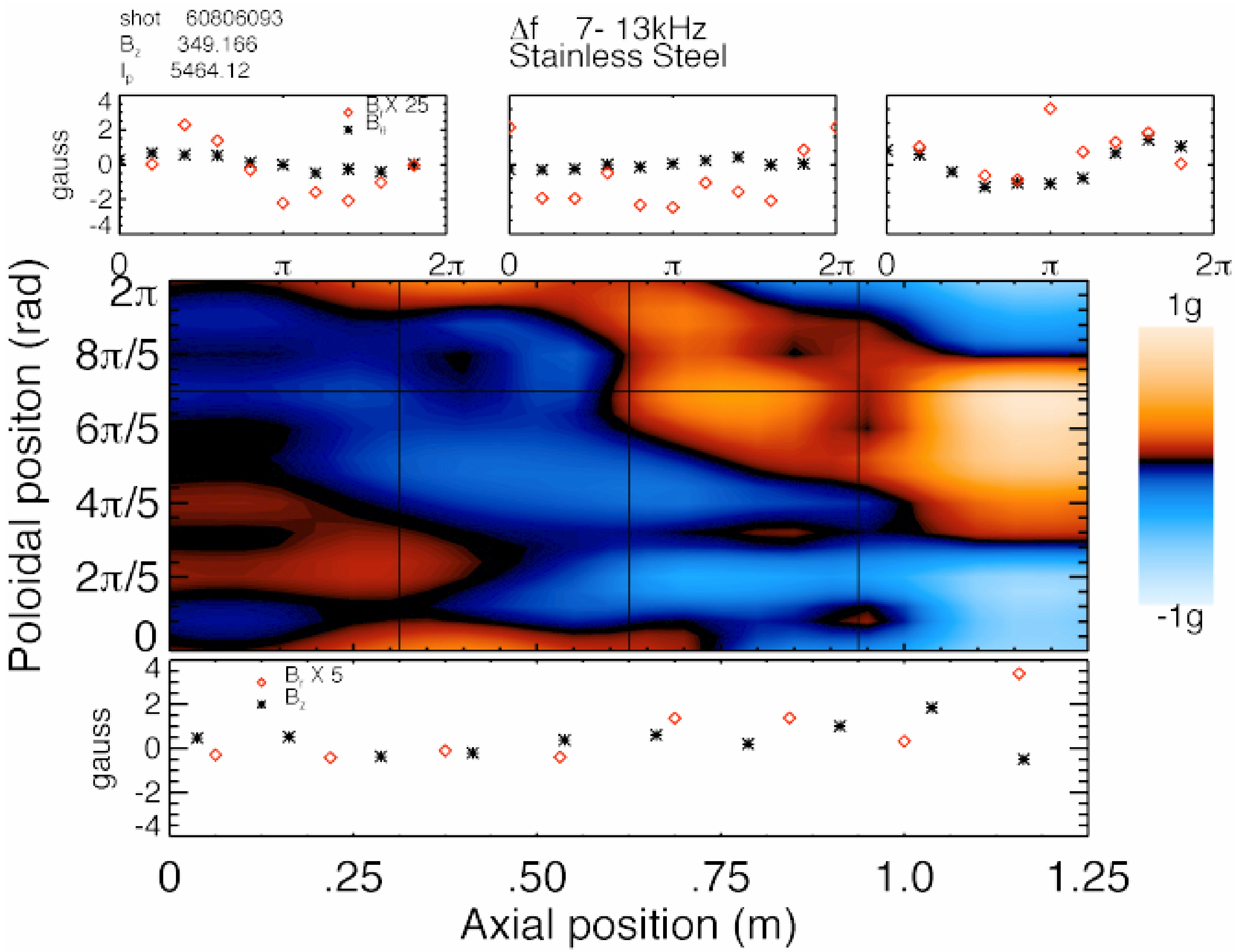
$$_w \qquad 0.5ms$$

Different boundary condition for B_r does not stabilize modes

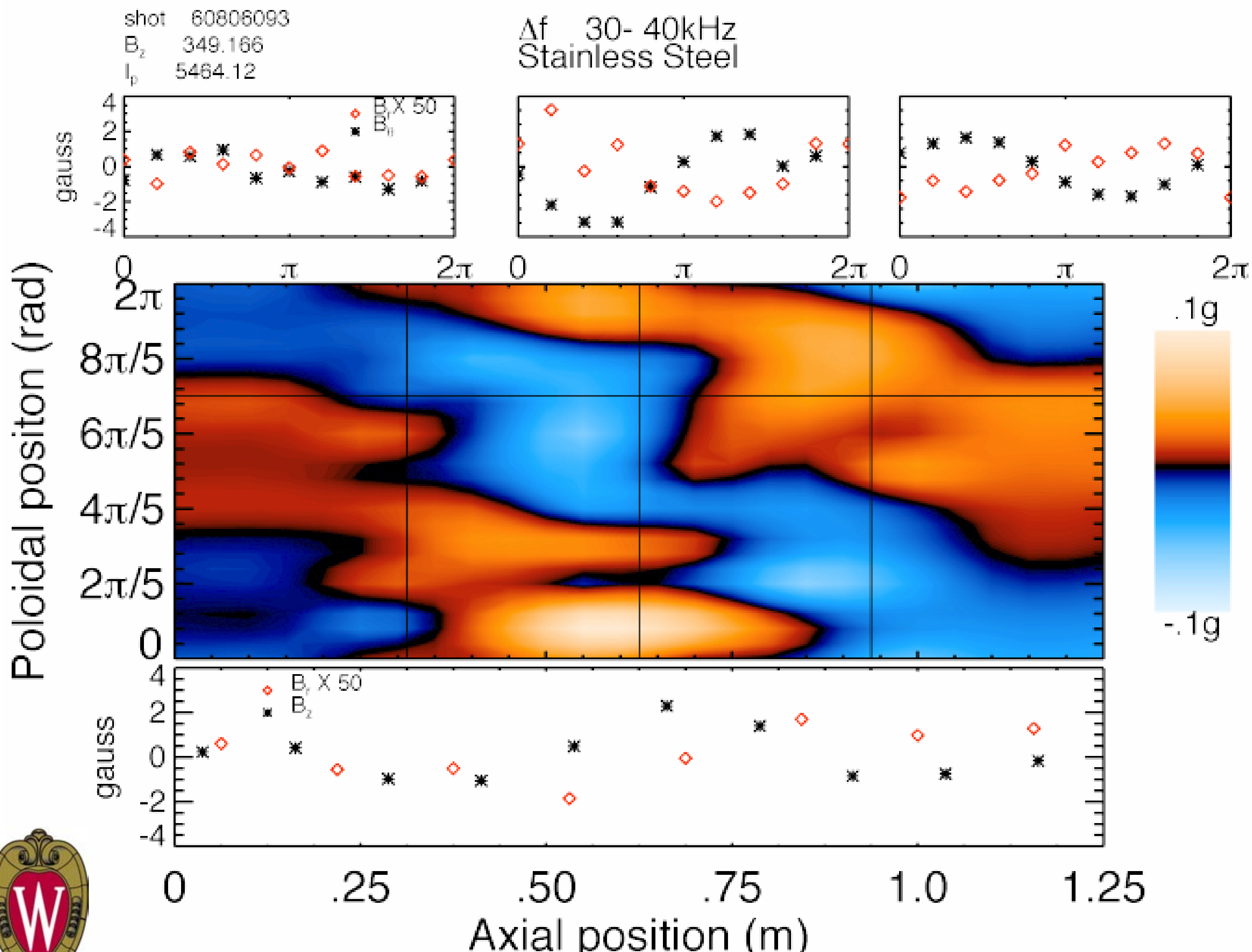


- Sawteeth dominate current profile
- Non-ideal mode associated with sawteeth
- Ideal mode peaked in middle
- B_p used for plot

Asymmetry of resistive mode maintained with s.s. wall

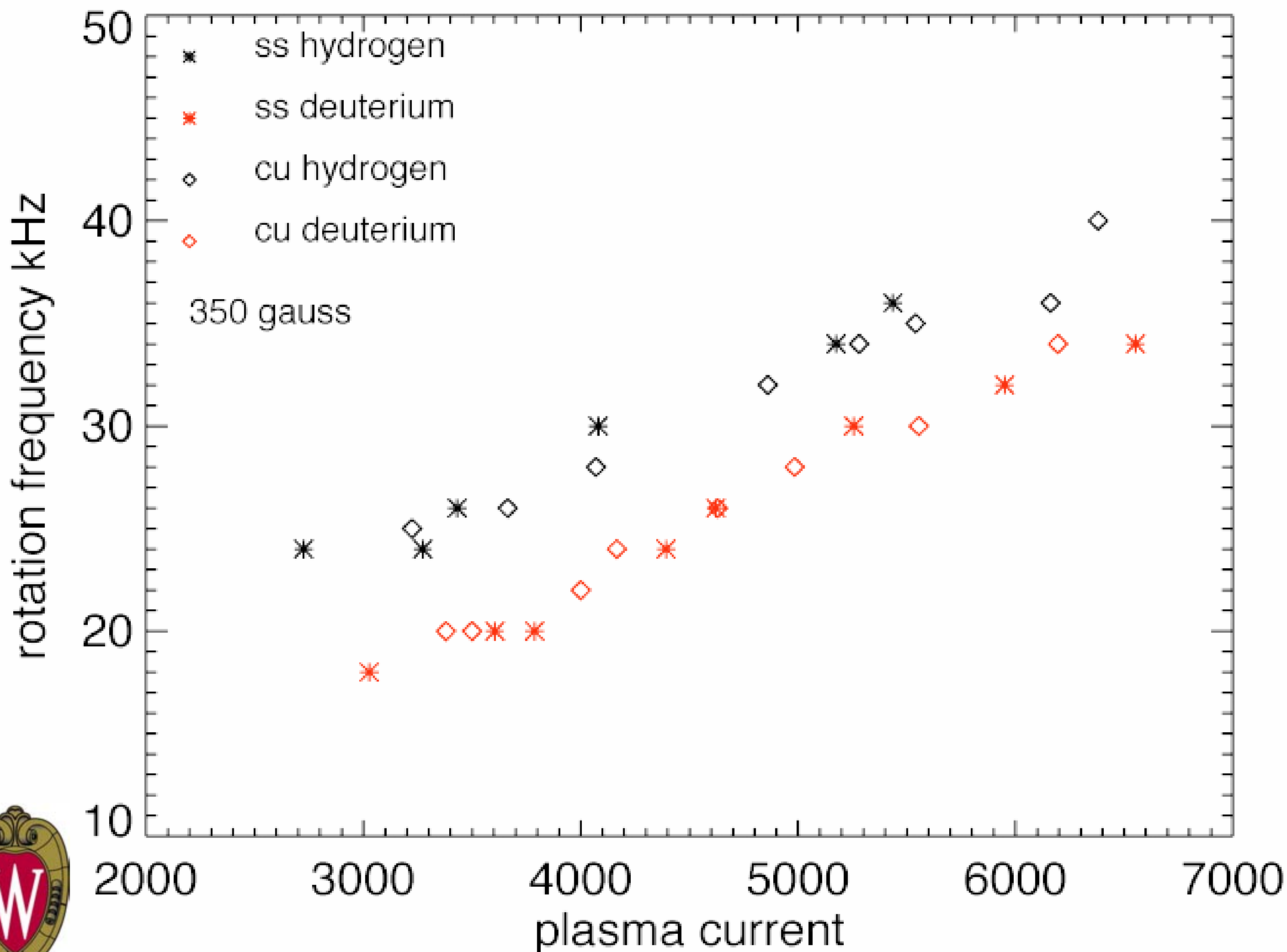


Ideal mode has smaller amplitude, but same eigenmode



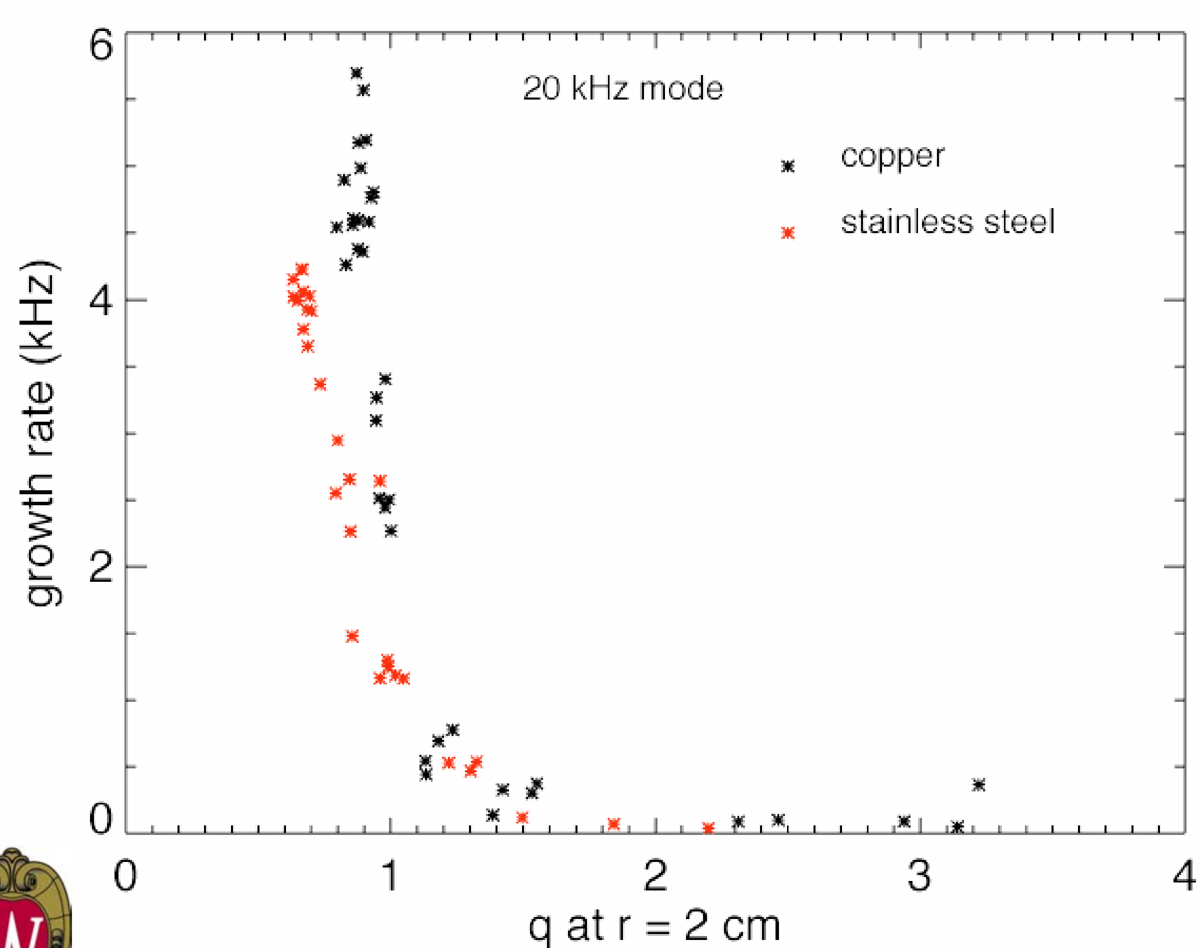
•B_r and B_p are 180^0 out of phase

Mode rotates faster with higher plasma current



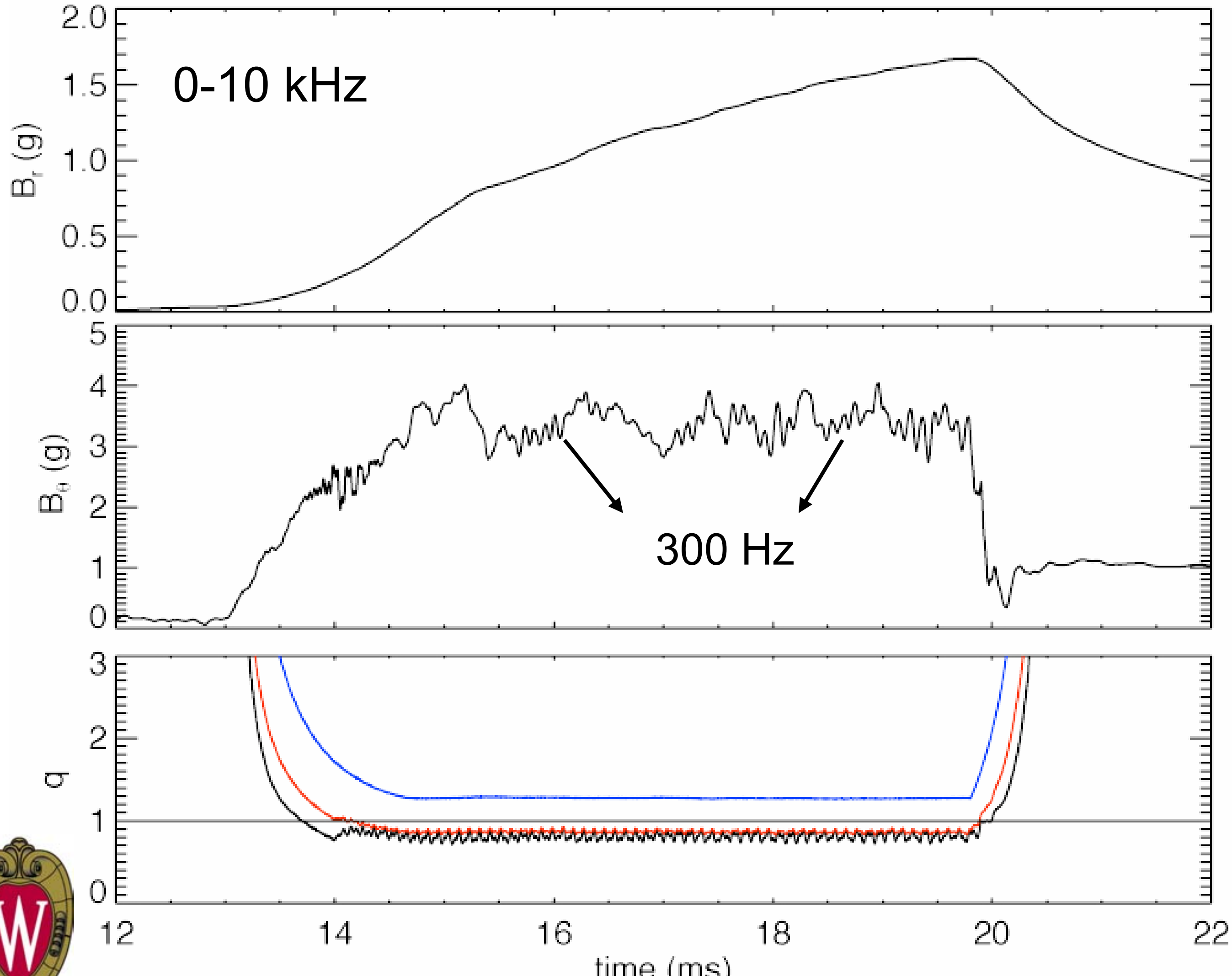
- Rotation independent of wall time
- Rotation slowed with deuterium
- Current is proportional to plasma bias

Growth rate of ideal mode unrelated to wall time



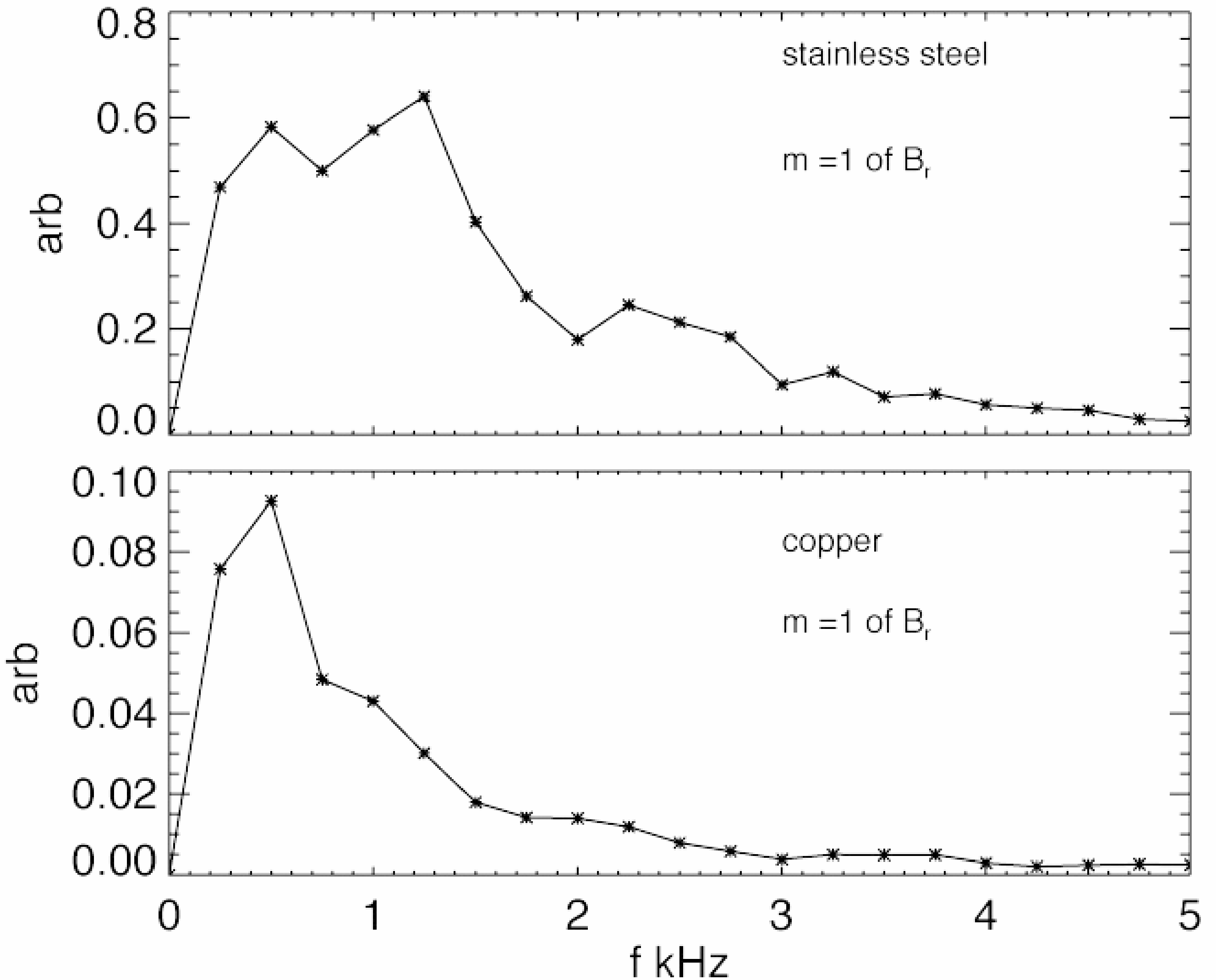
•Growth rate dependent on plasma current rise time

Candidate for RWM with Cu wall

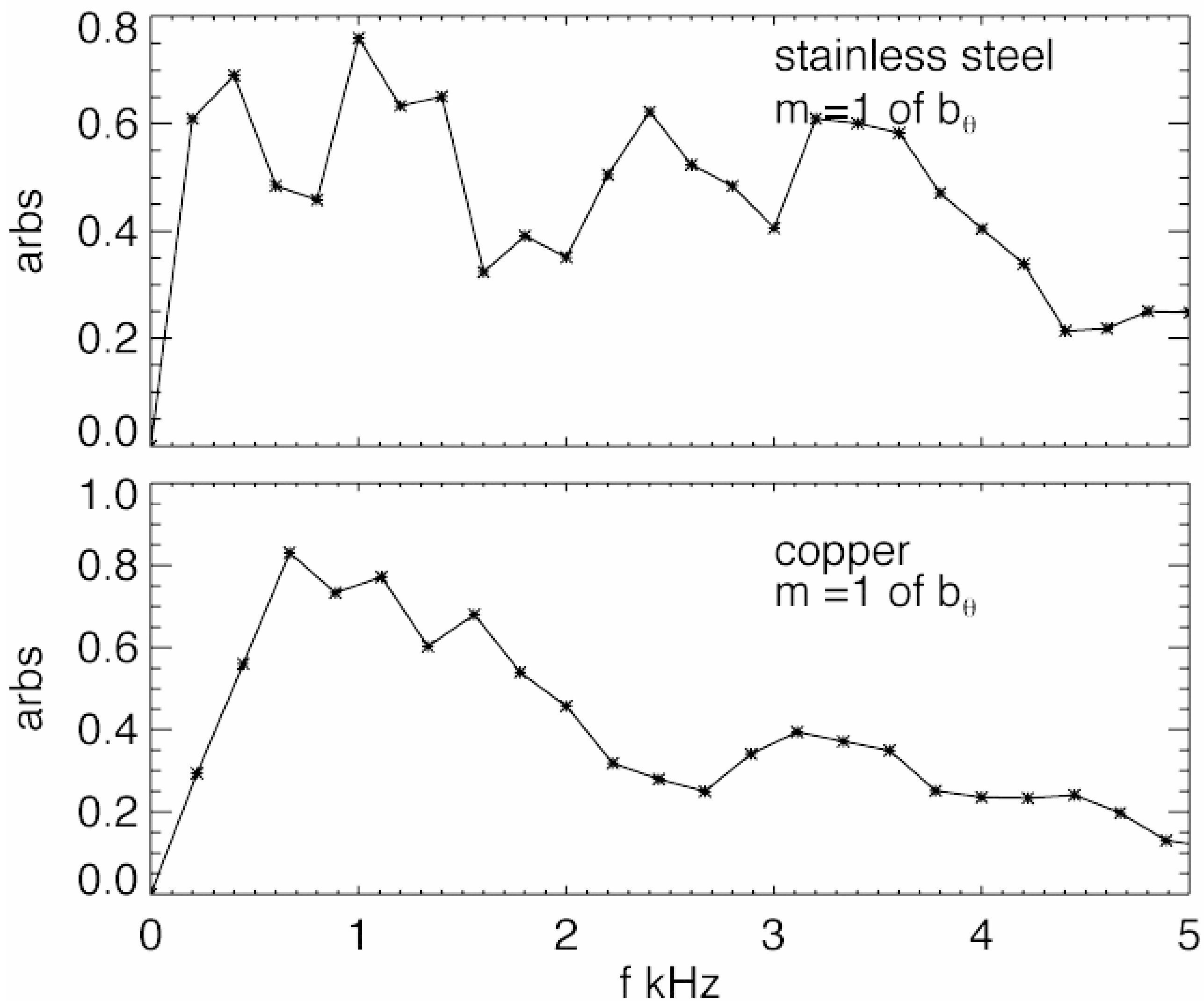


- Dynamics similar to S.S. case
- Events appear when edge q is below 1
- Linear growth rate close to wall time
- Events are seen in B_r and B_p

Frequency power spectrum of m1 in Br supports events on wall time



Frequency power spectrum of m1 in B_p supports events on wall time



Elucidation of low frequency mode

•Modeling by Lionello predicts b_r to be approximately zero at endplates without reconnection.

-this is seen experimentally in the high frequency mode

•Without reconnection field lines have some mapping between endplates. With reconnection, field lines now map to a different position

-plasma current is displaced outward
the coexistent axial modes originate similarly,
but terminate differently as seen in the eigenmodes

See Lionello et al, Astrophys. J. ’98