Identifying the Resistive Wall Mode in the Rotating Wall Machine

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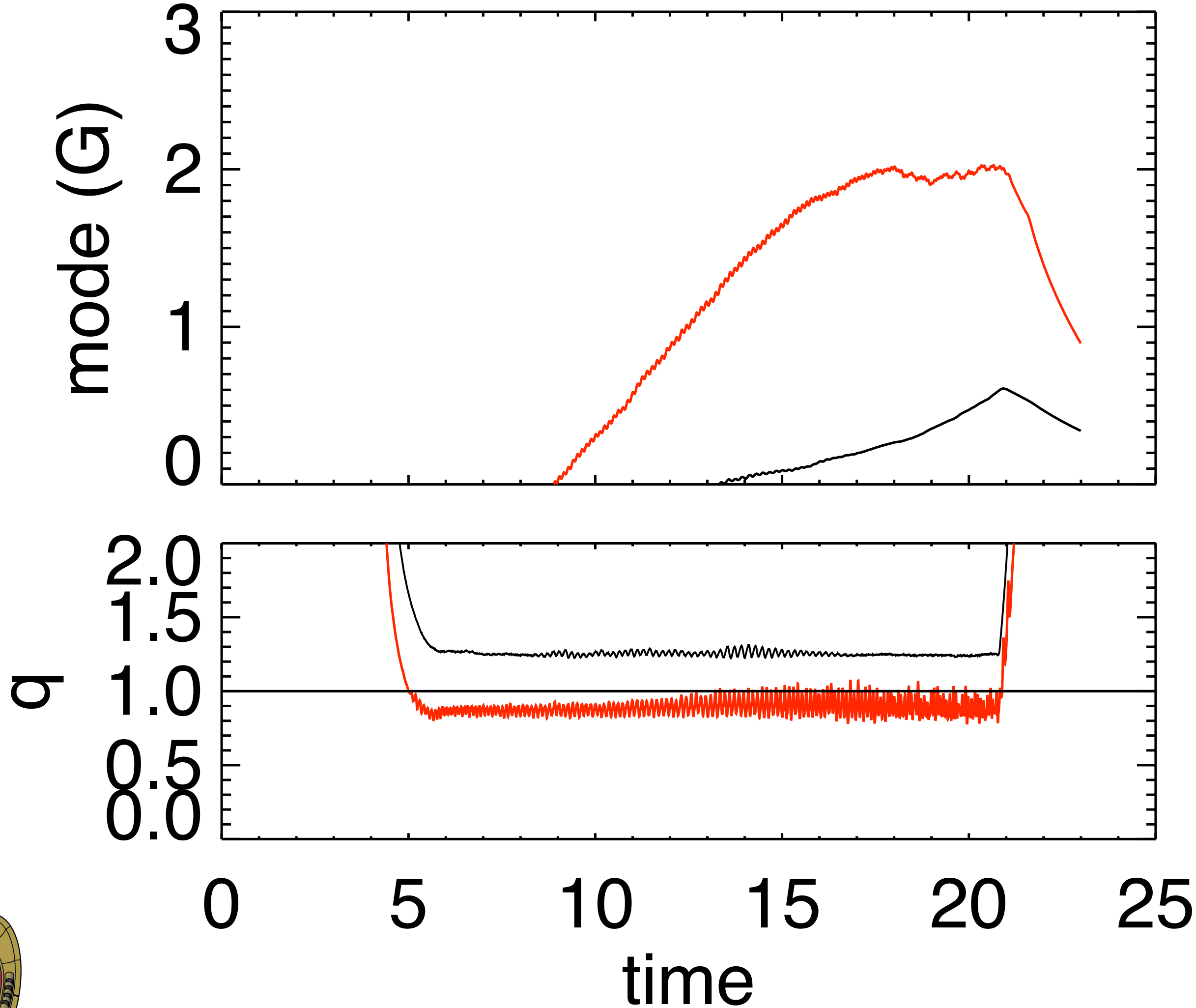
Resistive wall mode observed in line tied screw pinch

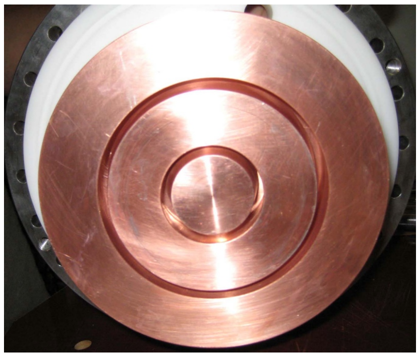


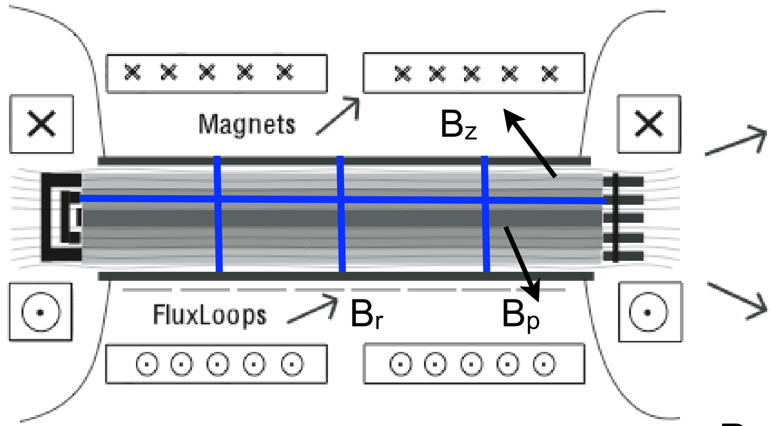
When $q < 1$, the mode is robustly present

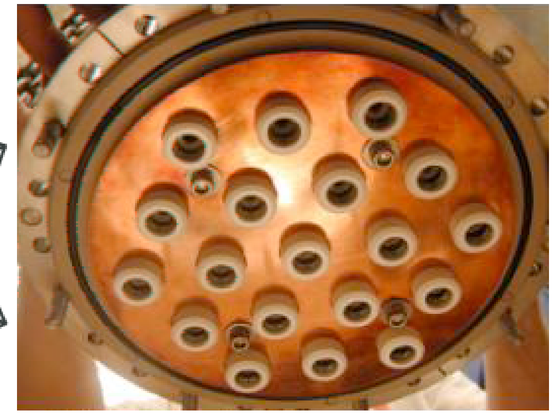
Outline

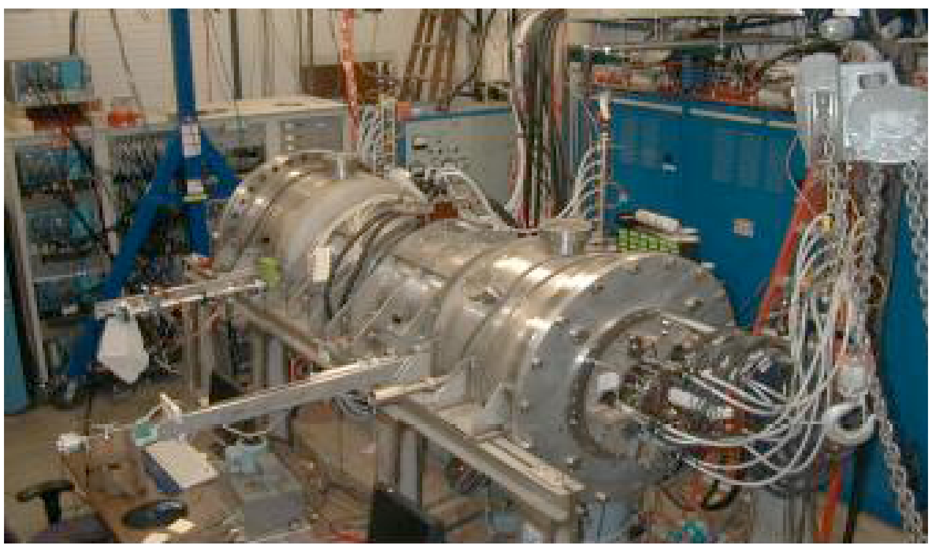
- Motivation
- Resistive wall mode (RWM) in a line tied plasma
  - Theory
  - Experimental data
- External mode without internal modes
- Summary

The rotating wall machine





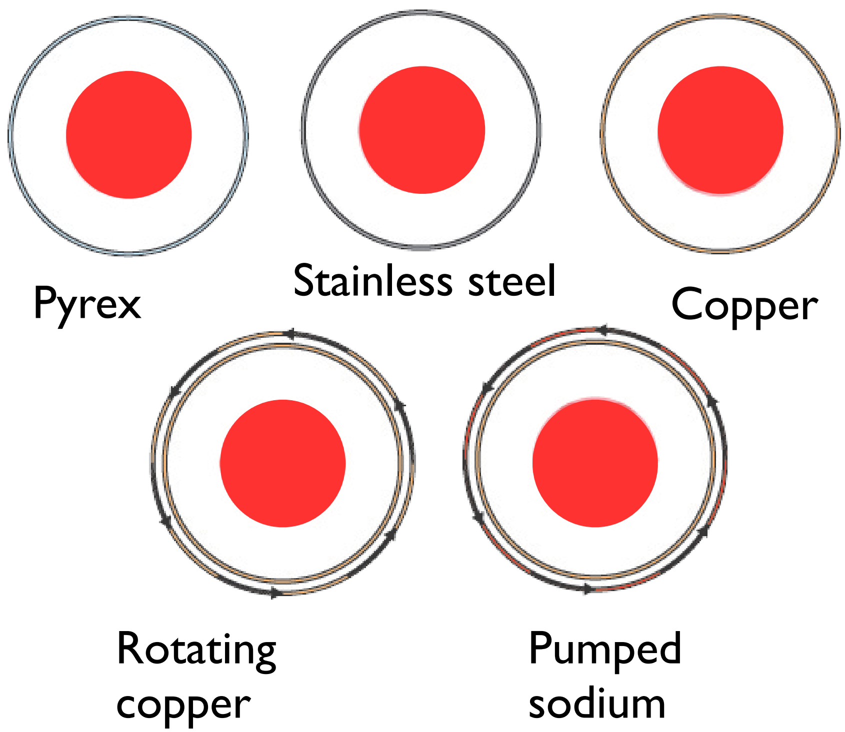




Parameters:

$a \leq 10$ cm
$L = 120$ cm
$B < 1000$ G
$n \sim 4 \cdot 10^{13}$ cm^{-3}
$T_e \sim 20$ eV
$t_A \sim 10\ \mu s$
$S \sim 60$
b ~ 3%

Goals of the rotating wall machine



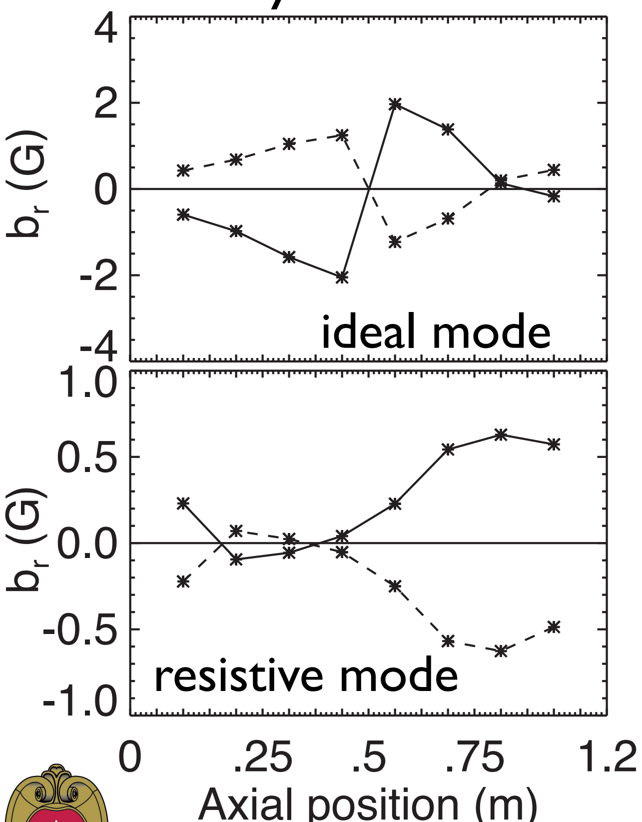
- Contrast MHD in periodic and line tied systems
- Passively stabilize RWM with spinning copper or flowing sodium
- Need to first identify the RWM

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).]

Plasma has two internal modes and evidence of reconnection

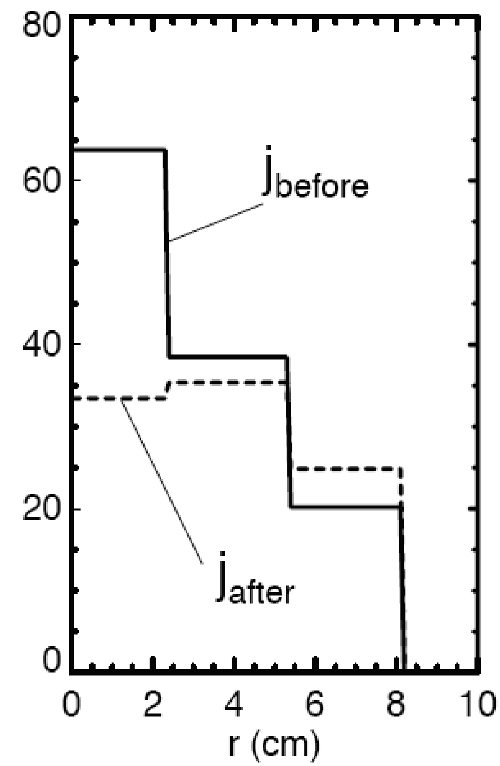
eigenmodes with Pyrex wall



Ideal mode onset when $q_0 = 1$

Resistive mode seen in conjunction with relaxation events in plasma that flatten current profile

fast relaxations in current profile



See Bergerson, *et al.* (PRL '05)

Ideal MHD stability of the line tied screw pinch

- Internal kink stability is sensitive to current profile
- External kink stability characterized by boundary condition
  - No-wall instability set by $q_a = 1$ (Kruskal Shafranov)

$$q_a < 1 \qquad\qquad q(r) = \frac{4\pi^2 r^2 B_z}{\mu_0 I_p(r) L}$$

  - Instability in presence of a perfectly conducting wall governed by wall location

a = plasma radius
b = wall radius

$$q_a - 1 + \left(\frac{a}{b}\right)^2 < 0$$

  - Resistive wall mode exists between no-wall and perfectly conducting wall limits

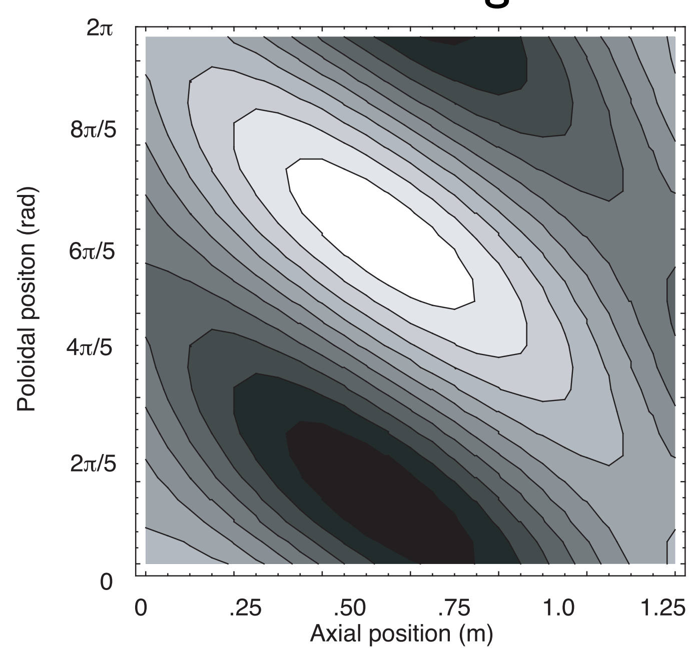
C.C. Hegna, Phys. Plasma 11, p4230 (2004)
D.D. Ryutov, et al. Plys. Plasma 11, p4740 (2004)

Theoretical predictions

- Mode onset when $q_a < 1$
- Mode growth rate determined by wall time and q_a
- Global mode present in B_r and B_p
- Agreement with B_r eigenmode
  - predicted at right

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

contour of B_r eigenmode



$$\tilde{\mathbf{B}_\mathbf{r}} = \mathbf{B_z} \frac{\partial \tilde{\xi}}{\partial z} + \frac{\mathbf{B}_\theta}{r} \frac{\partial \tilde{\xi}}{\partial \theta} - \tilde{\xi} \frac{\partial \mathbf{B}_\theta}{\partial r}$$

$$\tilde{\xi}_r(r, \theta, z) = f(r) e^{im\theta + in(\frac{2\pi}{Lq_a} + \frac{\lambda_0}{4})z} \sin \frac{n\pi z}{L}$$

Overview of experimental results

- Studied current driven MHD with different walls at boundary (varying wall time)
- Mode growth has RWM signature
  - Mode onset different from predicted values
  - Theory does not account for peaked current profile
- Internal kink stability is effected by magnetic geometry
  - With larger R_m internal kink more stable

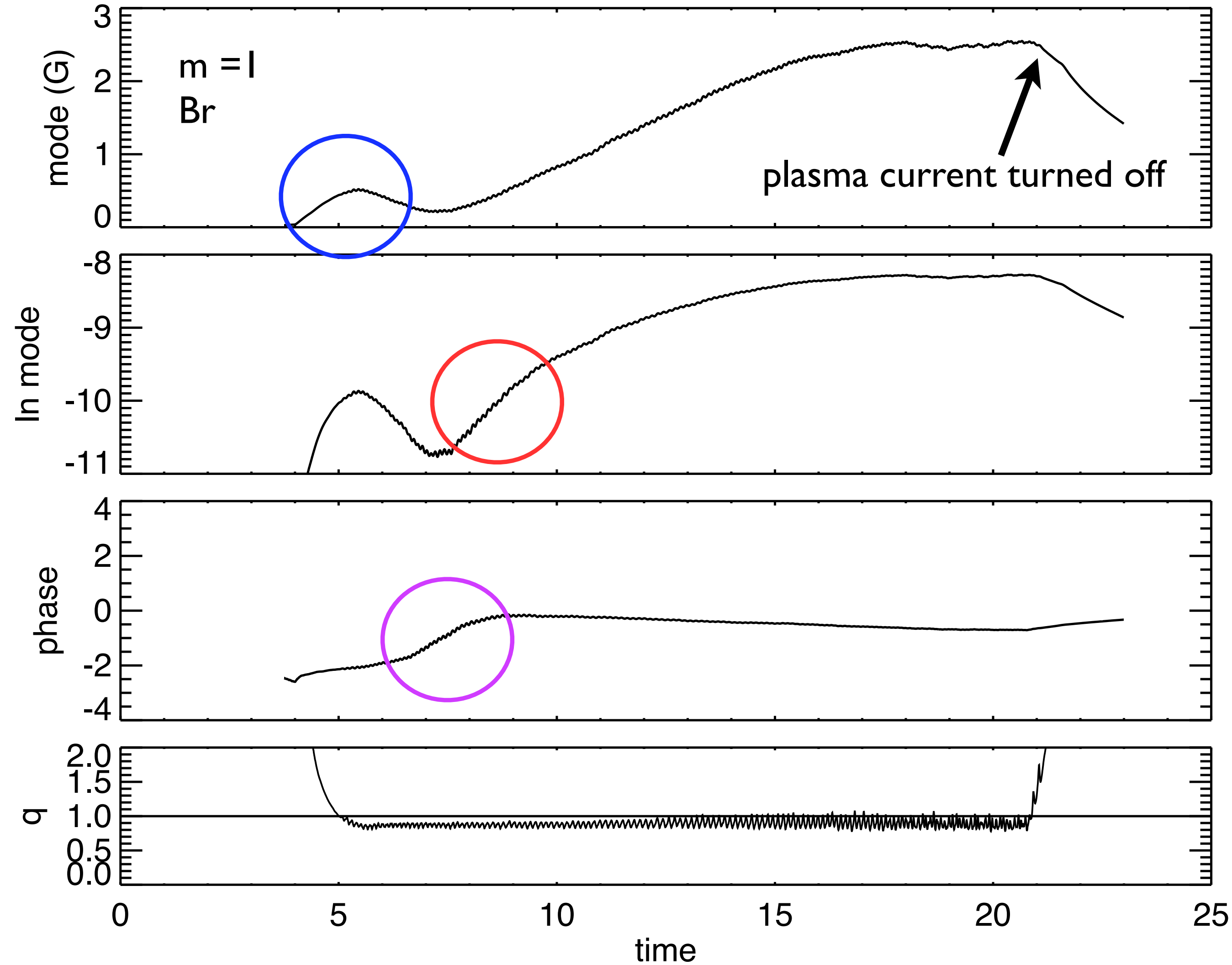
Analysis separates RWM from background field errors

Initial signal is residual field error

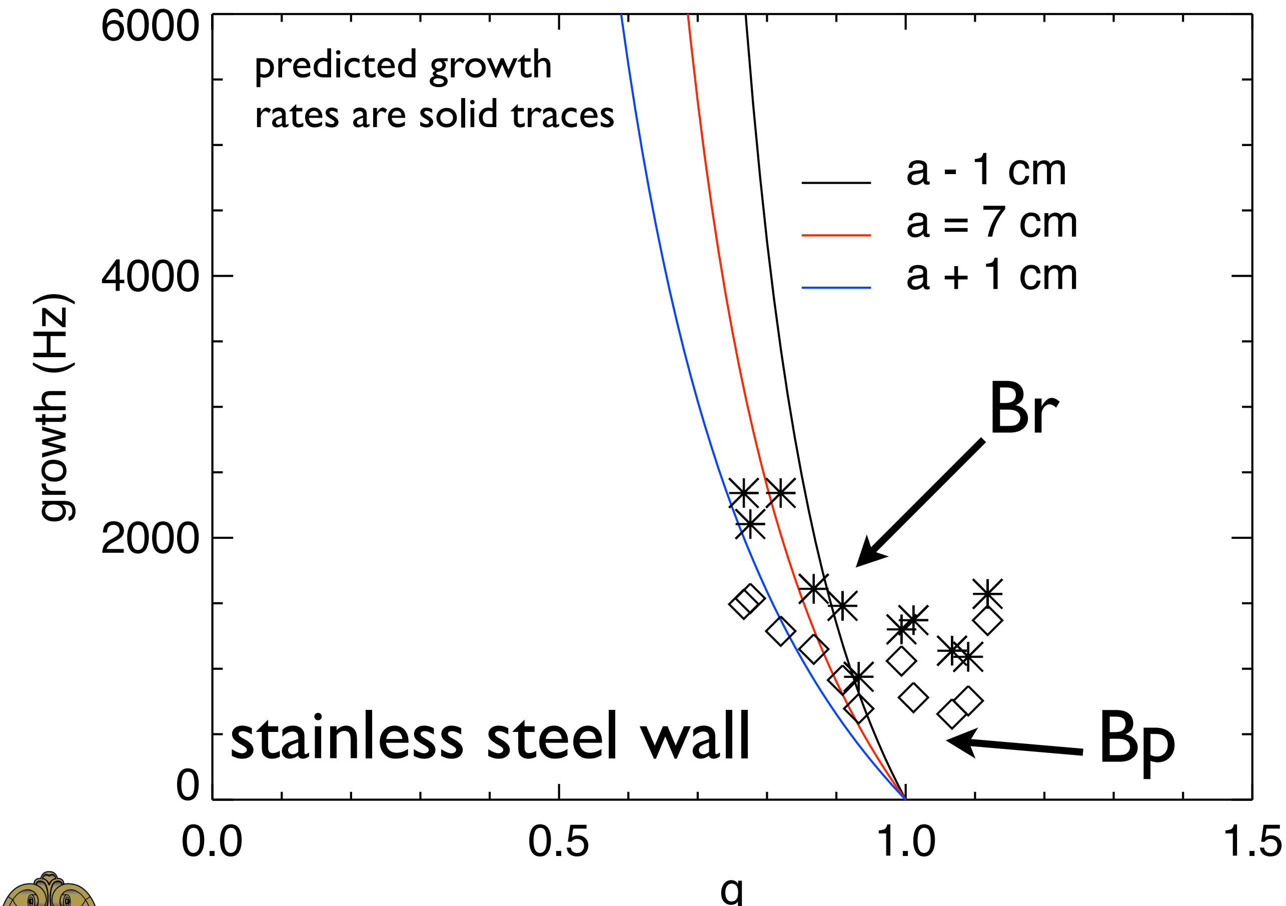
ln of mode (circled) is used to calculate growth

phase change indicates that signal is now plasma mode

$$q_a = \frac{4\pi^2 a^2 B_z}{\mu_o I_p L}$$



Growth rate of Bp and Br indicates global external kink



Bp is measured inside wall

Br is measured outside

No wall mode signal seen above q = 1.1

$$\gamma = \frac{2}{\tau_b} \frac{1 - q_a}{q_a - 1 + \frac{a}{b}^2}$$

$$\tau_b \approx .5ms$$

Wall time increased by sliding copper tube over stainless steel wall

stainless steel only

$\tau_w \cong .5ms$

Changed boundary condition

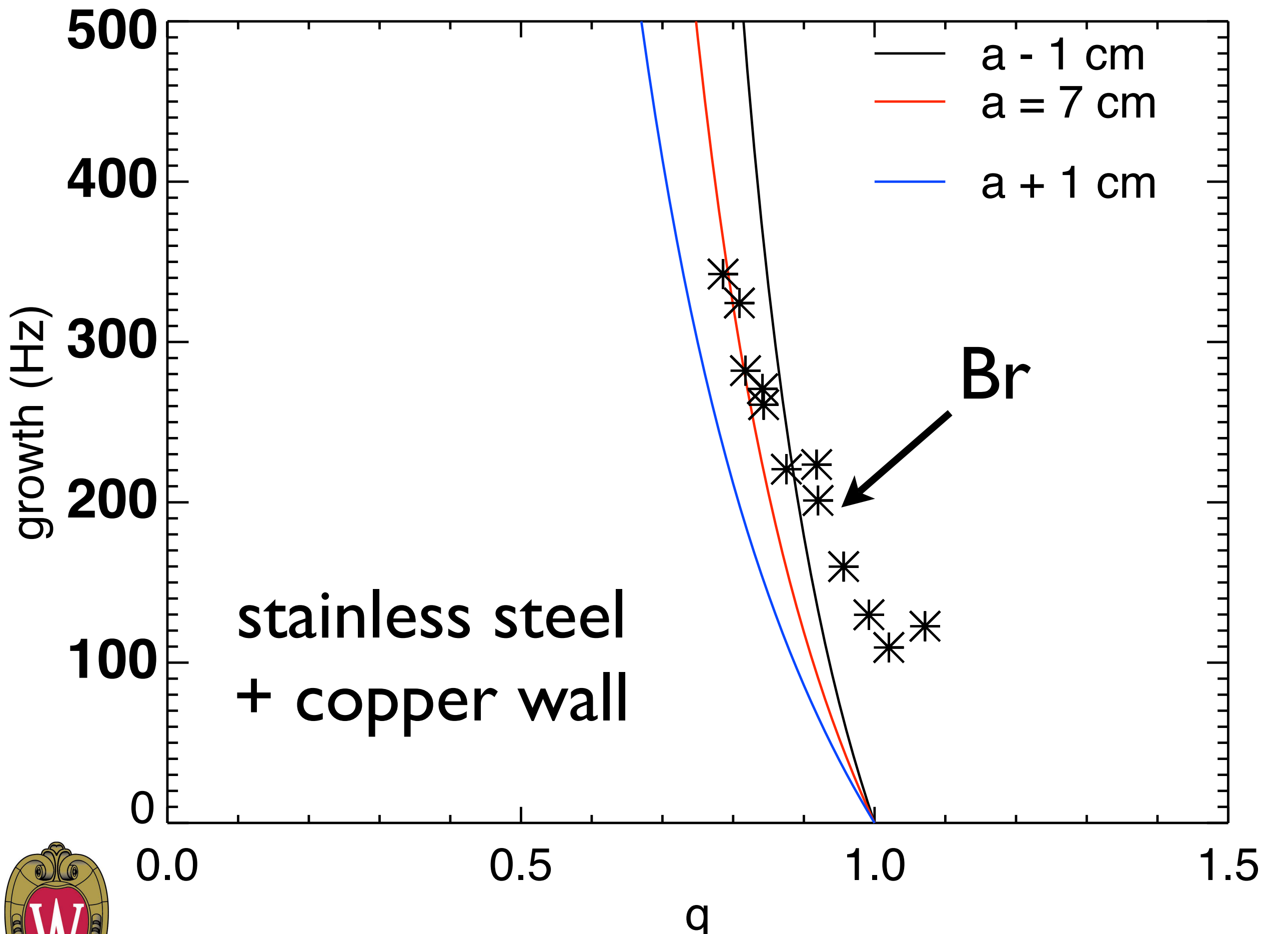
current carrying plasma

stainless steel + copper

$\tau_w \cong 7ms$

$$\tau_w = \mu_o r_w \delta_w \sigma_w$$

Mode growth scales with wall time



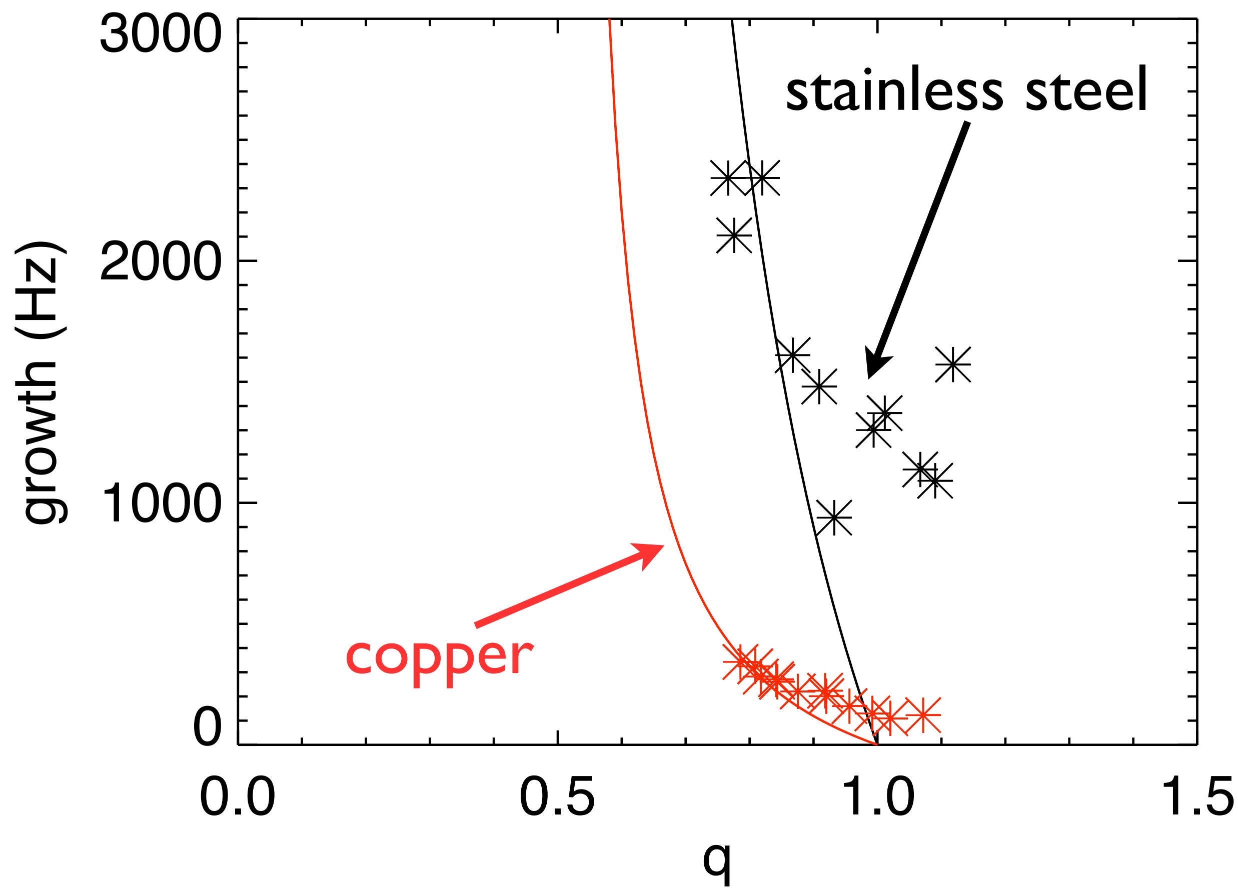
Growth rate changing with wall indicates RWM

No wall mode signal seen above q = 1.1

$$\gamma = \frac{2}{\tau_b} \frac{1 - q_a}{q_a - 1 + \frac{a}{b}^2}$$

$$\tau_b \approx 7ms$$

Comparison of growth with different walls

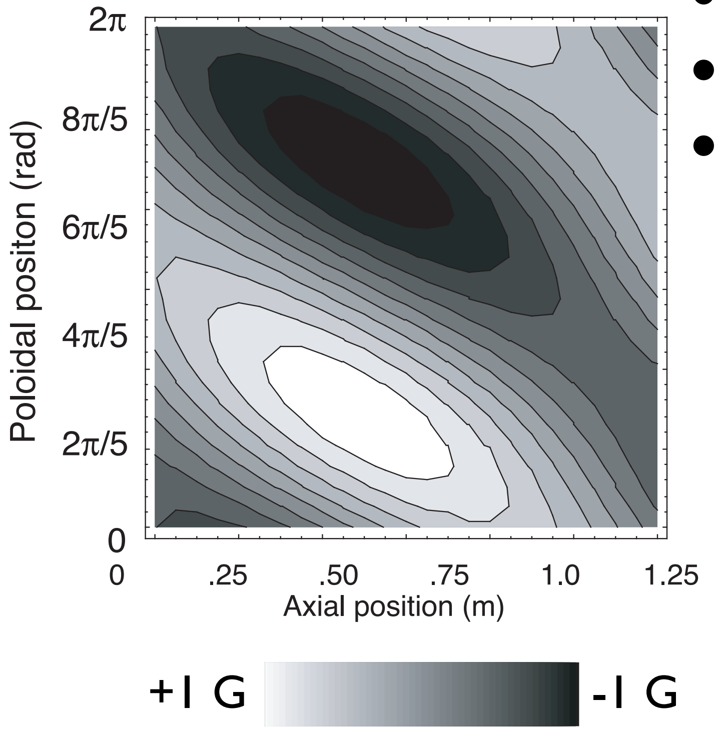


mode growth measured with B_r

mode growth determined principally by wall

Eigenmode of RWM matches prediction

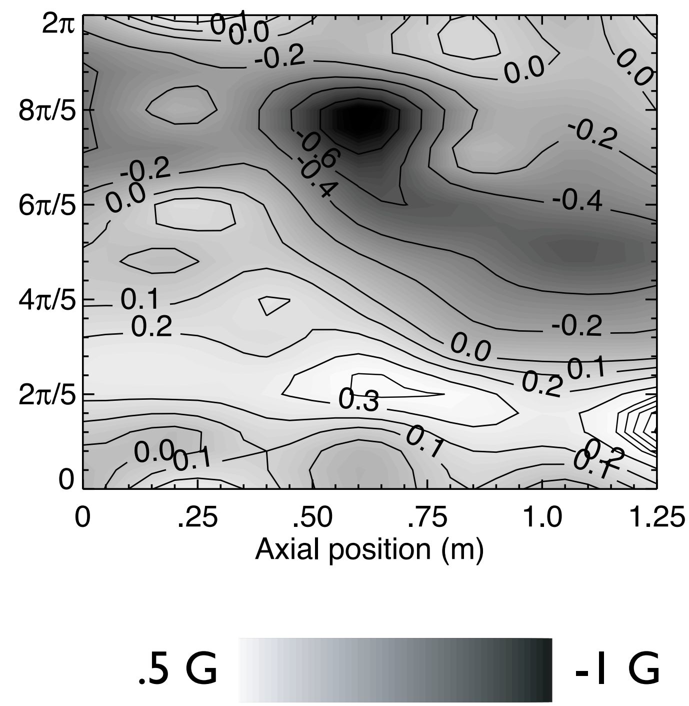
predicted
contours of B_r



mode has:

- m = 1 character
- peak in center
- helical structure

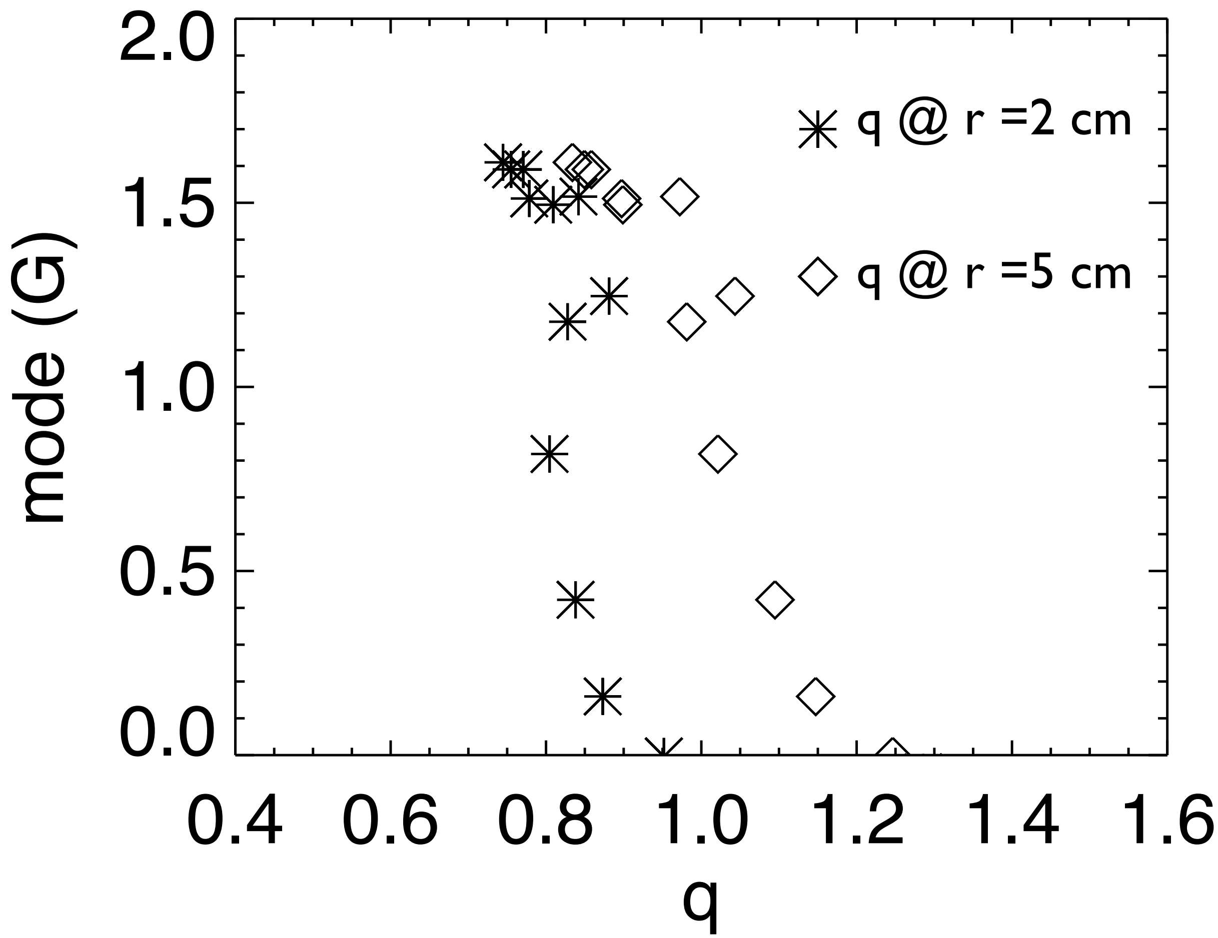
measured
contours of B_r



q at mode onset has internal or relaxed external characteristics

plasma condition for RWM onset might be $q_0 = 1$ or $q_a = 1.2$

theory predicts external mode to be governed by q_a

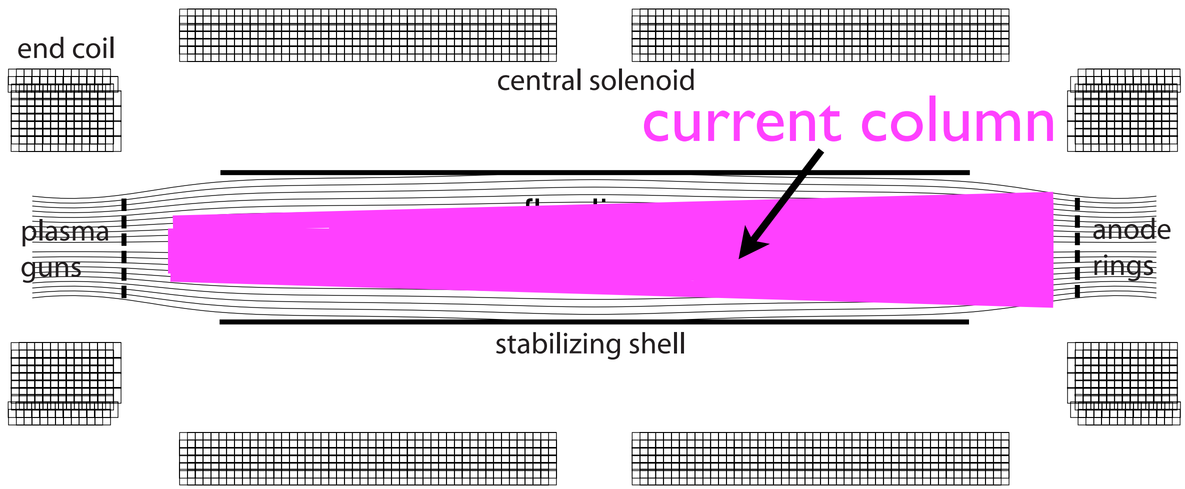


RWM observations consistent with theoretical predictions

- Mode is observed inside and outside the resistive shell as expected for the resistive wall mode
- Mode growth scales with wall time and plasma parameters
- Eigenmode agrees with expected structure
- Mode onset is around q_0 = 1 or q_a =1.2
  - Delzanno et al. predict internal mode onset at q >1 in resistive plasmas
  - Theory assumes plasma has axial symmetry and flat current profile
  - In reality plasma has non-axial symmetry and peaked current profile

Plasma current is not axially uniform

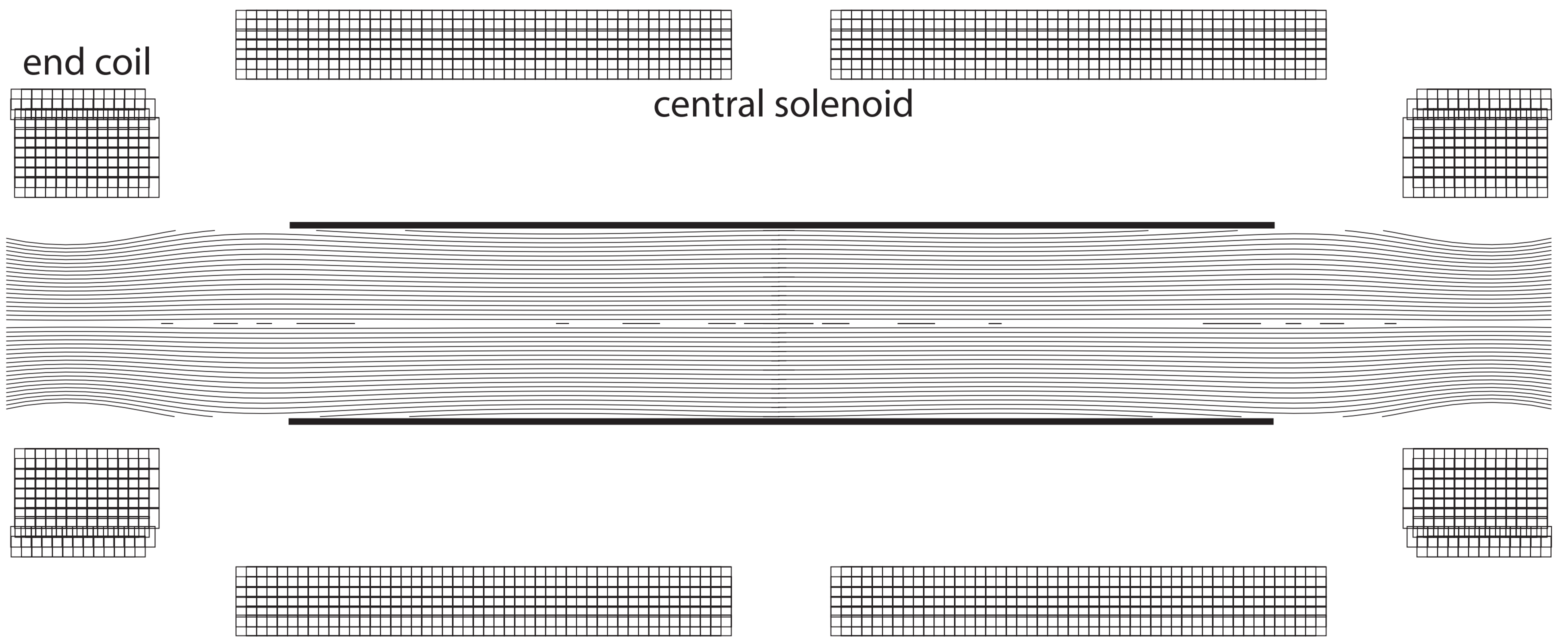
- Current diffuses radially from cathode to anode
- Below is an exaggeration of the current column



- Lack of symmetry complicates analytic theory
- Non-trivial current column may relax onset criteria of RWM

Alter magnetic geometry by increasing current in end coils

contour of flux surfaces

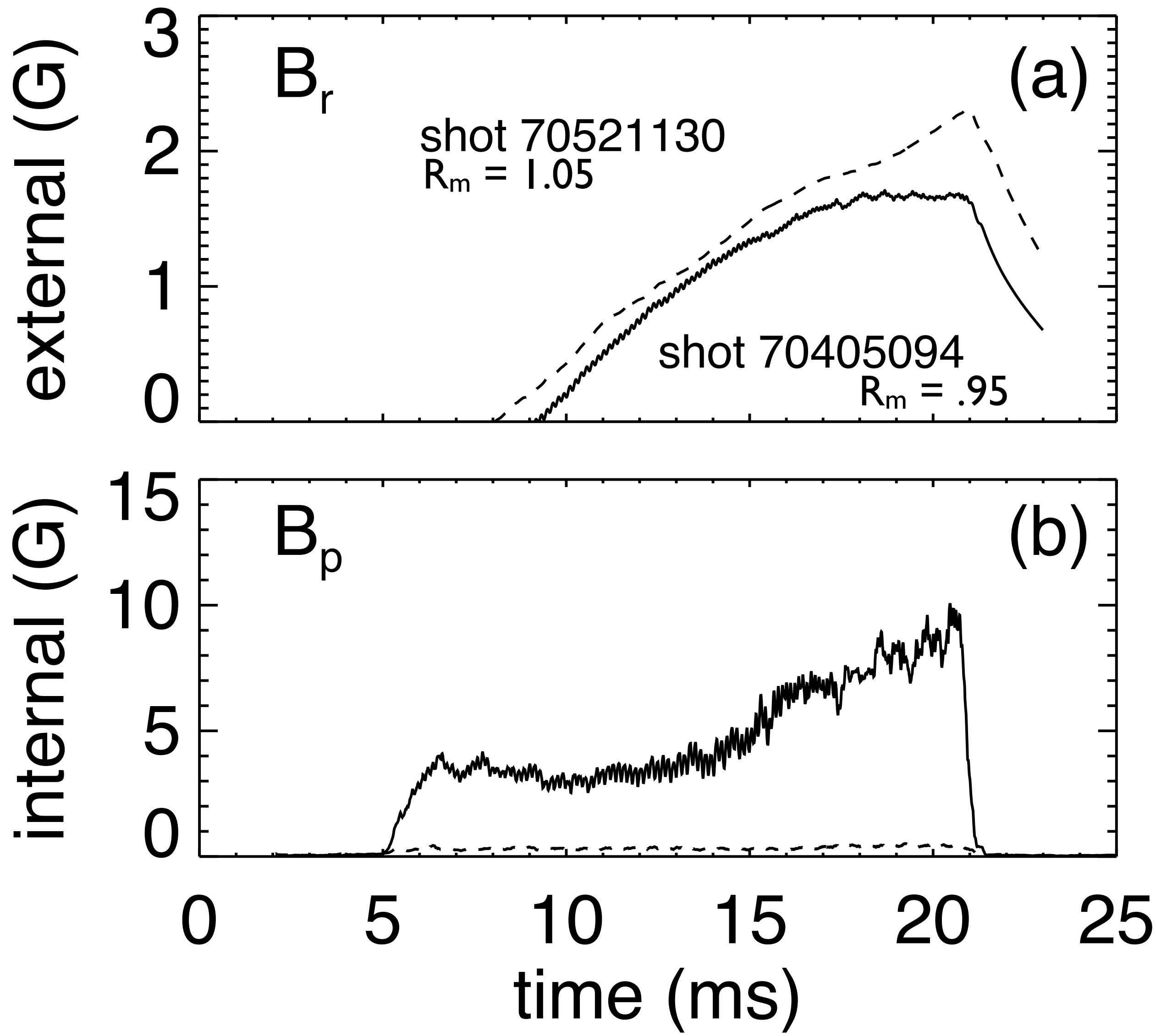


- Create *slight* adjustments to R_m by increasing current in the end coils

Changing R_m alters kink dynamics

With slightly higher R_m, the external mode grows throughout shot, seen in hashed trace

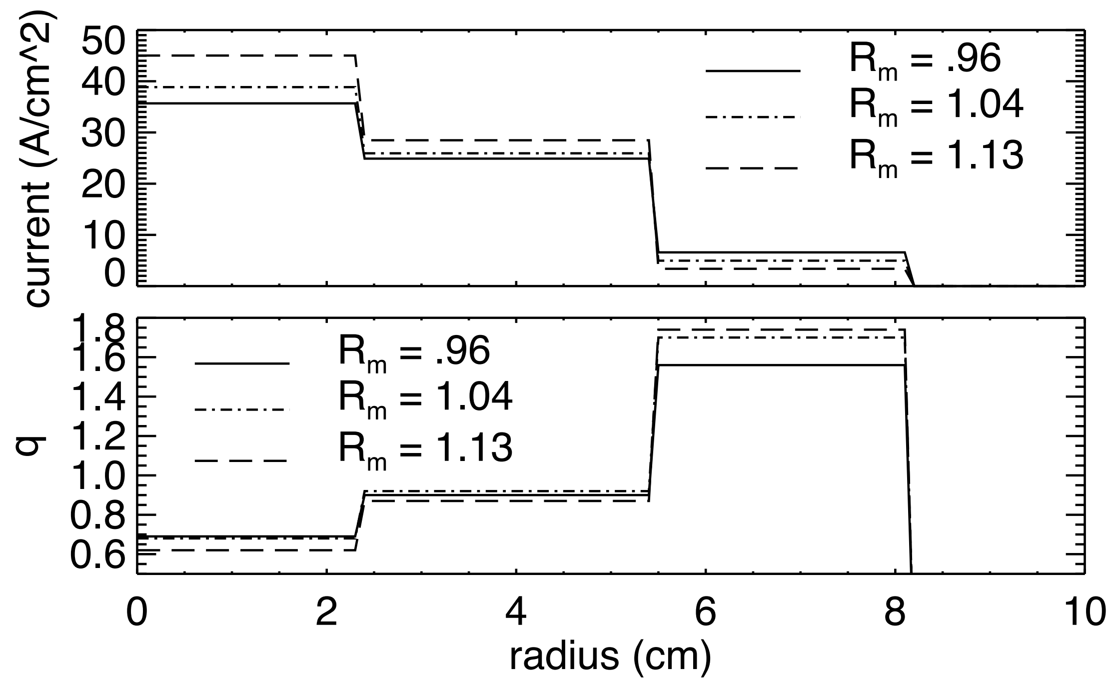
Concurrently, the internal mode is essentially stabilized by the higher R_m, again seen in hashed trace



Current profile steepened when R_m increases

Higher R_m associated with lower current diffusion

q is naturally lower with higher current density



- Unclear why current profile effected by R_m
  - could indicate change in confinement?
- Internal mode stabilization could stem from mode's sensitive dependence on the current profile

Summary

- Resistive wall mode has been identified in rotating wall machine
- RWM growth determined by wall time and *q* with onset at q ~ 1
- Internal mode can be stabilized by varying magnetic geometry

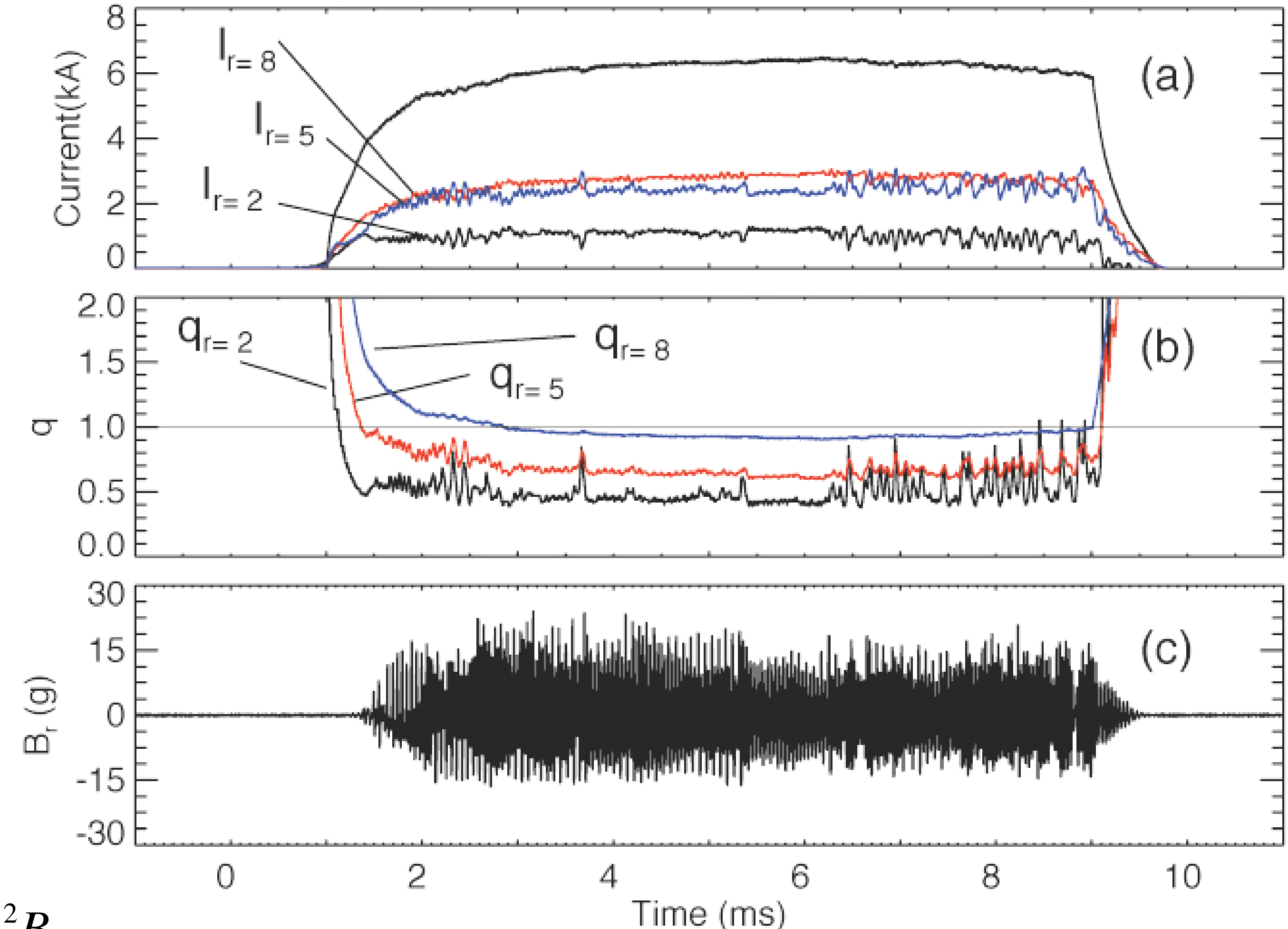
Future

- Perform experiments to identify and study the Ferritic Wall Mode
- Map out axial dependence of current distribution
- Begin work on rotating shell to stabilize RWM

MHD activity observed when q drops below 1

Safety factor q lowers as current increases

MHD activity present when q < 1

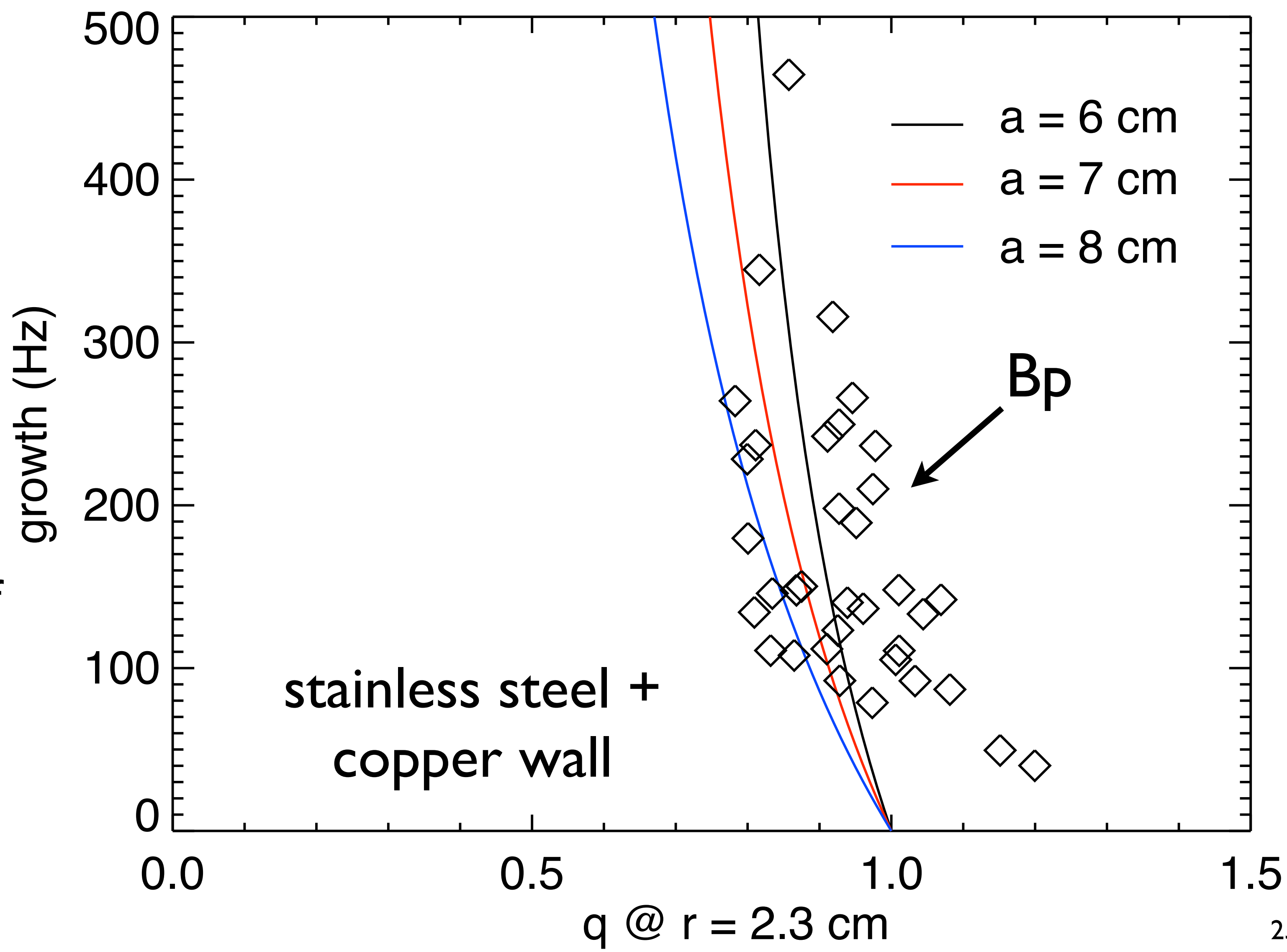


$$q_r = \frac{4\pi^2 r^2 B_z}{\mu_o I_p L}$$

Coincident mode growth seen in Bp

Mode is again seen inside and outside of wall

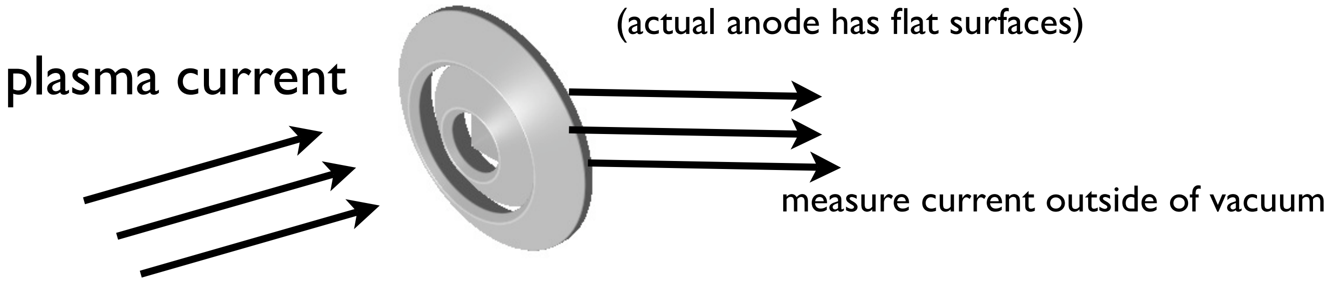
Growth in different polarization indicative of RWM



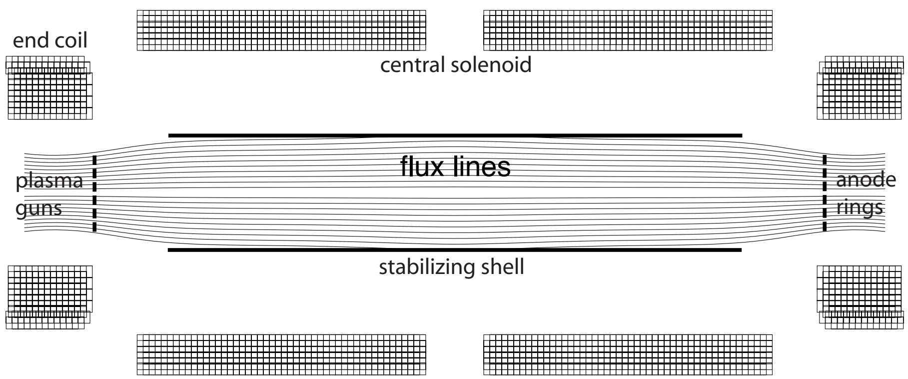
Measuring q

Historically, the following approach was taken

(1) Measure the amount of current within three radii in the plasma at anode



(2) Use a computer model to determine the local value of Bz close to where the current profile is measured based on currents in the solenoids and geometric position



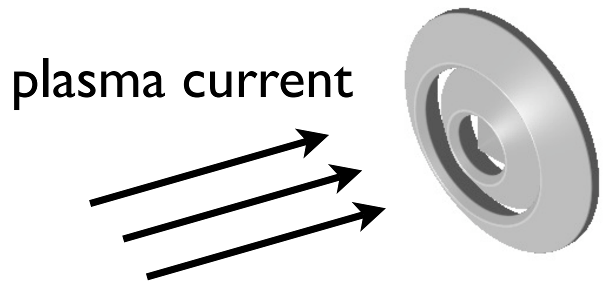
(3) Calculate q

$$q_a = \frac{4\pi^2 a^2 B_z}{\mu_o I_p L}$$

(4) Assume local measurement of q to be a good approximation for actually integrating along the field line to determine the amount of twist

Better measurement for q

(1) Measure the amount of current within three radii in the plasma at anode



(2) Assume current stays within flux surface (frozen flux)

(3) Obtain a series of local estimates for Bz from computer program

(4) Perform a runge-kunta integration, with estimates for Bz and measured current distribution, to calculate and follow field line along experiment

(5) Tabulate the twist of the field line to measure q

→ This approach takes non-uniformity of Bz field into consideration

This approach also results in a slightly higher value for q, be it q @ 2.3, 5, or 8 cm