Opportunities for Angular Momentum Transport Experiments

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Motivation for experiments

- Principle of universality – if a process governs turbulent transport in astrophysical objects (accretion disks, stellar interiors) then we should be able to replicate the fundamental components of the process in a controlled laboratory experiment

- Many turbulence theories rely on models of hydrodynamic turbulence that are insufficiently supported by experiment and simulations

- Particularly important is the problem of extrapolating scaling laws to astrophysically relevant scales

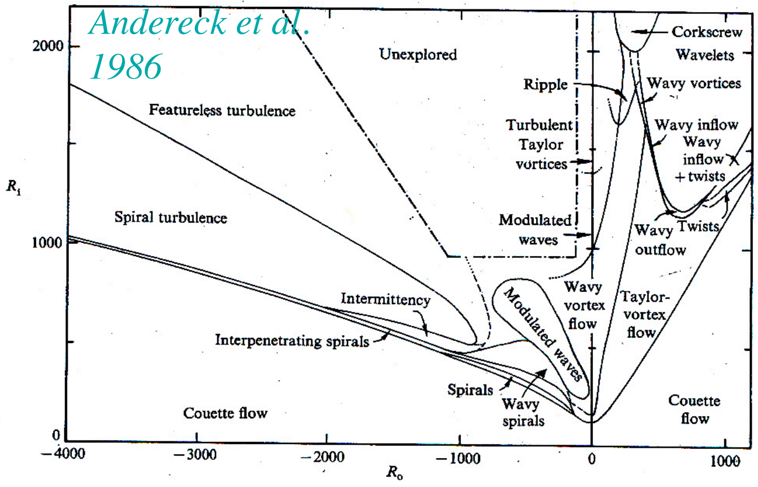
Opportunities and Tools

- Experimental Opportunities in momentum transport
  - Establish stability criteria and observation of first instability
    - Eg. Subcritical Hydrodynamic Instability, standard MRI, current driven instability
  - Identify saturation mechanisms
    - Parasitic instabilities, reconnection, α-dynamo, nonlinear coupling to other modes
  - Evaluate efficiency of transport
    - Measure Reynolds and Maxwell stress
  - Aid in determining scaling for extrapolation to astrophysical scales
    - Validate codes used to model astrophysical objects
    - Create scaling law from combined simulation/experiment results
- Experimental approaches
  - Hydrodynamic Centrifuge (Taylor-Couette) Experiments
  - Liquid Metal Centrifuge Experiments
  - Rotating magnetized plasmas
  - Plasma Centrifuge Experiments

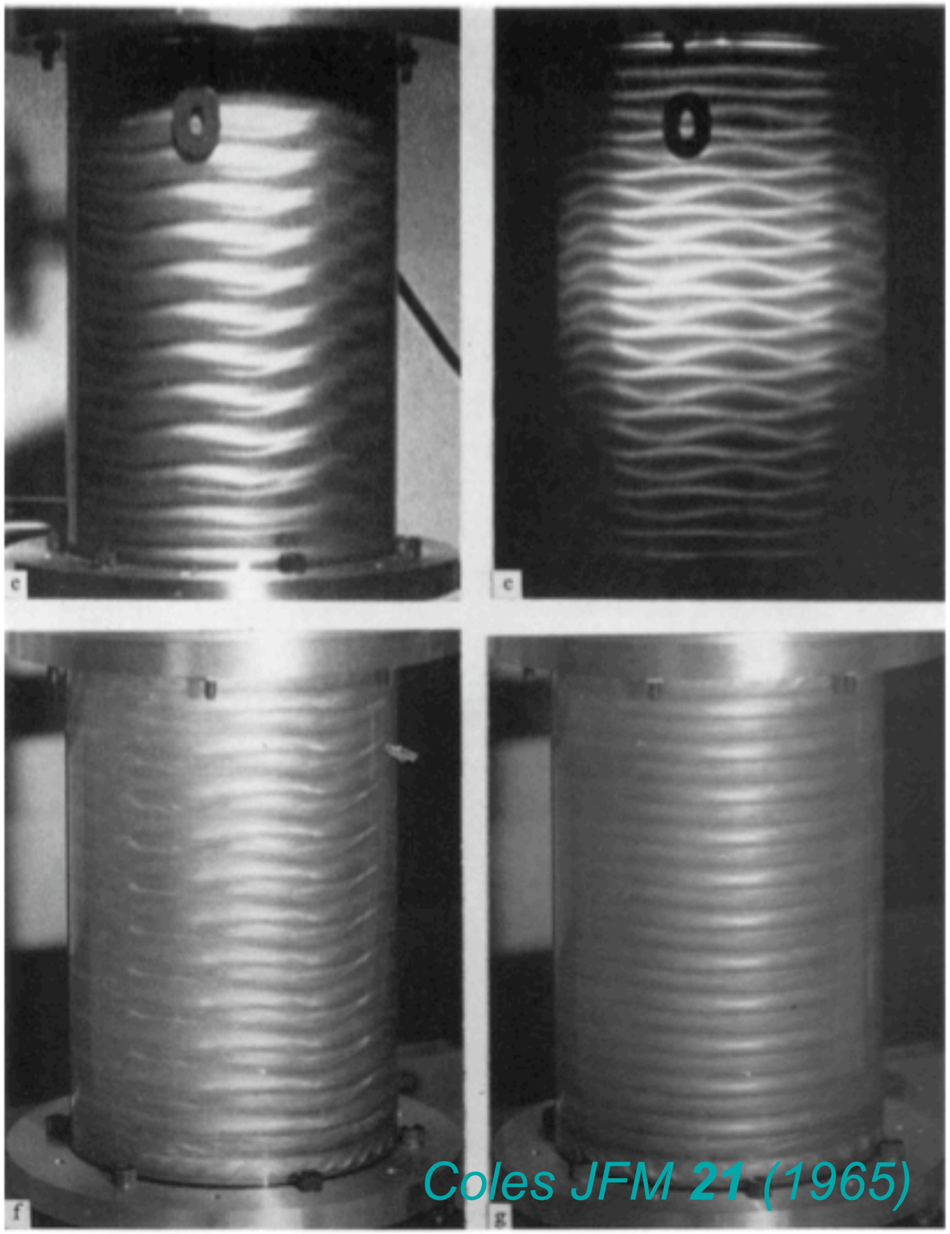
Taylor Couette Experiment

- Cyclonic flow between rotating cylinders demonstrates a wide variety of vortices, waves, and featureless turbulence
- Well-established transitions for Rayleigh instability

$$\frac{\partial r^2\Omega}{\partial r} < 0$$



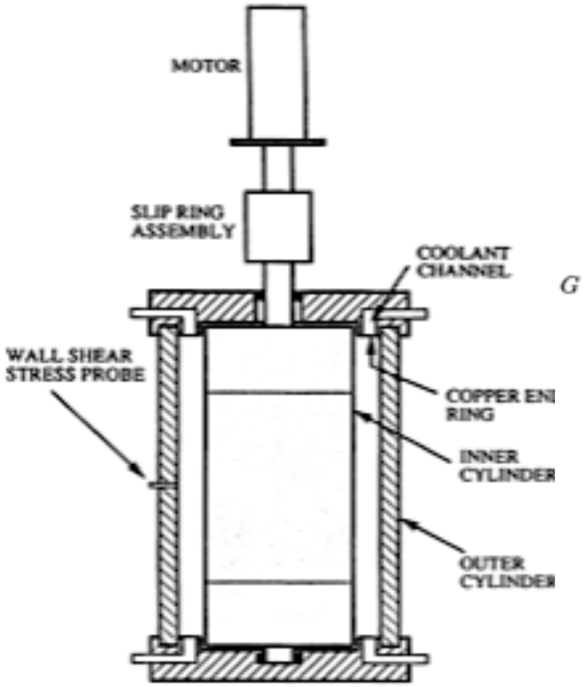
Andereck et al. 1986

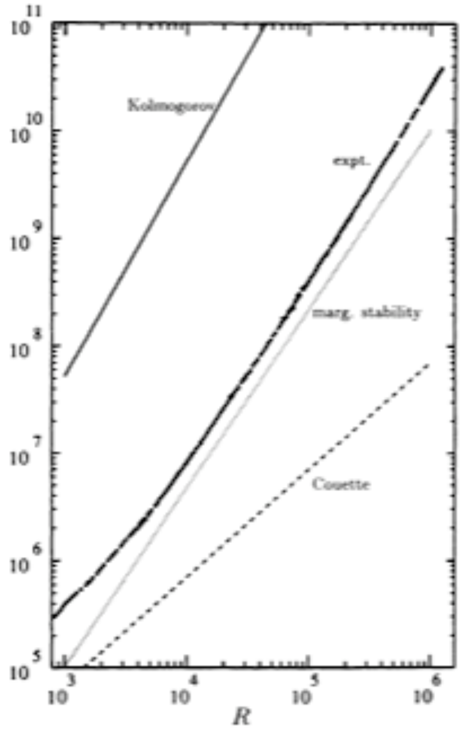


Coles JFM **21** (1965)

Transport in cyclonic turbulence

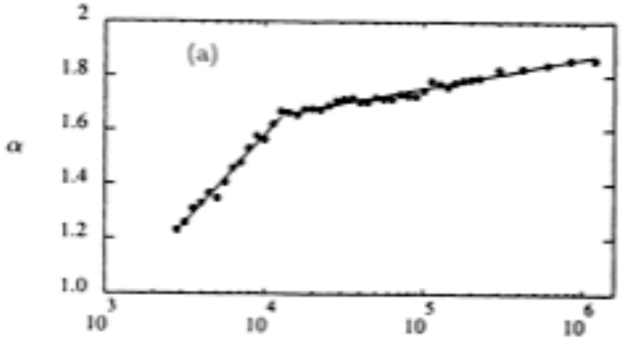
- Shear driven turbulence develops into boundary layers linked by marginally unstable interior
- Reynolds analogy works: scalar transport proportional to momentum transport, but neither is a simple power law
- Torque measurements in Taylor-Couette flow show logarithmic changes in the scaling with Re





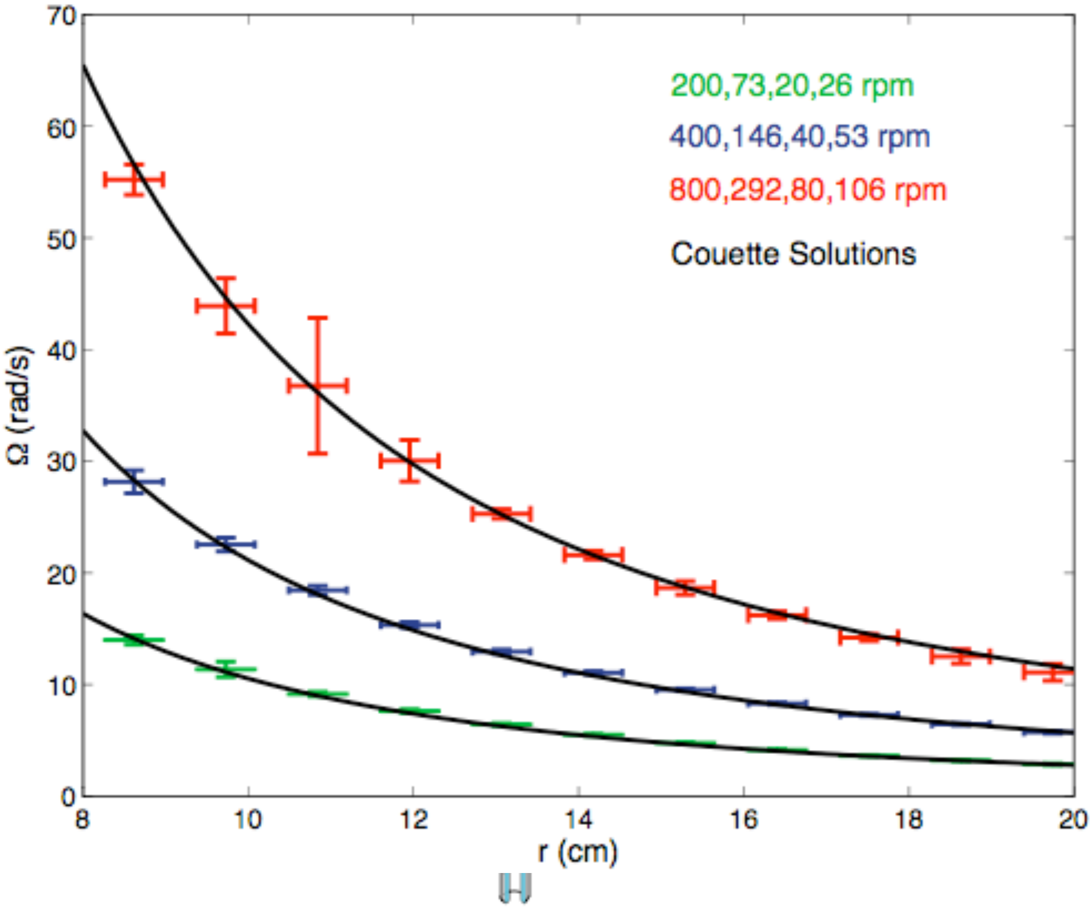
$$G = \frac{T}{\rho \nu^2 h} \propto R^\alpha$$

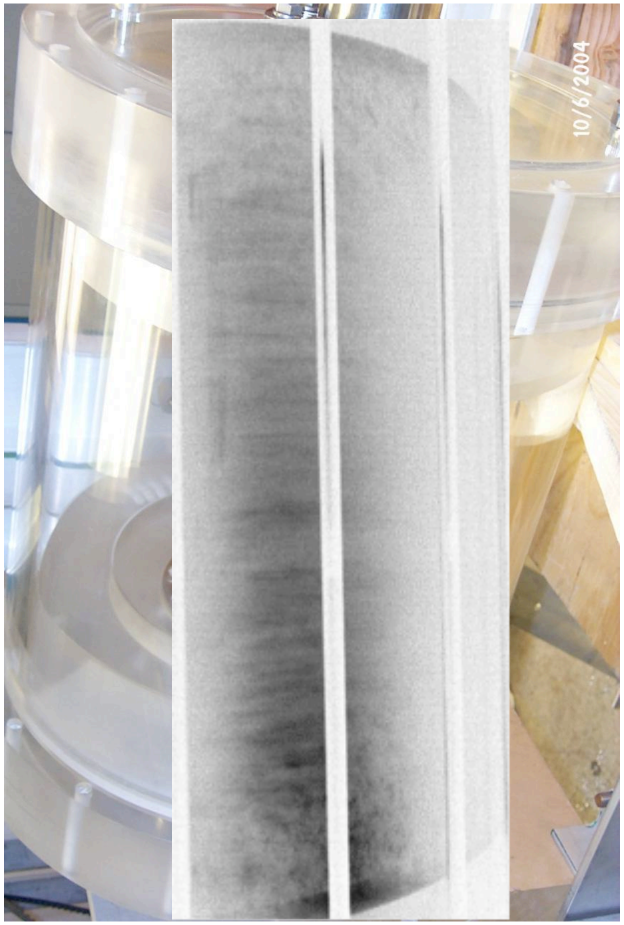
$$G = \frac{\eta^2}{2(1-\eta)^{3/2}} \frac{R^2}{\ln\left[\eta^2(1-\eta)R^2/10^4\right]^{3/2}}$$



Lathrop PRA ***46*** *(1992)*
Lewis & Swinney PRE (1999)

Boundary effects suppressed by segmented rings

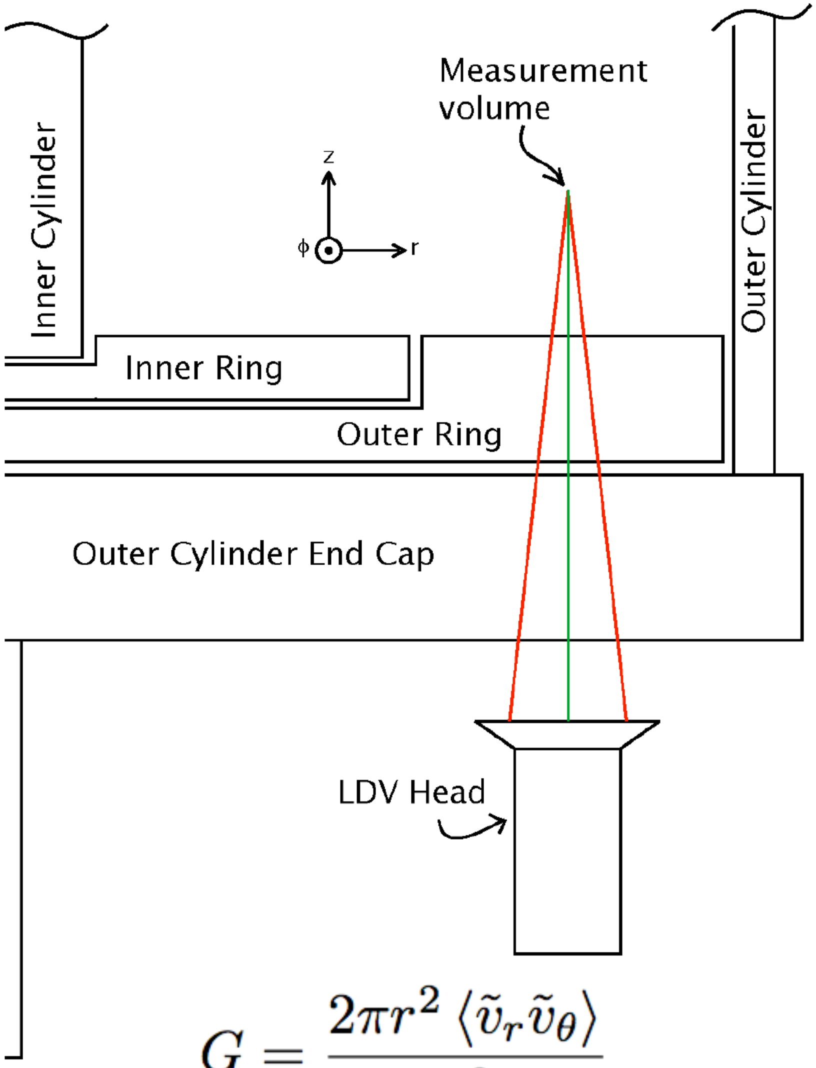




- High Reynolds number flows
- Control secondary flow due to boundary layers

Burin et al., Exp. Fluids, 2006

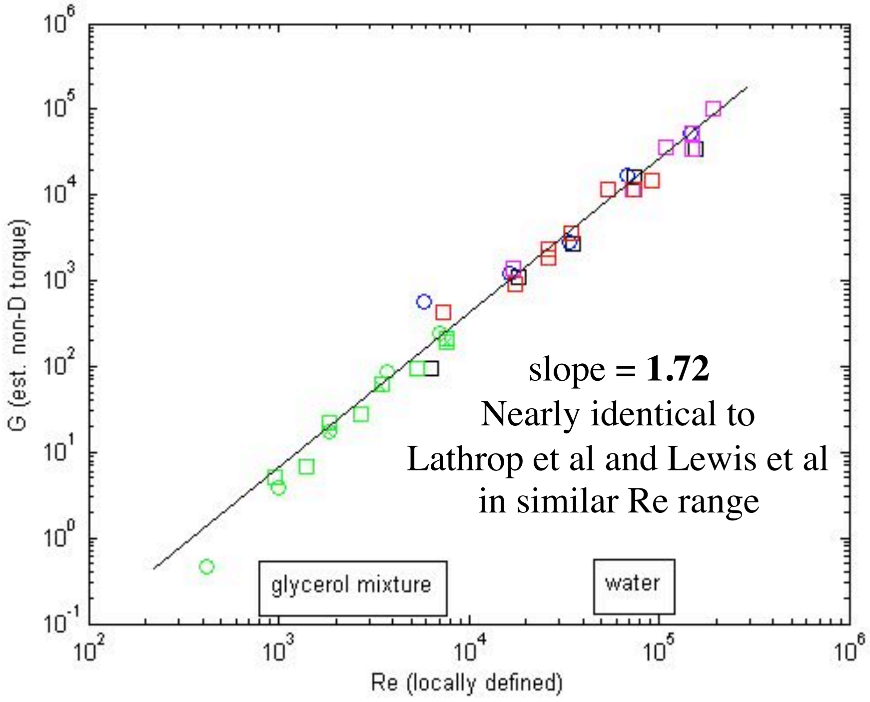
Local measurements of Reynolds stress



$$G = \frac{2\pi r^2 \langle \tilde{v}_r \tilde{v}_\theta \rangle}{\nu^2}$$

Burin et al., Exp. Fluids, 2009

- Measure $R_{r\Omega}$ directly
- Consistent with global torque measurements
- Possibility to look for subcritical instability decoupled from boundary flow



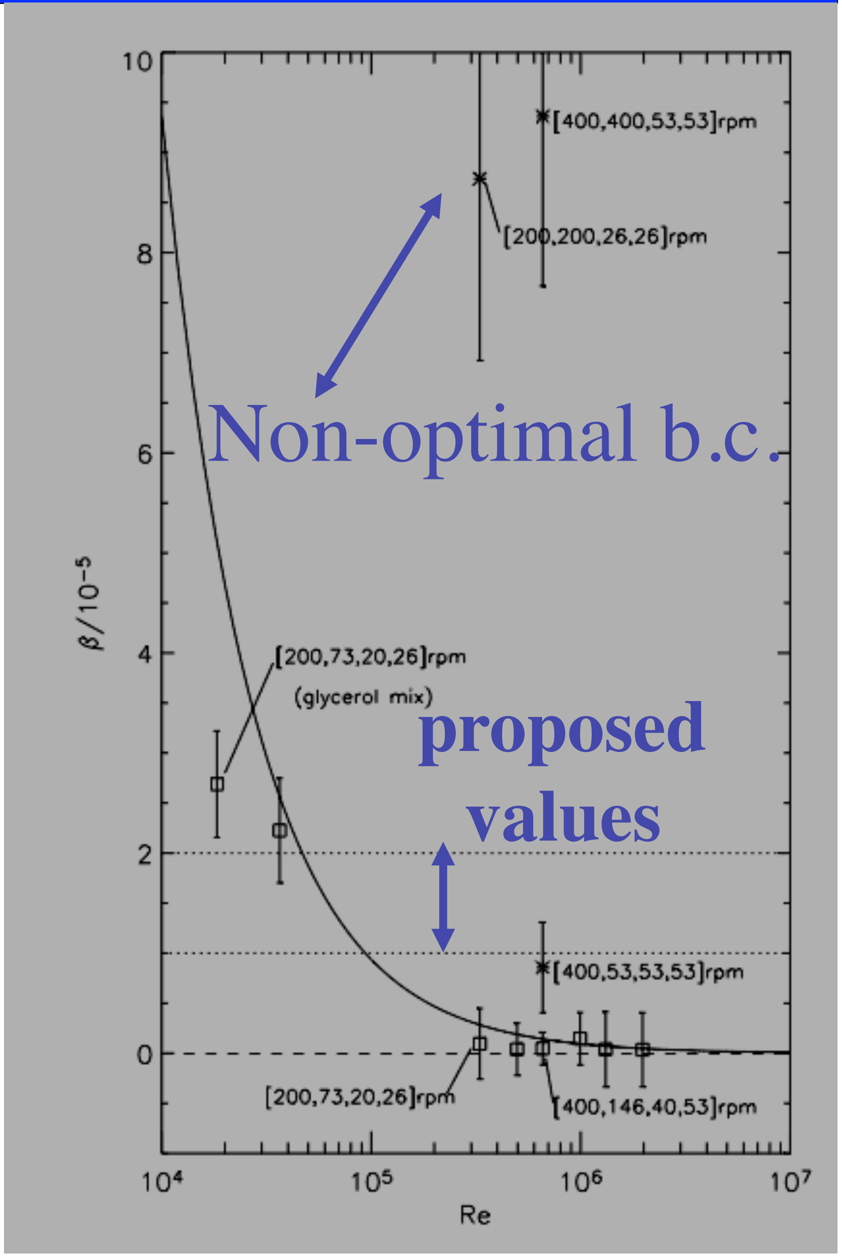
slope = **1.72**
Nearly identical to
Lathrop et al and Lewis et al
in similar Re range

Subcritical Hydrodynamic Instability

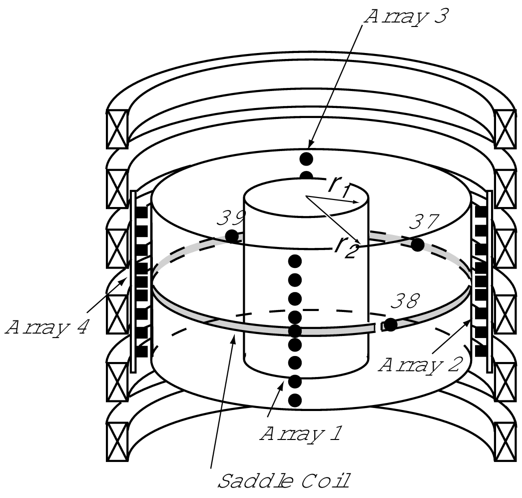
- One possibility of turbulent transport in Rayleigh stable flows (such as quasi-Keplerian) is a nonlinear hydrodynamic instability
- Observation claimed for Re ~ 10^5 but could not rule out Ekman flow
- Measurements up to Re~10^6 have failed to detect it when Ekman circulation is suppressed
- Still possible to observe at higher Re with more sensitive measurement

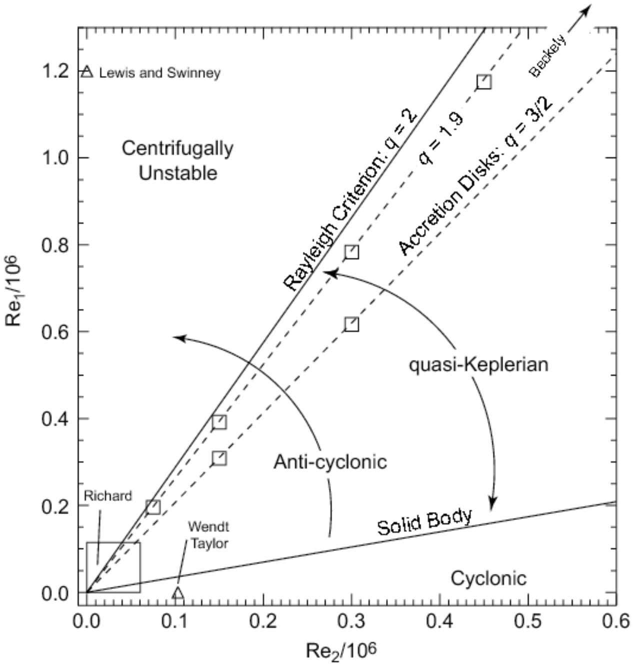
$$\nu_{turb} = \beta R^3 \left|\frac{\partial\Omega}{\partial R}\right| \qquad \beta \equiv \frac{\langle \tilde{V}_r \tilde{V}_\theta \rangle}{q^2 \langle V_\theta \rangle^2}$$

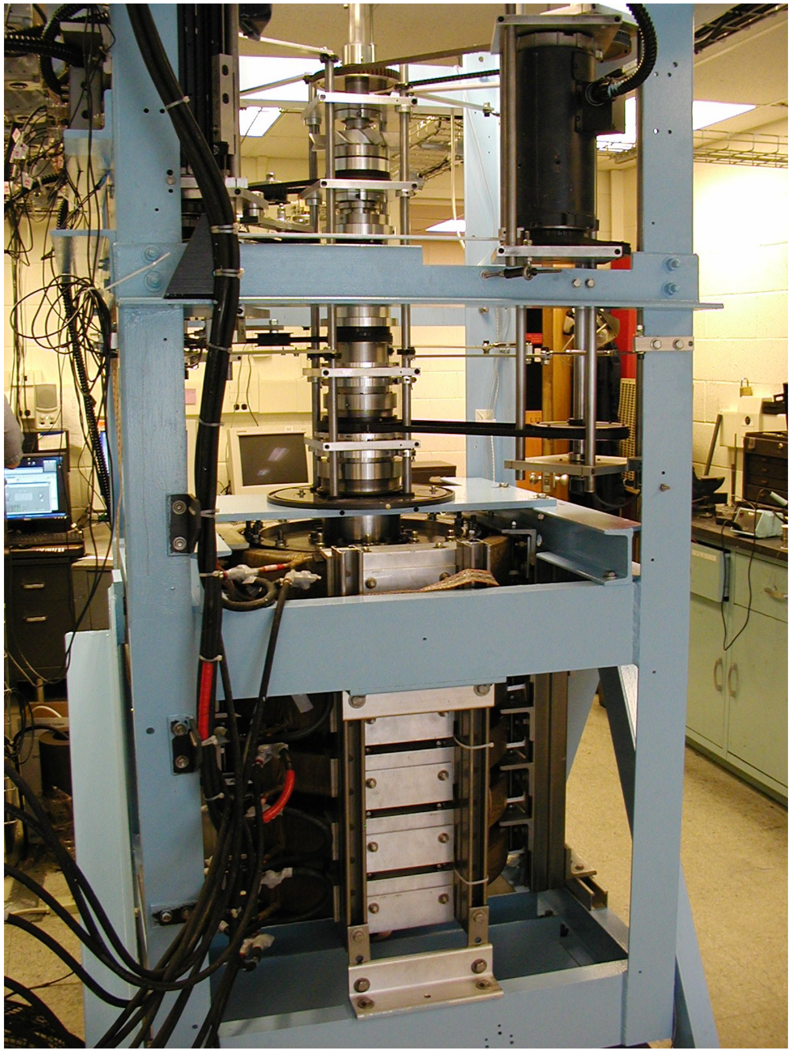
*Ji et al. Nature **444** (2006)*



Liquid metal experiments



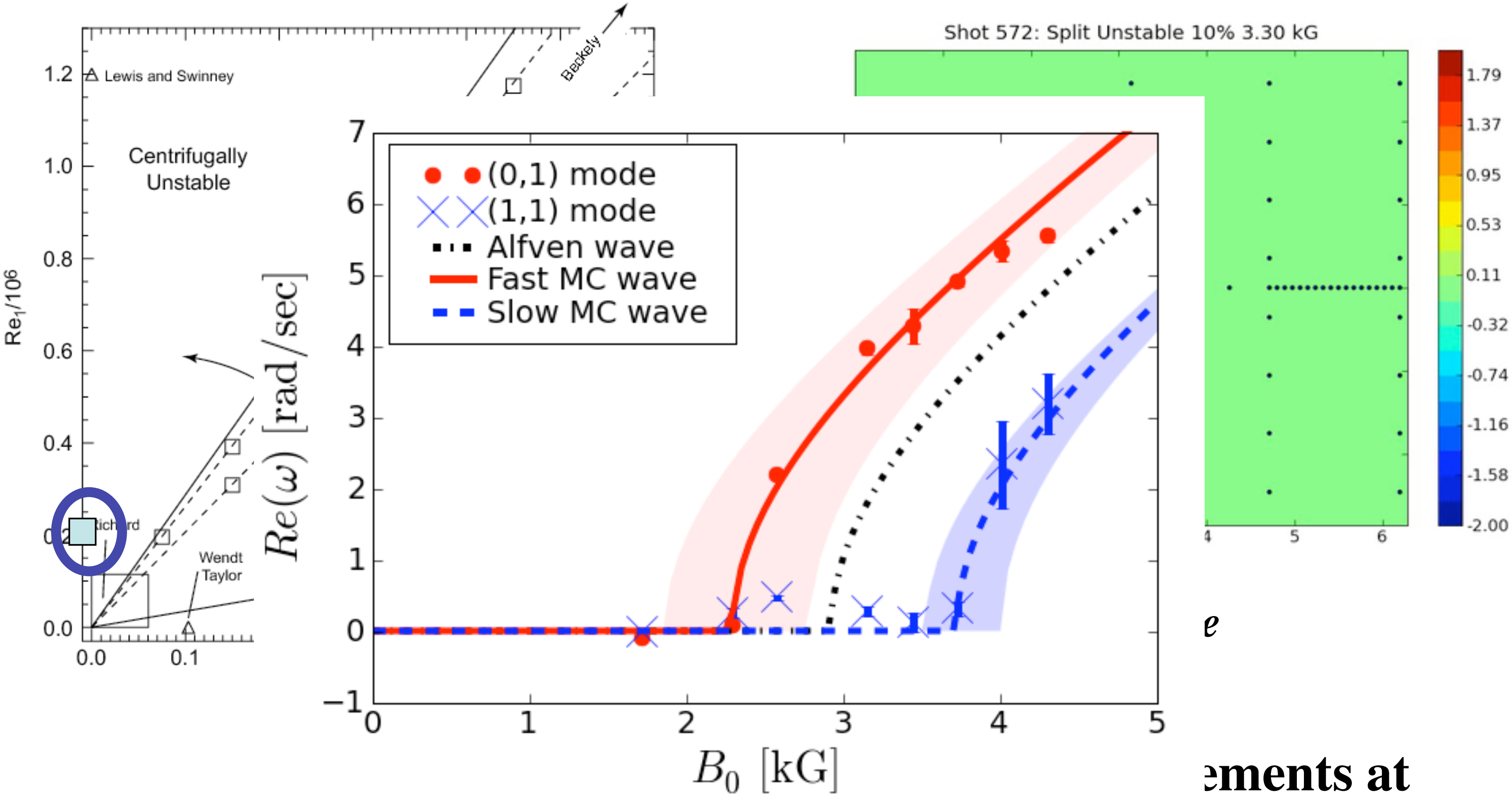




- Liquid metal Taylor-Couette flow suitable for MRI observation
- Diagnostics under development to characterize turbulent stresses to gauge efficiency of transport
- Initial studies of magnetized hydrodynamic turbulence

E. Schartman (thesis 2008)

Non-axisymmetric modes observed



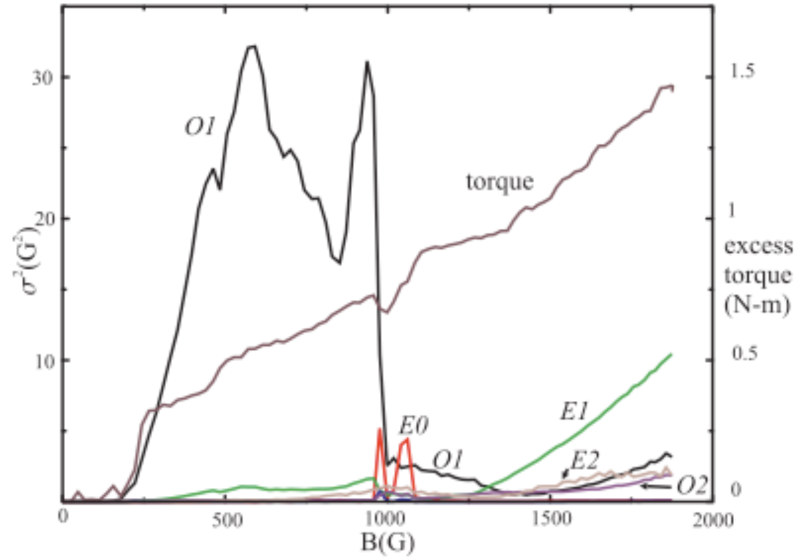
e

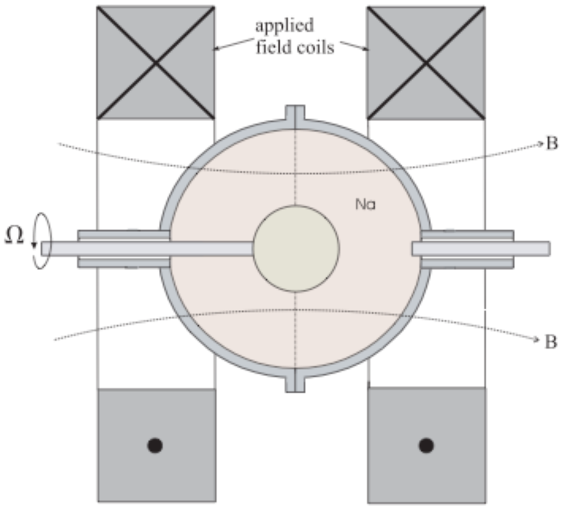
$B_0 = 3.30$ kG

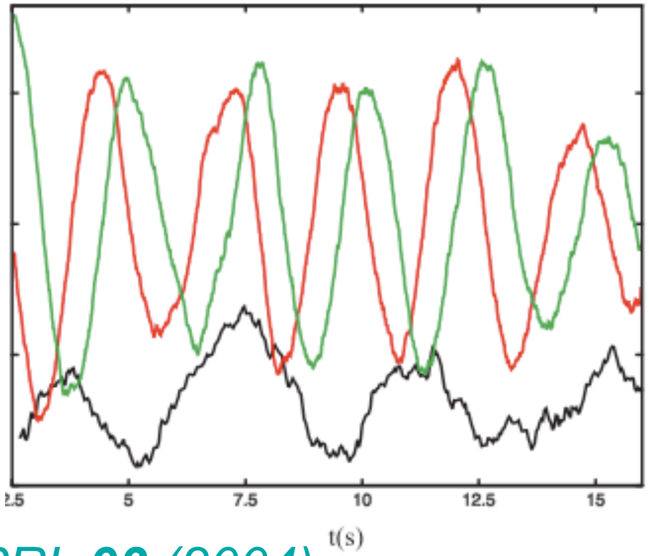
ements at surface show azimuthal (m=1) mode

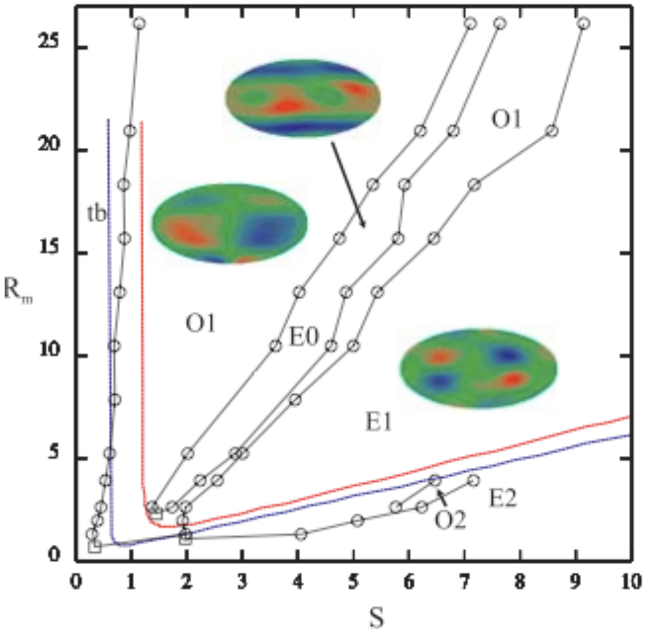
Maryland MRI Experiment

- Nonaxisymmetric patterns observed as field strength was varied
- Velocity and magnetic fluctuations are correlated
- Torque increase on inner sphere coincides with an increase in the variance of the dominant mode
- Role of boundary layers not yet clarified





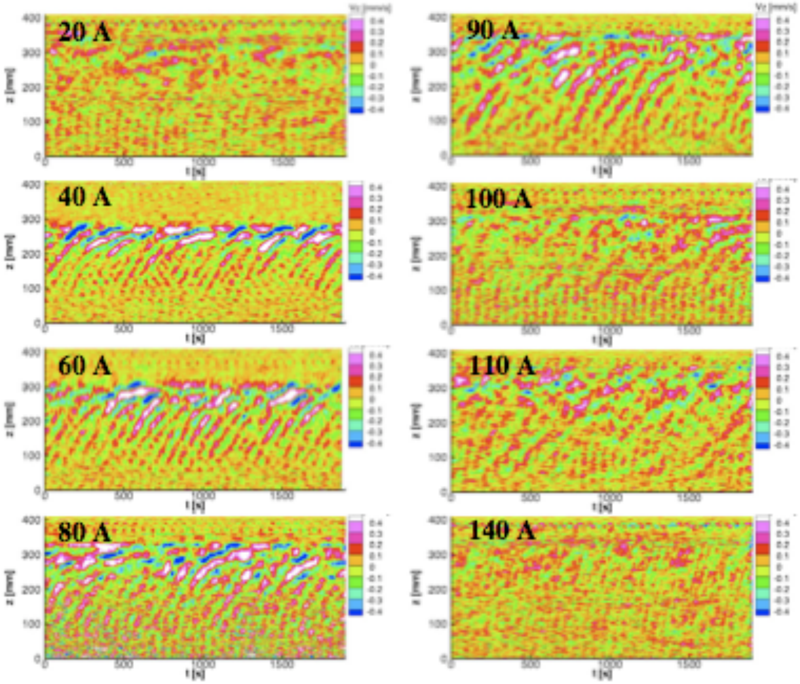


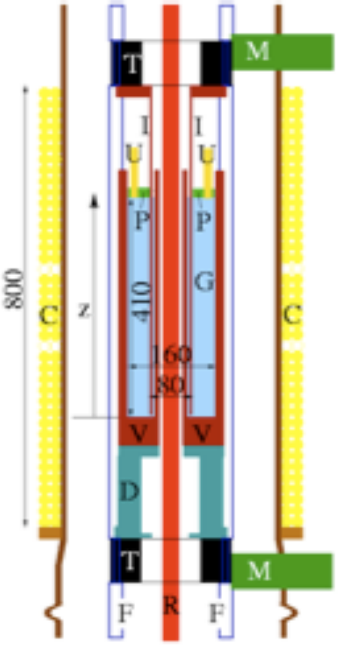


Sisan et al. PRL ***93*** *(2004)*

PROMISE Helical MRI Experiment

- Creating a helical externally applied field lowers the threshold for instability by supplying the azimuthal field induced by MRI
- A travelling wave appears for moderate field strength that is an absolute instability for a restricted range and is otherwise a convective instability
- Need measurements of stresses to determine transport





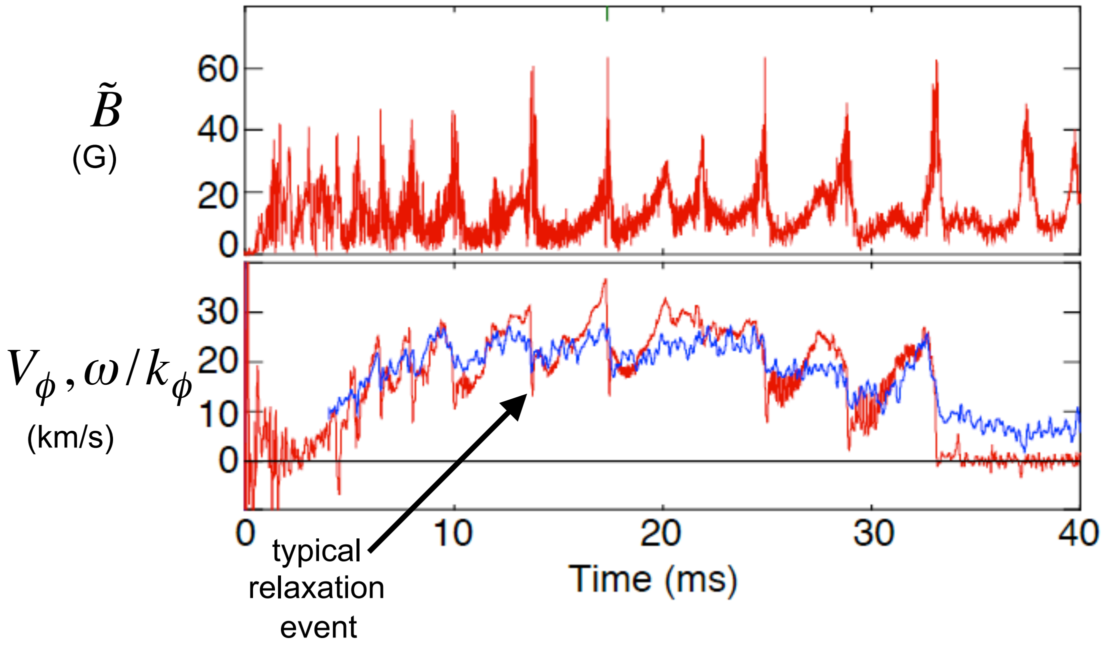
Stefani et al. NJP ***9*** *(2007)*

Current gradient driven transport in RFP

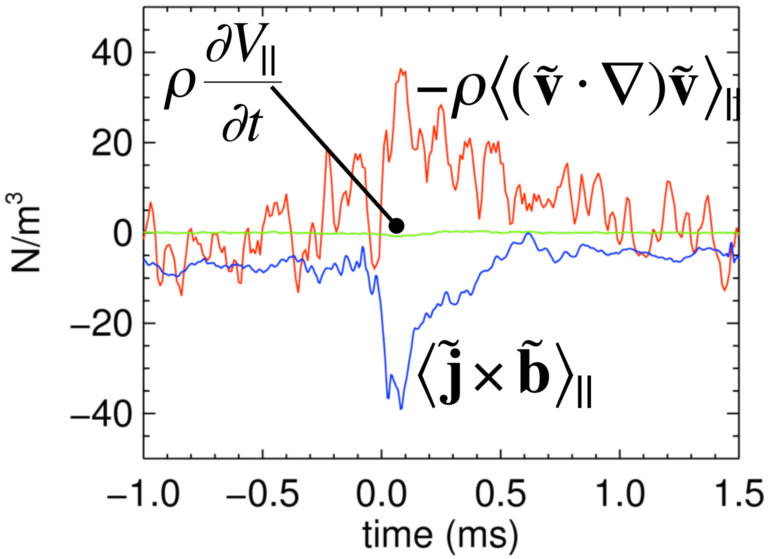
- Multiple resonant tearing modes become nonlinearly coupled to produce strong torques that are mostly balanced

$$\rho \frac{\partial V_{||}}{\partial t} = \langle \tilde{\mathbf{j}} \times \tilde{\mathbf{b}} \rangle_{||} - \rho\langle(\tilde{\mathbf{v}}\cdot\nabla)\tilde{\mathbf{v}}\rangle_{||} - \nabla_{||} p + \nu\rho\nabla^2 V_{||}$$

Results from measurements on MST at UW-Madison



typical relaxation event



Turbulent EMF and momentum transport coupled through the Hall term

Turbulent EMF:

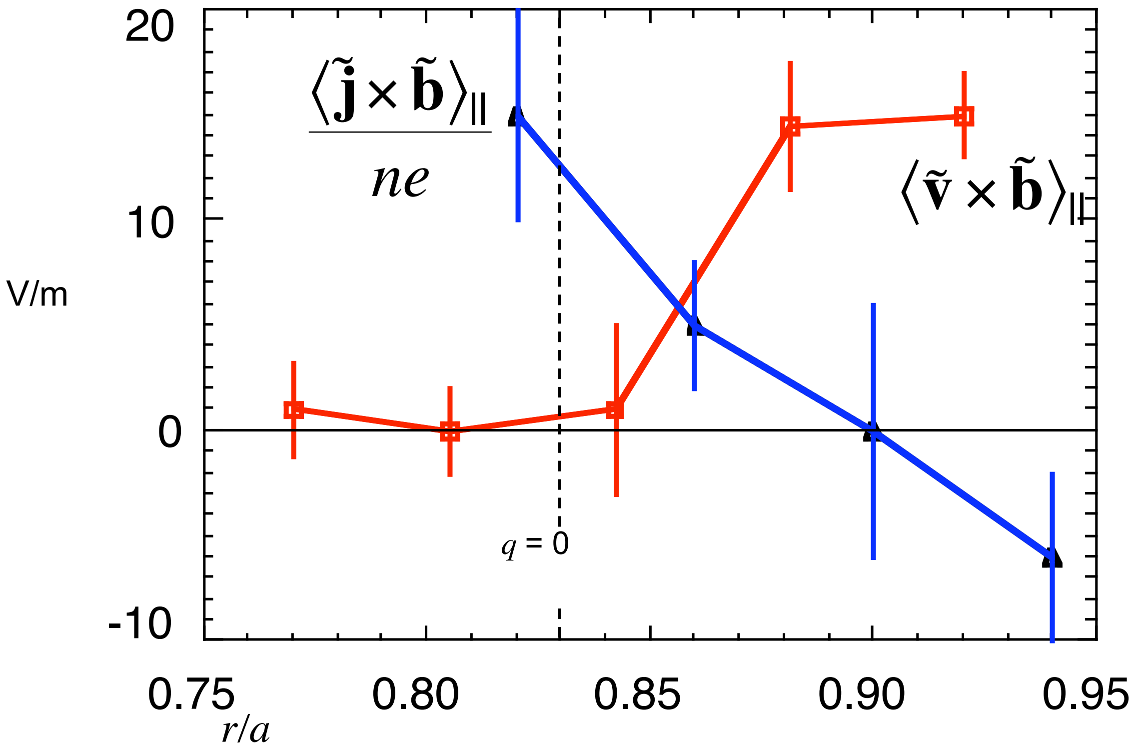
$$\langle E\rangle_{\parallel} - \eta\langle J\rangle_{\parallel} = \frac{1}{en}\langle \tilde{\mathbf{j}}\times\tilde{\mathbf{b}}\rangle_{\parallel} - \langle \tilde{\mathbf{v}}\times\tilde{\mathbf{b}}\rangle_{\parallel}$$

Momentum:

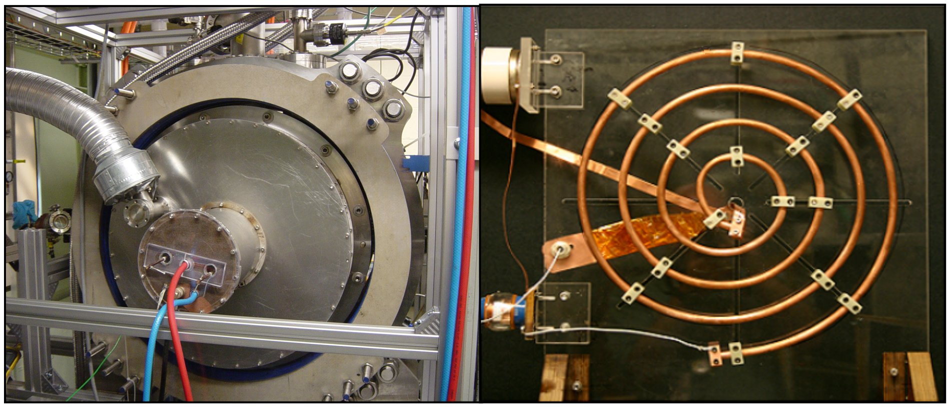
$$\rho\frac{\partial V_{\parallel}}{\partial t} = -\rho\langle(\tilde{\mathbf{v}}\cdot\nabla)\tilde{\mathbf{v}}\rangle_{\parallel} + \langle \tilde{\mathbf{j}}\times\tilde{\mathbf{b}}\rangle_{\parallel}$$

The RFP is a good example of dynamic coupling between a dynamically generated field and momentum transport

Possible building blocks for understanding physics of turbulent transport in jets



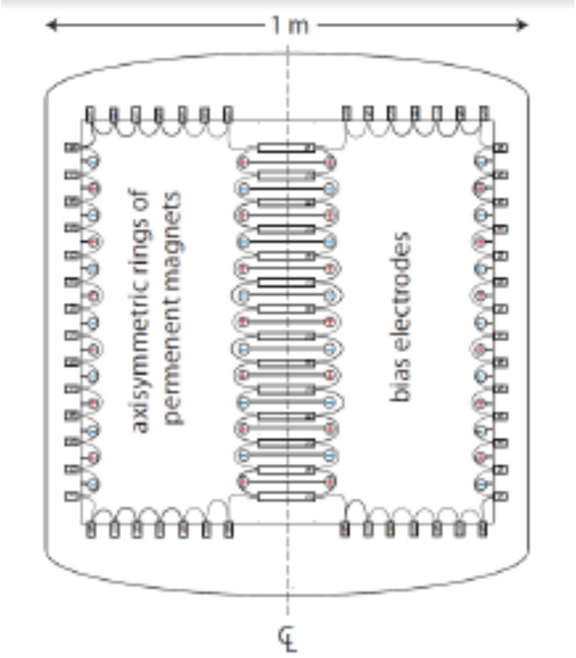
A Plasma Experiment Using Helicon Waves Under Prototyping at Princeton

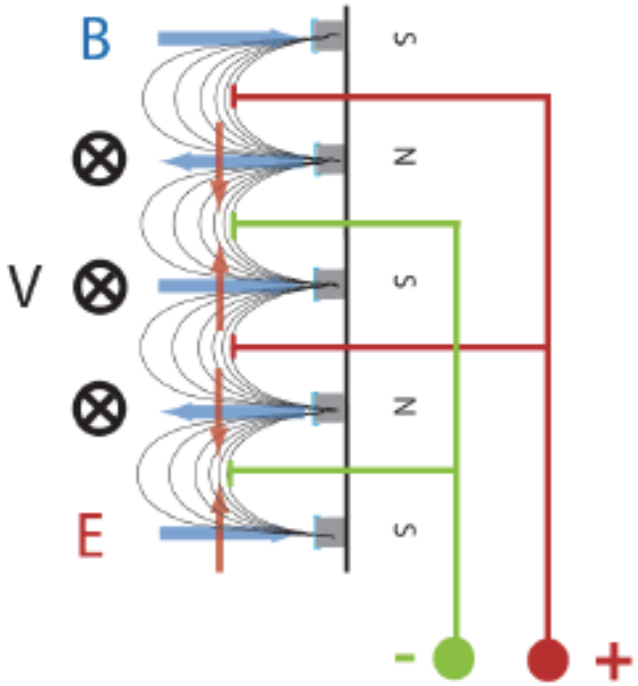


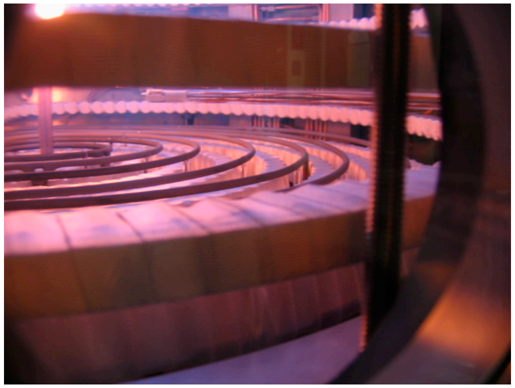
- Helicon discharge capable of steady state operation
- Electrons magnetized; ions are not
- Biased rings drive plasma rotation
- Motivation to study MRI beyond the MHD regime including neutral collisions and two-fluid effects

Apparent rotation of V_θ ~ 1km/s observed, “controllable” by electrodes

Experiments in unmagnetized plasma centrifuge







Plasma Couette Experiment at UW-Madison

- Plasma is created by a cathode source and is retained in the vacuum vessel by cusp field confinement with permanent magnets at the walls
- Confinement field is strong at the walls and weak inside allowing study of unmagnetized plasma
- Flows are generated with biased electrodes utilizing the confining field (prototype for demonstrating flow drive on Plasma Dynamo Experiment)
- Ability to study neutral drag, two-fluid Hall-MRI, kinetic effects

Opportunities

- Hydrodynamic experiments on subcritical hydrodynamic instability can confirm efficiency is insufficient at astrophysically relevant scales
- Liquid metal experiments provide both a means of validating MHD simulations and bridging gap to inaccessible parameter regimes for MRI, studying transition to turbulence, saturation mechanism, and efficiency of transport
- Next stage of experiments to address effects beyond MHD including two-fluid, neutral collisional drag, and kinetic effects

- Fundamental question is method of extrapolation – examples from hydrodynamic interchange turbulence suggest a more complicated model than a simple power law