Laboratory Study of Plasma Space/Astrophysics:

Magnetic Reconnection and Magneto-Rotational Instability

Hantao Ji

Princeton Plasma Physics Laboratory, Princeton University

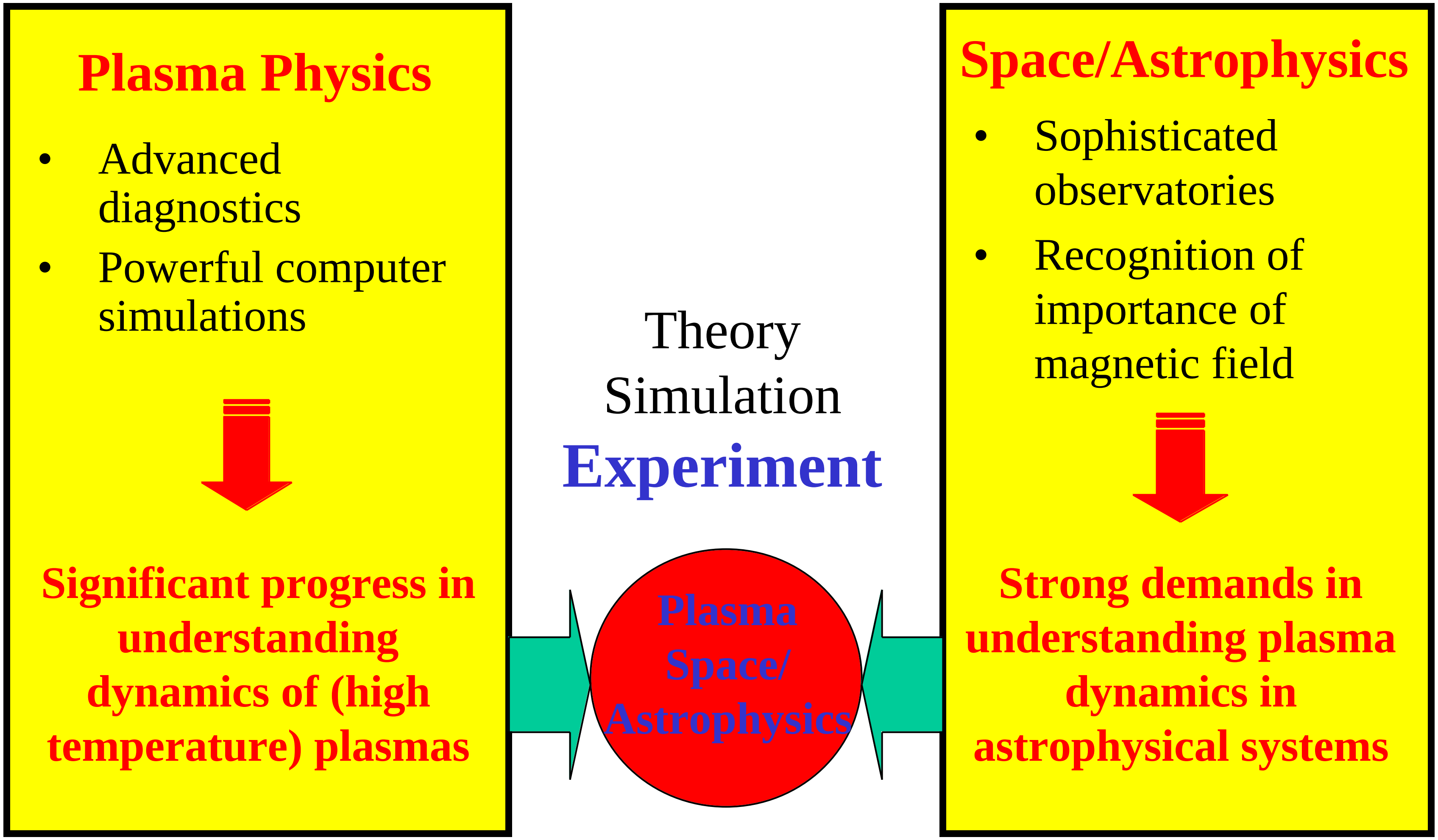
Collaborators:	**Troy Carter**
	Jeremy Goodman ***(Princeton U.)***
	Scott Hsu
	Akira Kageyama ***(NIFS)***
	Russell Kulsrud
	Ethan Shoshan ***(Rutgers U.)***
	Fedor Trinchouk
	Masaaki Yamada

ITC-12 & APFA’01
December 11-14, 2001 at Toki, Japan

Outline

- A Growing Field: Plasma Astrophysics
- Two Examples:
  - Magnetic reconnection
    - **Magnetic Reconnection Experiment** (MRX)
  - Magnetorotational instability (MRI)
    - **Rotating Gallium Disk** (RGD) Experiment
- Relation to **Fusion** Science and Technology
- Summary

A Growing Field: Plasma Space/Astrophysics



Plasma Physics

- Advanced diagnostics
- Powerful computer simulations

Significant progress in understanding dynamics of (high temperature) plasmas

Theory

Simulation

Experiment

Plasma Space/ Astrophysics

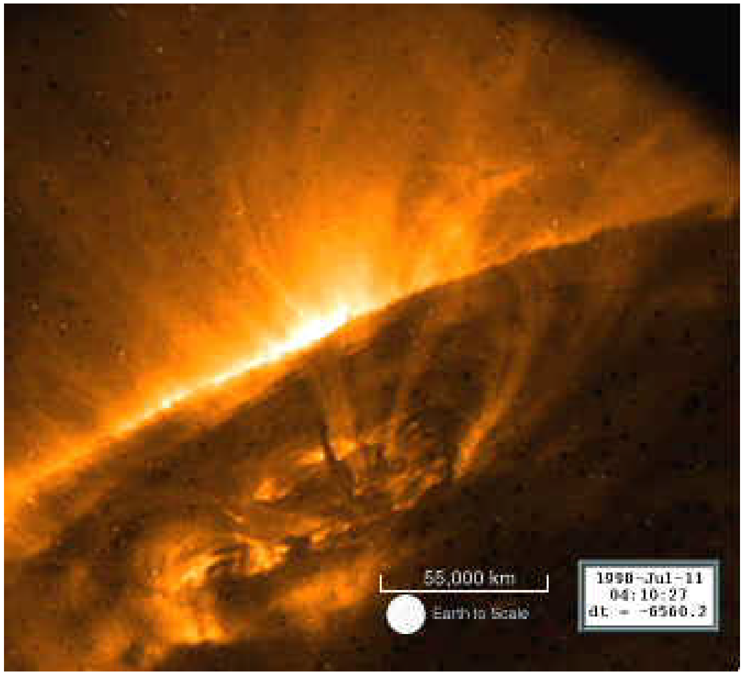
Space/Astrophysics

- Sophisticated observatories
- Recognition of importance of magnetic field

Strong demands in understanding plasma dynamics in astrophysical systems

Many Elementary Processes Can Be Studied in Laboratory

- **Magnetic field generation (dynamo)**
- **Effects of magnetic field**
  - **Mixing process**
  - **Angular momentum transport in accretion disks**
  - **Coronal activities on stellar/disk/galactic surfaces**
  - **Jet formation and particle acceleration**
- **Interactions between magnetic field and plasma (magnetic reconnection)**



Evolution of Solar Flare (minutes to hours)

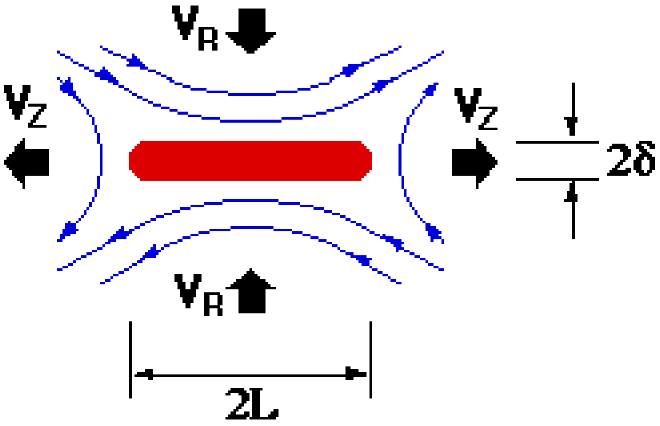
By TRACE satellite

Physics Issues for Understanding Fast Magnetic Reconnection

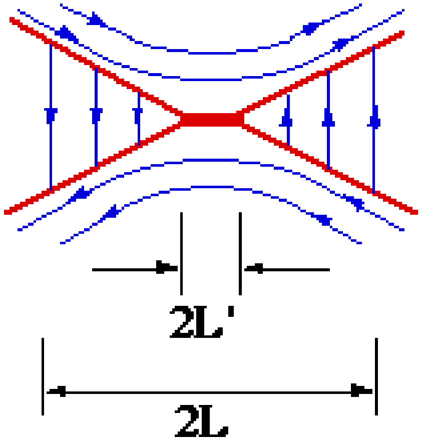
- Sweet-Parker versus Petschek models
- Collisional versus collisionless reconnection
  - Classical collisions and nonclassical collisions (fluctuations)
  - Dissipation mechanism of magnetic energy
- Local versus global
  - Global constraints (conservation of mass, flux…) provides boundary conditions for local physics
  - Local physics decides global magnetic topology and relaxation rate
- Steady state versus transient reconnection
- 2D versus 3D reconnection
  - 2D (w/o 3rd component) and 2.5 D (w/ 3rd component)
  - 3D dynamics in 2D symmetry
  - Reconnection through 3D null-point

Sweet-Parker Model vs. Petschek Model

Sweet-Parker Model



Petschek Model



- **2D & steady state**
- **Imcompressible**
- **Classical resistivity**

- **In addition:**
  - **A much smaller diffusion region (L'<<L)**
  - **Shock structure**

$$\frac{V_R}{V_A} = \frac{1}{\sqrt{S}}$$

S: Lundquest #

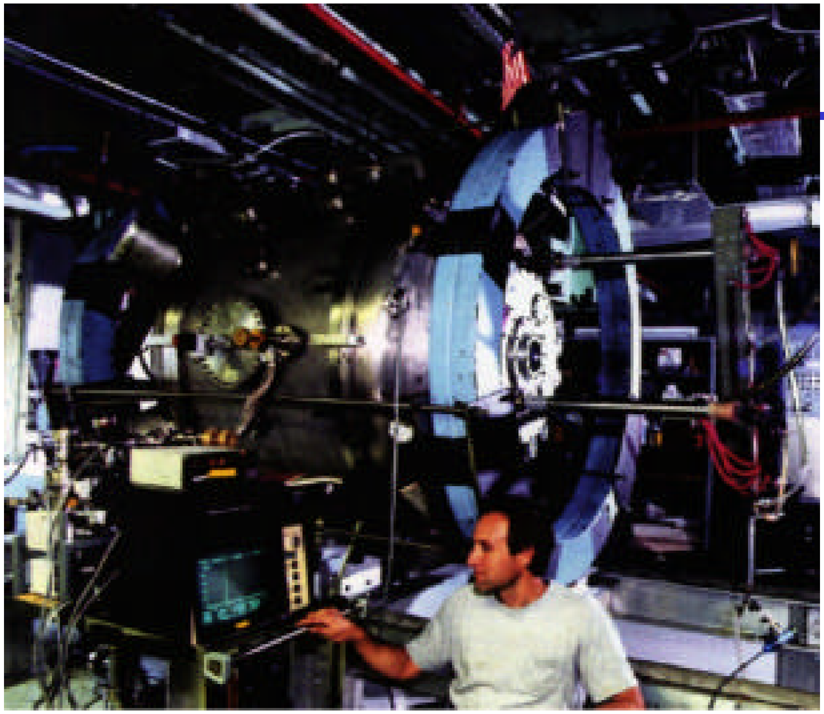
$\equiv \tau_{diff} / \tau_A$

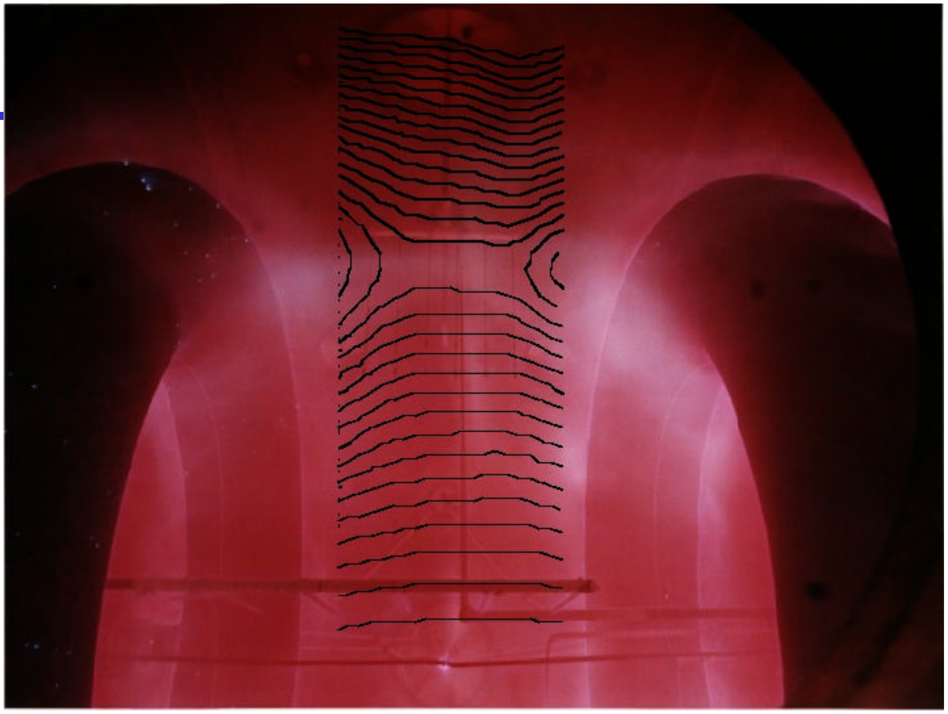
$$\frac{V_R}{V_A} \approx \frac{1}{\ln(S)}$$

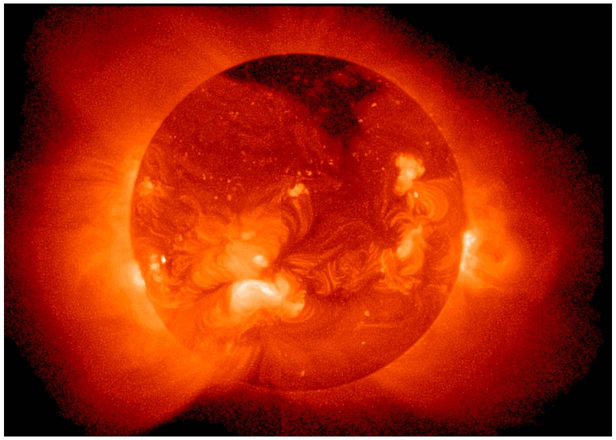
Prediction: a few months but can be shorter with anomalous resistivity

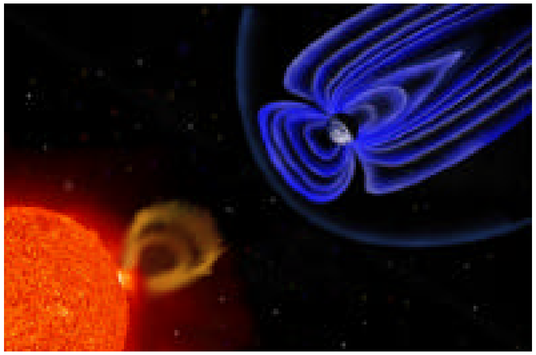
Prediction: <1 hour but inconsistent with uniform resistivity

Magnetic Reconnection Experiment



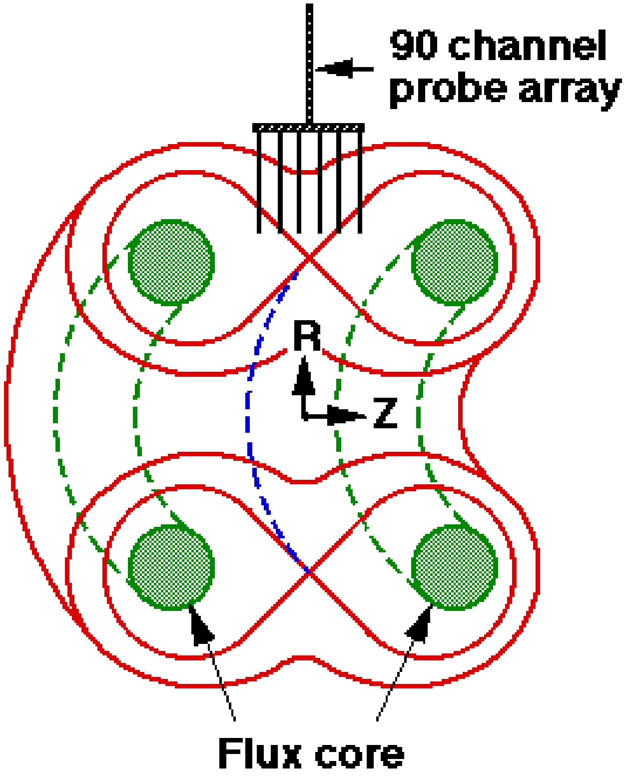


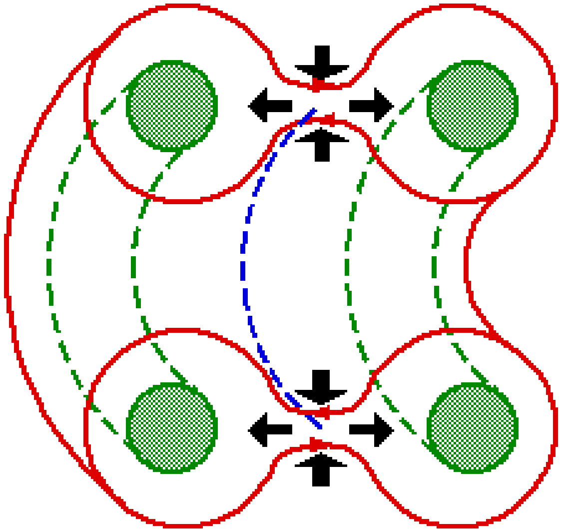




PPPL
PRINCETON PLASMA
PHYSICS LABORATORY

Experimental Setup in MRX



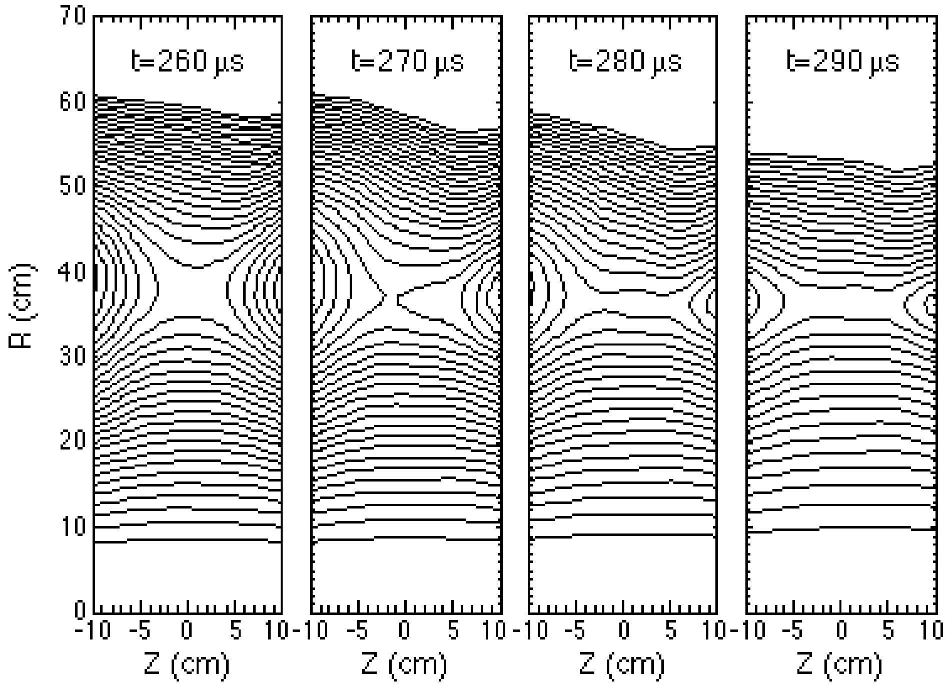


"Pull" reconnection

Realization of 2D Current Sheet and Steady Reconnection

Yamada et al. PRL (1997)

pull reconnection, no guide field

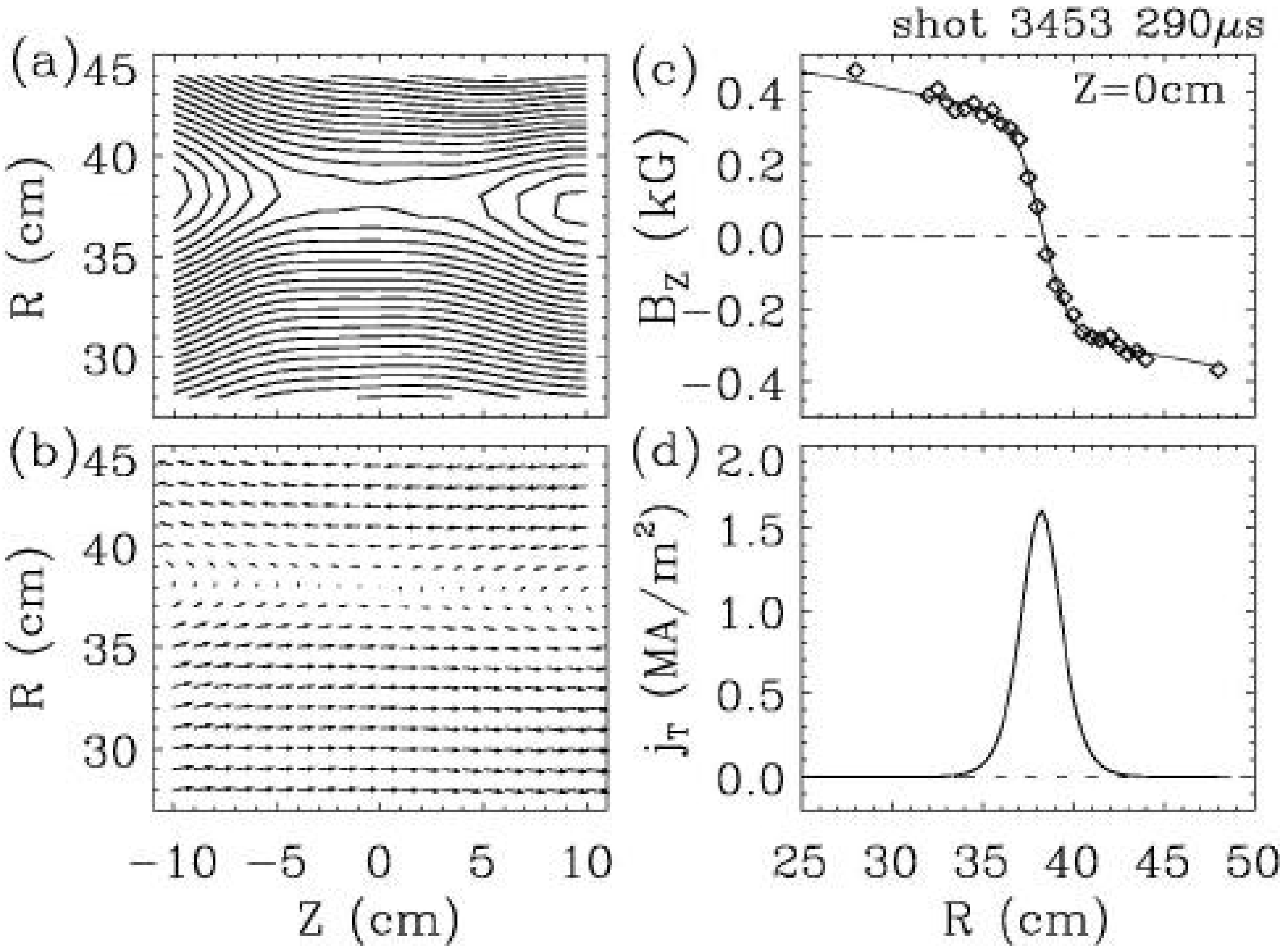


- Formation of stable 2D current sheet (~20-30 τ_{Alfven})
- Quasi-steady state reconnection realized.

Parameters: B<2kG, $T_e \sim T_i$=5-20eV, $n_e=(0.1-2)\times 10^{20}/m^3$

→**S<1000**

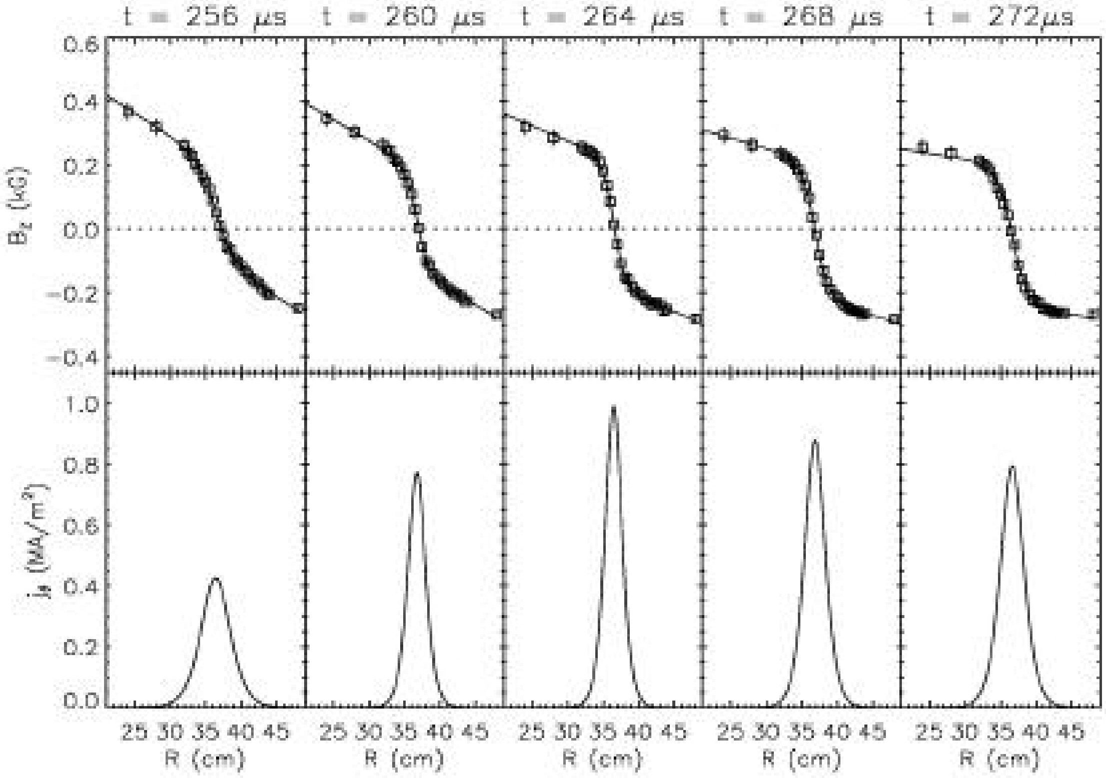
Diffusion Regions Qualitatively Consistent with Sweet-Parker Model



An example: Sweet-Parker like diffusion region

Measured Magnetic Profiles Agree Well with a Generalized Harris Solution

Yamada et al. PoP (2000)

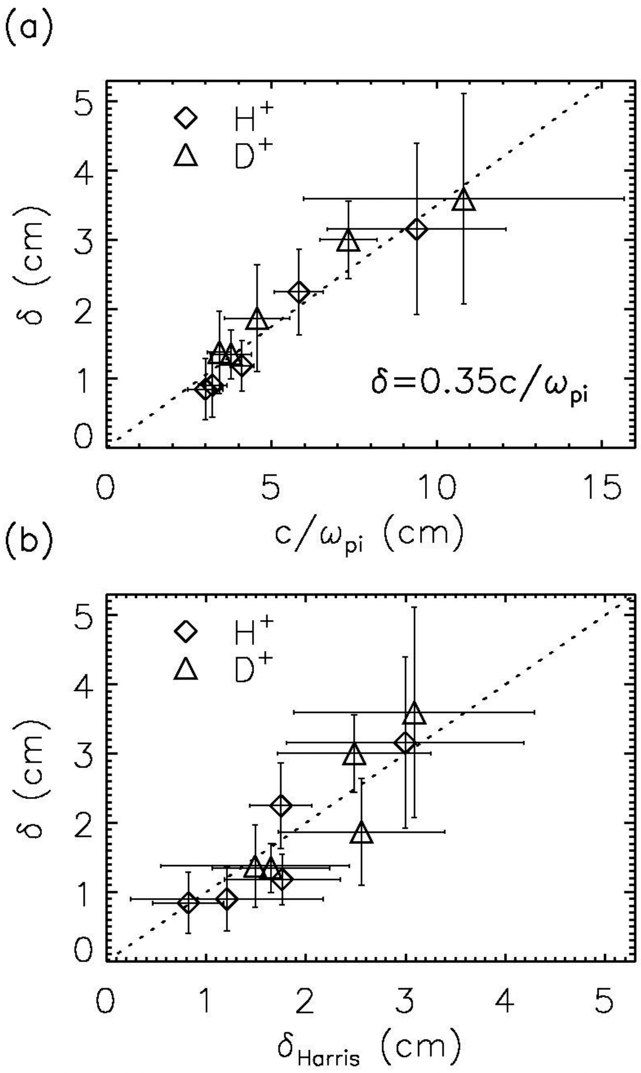


$$B_z(R) = -B_0\tanh\left(\frac{R-R_0}{\delta}\right) + b_1 R + b_2$$

$$j_T(R) = \frac{B_0}{\mu_0\delta}\,\mathrm{sech}^2\left(\frac{R-R_0}{\delta}\right)$$

- **Harris solution (generalized for the Te ≠ Ti case) predicts tanh form of B!**

Sheet Thickness Also Agrees Well With Harris Model

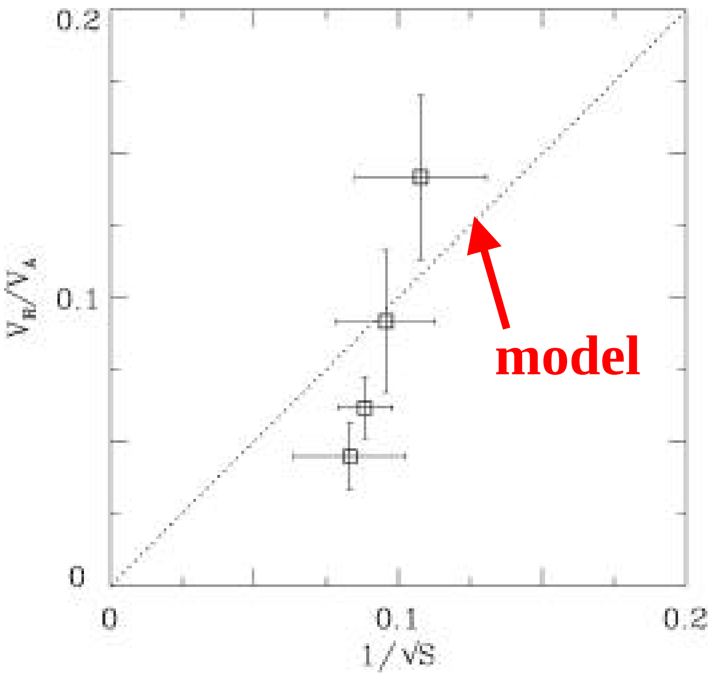


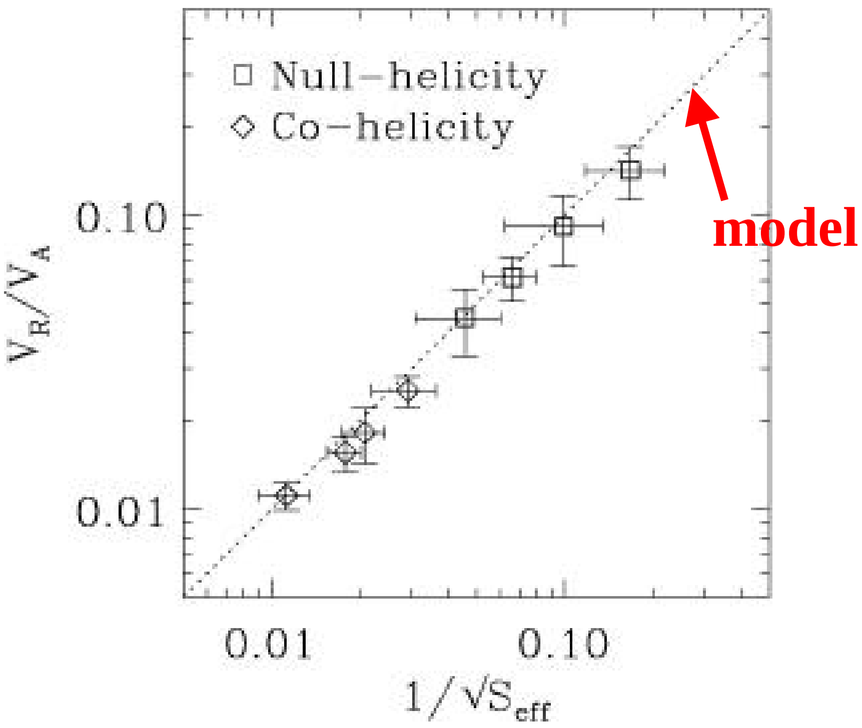
- **Consistent with Harris solution.**
- **δ scales with c/ω_{pi}**
  - **Constant normalized drift velocity**
  - **Not determined by Sweet-Parker thickness (L/√S)**
  - **Consistent with simulations**

$$\delta_{\text{Harris}} = \frac{c}{\omega_{pi}} \frac{\sqrt{2}V_s}{V_{drift}}$$

Measurements Agree Only with a Generalized Sweet-Parker Model

Ji et al. PRL (1998); PoP (1999)





Comparisons with classical Sweet-Parker model

A generalized model:

$$S_{\rm eff} = \frac{\mu_0 L V_A}{\eta^*} \cdot \frac{1}{1 + L\dot{n}/nV_Z} \cdot \frac{V_Z}{V_A}$$

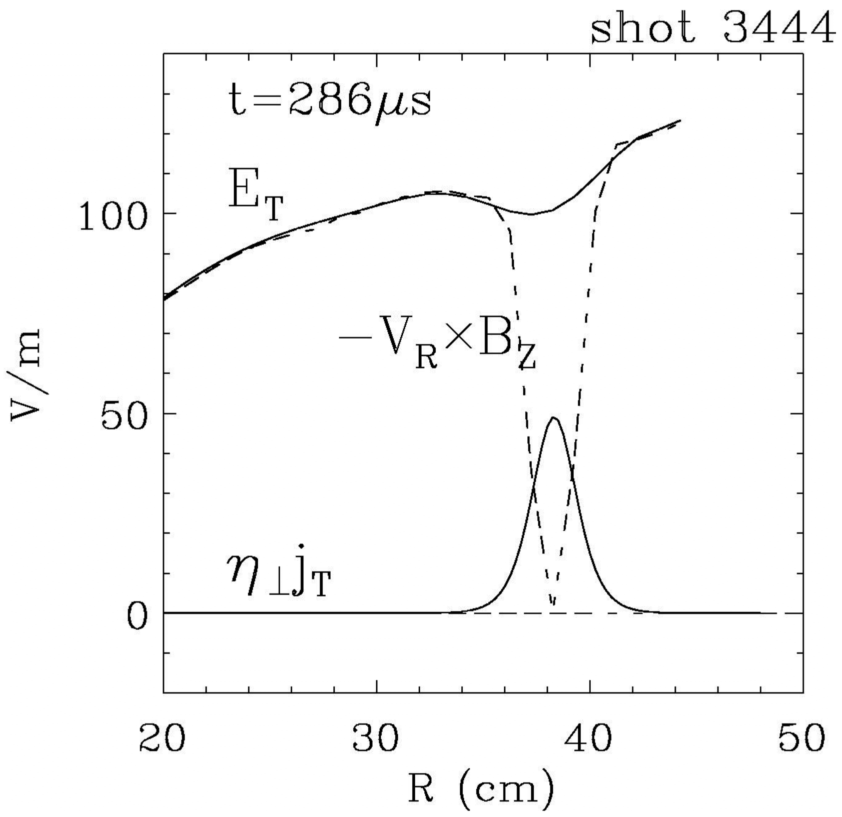
enhanced η

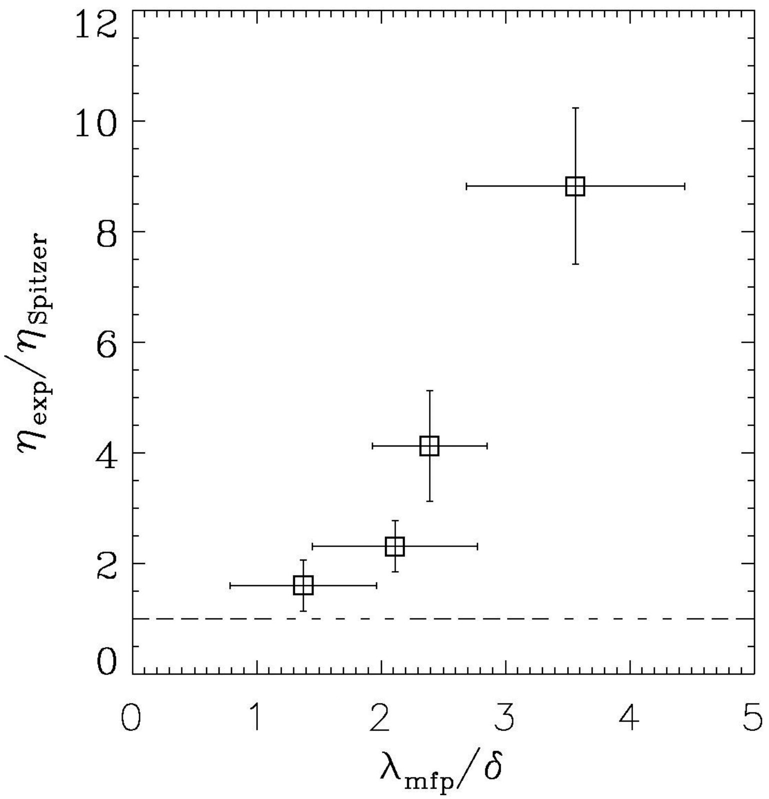
compressible

slowed outflow

Resistivity Determination and Dependence on Collisionality

Ji et al. PRL (1998)



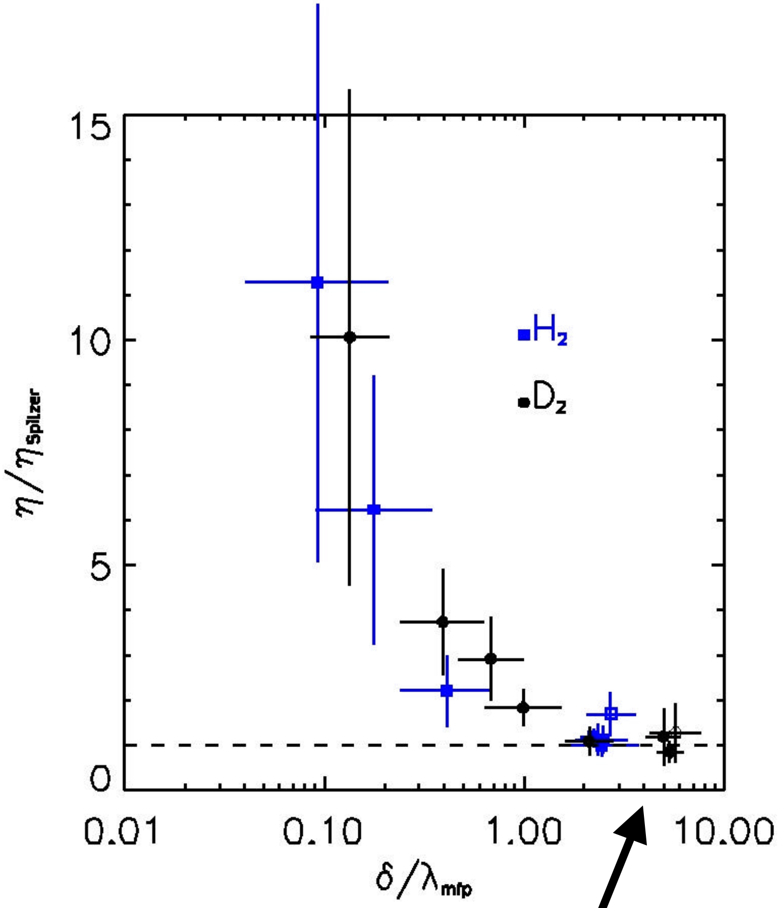


$$E_\theta + V_R \times B_Z = \eta j_\theta \qquad \eta^* \equiv \frac{E_\theta}{j_\theta}$$

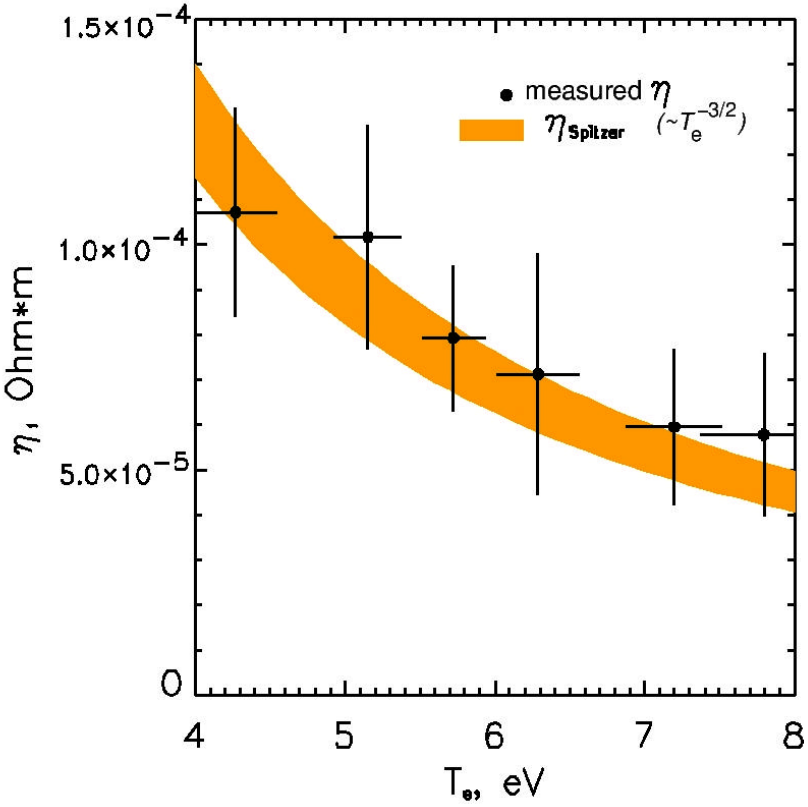
Significant enhancement in low collisionality plasmas

Measurements of Perpendicular Resistivity Extended Well into Collisional Regime

Trinchouk et al. PRL (2001)



($\lambda_{mfp} << \delta$)



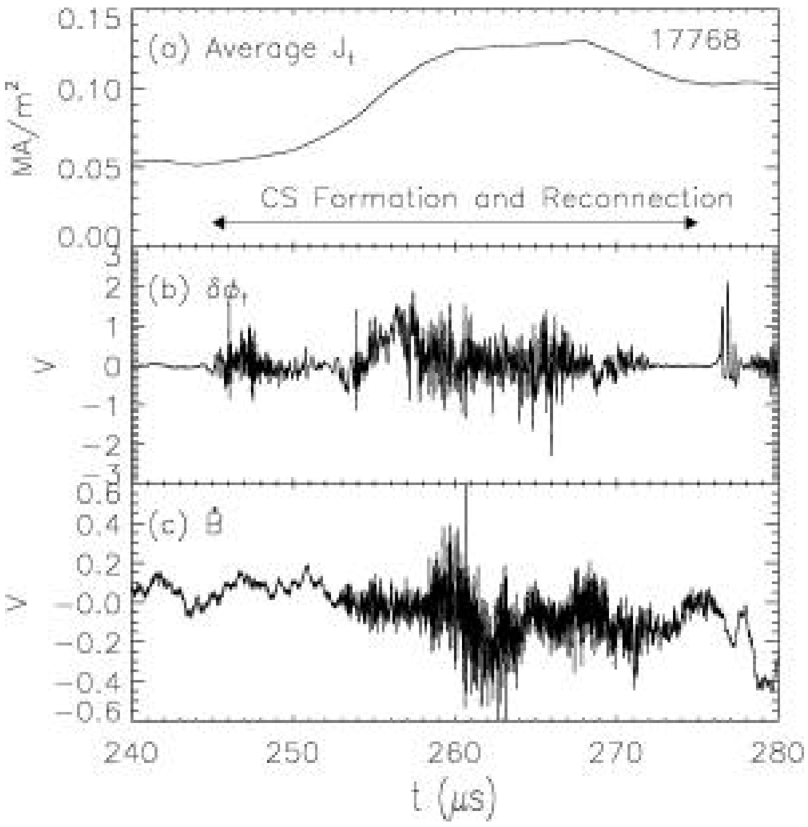
First experimental demonstration of Spitzer perpendicular resistivity

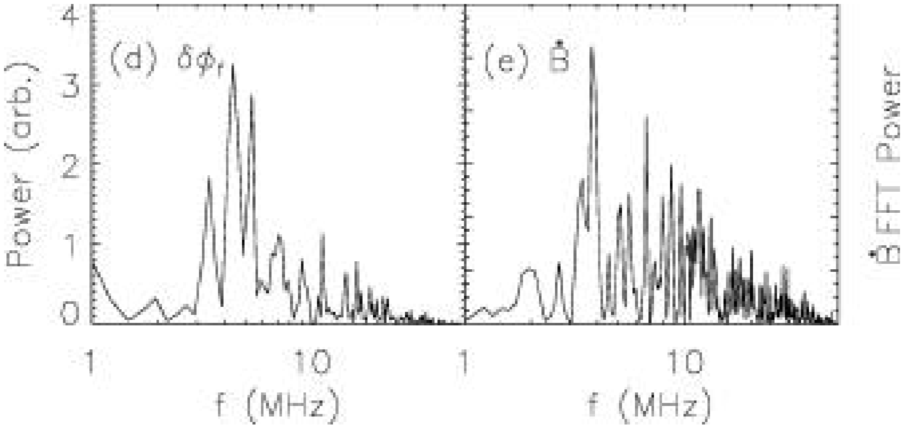
How is the Resistivity Enhanced in MRX?

- Turbulent resistivity due to current driven micro-instabilities (i.e., lower hybrid drift wave)
  - Wave-particle interactions to dissipate current/energy
  - Intensive works since ‘70
  - Not consistent with fluctuation measurement (Carter et al. 2001)
- Facilitation by non-dissipative Hall terms
  - Formation of thin dissipative electron layer
  - Demonstrated in simulations and theories
  - Have not been detected (electric field, fine structures…)
- “Speiser effect” or single-particle orbit
  - Loss of particle, current and energy
  - Not self-consistent and not likely
- Electron neutral collisions

Lower-Hybrid Drift Fluctuations Measured in Current Sheet Region

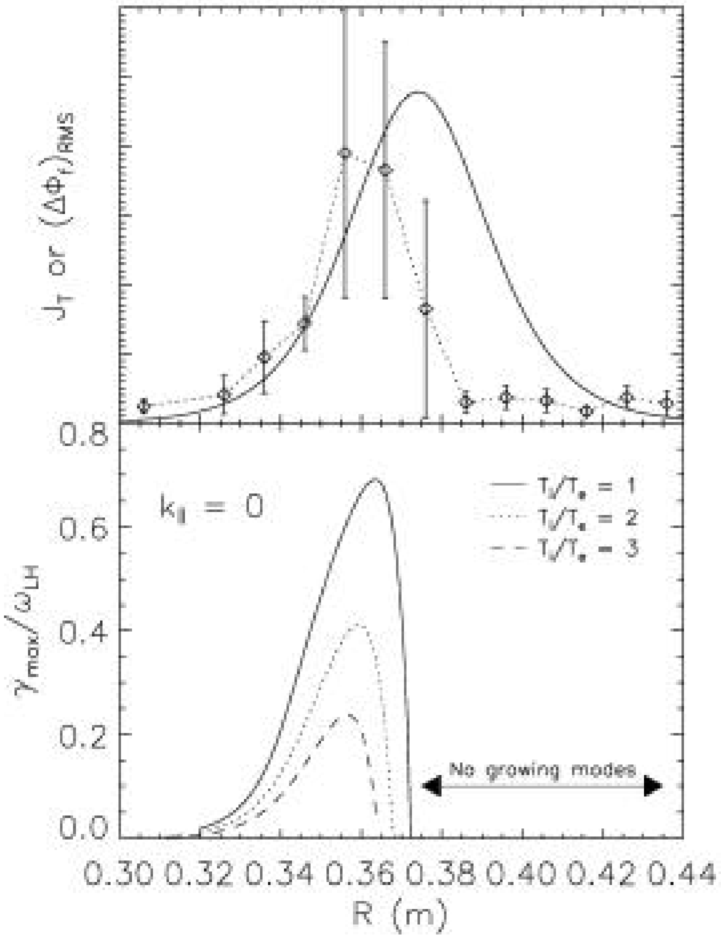
Carter et al. PRL (2001)



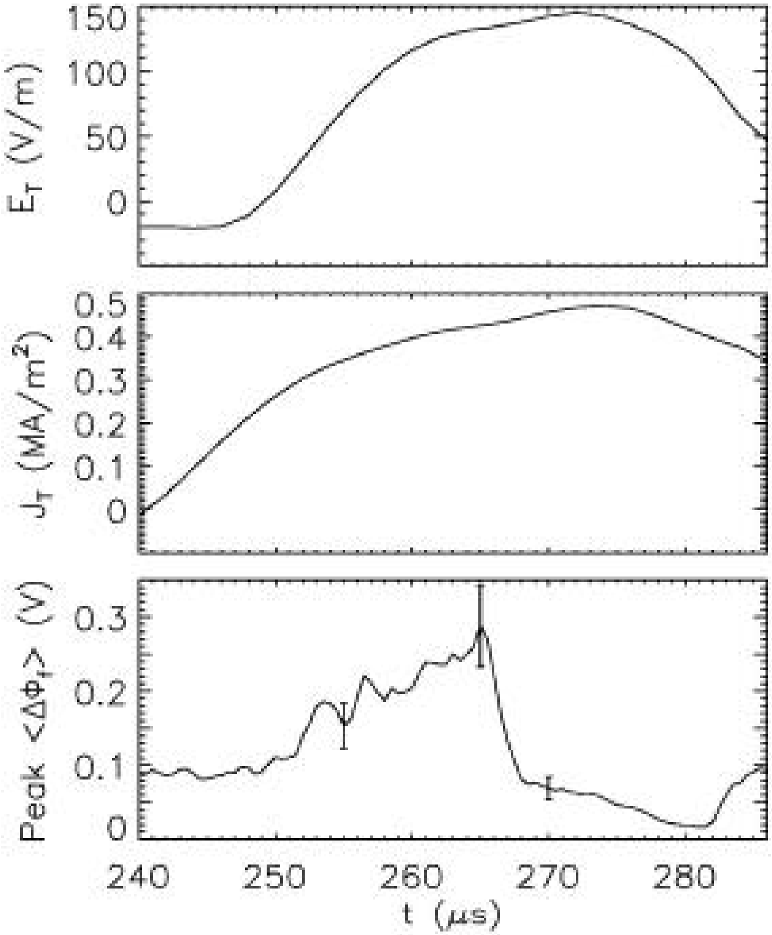


- Both electrostatic and electromagnetic fluctuations detected
- Frequency scales with lower-hybrid freq.

Measurements Consistent with Theory But Inconsistent with Resistivity Enhancement



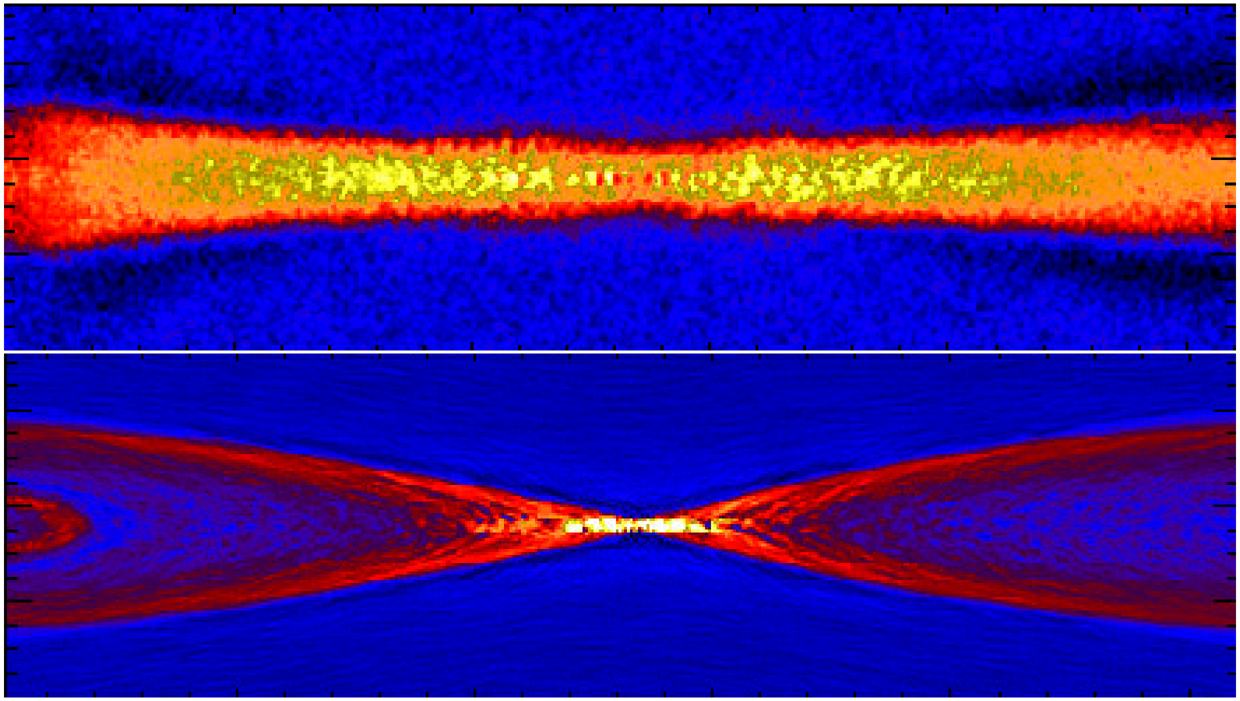
Radial profiles consistent **with linear theory**



Time dependence inconsistent **with resistivity enhancement**

Fast Reconnection Facilitated by Hall Effects

Drake et al. (1998)



Ion Current
(ion skin depth,
similar to S-P
model)

Electron Current
(similar to
Petschek Model)

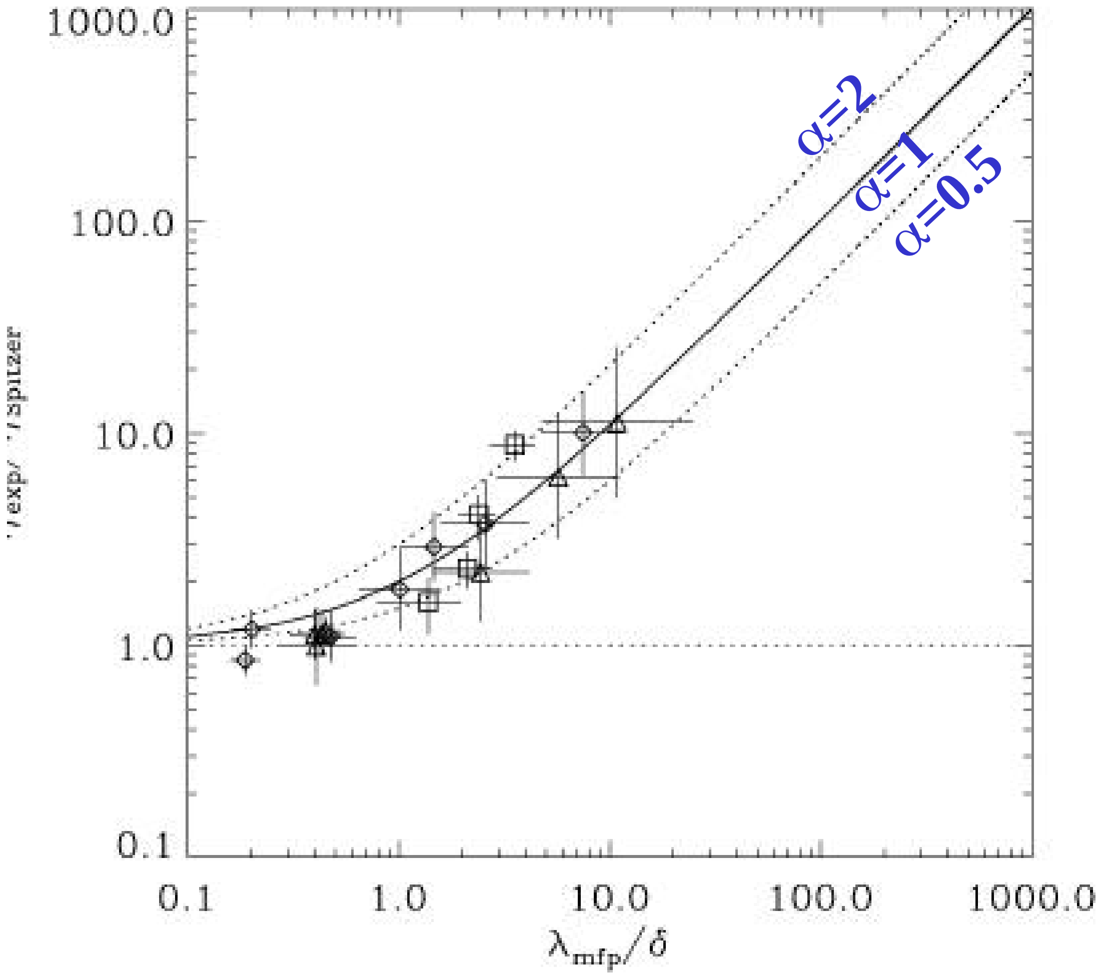
A combination of both models through electric field!

Generalized Ohm's law:

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J} + \frac{\mathbf{J} \times \mathbf{B} - \nabla p}{en} + \frac{m_e}{e^2} \frac{\mathrm{d}\mathbf{V}_e}{\mathrm{d}t}$$

Hall terms electron inertia

Resistivity Enhancement Depends on Collisionality



- **Experiments:**

$$\frac{\eta^*}{\eta} = 1 + \alpha \frac{\lambda_{\text{mfp}}}{\delta}$$

- **Define:**

$$\eta = \frac{m_e}{e^2}\frac{\nu_{ei}}{n_e} \qquad \eta^* = \frac{m_e}{e^2}\frac{\nu_{ei} + \nu^*}{n_e}$$

➡ $$\frac{\eta^*}{\eta} = 1 + \frac{\nu^*}{\nu_{ei}}$$

- **Effective collision frequency:**

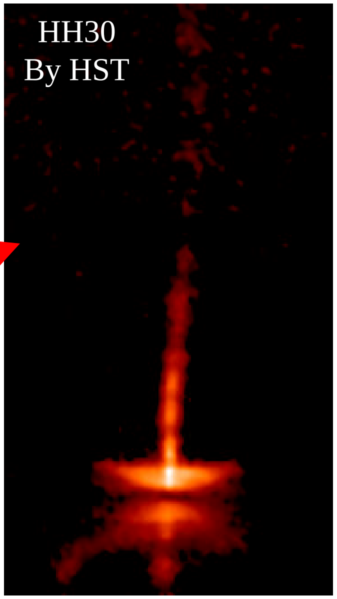
$$\nu^* = \alpha \frac{V_{\text{th,e}}}{\delta} \approx 3\alpha \frac{V_{\text{th,e}}}{c/\omega_{\text{pi}}}$$

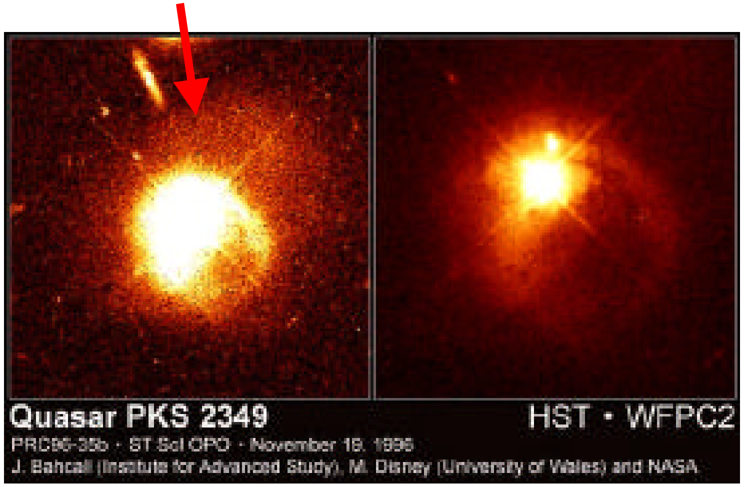
- **Predicts ~9 hour flare time.**

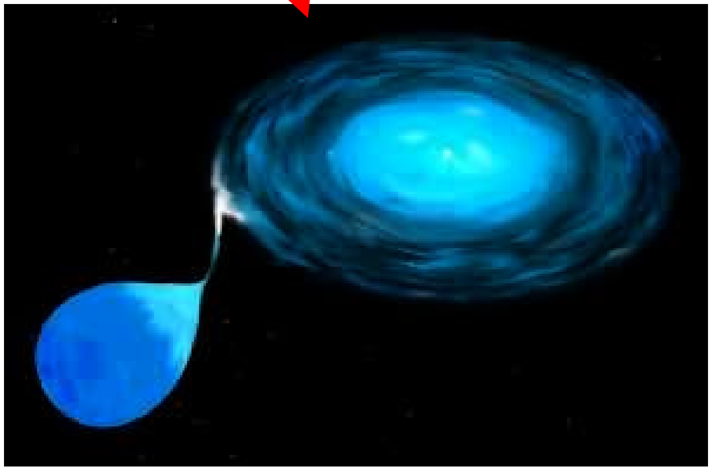
$$\left(\eta^*/\eta = 4 \times 10^4\right)$$

Accretion Disks

- **An accretion disk consists of gas, dust and plasmas rotating around and slowly accreting onto a central point-like object.**
- **Many important astrophysical processes happen in accretion disks:**
  - **Formation of stars and planets in proto-star systems**
  - **Mass transfer and energetic activity in binary stars**
  - **Release of energy (as luminous as 10^{15} of Sun) in quasars and AGNs**

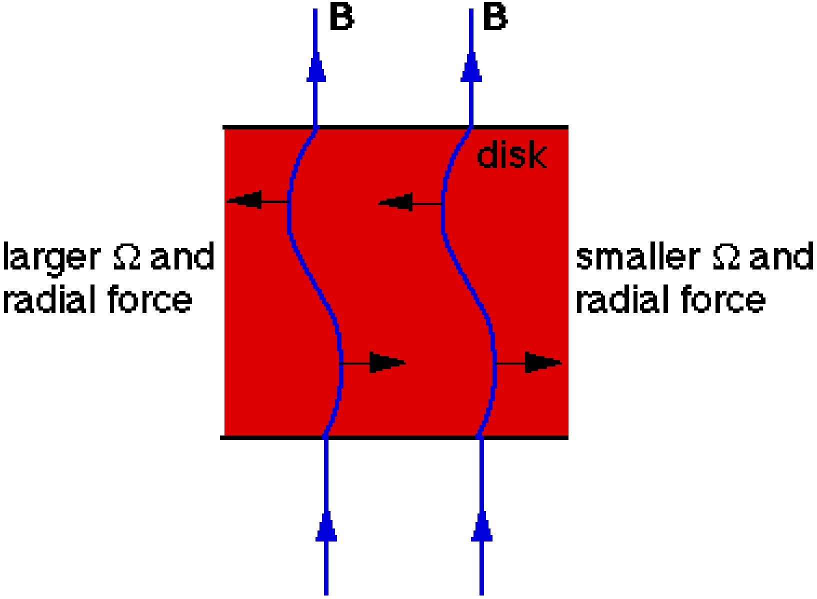






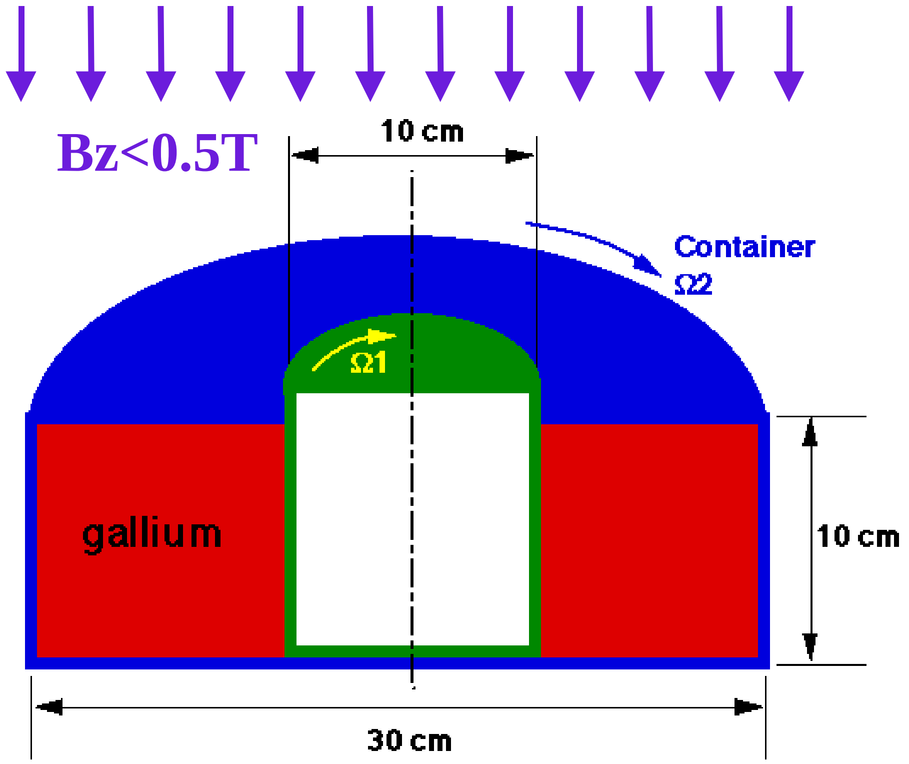
Magnetorotational Instability and Angular Momentum Transport in Accretion Disks

- A long-standing question is why the accretion is fast or angular momentum outward transport is fast.
  - Classical viscosity provides negligible transport
  - Hydrodynamically steady state disks (Keplerian disks) are stable satisfying Rayleigh's criterion $d(R^2\Omega)/dR>0$ since $\Omega \propto 1/R^{3/2}$ and $R^2\Omega \propto R^{1/2}$
- However, disks can be unstable in MHD: Magnetorotational Instability
  - Originally discovered by Velikhov (1959) and Chandrasekhar (1960)
  - Rediscovered by Balbus & Hawley (1991)
- MRI occurs when $d\Omega/dR<0$ with a vertical B:
  - Radially displaced fluid elements are linked by B.
  - Fast part is slowed and slow part is accelerated, → angular momentum transport.
- Stable if B is too strong or too resistive



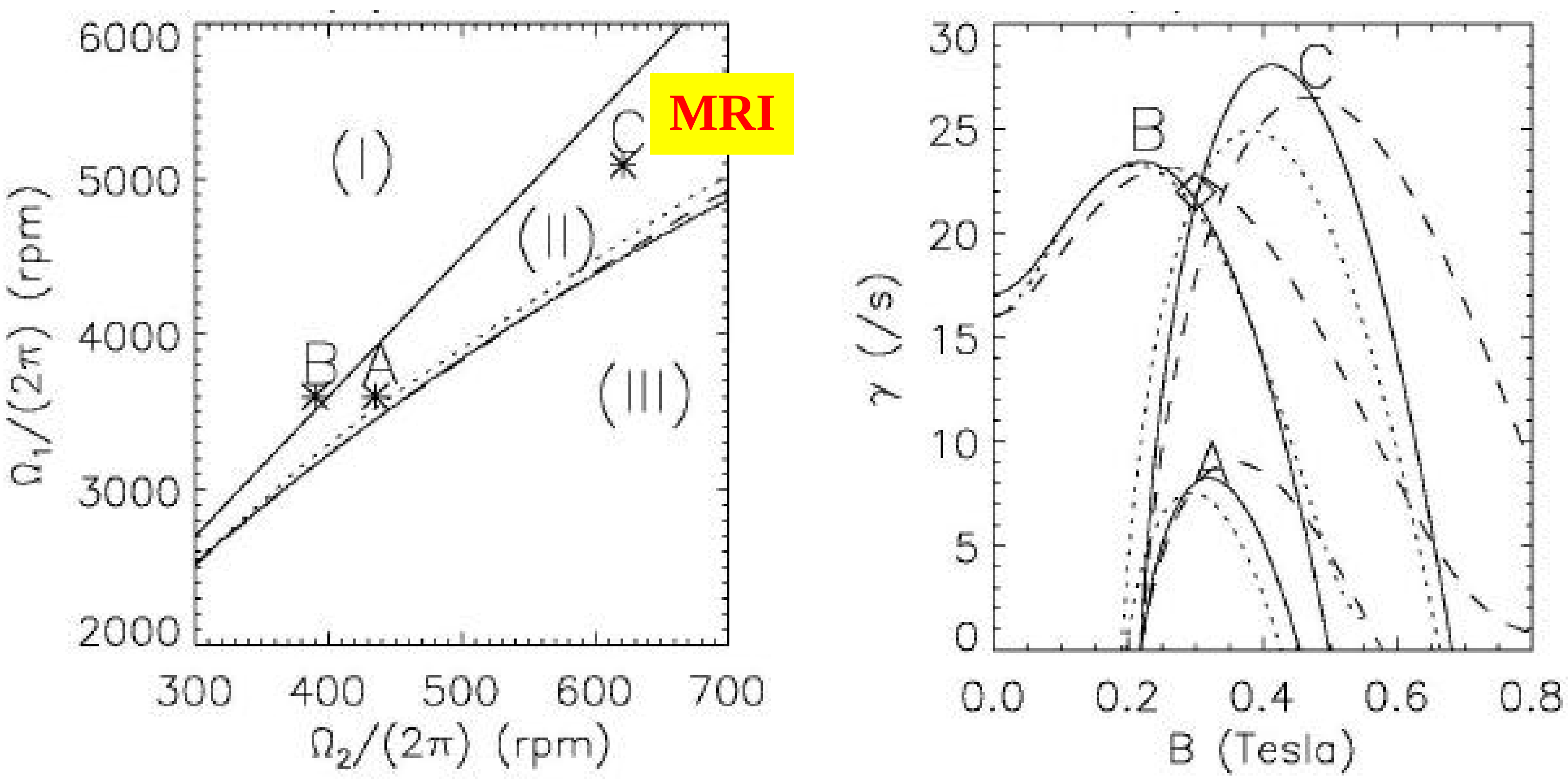
A Rotating Gallium Disk Experiment to Demonstrate and Study MRI

- **MRI exists so far only in theories and numerical simulations**
  - **Theories:** Curry, Pudritz, & Sutherlan (1994), Blaes & Balbus (1994), Gammie (1996), Jin (1996), Sano & Miyama (1999)…
  - **Simulations:** Brandenburg et al. (1995,1996), Matsmoto & Tajima (1995), Hawley et al. (1996,2000), Stone et al. (1996), Fleming & Stone (2000)…
- **RGD experiment is to demonstrate MRI for the first time:**
  - **In a short Couette flow geometry.**
  - **Centrifugal force $\rho V^2/R$ is balanced by pressure force $-dp/dR$ from the wall, acting like gravity force in accretion disks.**
  - **MRI can be destabilized with appropriate Ω_1, Ω_2 and Bz in a table-top size.**



Local and Global Analyses Predict MRI at Moderate Speeds and Sizes

Ji et al., MNRAS (2001)



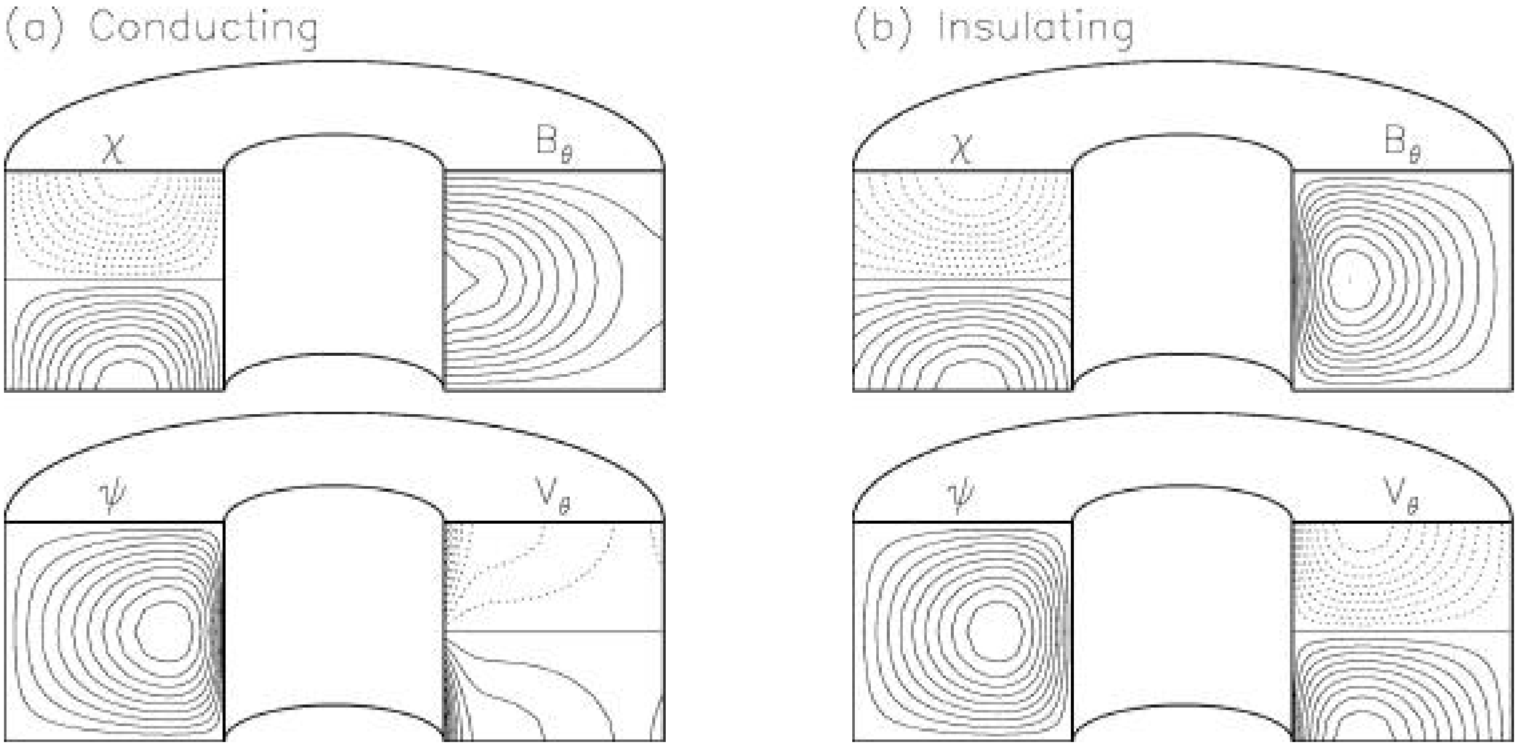
(I): Unstable but can be stabilized by B

(II): Stable but can be destabilized by B: MRI

(III): Always stable

Importance of Boundary Conditions Revealed by Global Analysis

Goodman and Ji, JFM (2001)

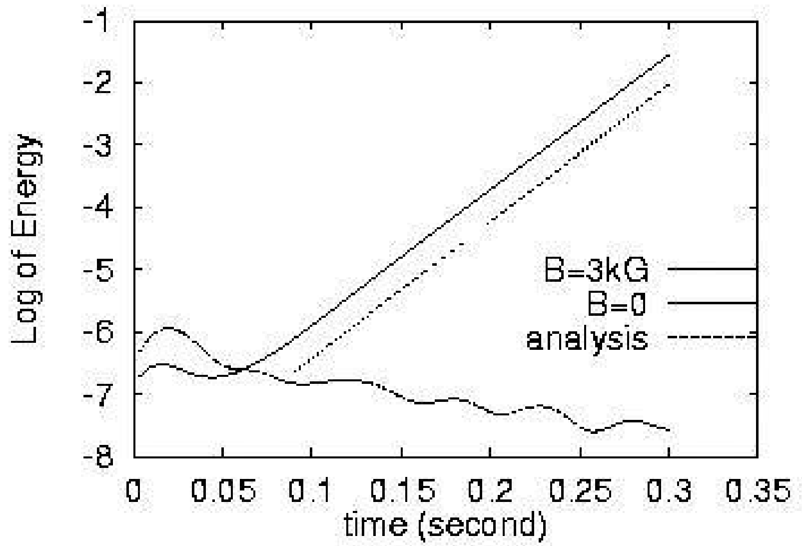


- **Boundary layer forms at inner conducting wall**
- **Ekman layers at top and bottom plates**

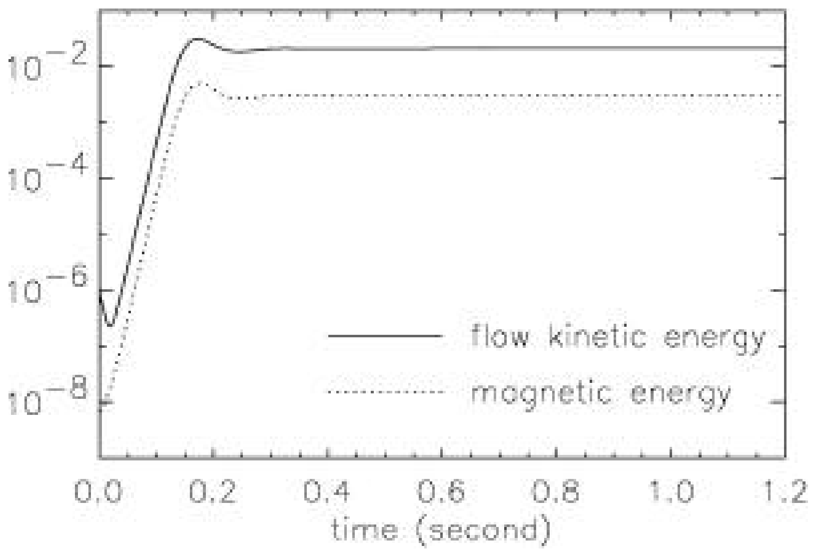
Incompressible Nonlinear MHD Simulations

Kageyama et al. (2001)

- **3-D code (periodic in axial direction)**
  - Spectral method (Chebyshev-Fourier)
  - Time splitting scheme (Green function method for incompressibility)
- **2-D code (finite size in axial direction)**
  - Ekman layer effects

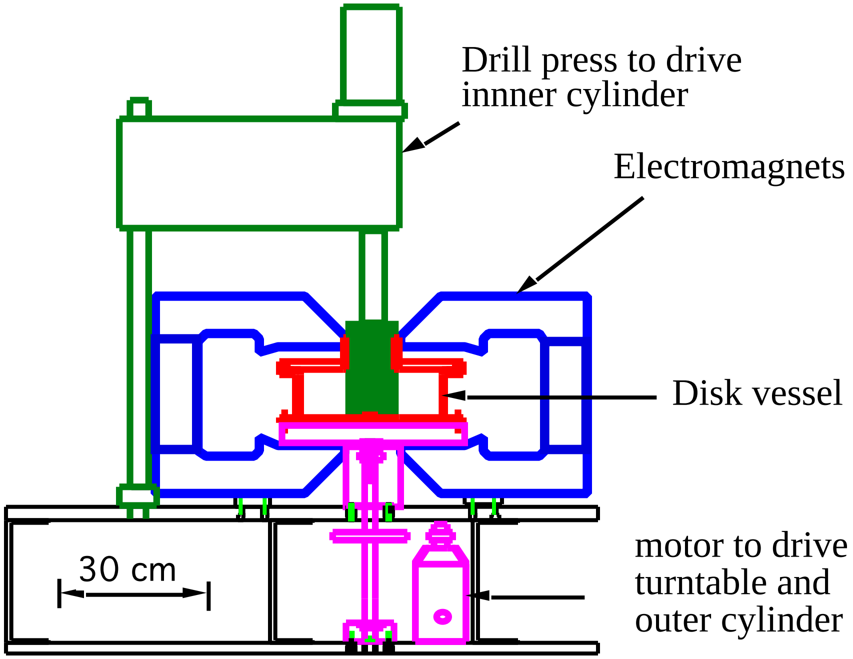


2D linear run

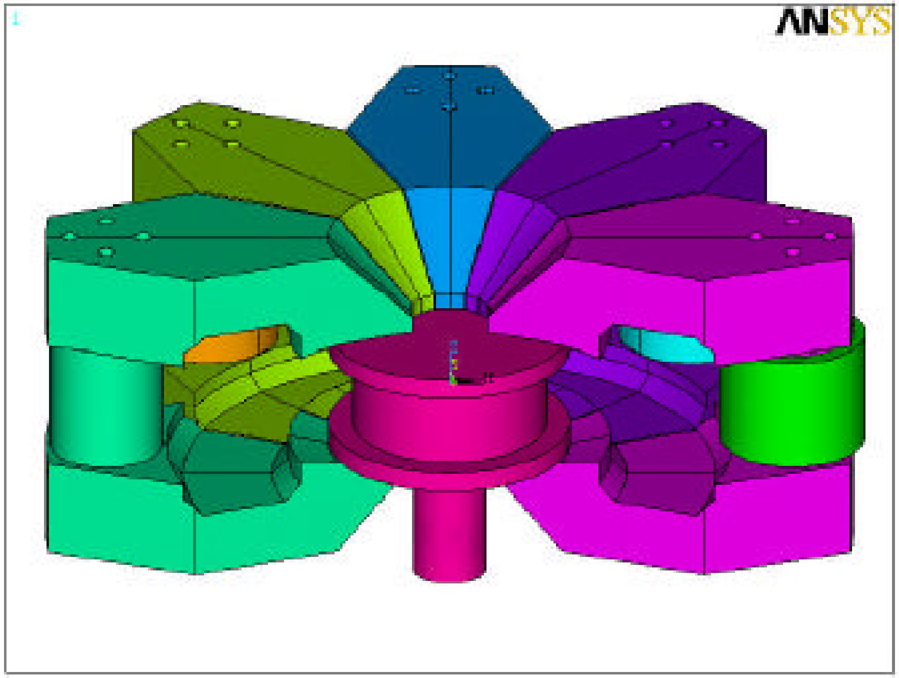


3D nonlinear run

Concept Design of Rotating Gallium Disk



Side view

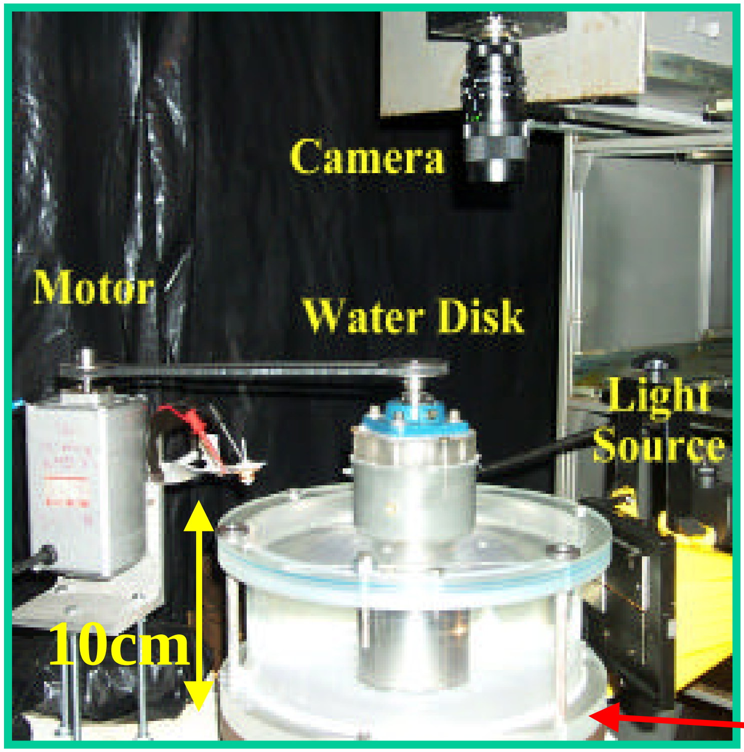


3D electromagnetic analysis

- **120kg of gallium and its alloy has been acquired.**

Prototype Water Disk Experiments Under Way

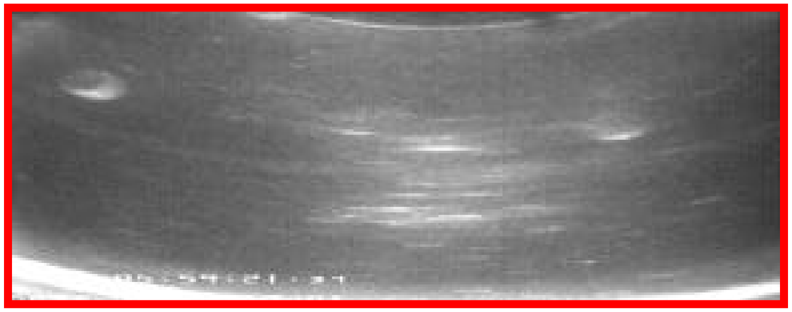
- Establish hydrodynamic reference at fast rotations
  - Study effects of Ekman layers and its control
  - Examine effects of nonlinear instability
- Seed particles to monitor stability and to measure flow



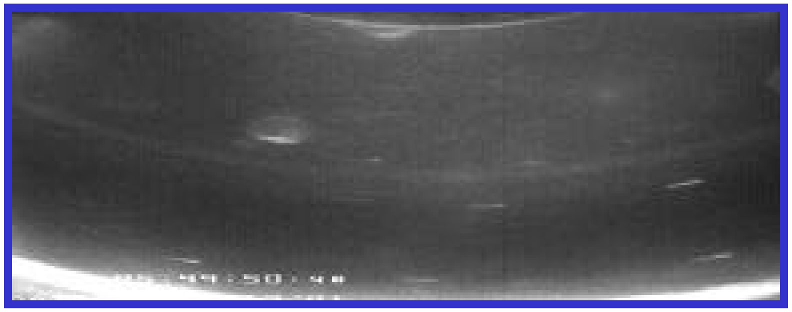
Potter’s wheel

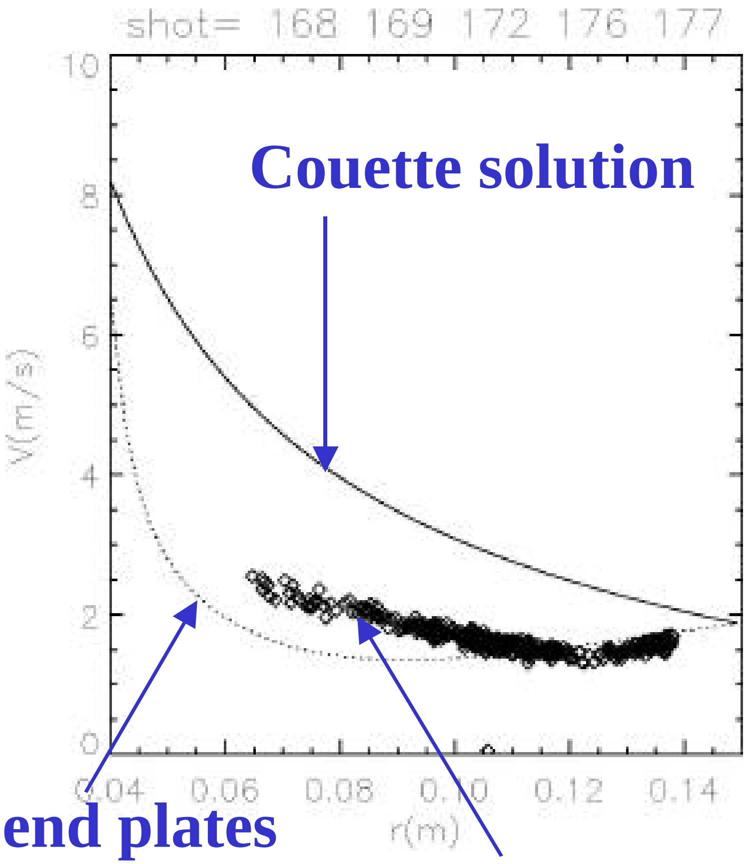
Stability and Flow Measurements

Unstable flow



Stable flow





Couette solution

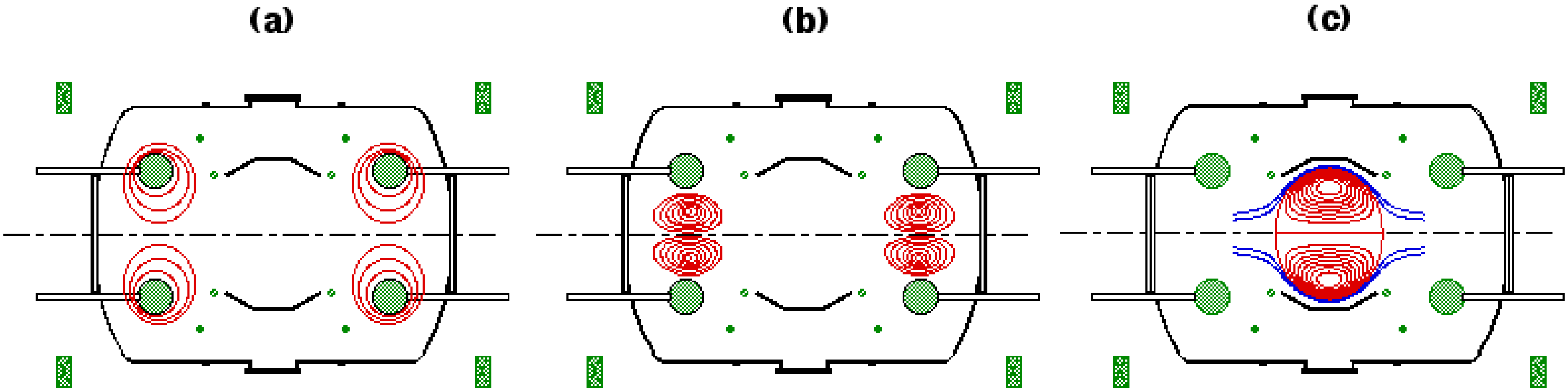
solution w/ end plates but w/o Ekman layer

measurements

- **To modify end plates to optimize flow profiles**

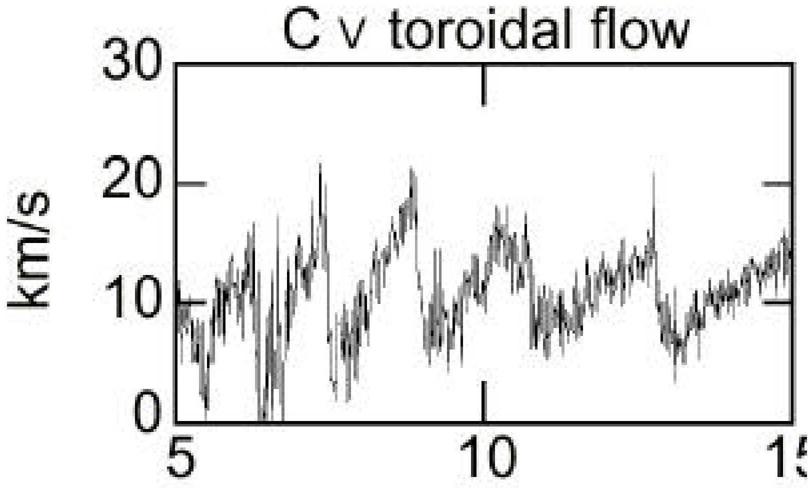
Laboratory Plasma Astrophysics Can Contribute to Fusion Science and Technology

- Reconnection experiments
  - Better understanding of reconnection help avoidance of disruptive phenomena observed in fusion plasmas
  - Help develop innovative confinement concepts
    - A new way to formation of Field-Reversed Configuration (FRC) with large flux



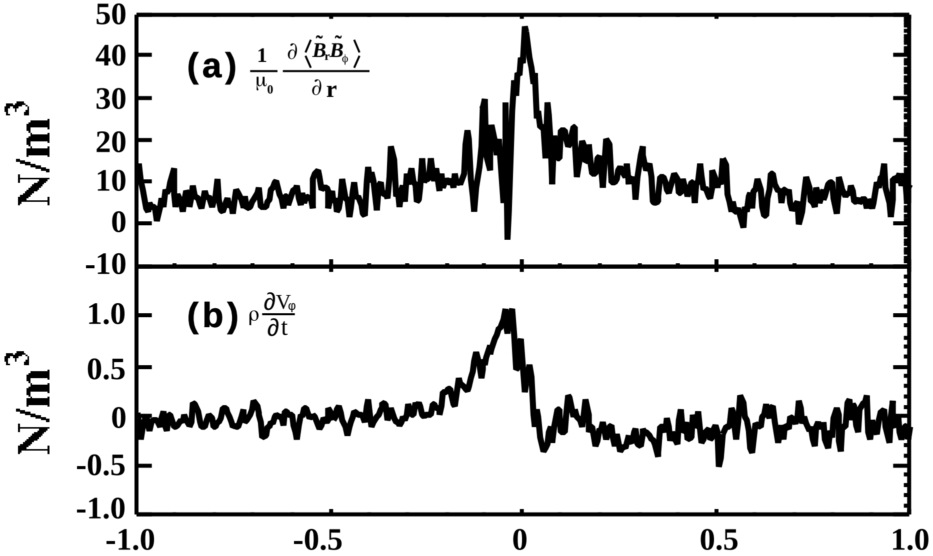
Laboratory Plasma Astrophysics Can Contribute to Fusion Science and Technology

- **Liquid metal experiments**
  - **Angular momentum transport due to MHD effects (Maxwell stress) relevant to flow dynamics in high-β plasmas (e.g. RFP's)**
  - **Related to new ideas utilizing flows (e.g. Centrifugal Confinement, double-Beltrami flow, ITB physics, etc.)**
  - **Better understanding of (free-surface) liquid metal MHD helps fusion concepts using liquid metal first walls**



Den Hartog (1995)

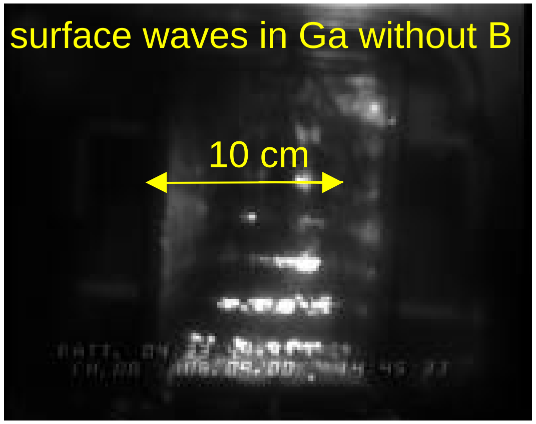
slowdown time ~ 100μs at MST

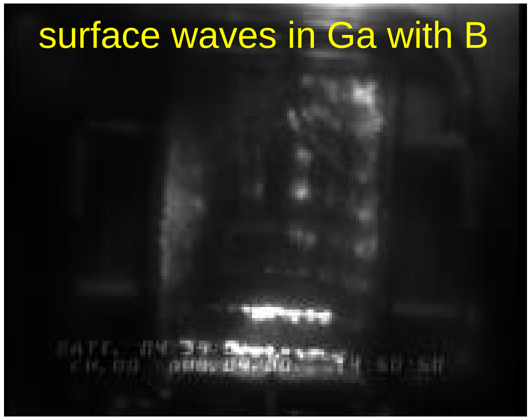


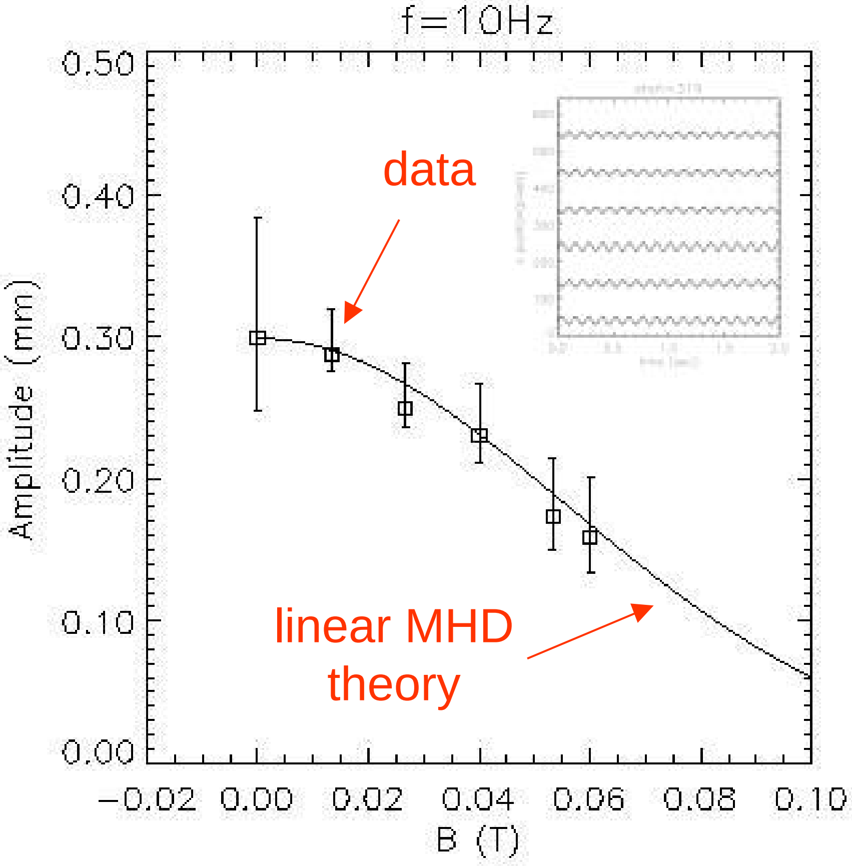
Fiksel et al. (1999)

Liquid Metal Surface Wave Experiment

Ji and Fox (2001)


surface waves in Ga without B


surface waves in Ga with B



data

linear MHD theory

To study MHD surface waves relevant to astrophysical mixing and liquid metal wall application in fusion reactors

Summary

- **Plasma astrophysics is a growing field because of mutual interests in plasma physics and astrophysics**
- **Laboratory experiments, using plasmas or liquid metals, represent a significant component of this field**
  - **Study basic physics mechanisms in controlled and systematic manners**
  - **Quantitative tests of theories and state-of-art numerical simulations**
- **Two examples:**
  - **MRX has provided fundamental data on reconnection, impacting theories and simulations of the observed disruptive phenomena**
  - **RGD experiment will test MRI for the first time and study angular momentum transport**
- **Better understanding of plasmas and liquid metals can promote fusion research and can lead to better fusion concepts and technology**