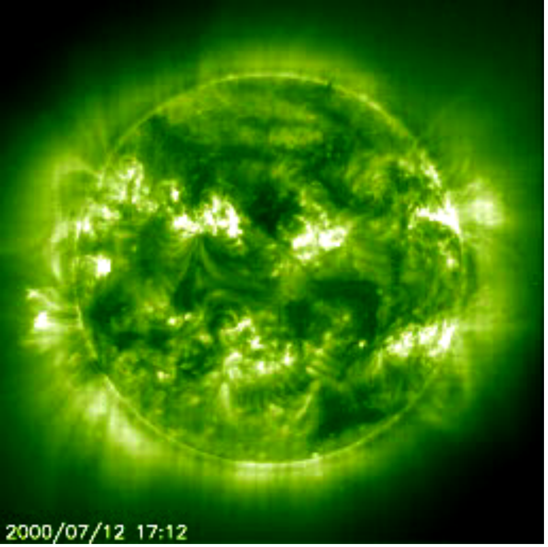

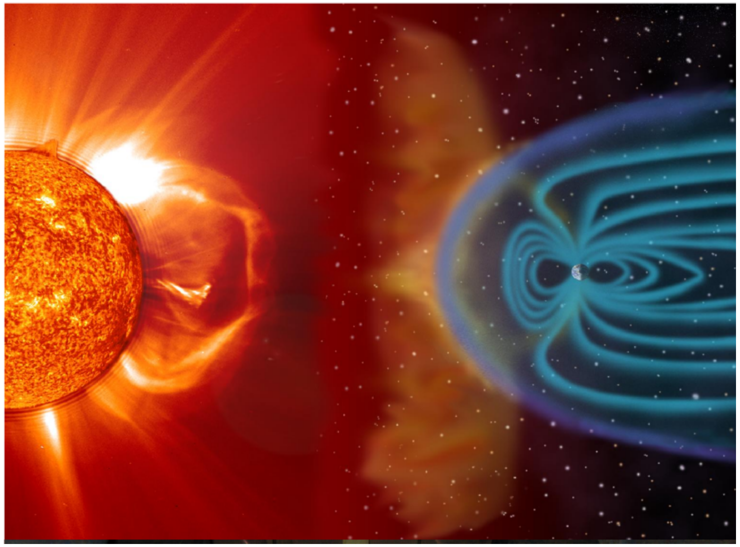
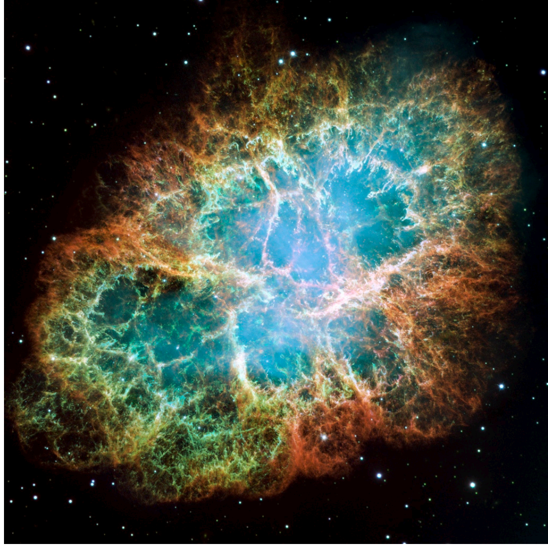

MRX research in the context of reconnection phenomena in space-astrophysics

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Princeton Plasma Physics laboratory

Princeton University

In collaboration with H. Ji, R. Kulsrud, S. Dorman, J. JaraAlmonte, E. Lawrence, C. Myers, T. Tharp, J. Yoo and CMSO members

US-Japan Workshop on Magnetic Reconnection

Princeton University, Princeton NJ

May 23-25, 2012

Outline

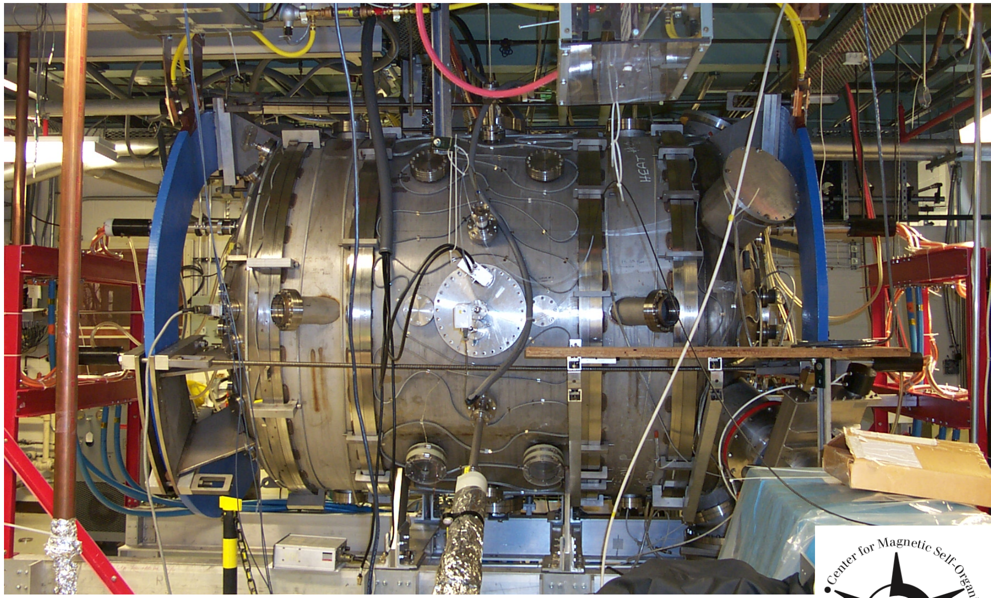
- **Magnetic reconnection has become a popular subject.**
  - Leading issue in space, astro- and fusion plasma physics
  - A major question: Why does it occur so fast?
  - Isolation of a single reconnection layer: Parker
- **Generation of a reconnection layer on MRX => Local analysis**
  - Creation of a Sweet-Parker reconnection layer
  - Fast reconnection <=> Resistivity enhancement

- **Two fluid physics analysis**

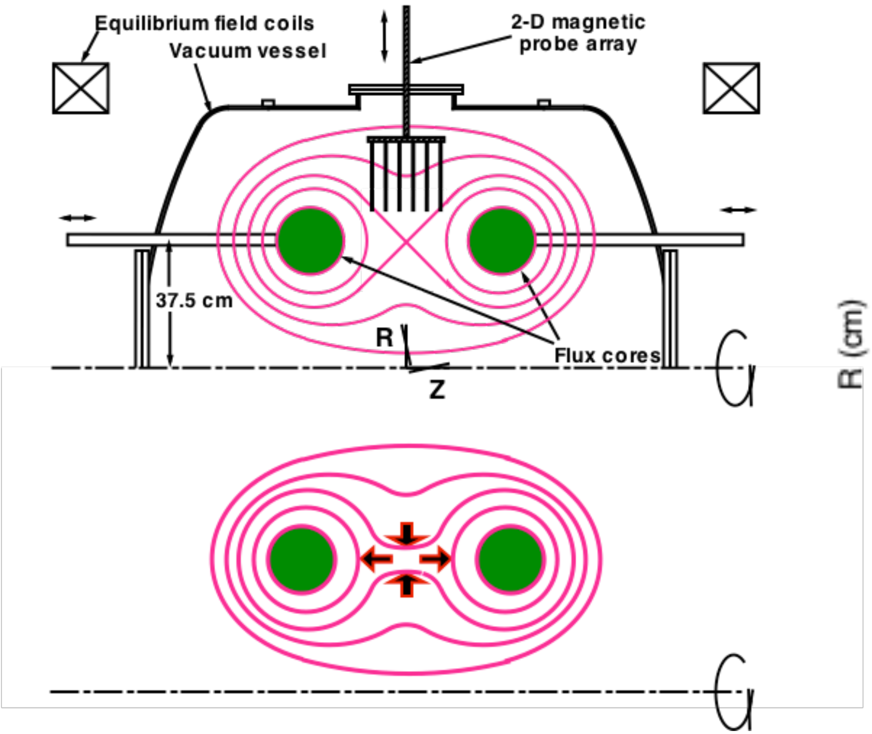
- **Energy conversion processes from B^2 to ions and electrons**
- **A new series of experimental campaign and the recent results**
  - Plasma jog experiment: Addresses heating and acceleration issues
  - Guide field effects on two-fluid reconnection
  - Reconnection in partially ionized plasmas
  - Solar flare relevant plasma arcs

We have learned from MRX about the fundamental physics of magnetic reconnection

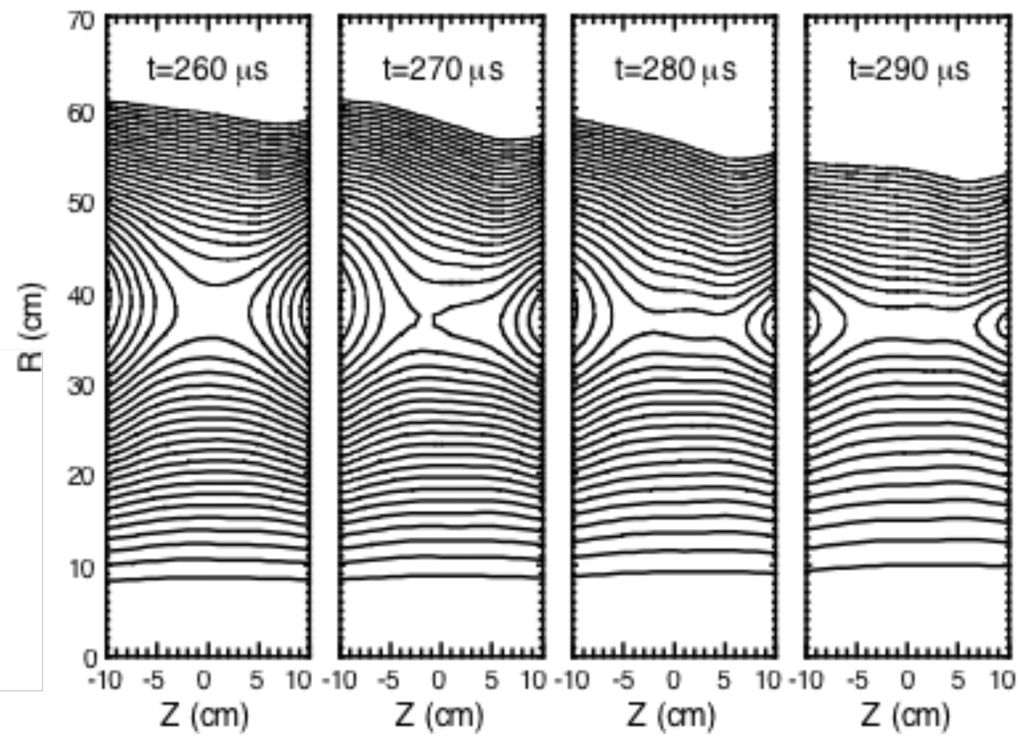
- Generation of a reconnection layer => Local analysis
  - Creation of a Sweet-Parker reconnection layer
- Local analysis by two-fluid physics
  - Collision-free reconnection => an X-shaped neutral sheet
  - Hall effect and experimental verification
  - Identification of fluctuations (EM-LHDW)
  - Electron diffusion identified
- Magnetic self-organization: Global analysis
  - Multiple reconnection
  - Impulsive reconnection



Experimental Setup and Formation of Current Sheet



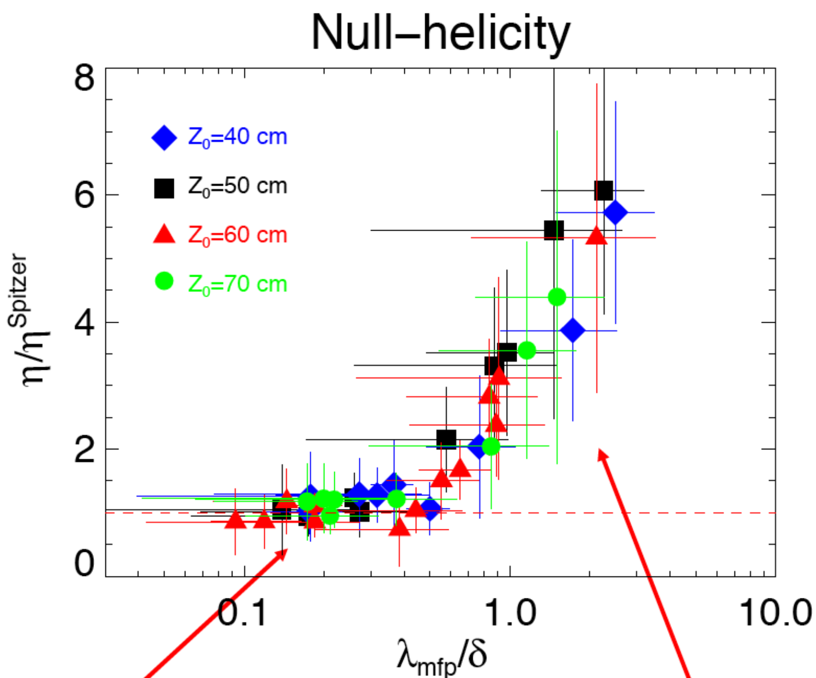
Experimentally measured flux evolution



n_e= 1-10 x10^{13} cm^{-3},
T_e~5-15 eV,
B~100-500 G,

Resistivity increases as collisionality is reduced in MRX

Effective resistivity



Close to classical Spitzer

$$\eta_{\perp}^{Spitzer} = 1.03\times10^{-4} T_e^{-3/2} Z \ln\Lambda$$

Enhanced in low collisional plasma

Ji et al. '98
Trintchouk et al, '03
Kuritsyn et al, '06

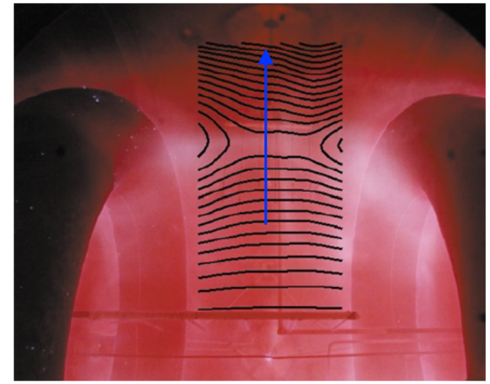
$$\eta^* \equiv \frac{E_\theta}{j_\theta}$$

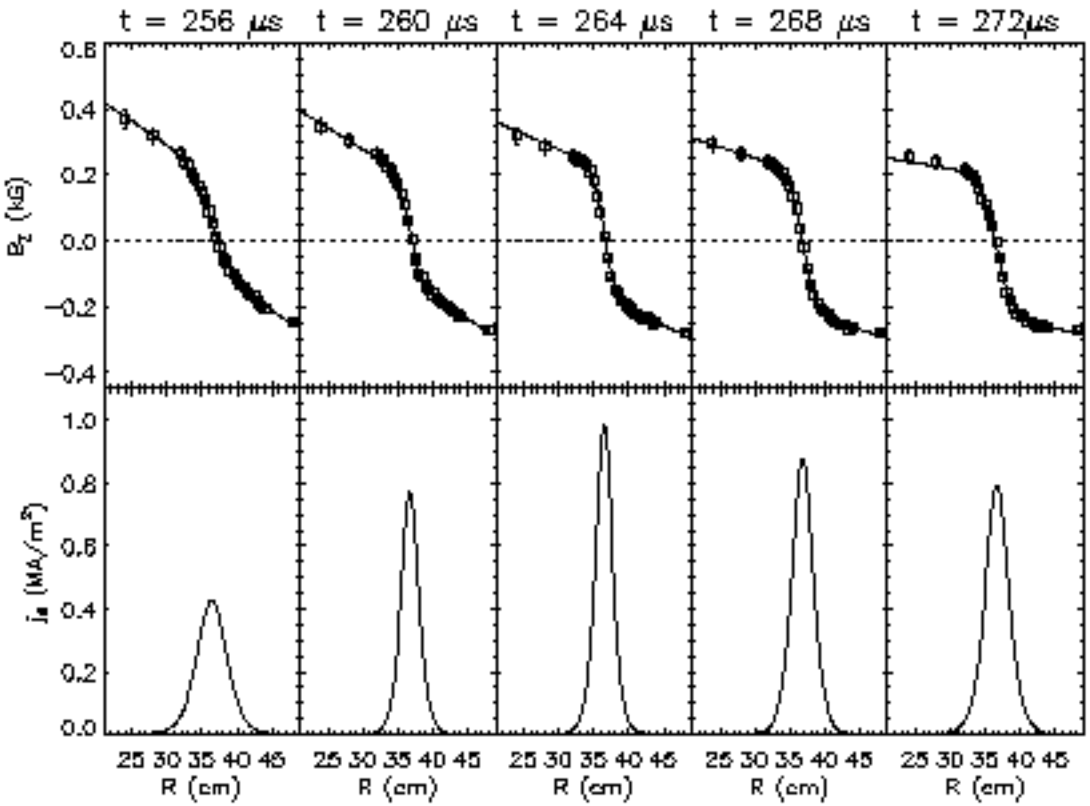
The cause of enhanced η was unknown.

Local Reconnection Physics

1. MHD analysis
2. **Two-fluid analysis**

The measured current sheet profiles agree well with Harris theory





$$B_z = -B_0 \tanh\left(\frac{x}{\delta}\right)$$

$$j_y = \frac{B_0}{\mu_0 \delta} \operatorname{sech}^2\left(\frac{x}{\delta}\right)$$

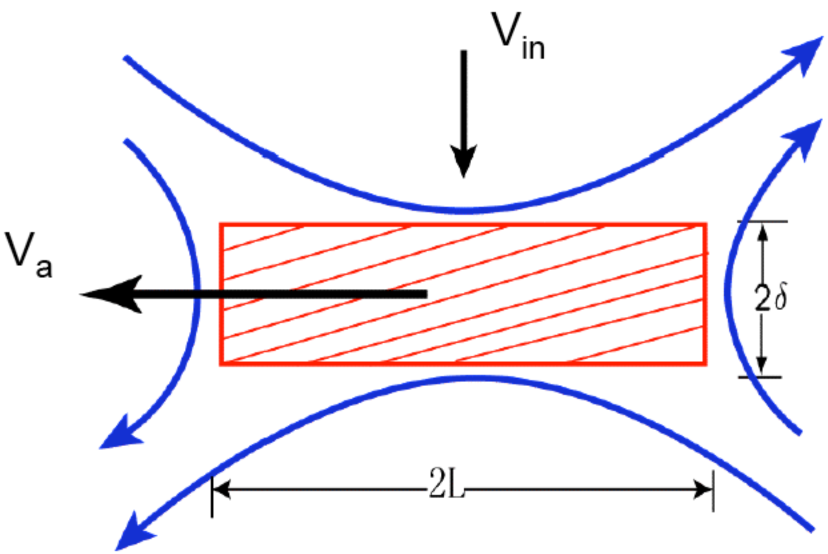
$$p = n_0 (T_e + T_i) \operatorname{sech}^2\left(\frac{x}{\delta}\right)$$

$$\delta = \frac{c}{\omega_{\rm pi}} \frac{\sqrt{2(T_e + T_i)/m_i}}{V_i - V_e}$$

$$= \frac{c}{\omega_{\rm pi}} \frac{\sqrt{2} V_s}{V_{\rm drift}}$$

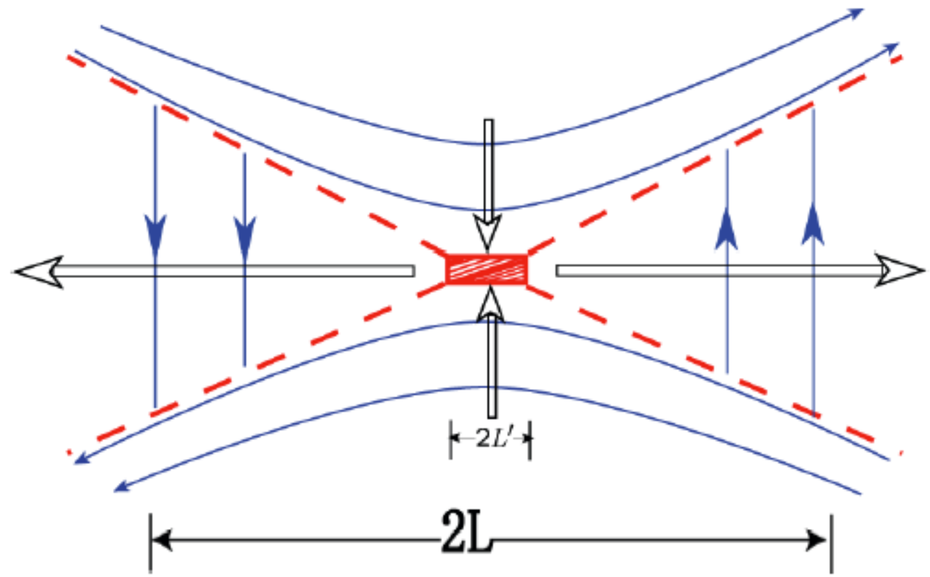
(Yamada, Ji, Kulsrud, et al., **Phys. Plasmas, 7, 1781, 2000**)

Descriptions of Fast Reconnection



Generalized Sweet-Parker model with enhanced resistivity

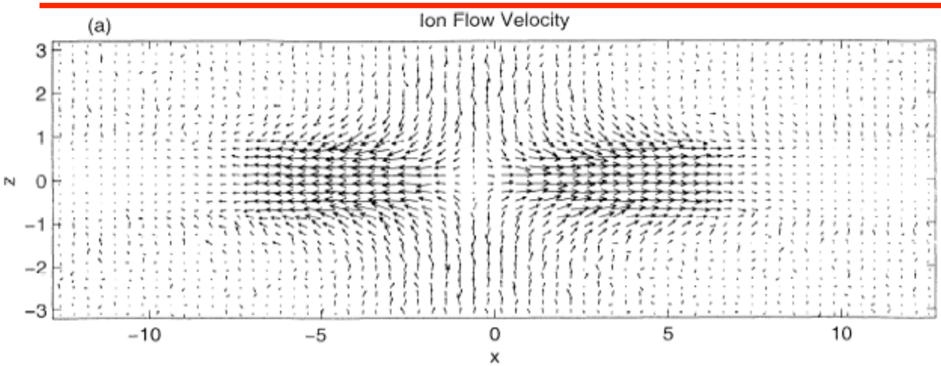
$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J}^*$$

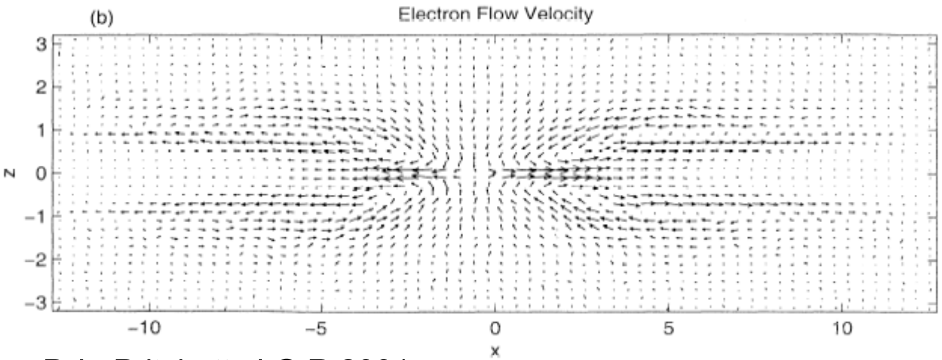


Two-fluid MHD model in which electrons and ions decouple in the diffusion region ($\sim c/\omega_{pi}$).

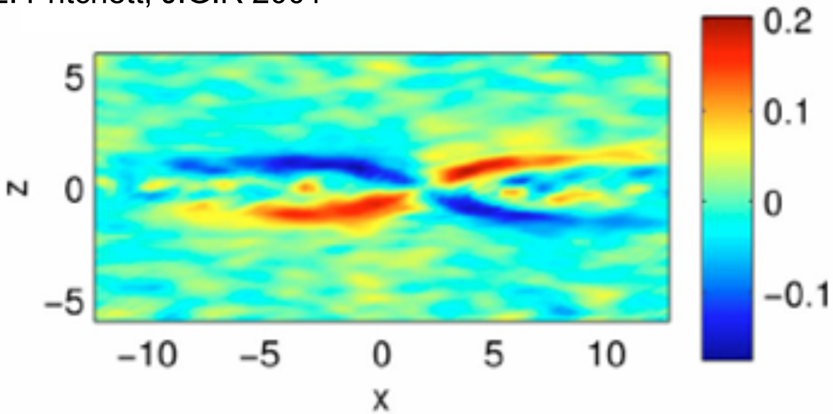
$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J} + \frac{\mathbf{J} \times \mathbf{B} - \nabla p}{en} + \frac{m_e}{e^2} \frac{\mathrm{d}\mathbf{V}_e}{\mathrm{d}t}$$

Extensive simulation work on two-fluid physics carried out in past 15 years





P. L. Pritchett, J.G.R 2001



Sheath width ~ ρ_i

--Different motions of ions and electrons => in-plane Hall current and out-of-plane magnetic field.

J. Drake et al,

J. Birn et al GEM challenge,

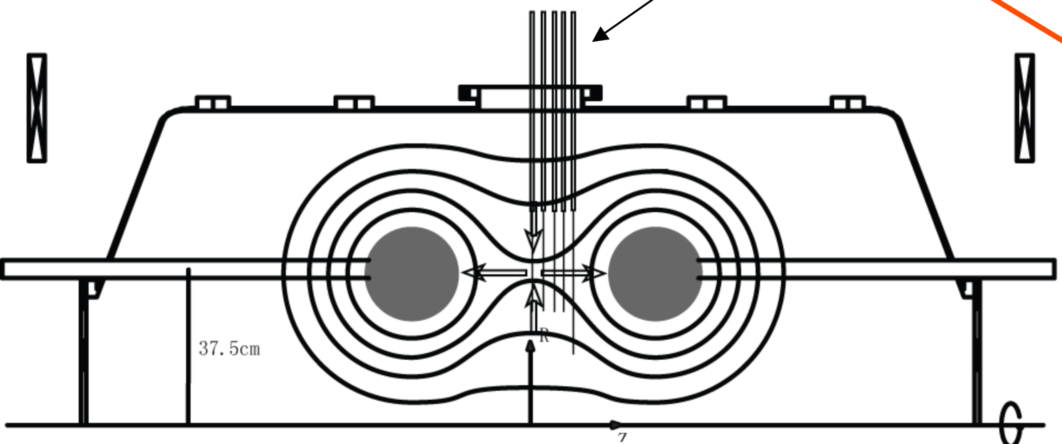
R. Horiuchi et al,

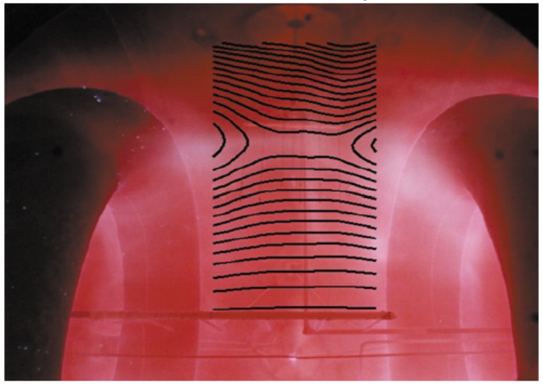
A. Bhattcharjee, M. Hesse, P. Pritchett, W. Daughton…

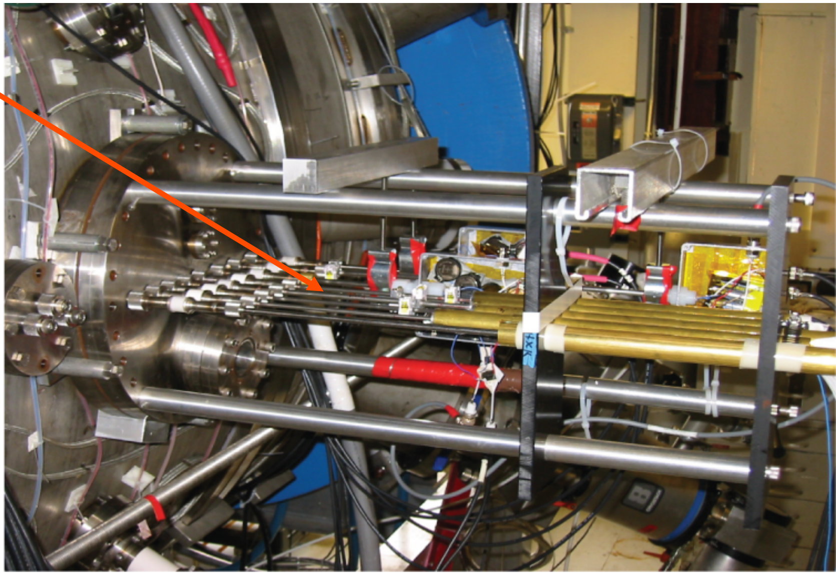
Out of plane magnetic field is generated during reconnection

MRX with fine probe arrays

Linear probe arrays

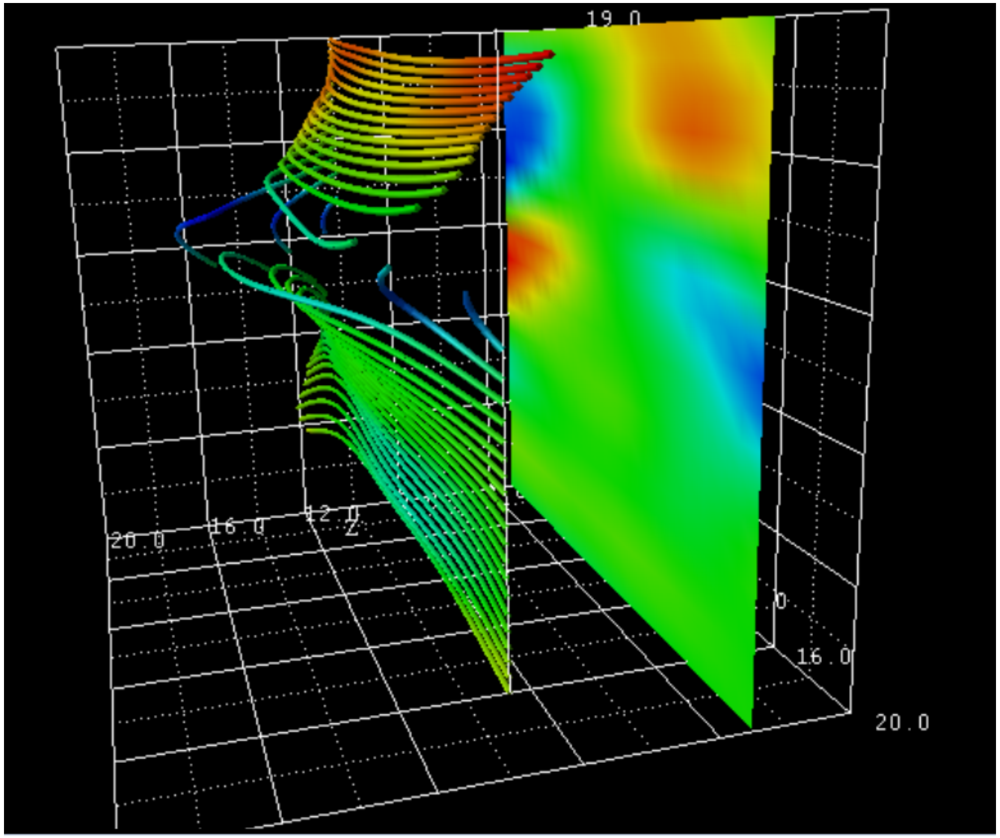




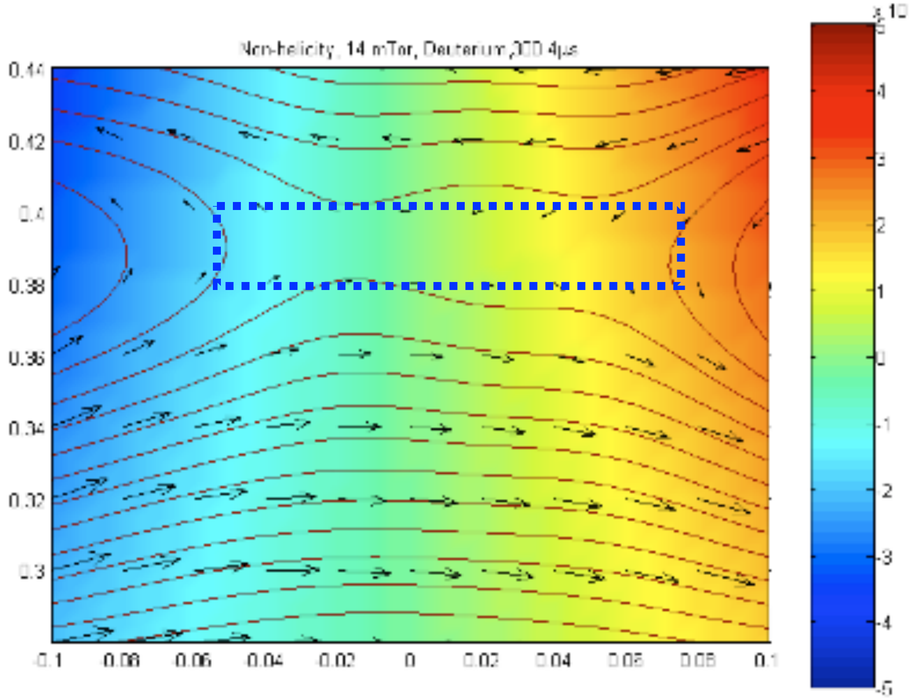


- Five fine structure probe arrays with resolution up to Δx= 2.5 mm in radial direction are placed with separation of Δz= 2-3 cm

Experimentally measured field line features in MRX



- Manifestation of Hall effects in MRX
- Electrons would pull magnetic field lines with their flow



Neutral sheet Shape in MRX

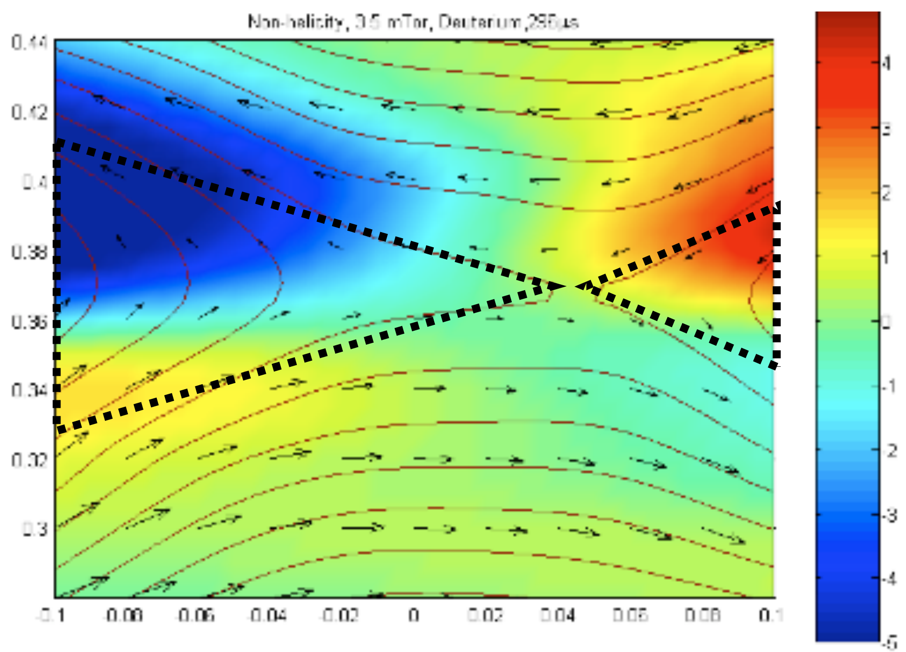
Changes from “Rectangular S-P” type to “Double edge X” shape as collisionality is reduced

Rectangular shape

Collisional regime: $\lambda_{mfp} < \delta$

Slow reconnection

No Q-P field



X-type shape

Collisionless regime: $\lambda_{mfp} > \delta$

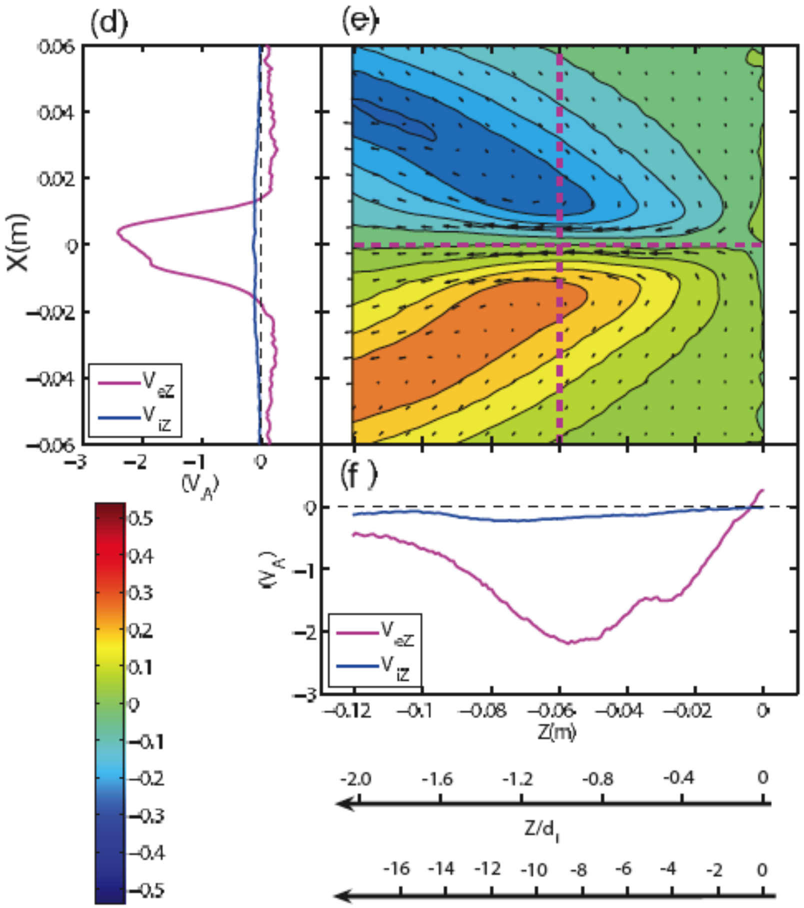
Fast reconnection

Q-P field present

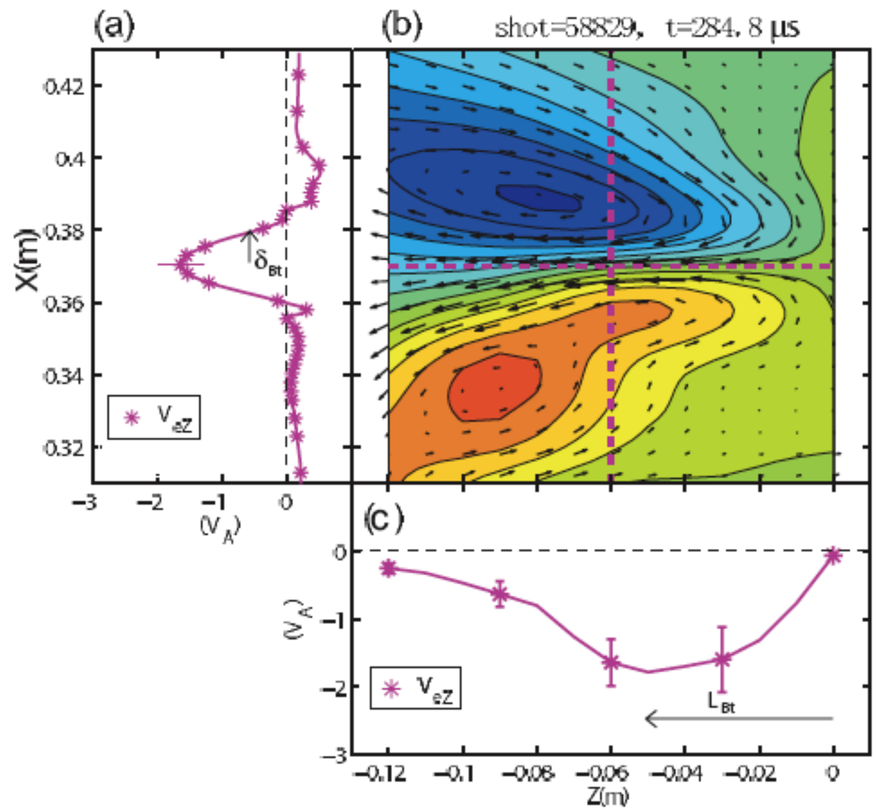
Yamada et al, PoP 2006

Experimental identification of e-diffusion region

PIC Simulation



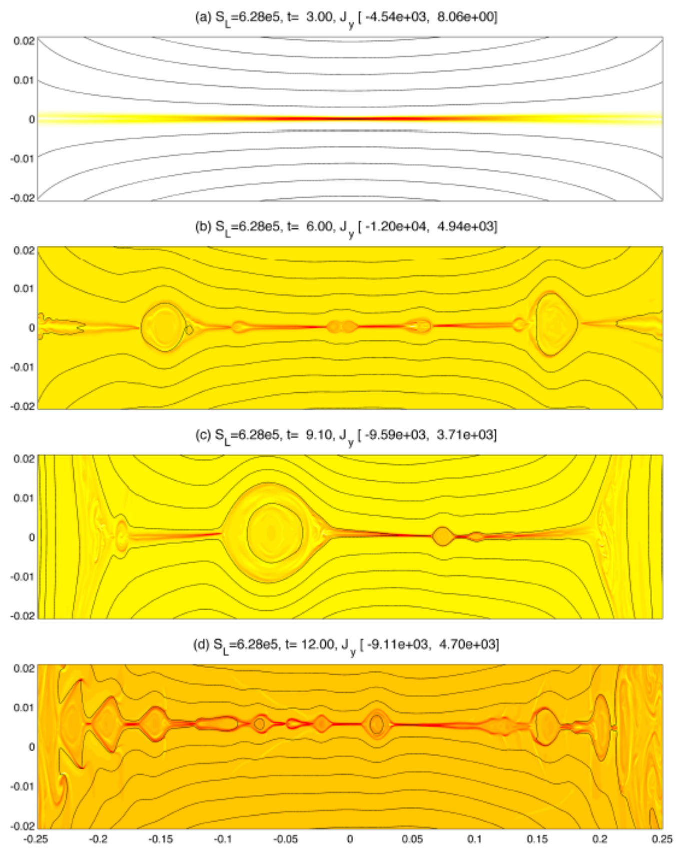
Experiment



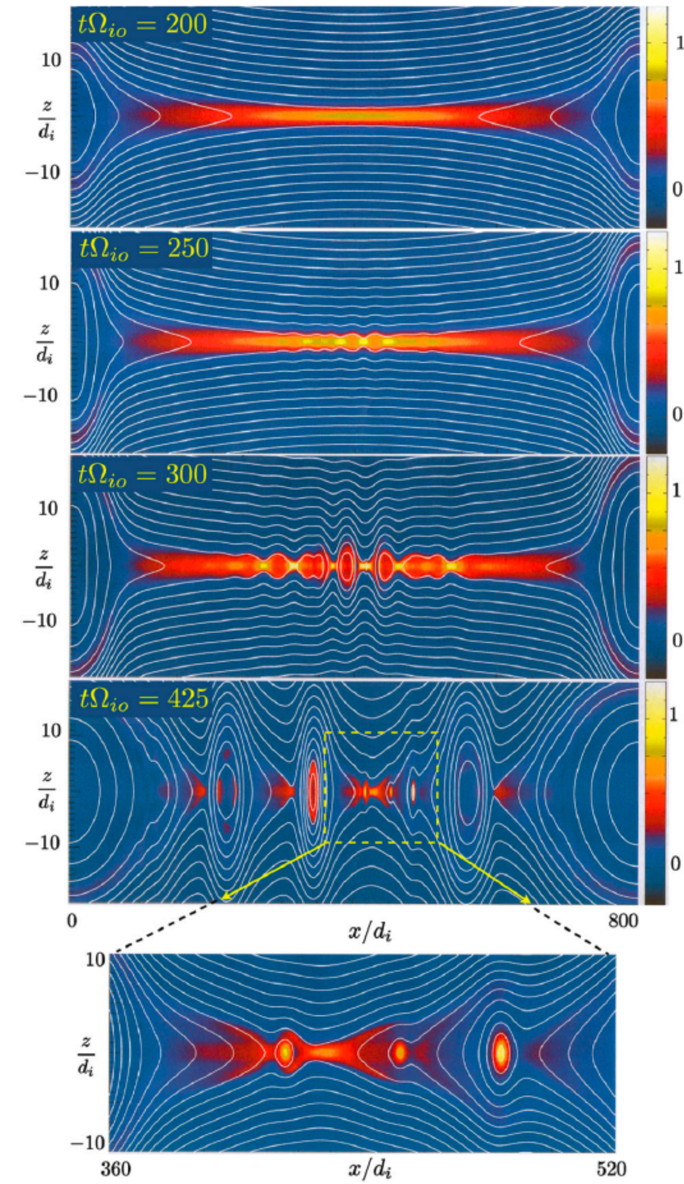
The electron diffusion region identified
inside of the ion diffusion region in a laboratory plasma
<=> The first observation of two-scale diffusion region
[Ren et al, PRL 08, Ji et al GRL, 08, Dorfman et al '10]

Recent (2D) Simulations Find Multiple Flux Ropes

Bhattacharjee et al. (2009):MHD



Daughton et al. (2009): PIC

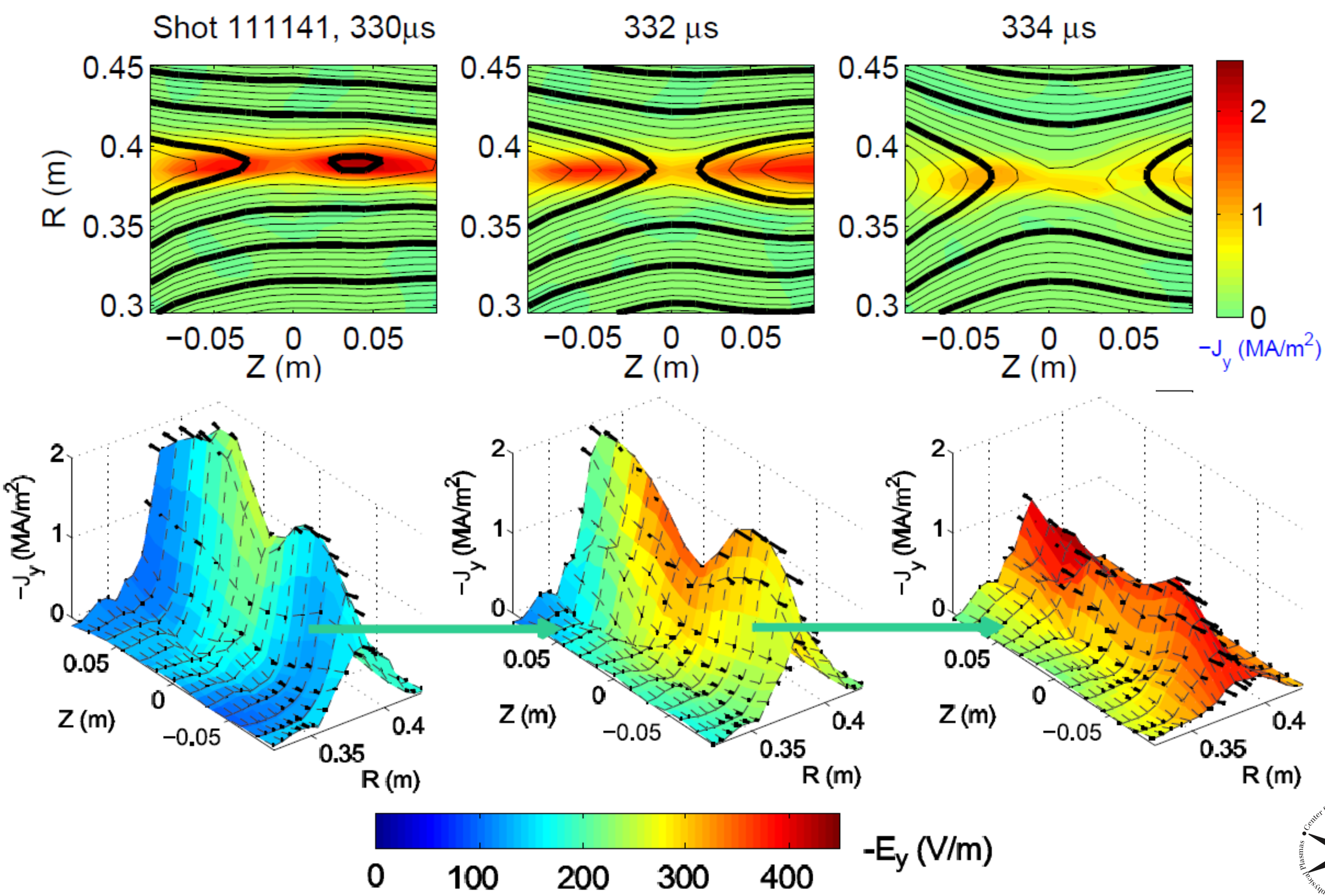


The Sweet-Parker layer breaks up to form plasmoids when S > ~10⁴ ***=> Turbulent reconnection?***

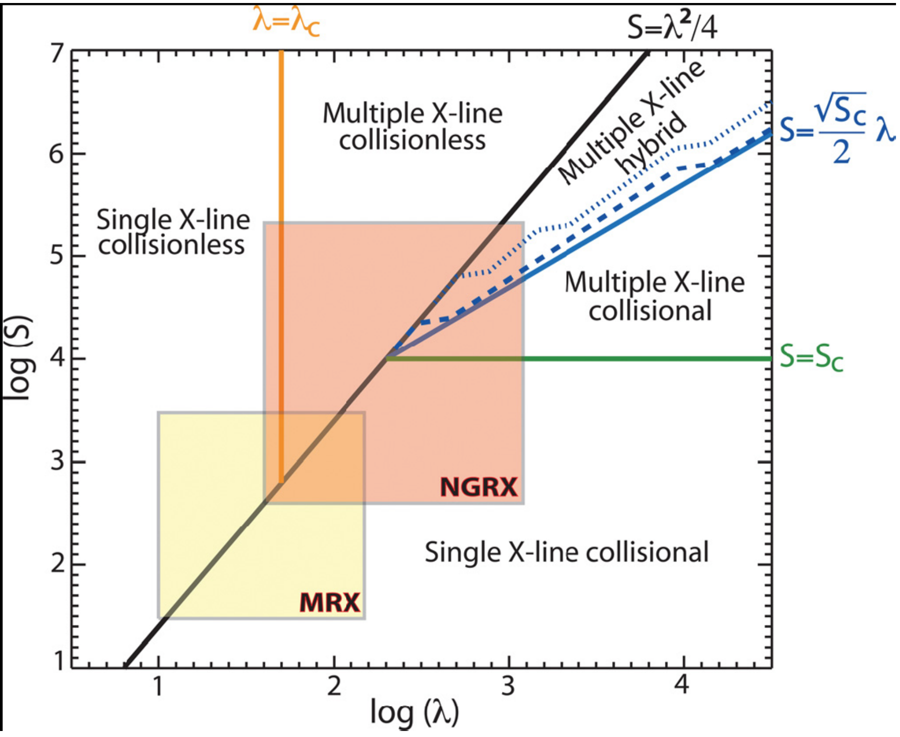
Impulsive fast reconnection with multiple X points Shibata & Tanuma: 2001

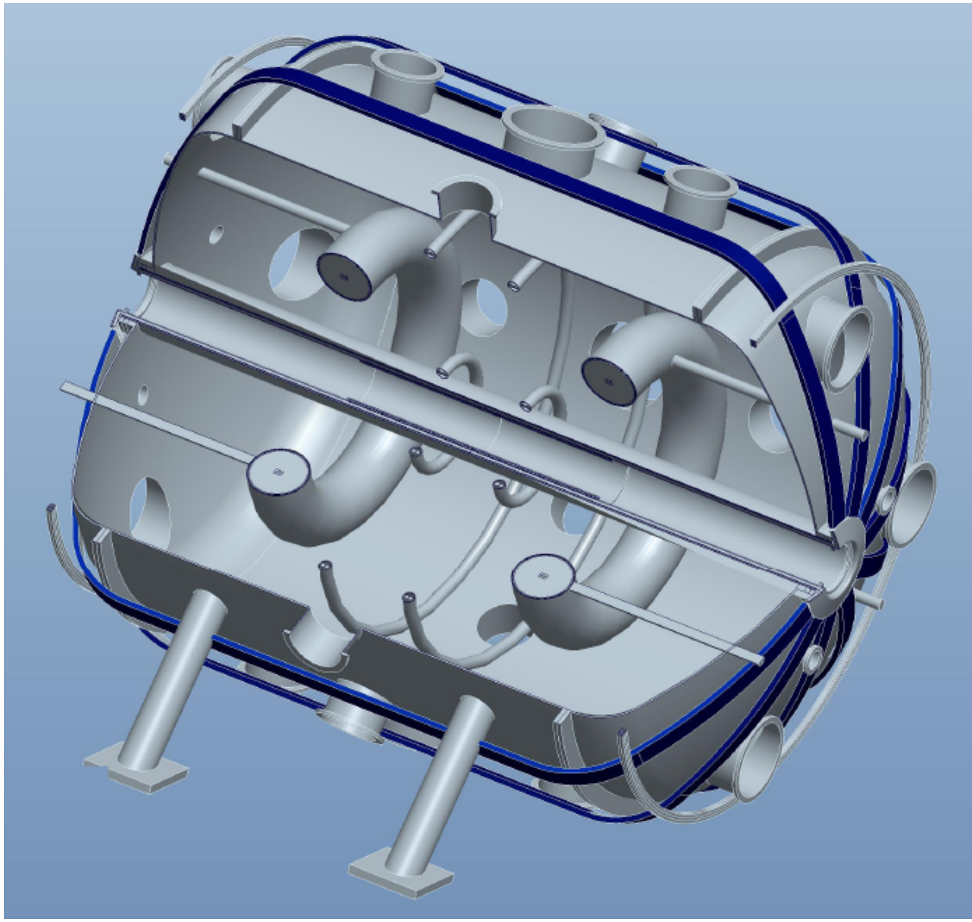
Current layer observed to disrupt over a fast timescale in MRX

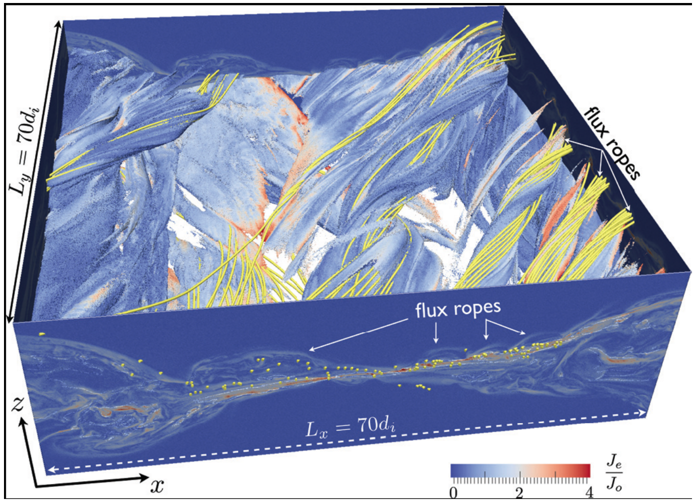
APS News Release 2011



Phase Diagram for Reconnection (Ji/Daughton) and MRX-U



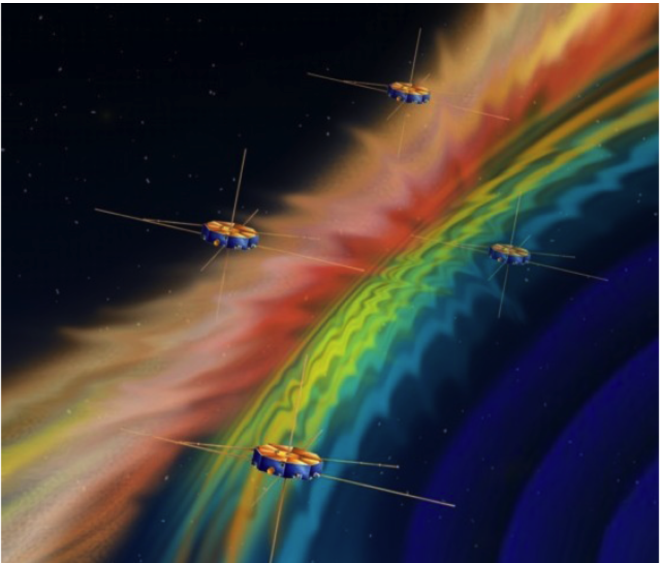


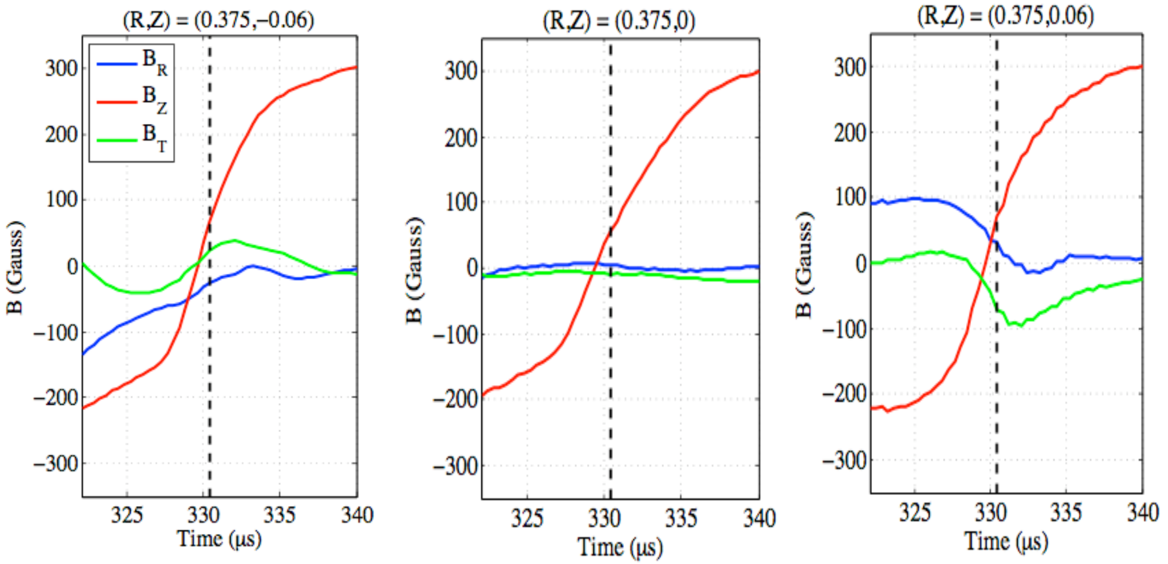


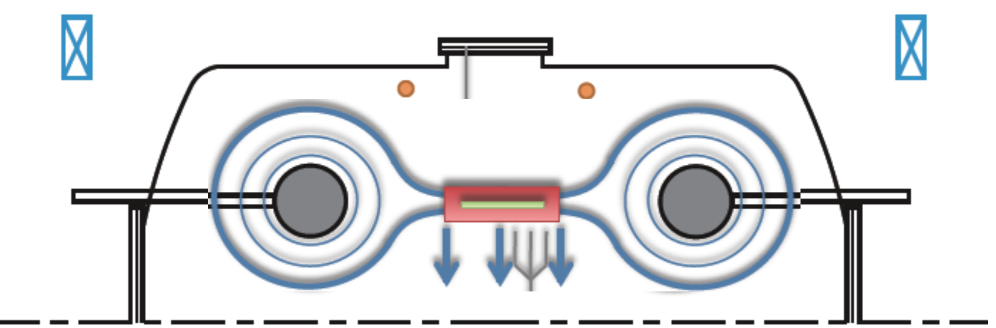
MRX-U will generate a collsionless Plasma of $S=10^4$ - 10^5

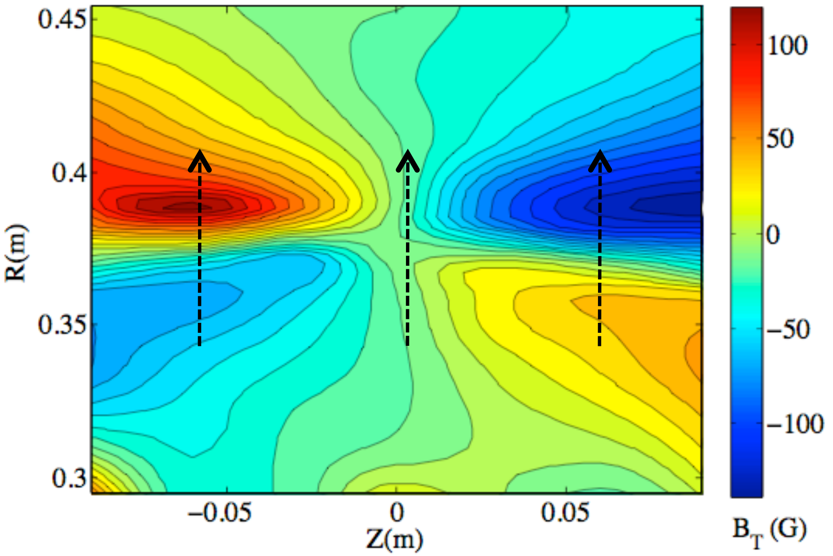
=> Hantao's talk tomorrow

A jog experiment on MRX (2011)



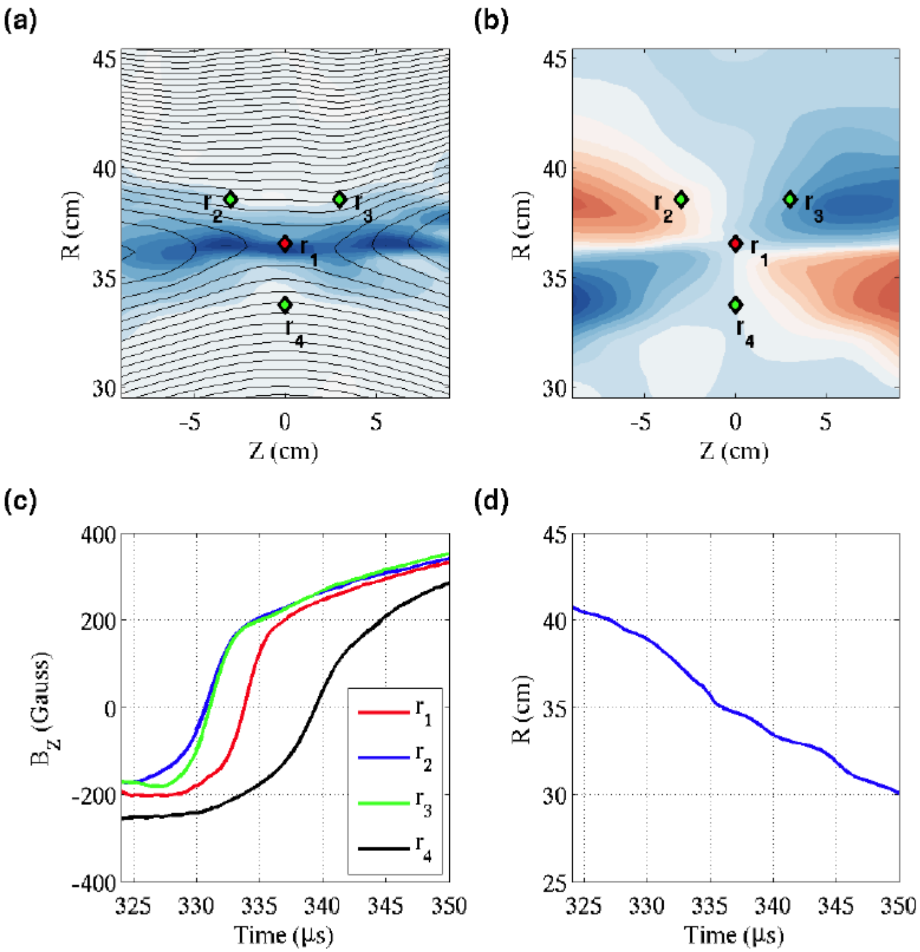






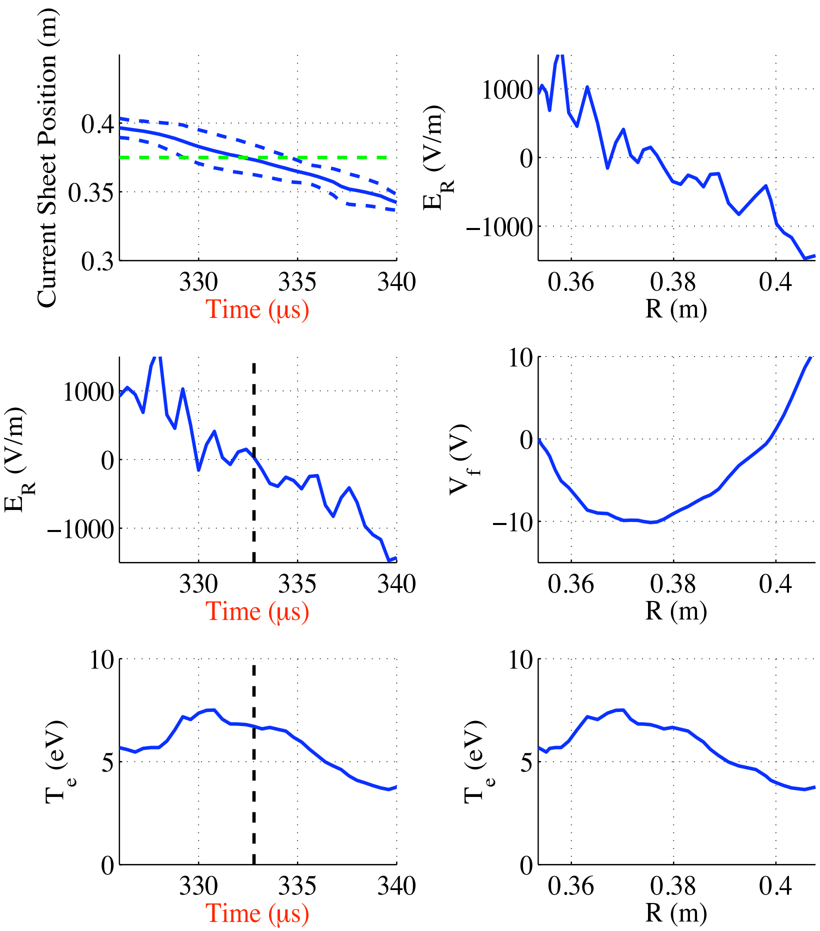
In collaboration with UNH, MMS, UC-Berkeley.

Boundary-crossing Time Analysis

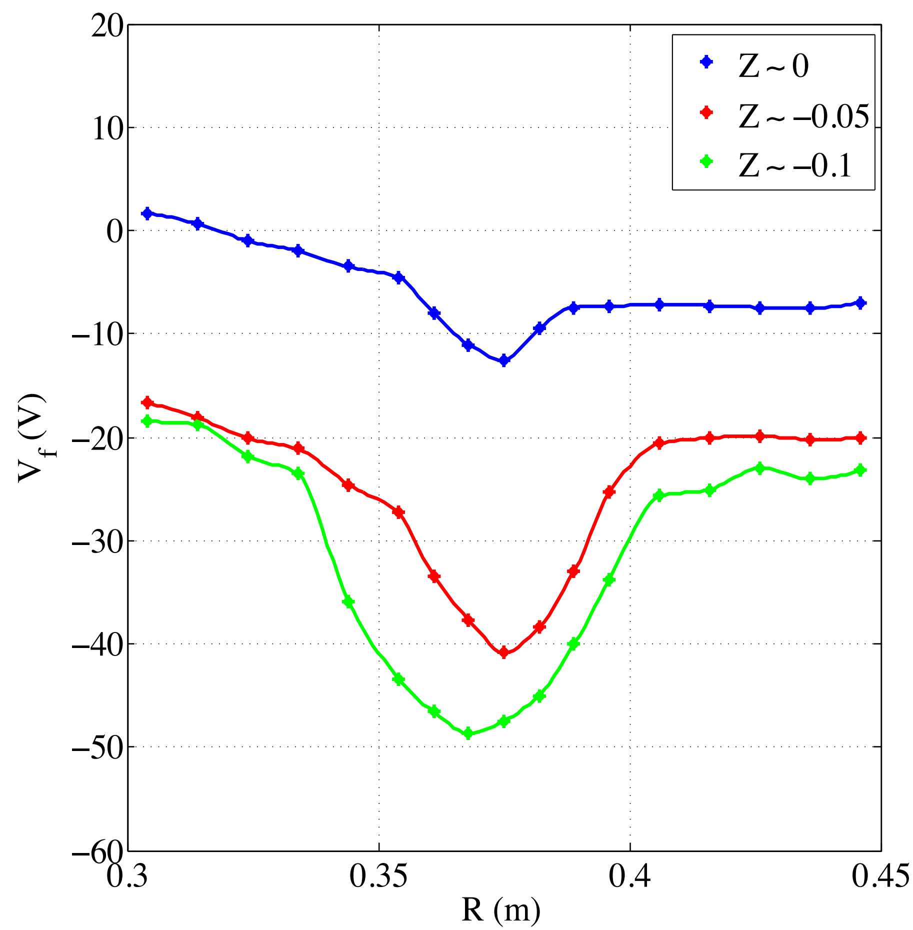


- Minimum Variance Analysis of B (MVAB) does not always produce a proper normal vector due to 2-D or 3-D structures.
- Better normal vectors can be obtained from boundary-crossing time analysis with four measurement points on a tetrahedral formation.
- With the combination of MVAB and Boundary crossing timing analysis, a relatively accurate local magnetic geometry can be decided.

Plasma jogging significantly improves diagnostics capability of MRX



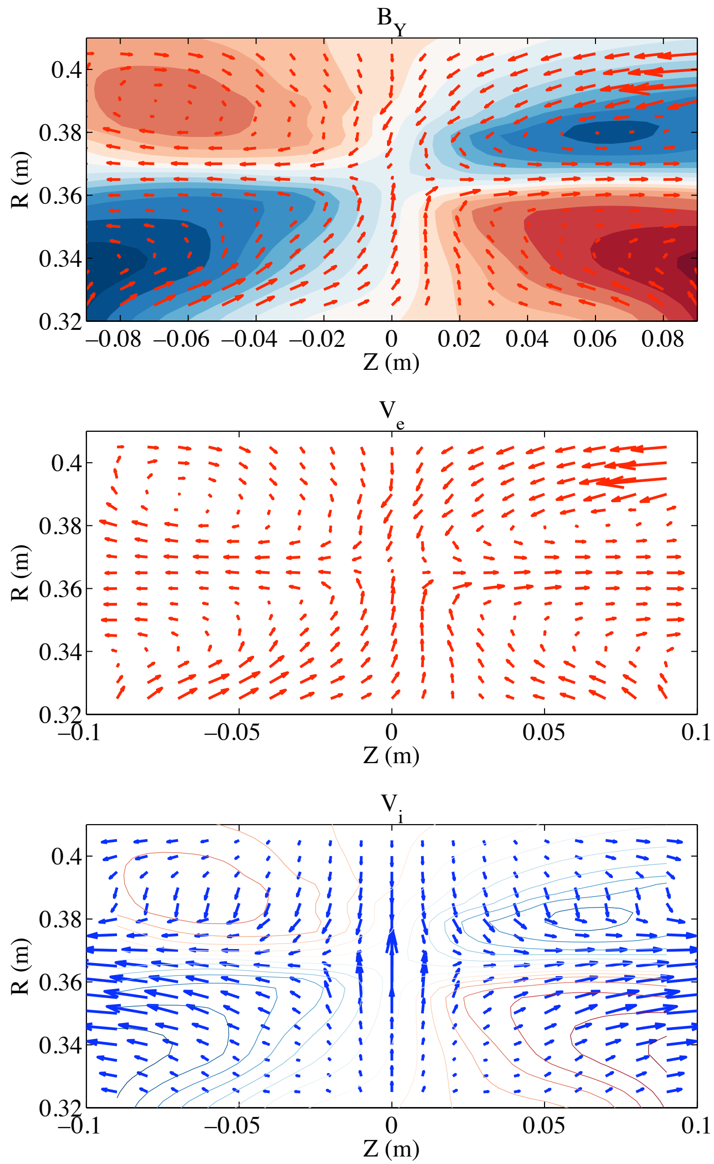
Radial potential profiles



<=> J. Wygant et al. JGR 2005

J. Egedal 2012

Simultaneous measurement of ion and electron flow vectors by plasma jogging



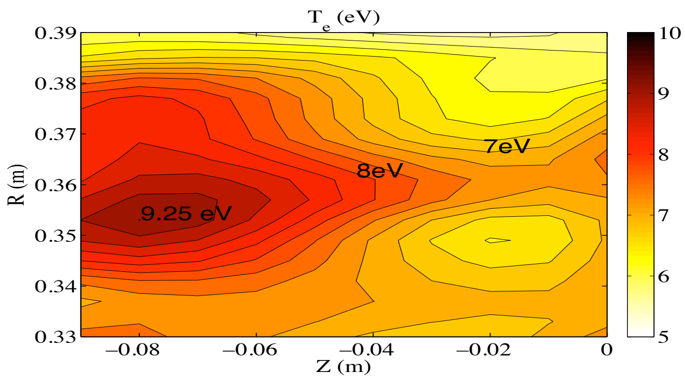
From magnetic data

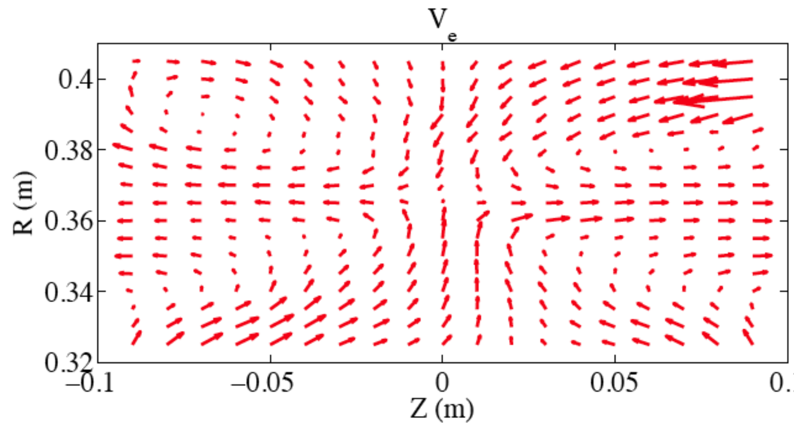
Electron flows

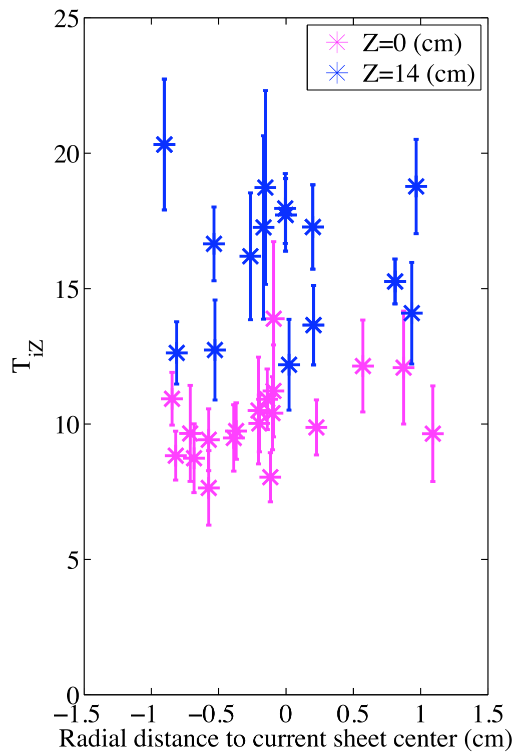
Ion flows
from Mach probe data

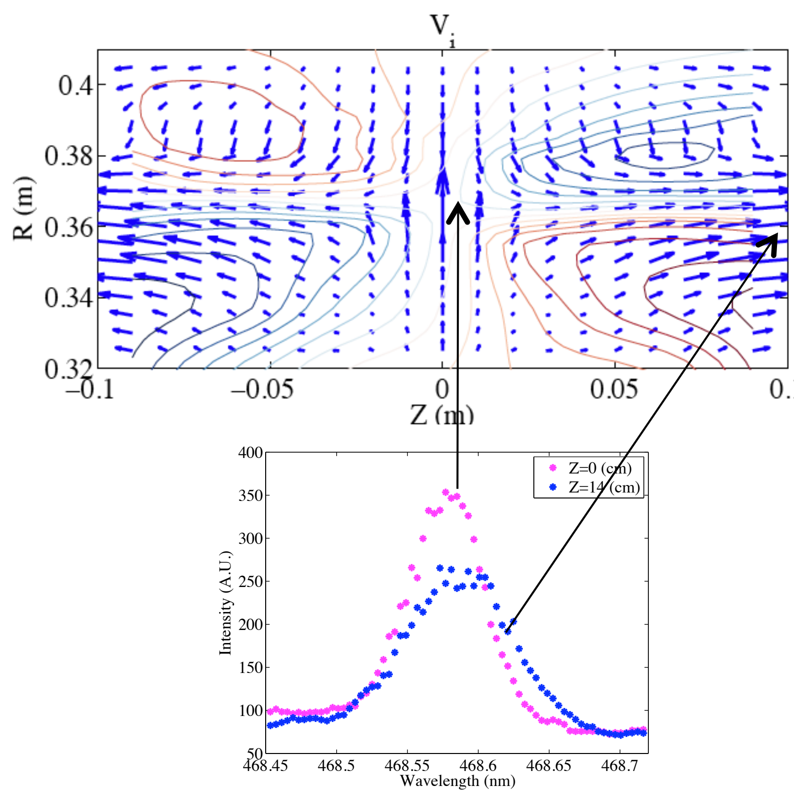
J. Yoo, 2011

Both ion and electron temperature measured by plasma jogging



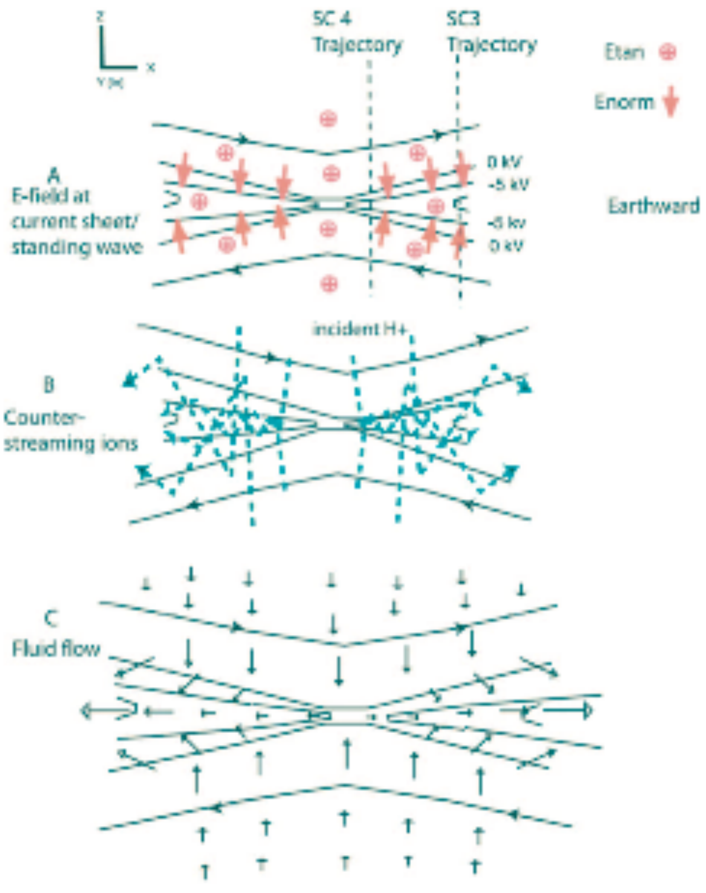




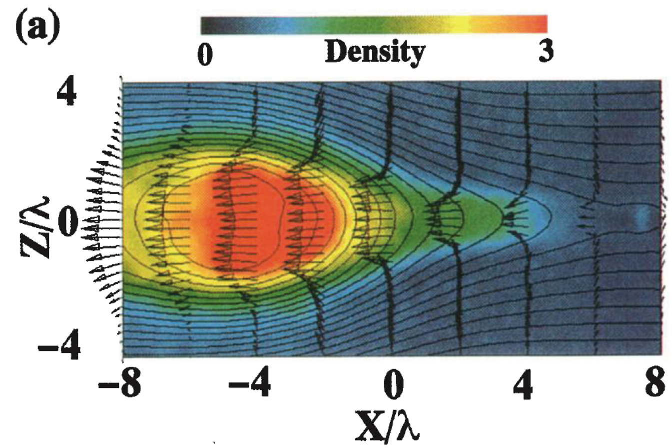


J. Yoo, 2012

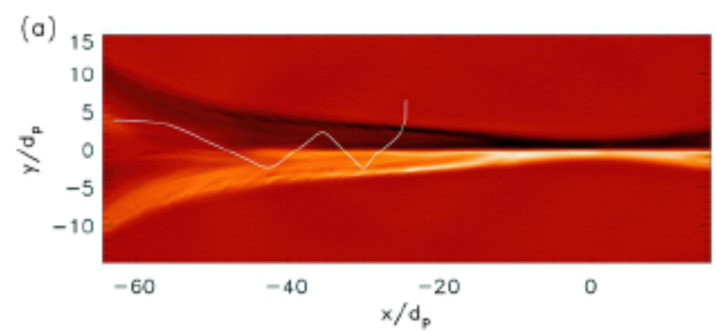
Ion acceleration data and simulation results



Wygant JGR 2005

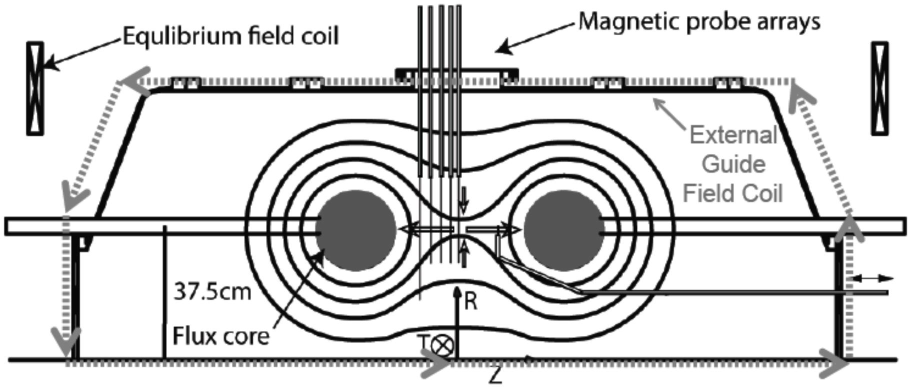


Hoshino et al 1998

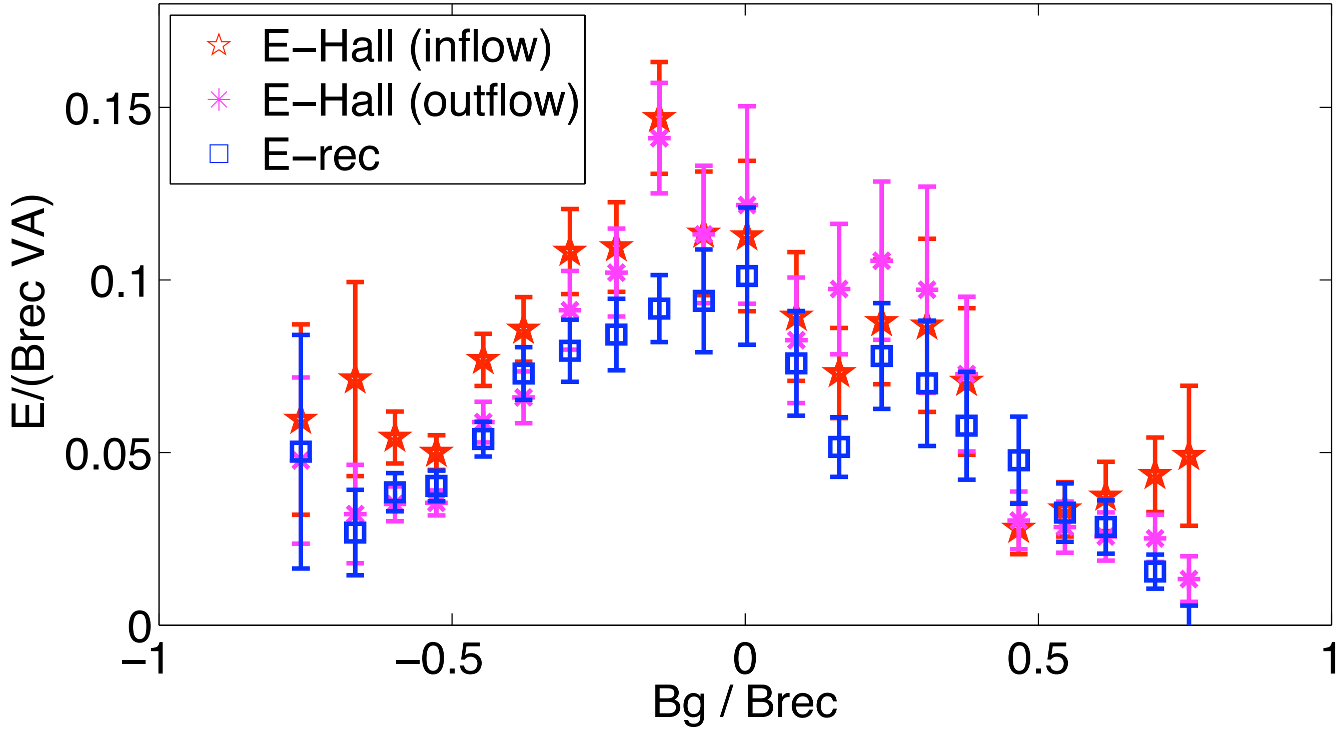


Drake et al., 2009

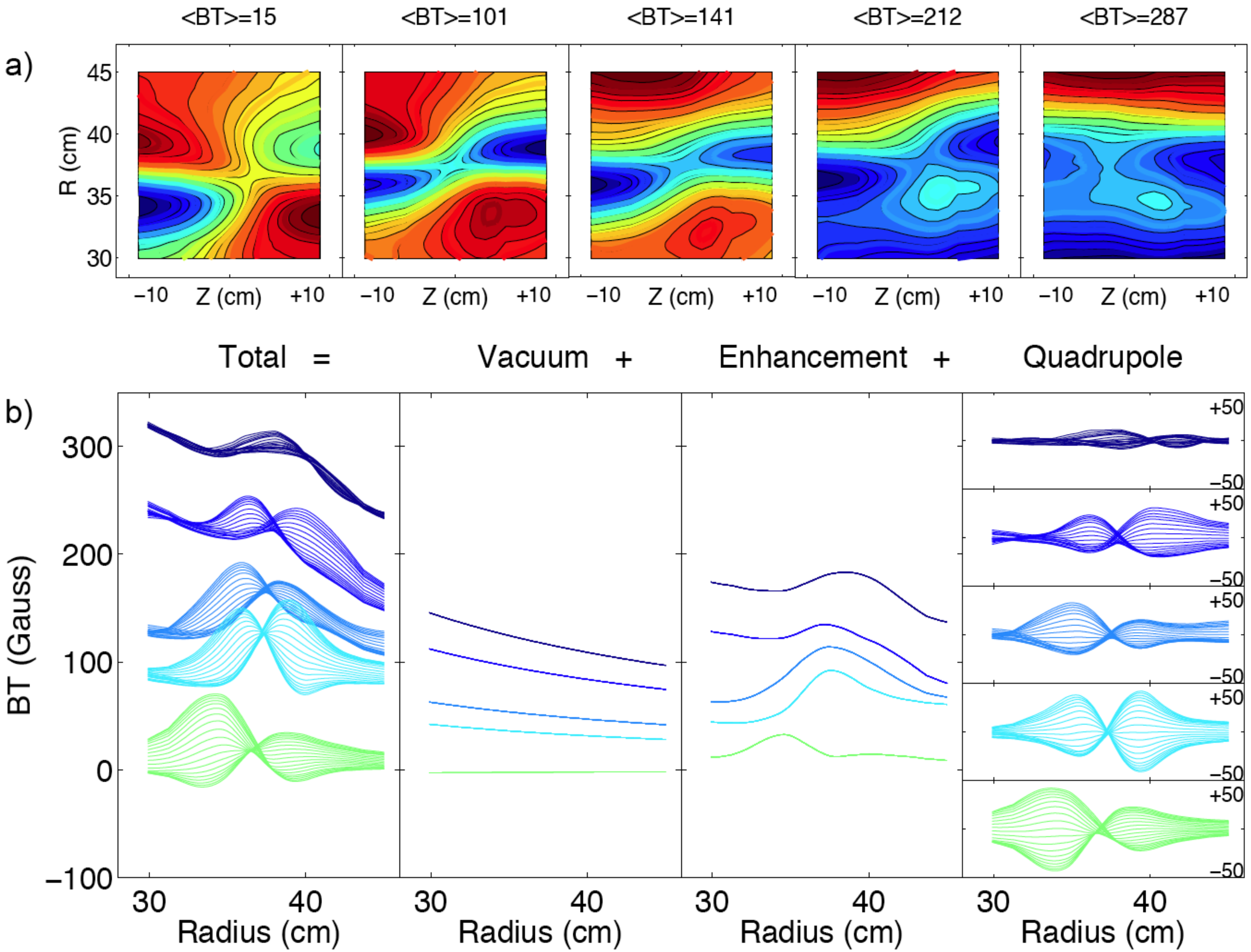
Hall Effects on Guide Field Reconnection in MRX



Effects of Guide Fields
On Collision-less Reconnection



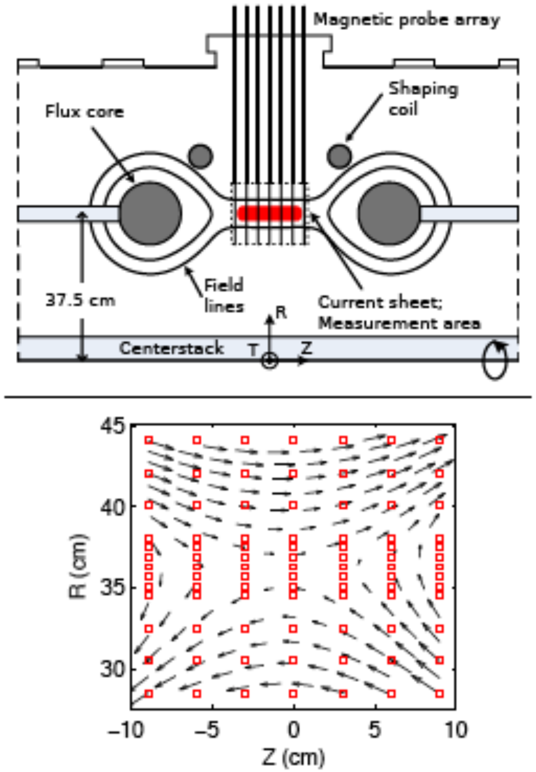
Effects of Guide Field on Hall Reconnection



Reconnection in Partially Ionized Plasmas

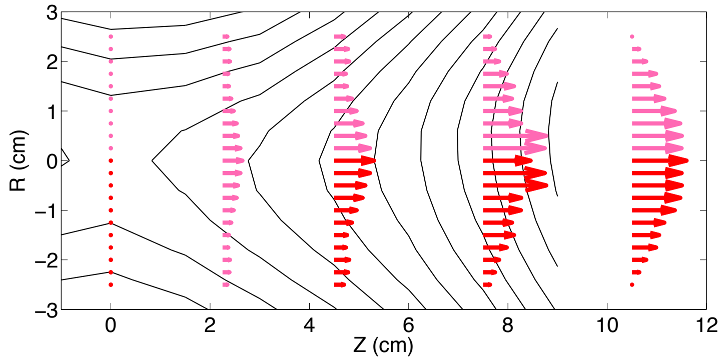
- Ion-neutral drag can effectively increase the ion mass: $V_A \rightarrow V_A (\varrho_i/\varrho_n)^{1/2}$; $c/\omega_{pi} \rightarrow c/\omega_{pi}(\varrho_n/\varrho_i)^{1/2}$
  - **Length scale**: Predicted to increase for fast Hall reconnection (Zweibel ApJ 1989 739:72, Malyshkin et al ApJ 2011).
  - **Key physics:** Often treated as ambipolar diffusion, but multi-fluid approach may be needed to see all effects.

$\Rightarrow$A reconnection layer was generated on MRX with presence of 100 times larger density of neutrals: Similar to Chromosphere situation

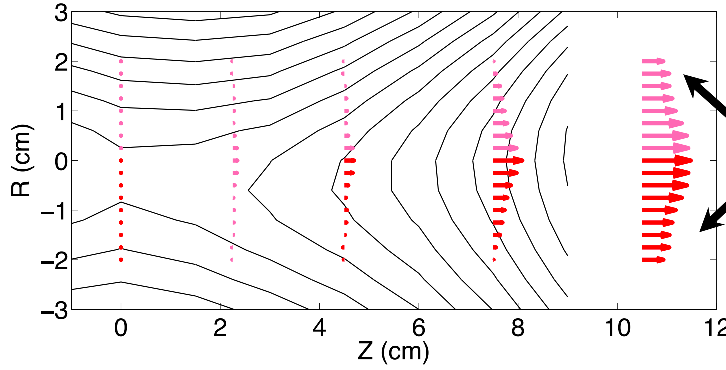


2D Ion Outflow Profiles

Ionized case *(n_i~2×10[13] cm[-3]; n_i/n_n~12%; L/λ_{in}~2)*



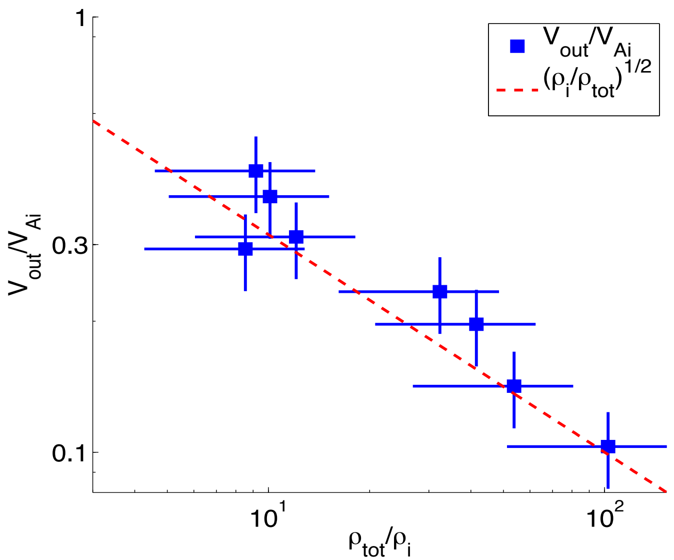
Weakly ionized case *(n_i~2×10[13] cm-3, ni/n_n~0.9%; L/λ_{in}~50)*



Outflow channel broadens

Contours show magnetic flux

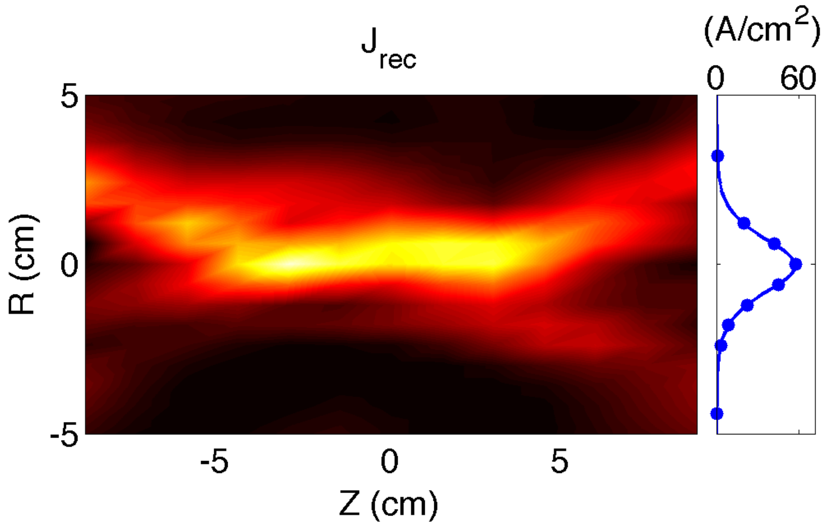
Ion outflow speed is reduced to Alfvén speed based on total (ion+neutral) mass density.

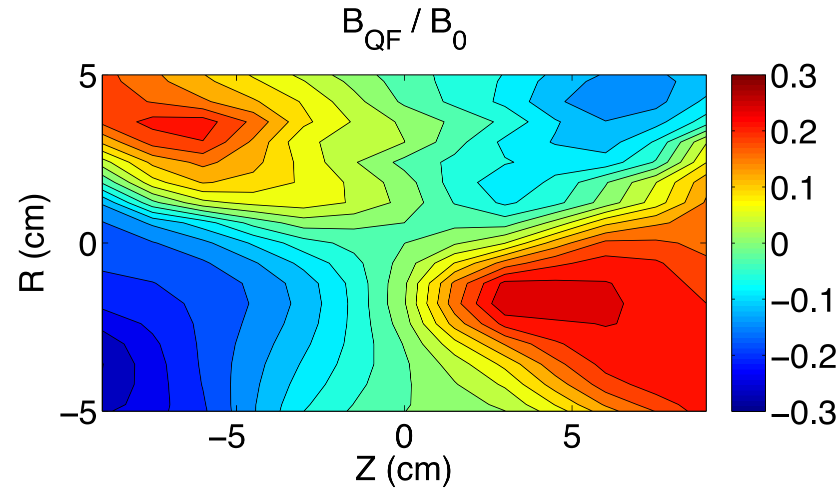


E. Lawrence et al, Submitted to PRL

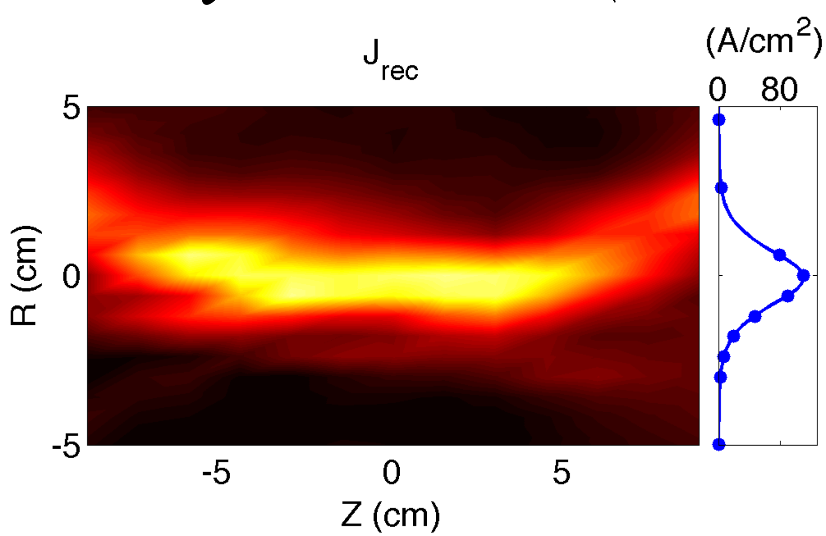
Current sheet and out-of-plane B field unaffected

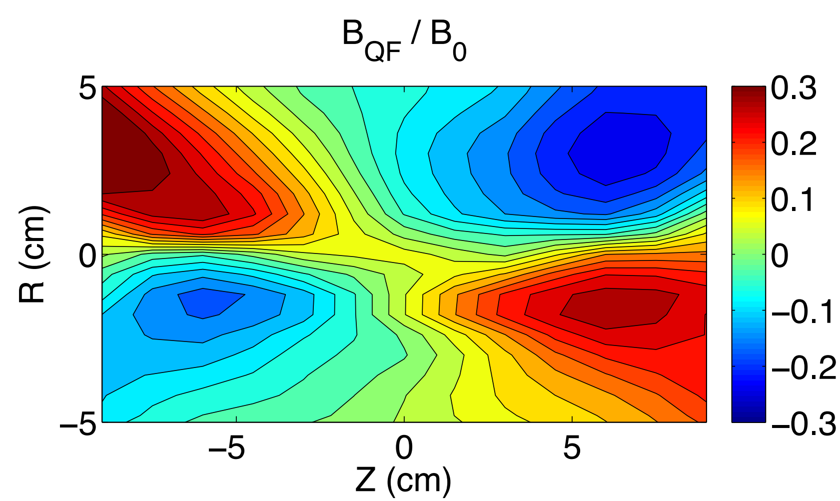
Ionized case ($n_i/n_n \sim 12\%$; $\eta_{en} \sim 0.5\eta_{ei}$; $\nu_{en}, \nu_{ei} \ll \nu_{ce}$)





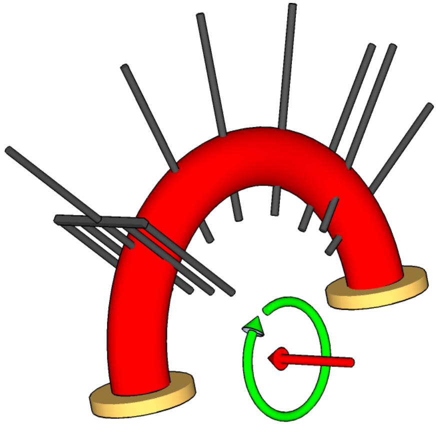
Weakly ionized case ($n_i/n_n \sim 0.9\%$; $\eta_{en} \sim \eta_{ei}$; $\nu_{en}, \nu_{ei} \ll \nu_{ce}$)

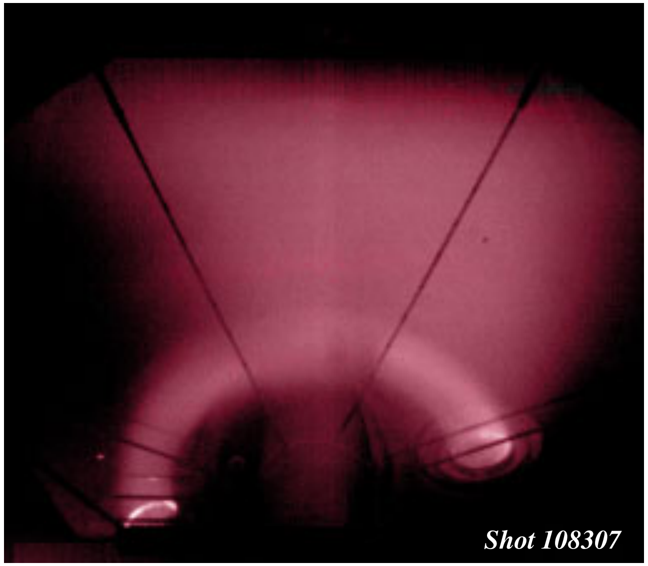


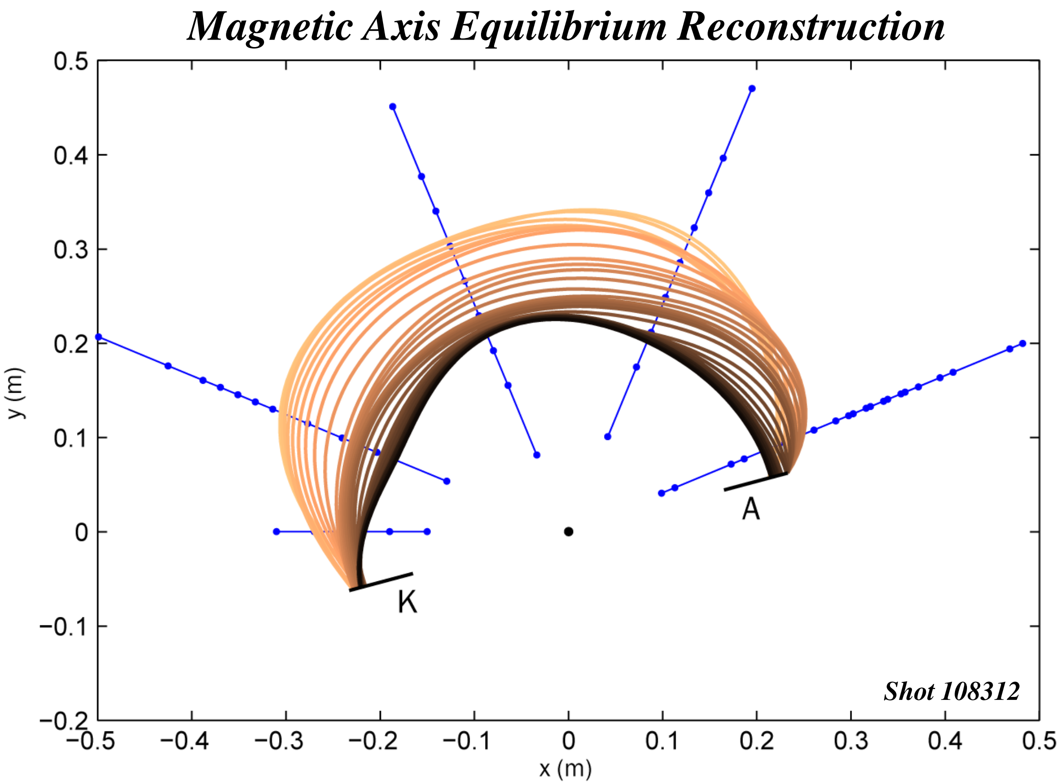


Line-tied magnetic flux rope experiments

- Magnetized partial-toroidal arc discharges are formed between two copper electrodes in MRX
- Magnetic probes and a fast camera are used to analyze **quantitatively** the evolution of the flux rope discharges





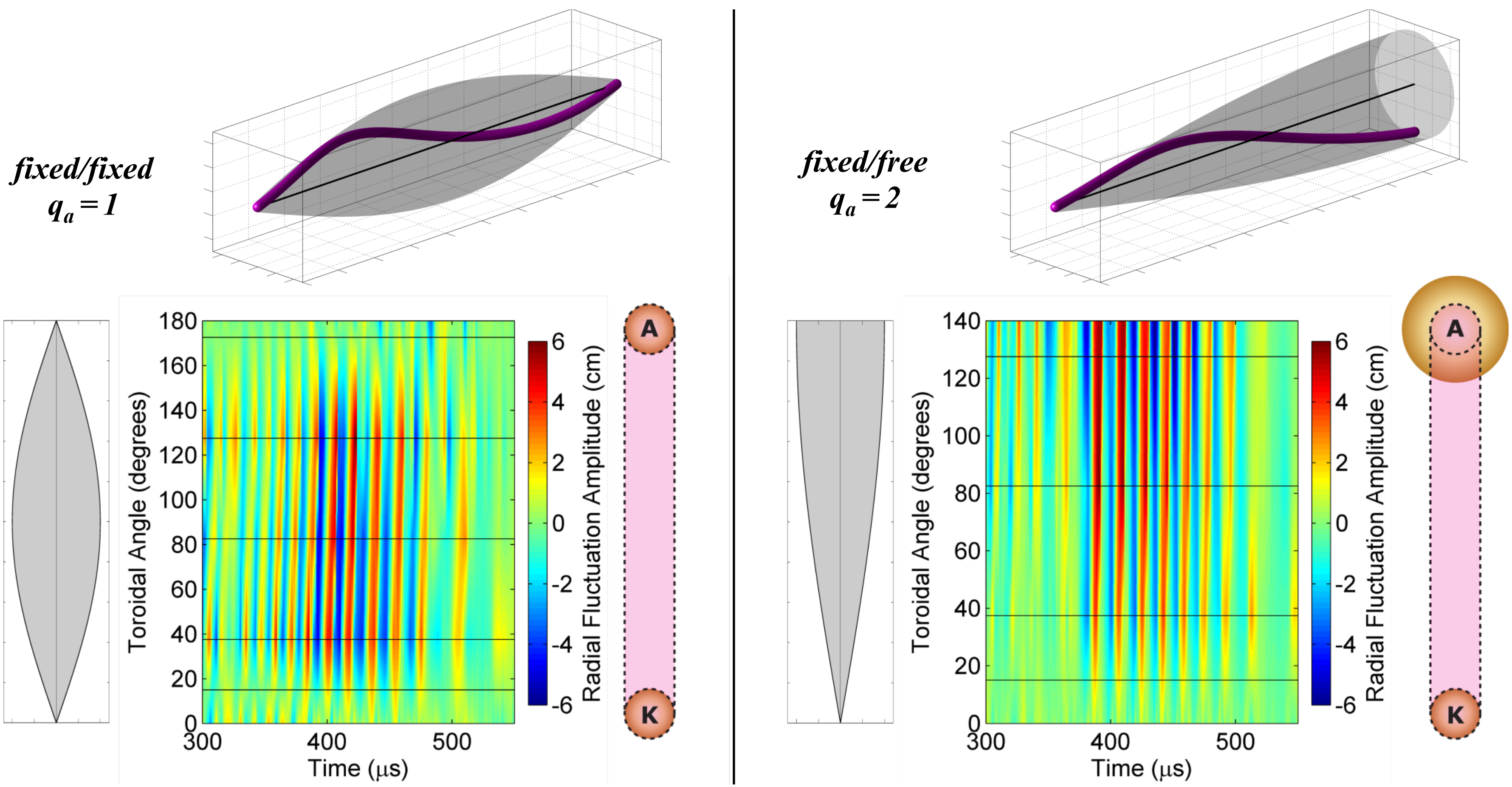


C. Myers: Poster

Kink eigenmode & stability measurements

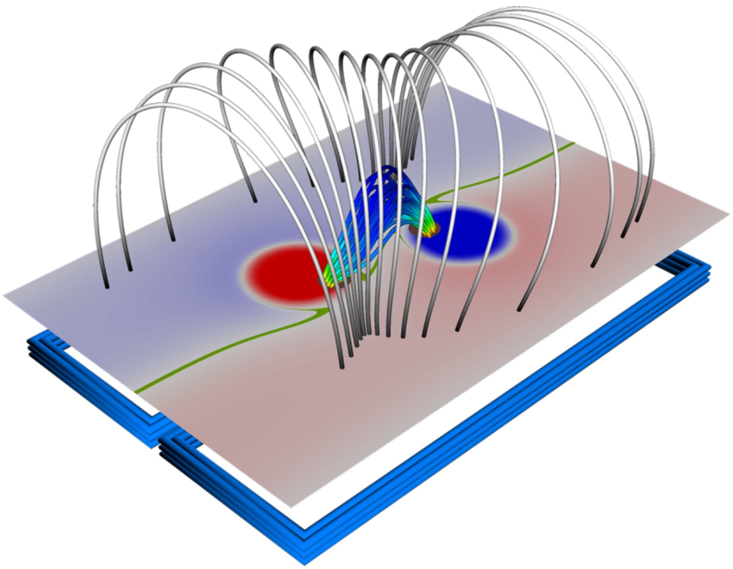
- Definitive measurements of $q_a = 1$ stability threshold for flux rope with two fixed ends:
  - E. Oz, C. E. Myers, et al., *Phys. Plasmas* **18**, 102107 (2011)

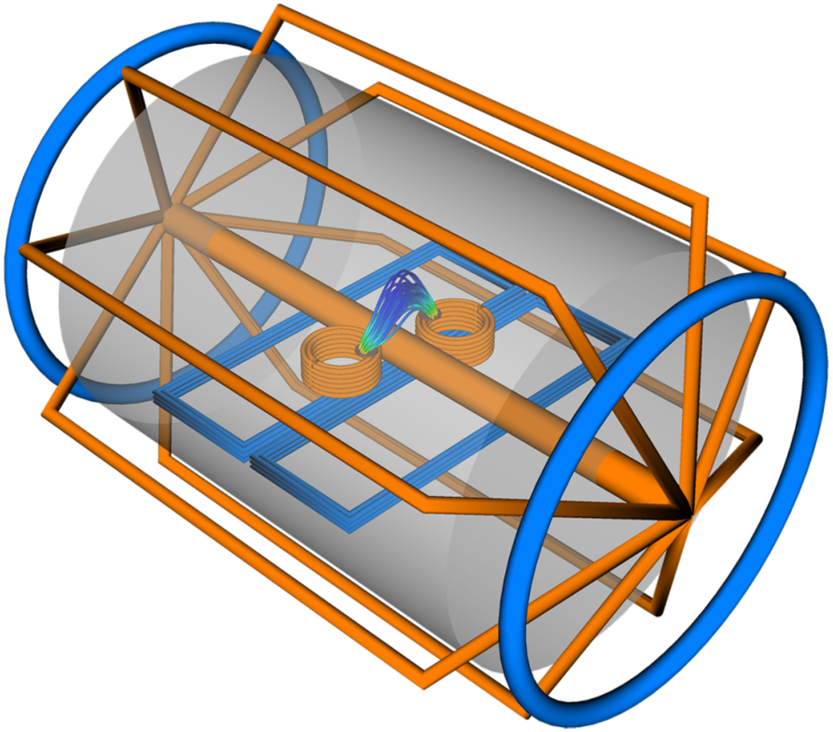
- Changing the boundary condition at one end of the flux rope changes the kink eigenmode and the stability threshold (large anode develops free-sliding resistive sheath).

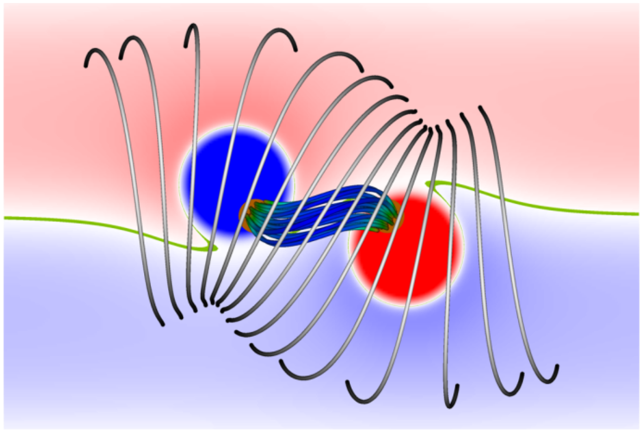


Studies of solar-relevant eruptive mechanisms: loss-of-equilibrium and/or torus instability

- Generate a static potential field configuration that falls off rapidly with height (similar to a solar active region)
- Drive the system *quasi-statically* by injecting magnetic flux over hundreds of Alfvén times
- If enough magnetic flux is injected into the system, it will erupt due to a loss-of-equilibrium or the torus instability







Recent Major Progress on MRX

- **Progress has been made in plasma jog experiments on MRX**
  - Minimum/Maximum Variance Analysis tested
  - Boundary Crossing Timing Analysis (BCTA) works well
  - **Ion flow vector plots measured at the neutral sheet**
  - **Electric potential profiles measured**

- **Ion and electron heating observed in the down stream of the current sheet**
  -Mechanisms of particle acceleration and heating yet to be determined

- **Systematic guide field reconnection research restarted**
  - Hall fields survive even with a large guide field
  - Reconnection rate decreases notably w.r.t. B_g/B_rec

- **Reconnection in partially ionized plasmas: Theory and experiments**

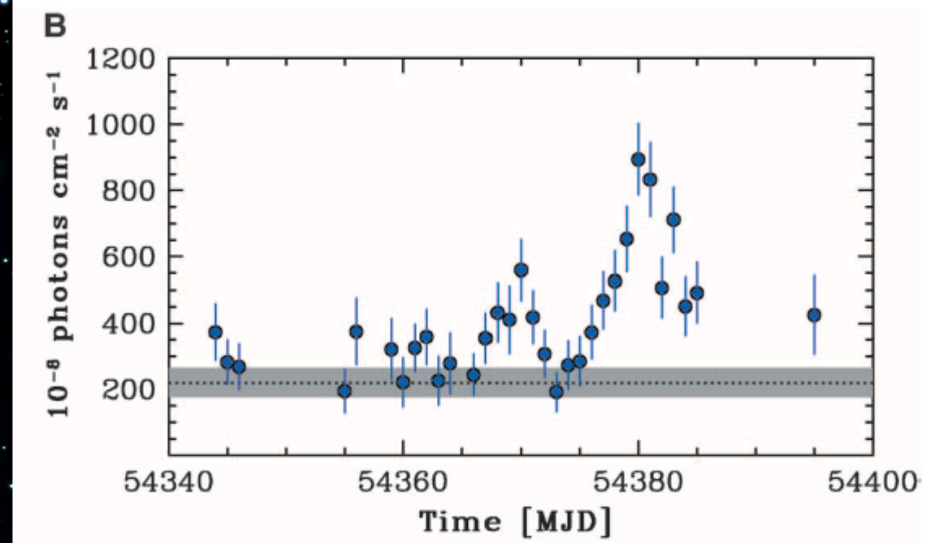
Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas

Future plans for MRX research

- **Near term thrust**
  Effects of guide field (Hall effects, reconnection rate)
  Global reconnection and boundary conditions (including line tying)
  Particle acceleration and heating

- **Major thrust:**
  Particle Acceleration, Heating!!!
  Local problem => Global problem

- **Preparation for a new-generation reconnection experimental facility**
  Flux rope reconnection
  Particle acceleration and heating



Gamma ray flares
in Crab Nebura

Reconnection could explain high energy gamma ray emission from the center of Crab Nebula (J. Arons, R. Blandford, et al) Uzdensky et al 2011