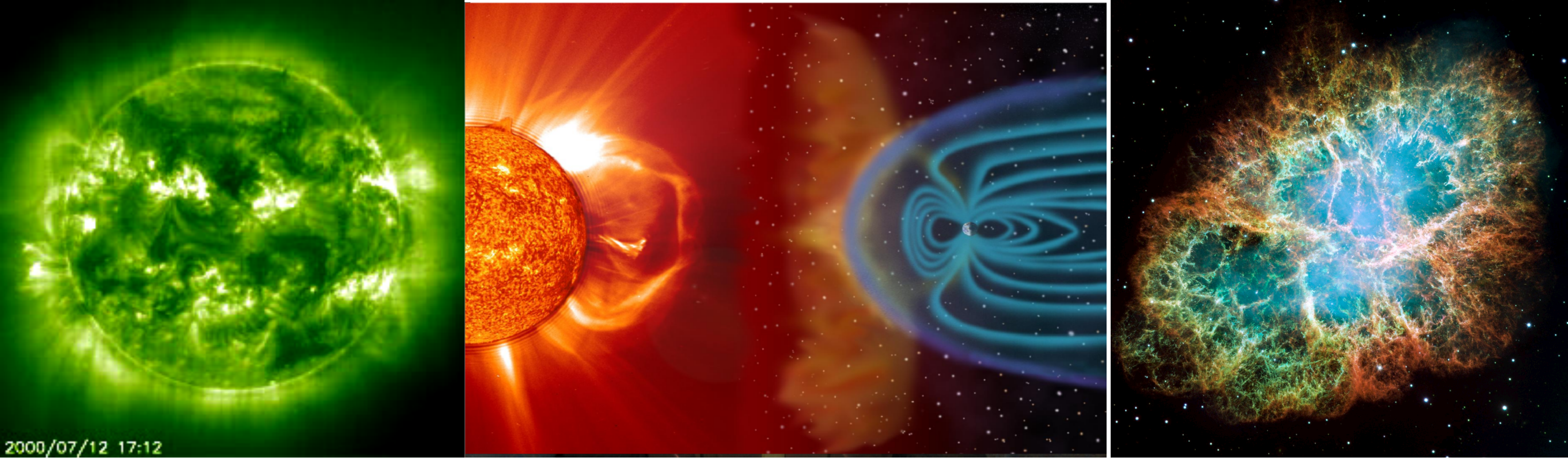


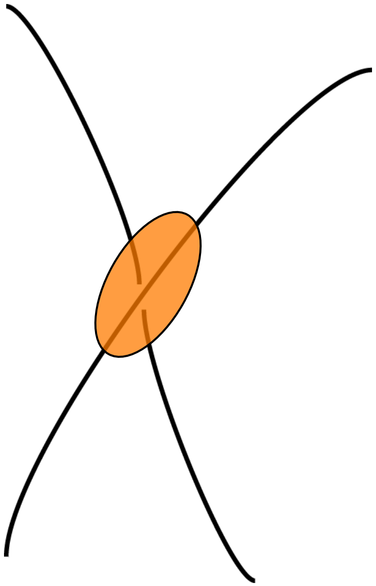
Laboratory Study of Magnetic Reconnection

Masaaki Yamada
Princeton Plasma Physics Laboratory,
Princeton University

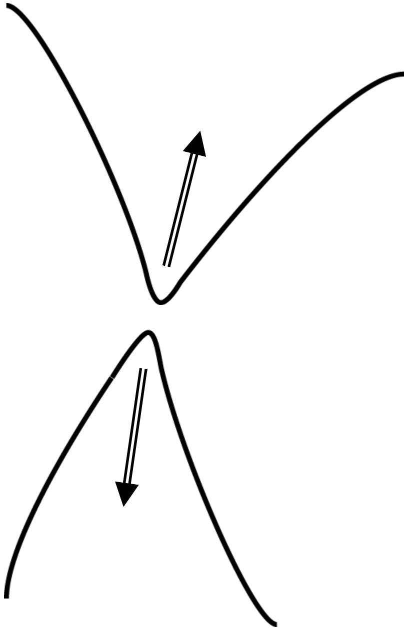
April 4, 2013

In collaboration with members of MRX group and
NSF-DoE Center of Magnetic Self-organization

Magnetic Reconnection



Before reconnection



After reconnection

- **Topological rearrangement of magnetic field lines**
- **Magnetic energy => Kinetic energy**

Outline

- **Magnetic reconnection**
  - Why does it occur so fast compared with classical MHD?
  - Lower collisionality <=> faster reconnection
  - Two fluid effects

- **Local analysis based on two-fluid physics through cross validation with numerical modeling**
  - Collision-free reconnection => an X-shaped reconnection layer
  - Hall effect and experimental verification
  - Two-scale reconnection layer identified
  - 3-D picture of magnetic reconnection layer

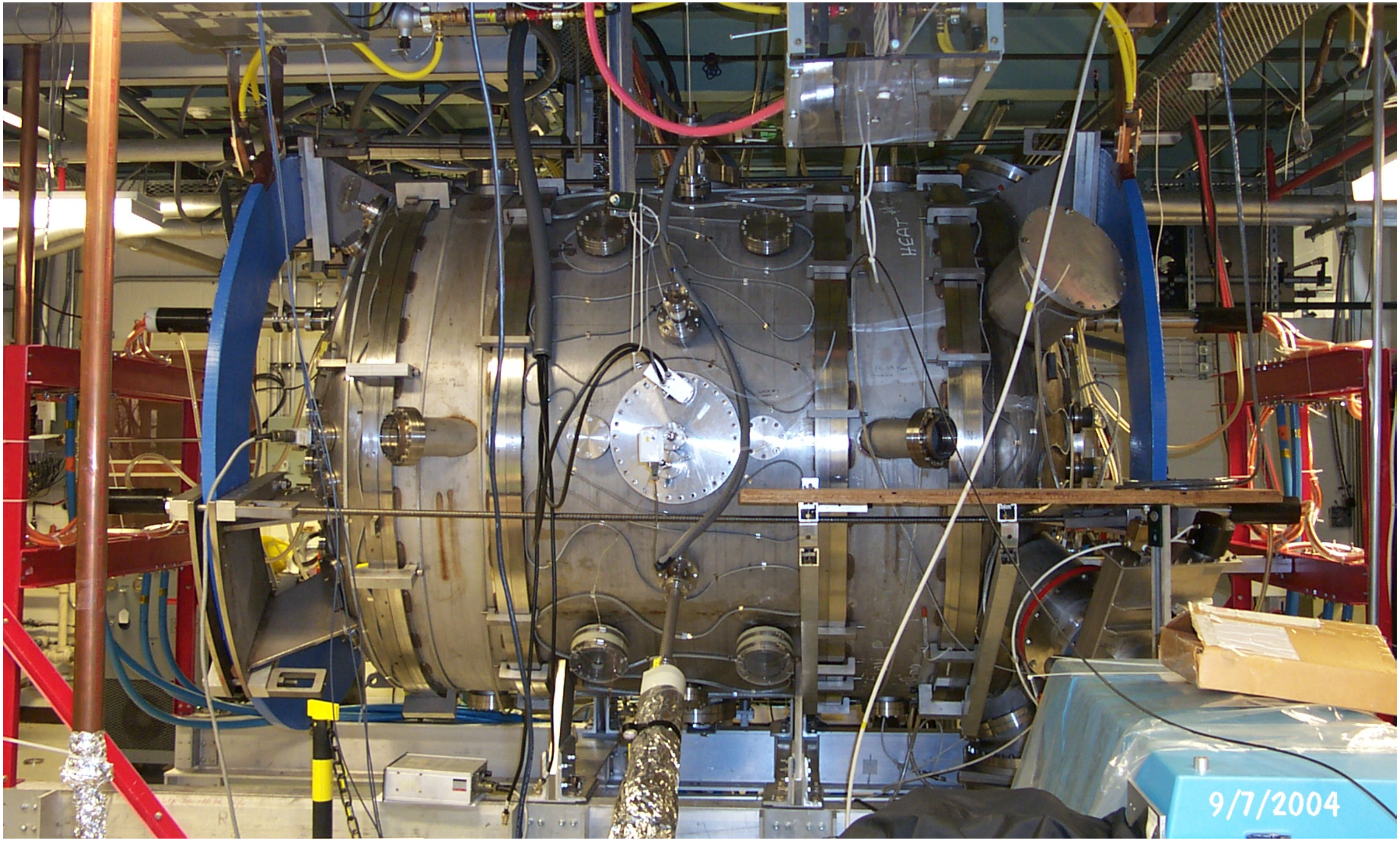
- **Recent Discoveries on energy conversion on MRX**
  - **Heating of ions and electrons**
  - **New picture of particle dynamics**
- Other findings on MRX

- Future Plans

Samples of Reconnection Experiments

Device	*Where*	*When*	*Who*	*Geometry*	*Q's*
3D-CS	Russia	1970	Syrovatskii, Frank	Linear	3D, heating
LPD, LAPD	UCLA	1980	Stenzel, Gekelman	Linear	Heating, waves
TS-3/4	Tokyo	1990	Katsurai, Ono	Merging	Rate, heating
MRX	Princeton	1995	Yamada, Ji	Toroidal, merging	Rate, heating, scaling
SSX	Swarthmore	1996	Brown	Merging	Heating
VTF	MIT	1998	Egedal	Toroidal with guide B	Trigger
RSX	Los Alamos	2002	Intrator	Linear	Boundary
RWX	Wisconsin	2002	Forest	Linear	Boundary

Magnetic Reconnection Experiment (MRX)



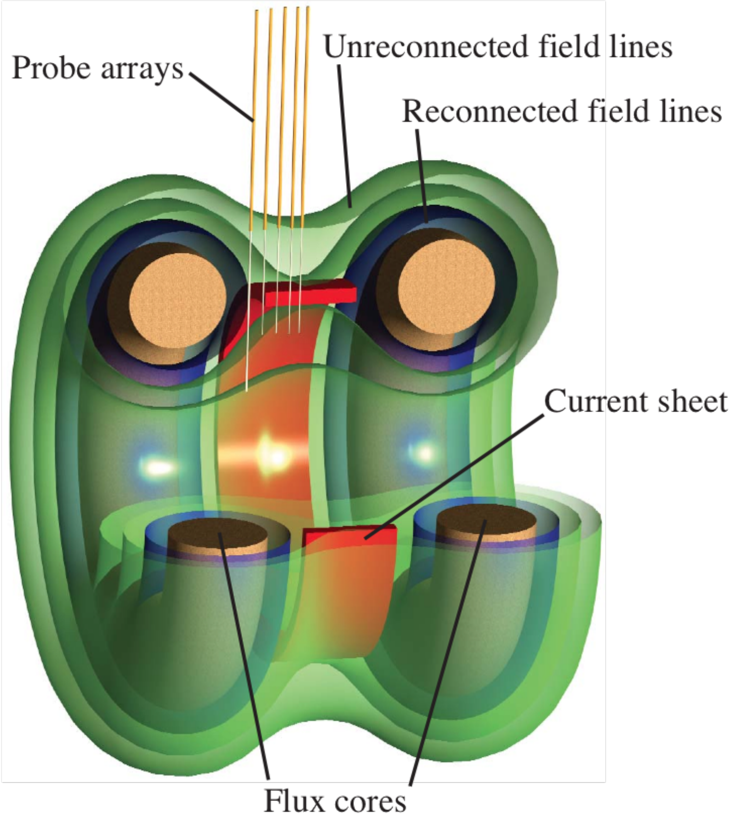
How do we study magnetic reconnection in dedicated lab experiments?

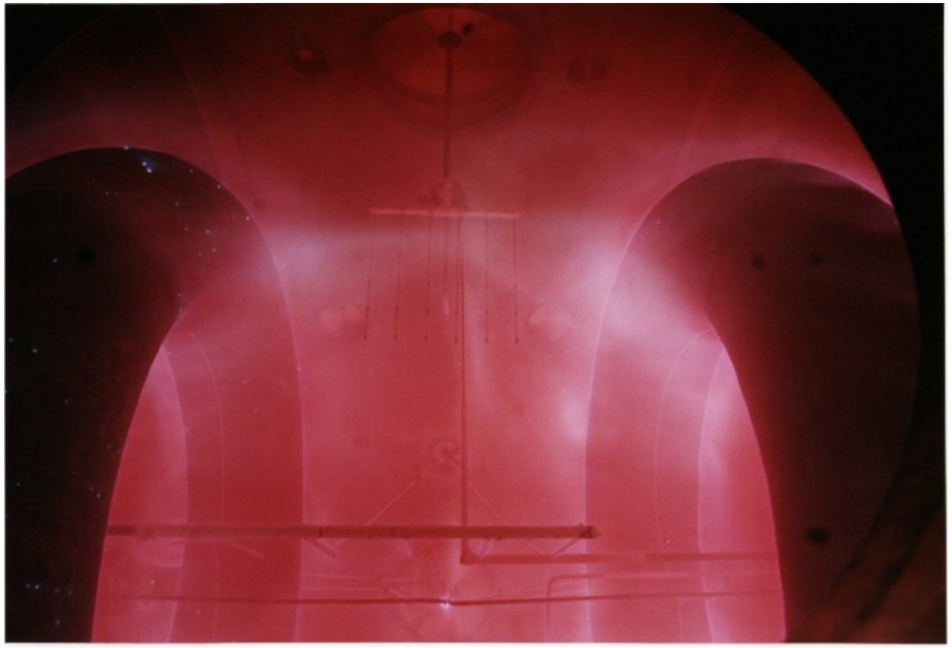
1. We create a proto-typical reconnection layer in a controlled manner and study the fundamental plasma dynamics
2. Cross-validation of experiment and numerical modeling

The primary issues/questions;

- Why does reconnection occur so fast so explosively?
- Dynamics of electrons and ions
- How does local reconnection determine global phenomena?
- How is magnetic energy converted to plasma flows and thermal energy?

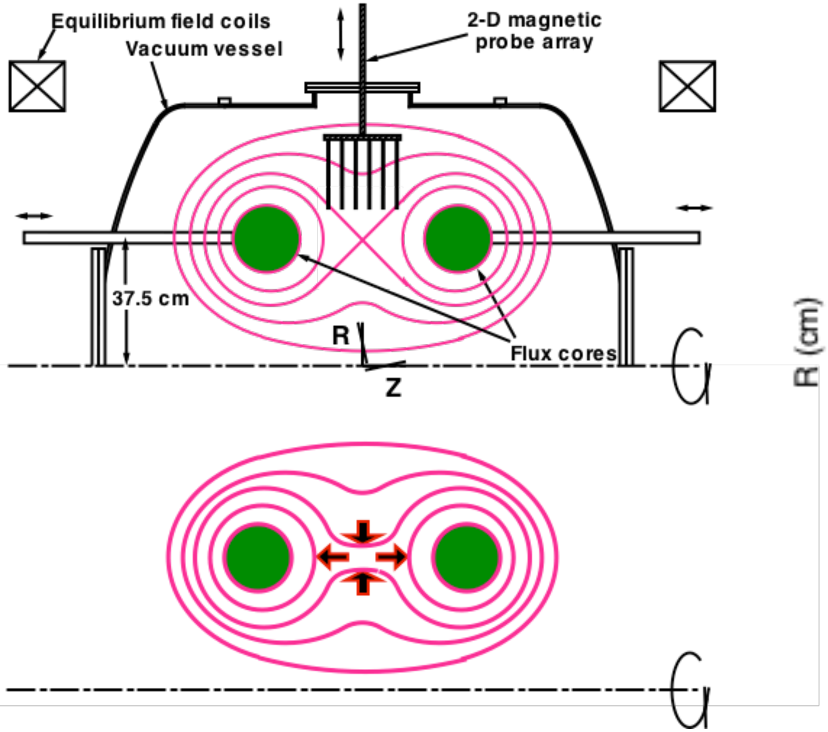
Plasma Production in MRX



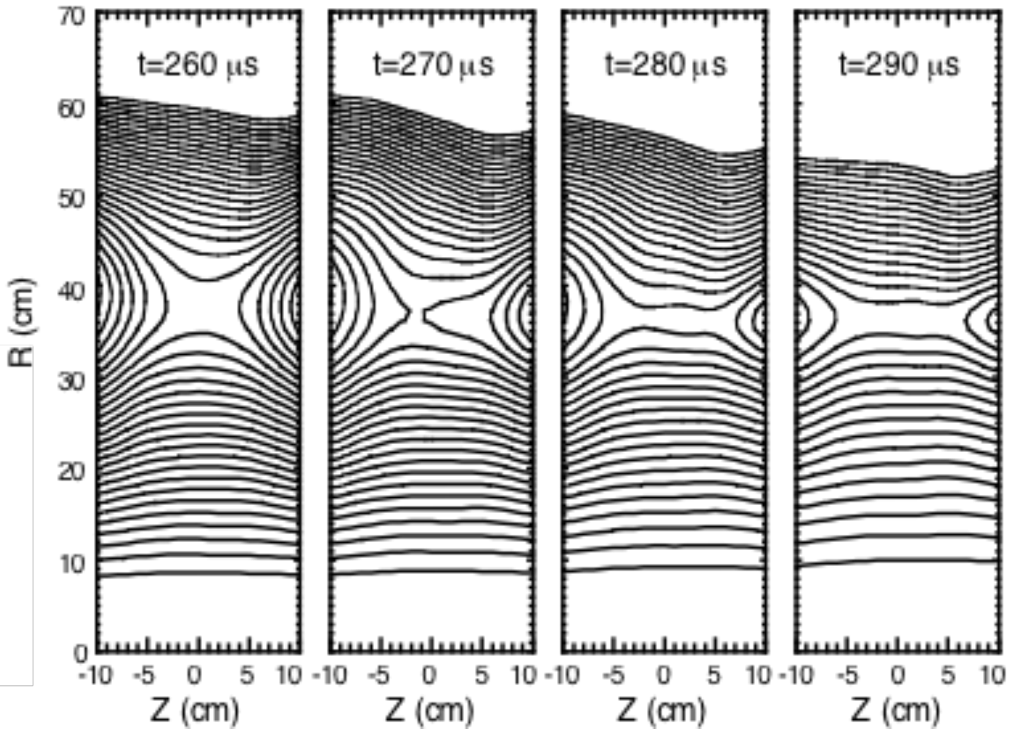


1) ***Gas is injected into the vacuum vessel.***
2) ***Currents through the "flux cores" ionize plasma and drive reconnection by forming a current sheet.***
3) ***Probes measure magnetic field, temperature, and density.***

Experimental Setup and Formation of Current Sheet



Experimentally measured flux evolution

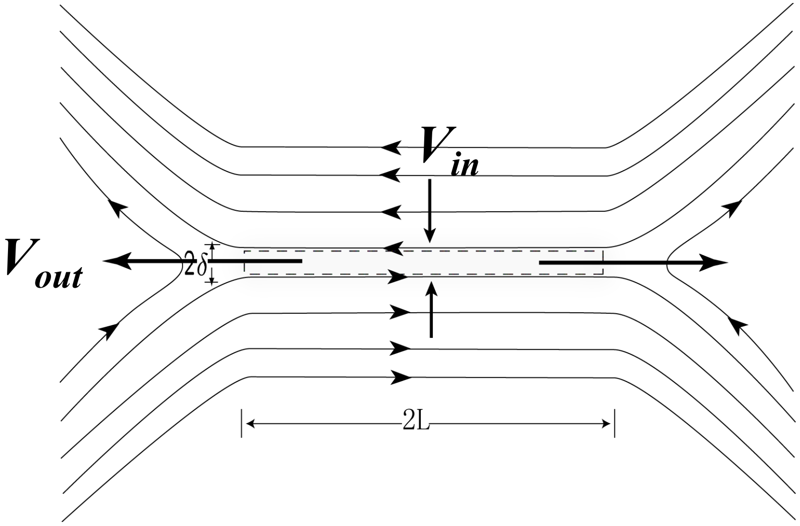


n_e= 1-10 x10^{13} cm^{-3},
T_e~5-15 eV,
B~100-500 G,

The Sweet-Parker 2-D Model for Magnetic Reconnection

Assumptions:

- 2D
- Steady-state
- Incompressibility
- Classical Spitzer resistivity



B is resistively annihilated in the sheet

$\tau_{reconn} \ll \tau_{SP} \sim$ 6–9 months

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B}$$

⇨

$$V_{in} B = \frac{\eta_{Spitz}}{\mu_0} \frac{B}{\delta}$$

➡

$$\boxed{\frac{V_{in}}{V_A} = \frac{1}{\sqrt{S}}}$$

$$S = \frac{\mu_0 L V_A}{\eta_{Spitz}}$$

S=Lundquist number

Mass conservation: $V_{in} L \approx V_{out} \delta$

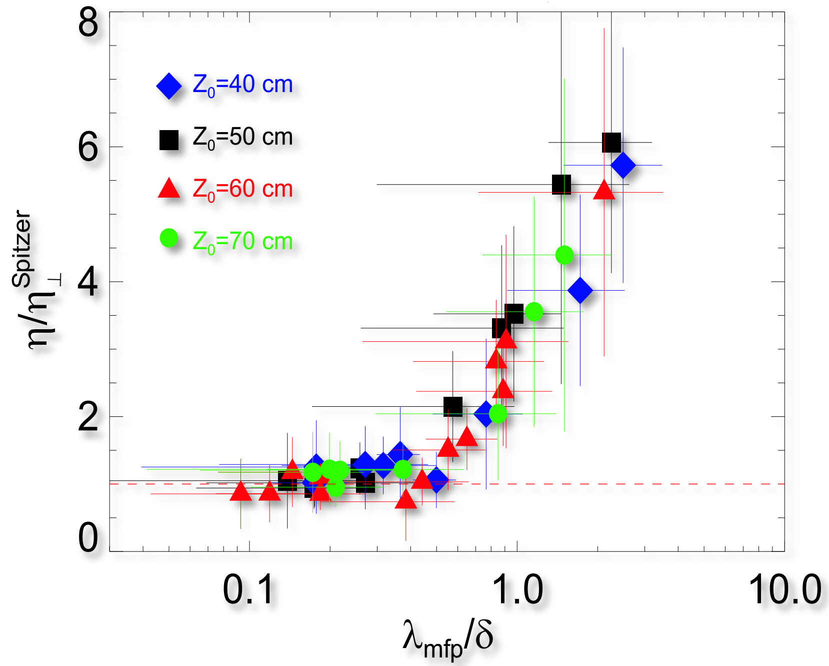
Pressure balance: $\frac{1}{2} \rho V_{out}^2 \approx \frac{B^2}{2\mu_0} \Rightarrow V_{out} \approx V_A$

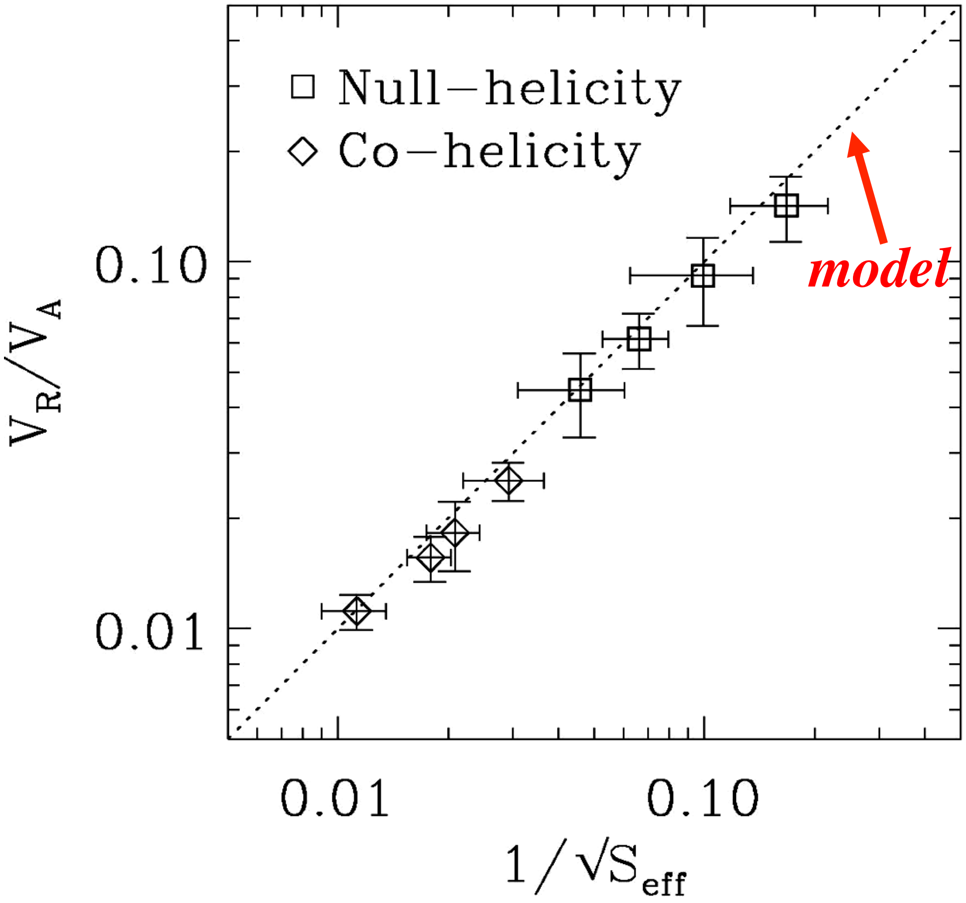
Sweet-Parker model works only in *Collisional MHD*

- **Adjustments by compressibility and boundary conditions**

Ji et al., PRL (1998)

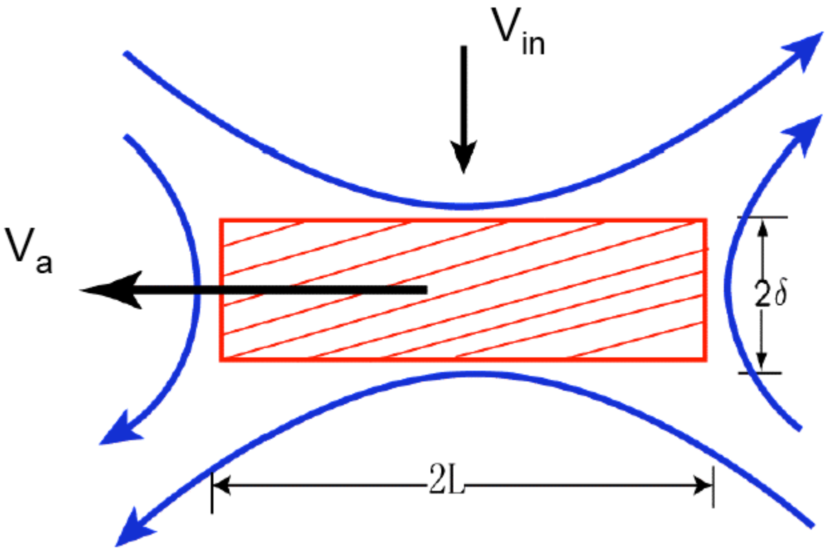
- ***When collision rate is reduced , the effective resistivity (E/j) increases beyond Spitzer values (Kuritsyn et al. 2006)***

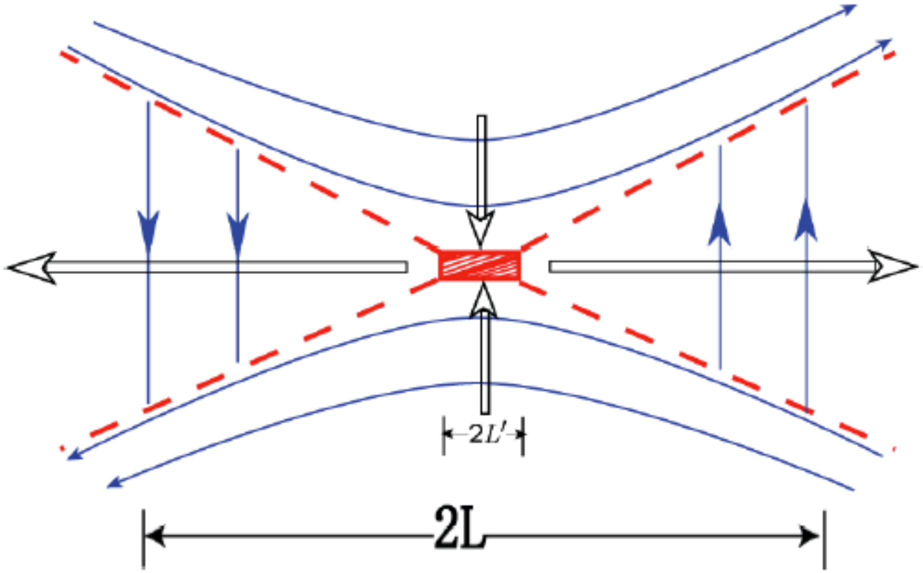




Main Q: what causes the enhanced resistivity?

Models for Fast Reconnection





Generalized Sweet-Parker model with enhanced resistivity

$$\frac{\delta}{L} = \frac{1}{\sqrt{S}}$$

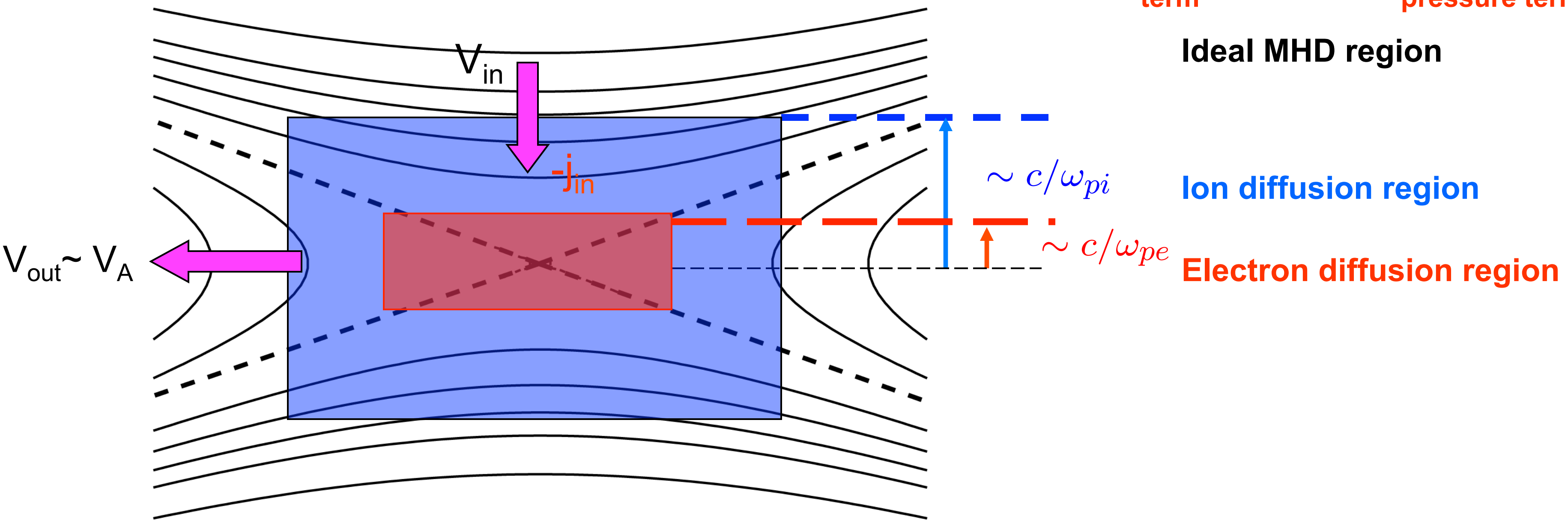
Two-fluid MHD model in which electrons and ions decouple in the diffusion region ($\sim c/\omega_{pi}$).

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

Generalized Ohm’s Equation in Collisionless Plasmas

Normalized with $x/\Delta \to x,\ V/V_A \to V,\ B/B_0 \to B$

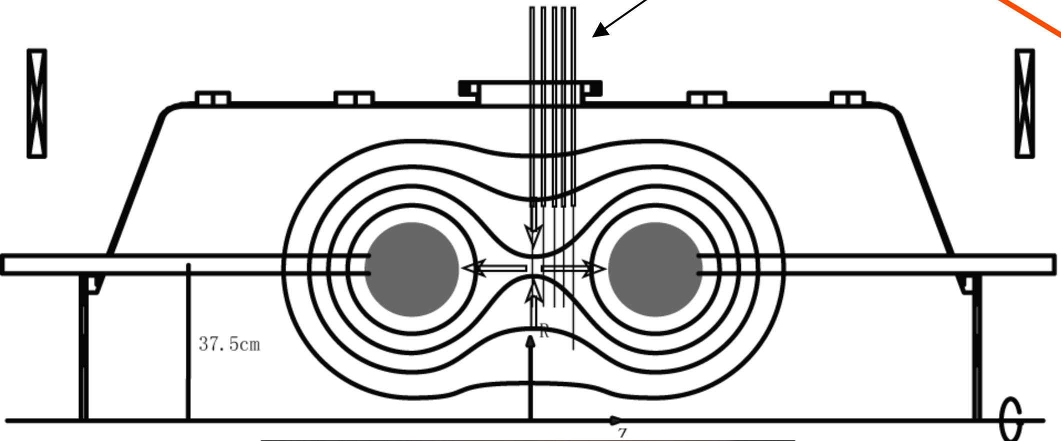
$$E_{rec} + V_{in} \times B_{rec} = 0 + \frac{\delta_i}{\Delta}\underbrace{\frac{j_{in}\times B_{rec}}{n}}_{\text{Hall term}} - \frac{\delta_e^2}{\Delta^2}\underbrace{\frac{1}{n}\frac{dj_{rec}}{dt}}_{\text{Electron inertia term}} + \frac{\delta_i}{\Delta}\underbrace{\frac{(\nabla\cdot P_e)_{off}}{n}}_{\text{Electron pressure term}}$$

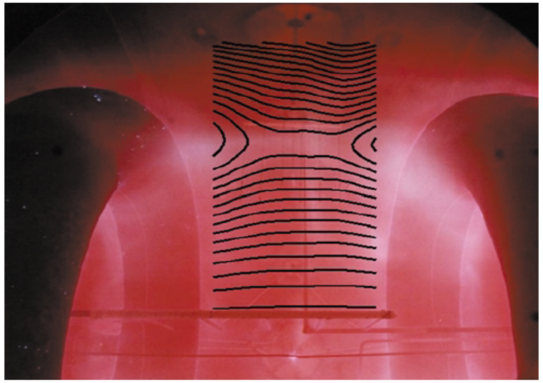


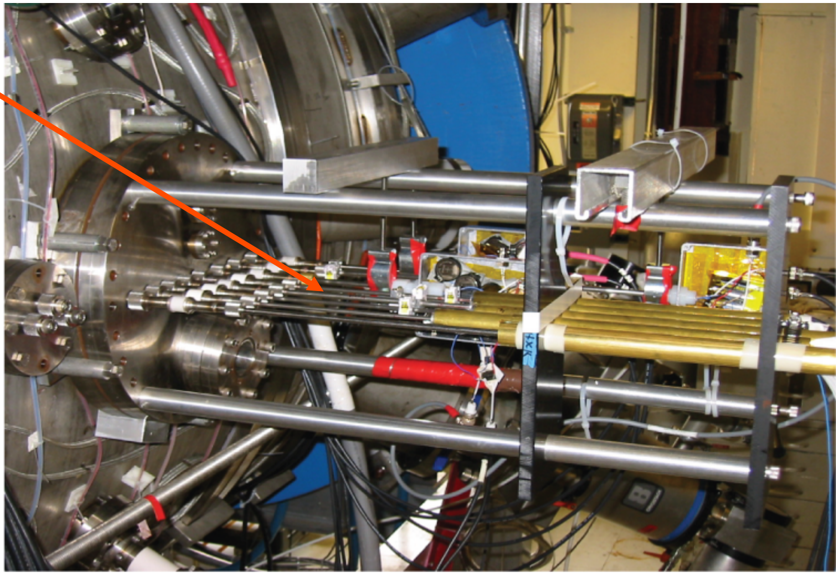
- The width of the ion diffusion region is c/ω_{pi}
- **The width of the electron diffusion region is c/ω_{pe} where energy dissipation occurs**

MRX with fine probe arrays

Linear probe arrays



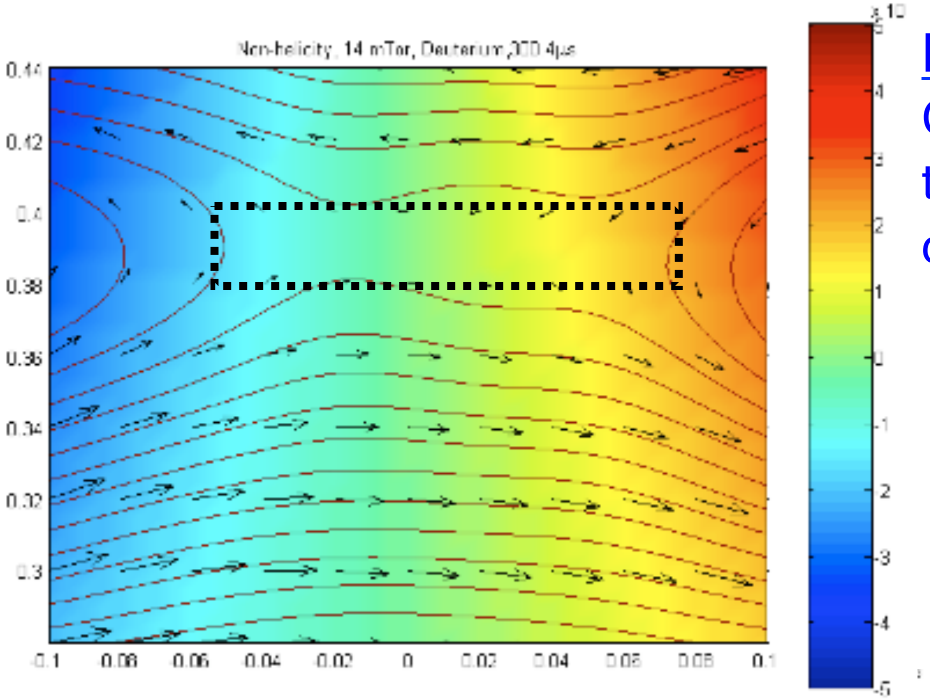




- Five fine structure probe arrays with resolution up to Δx= 2.5 mm in radial direction are placed with separation of Δz= 2-3 cm

Neutral sheet Shape in MRX

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

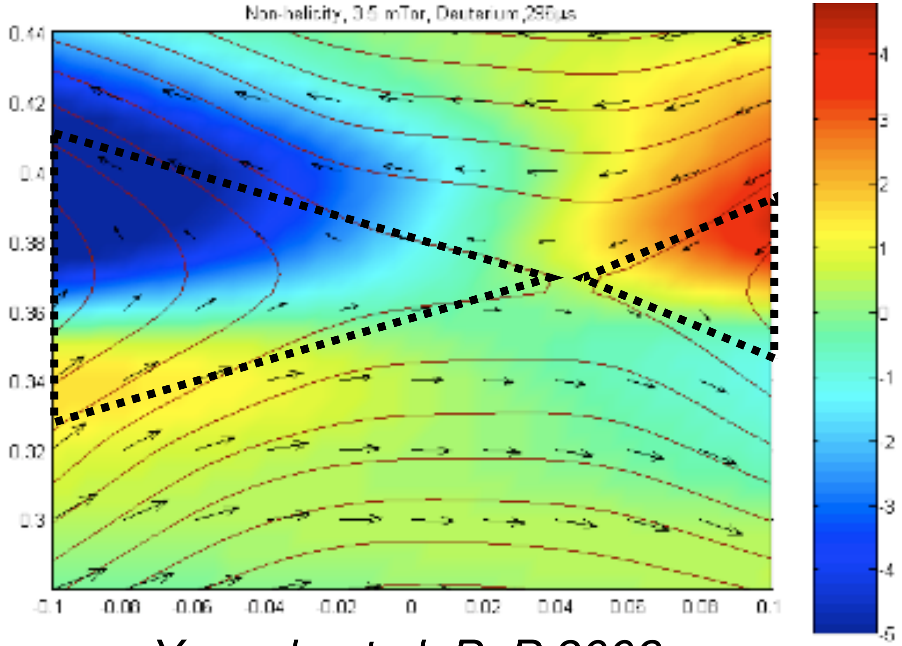


Rectangular shape

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

Slow reconnection

No Q-P field



X-type shape

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

Fast reconnection

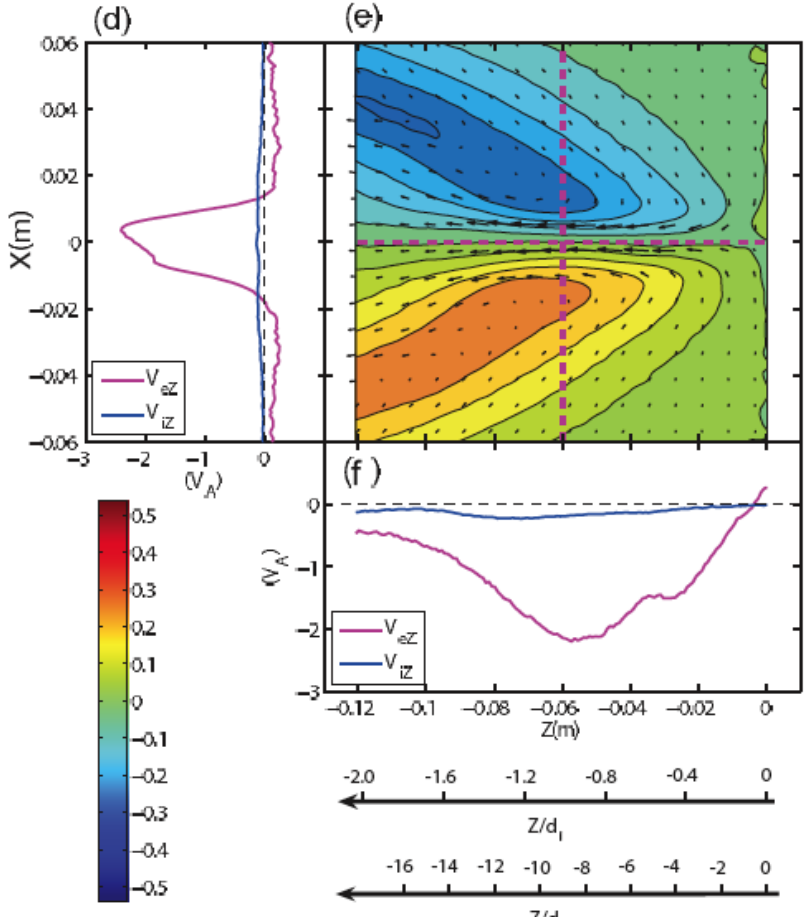
Q-P field present

Yamada et al, PoP 2006

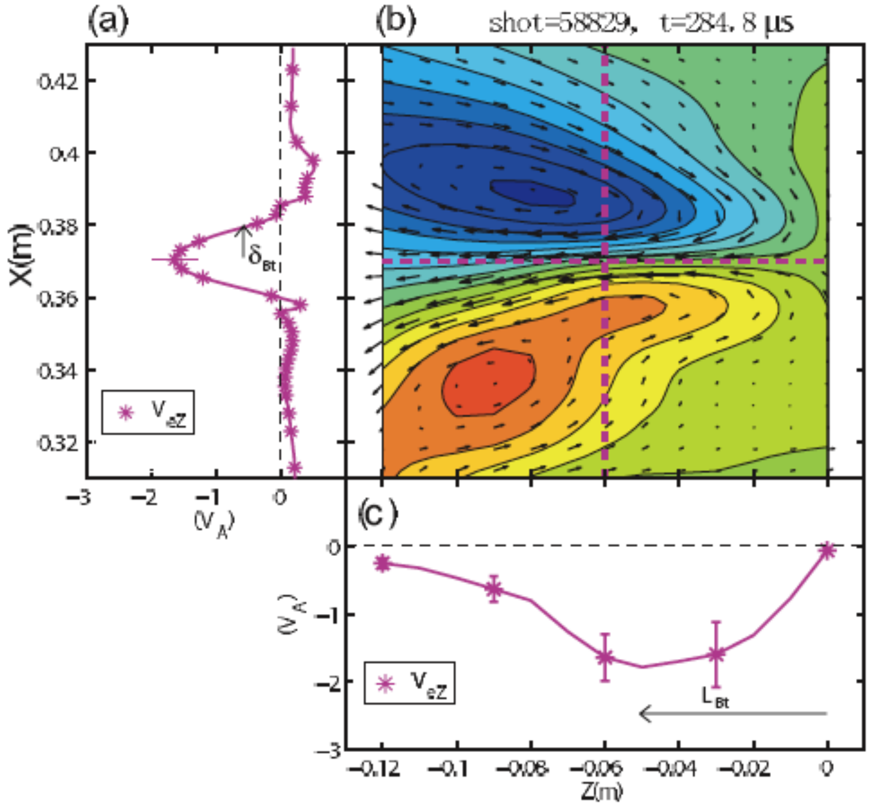
Predicted by Ma & Bhattacharjee’ 96

Experimental identification of the two-scale reconnection layer: e-diffusion regime inside the ion diffusion region

PIC Simulation

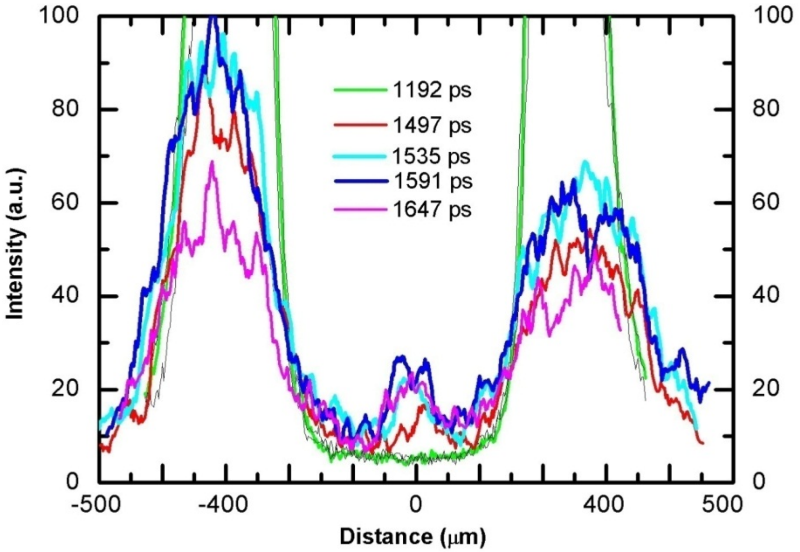


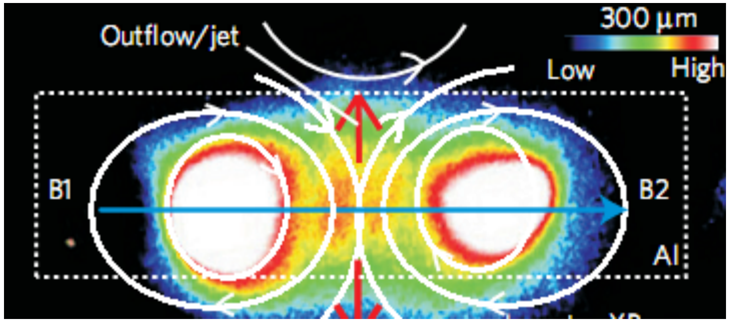
Experiment



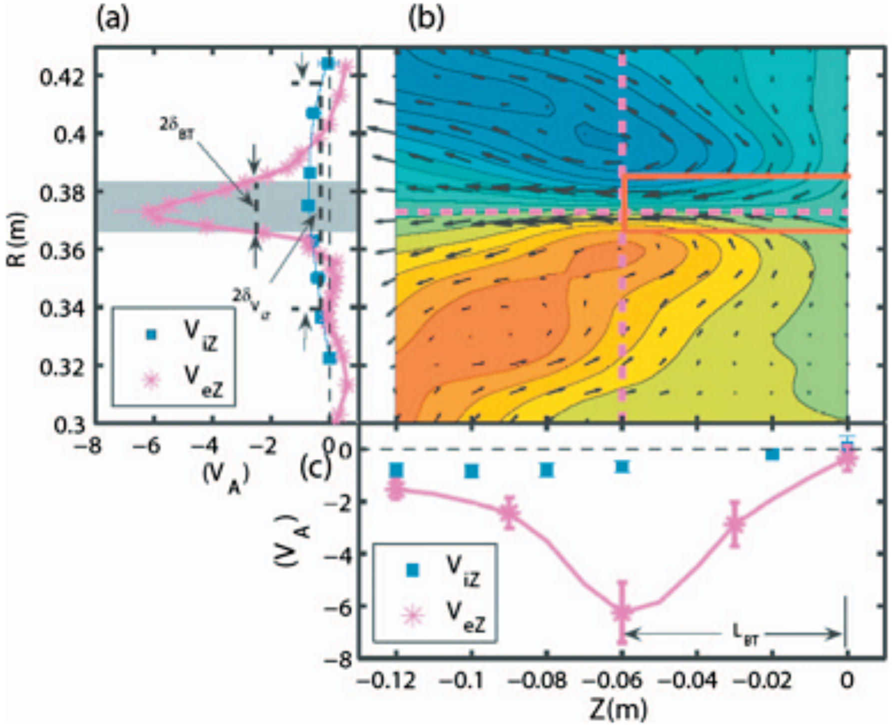
Observed δ_e ~ 5 δ_e (theory): 3D effects?
[Ren et al, PRL 08, Ji et al GRL, 08, Dorfman et al ‘10]

Recent study of reconnection region in a laser plasma
J. Zhong et al,





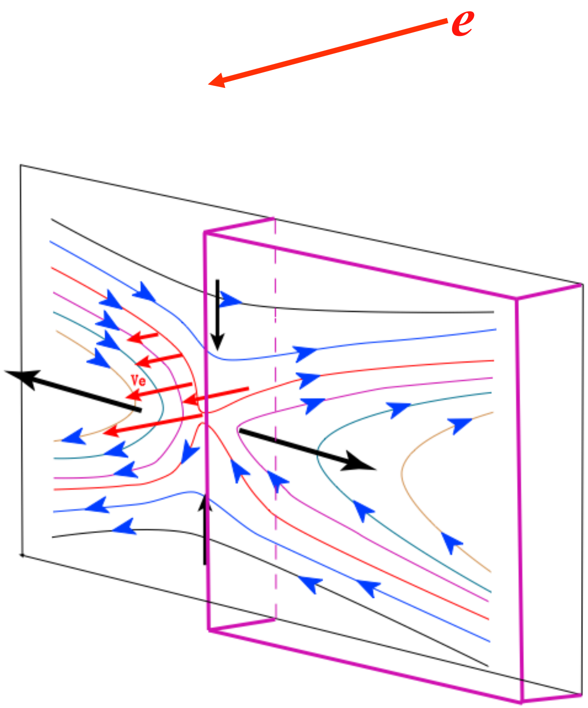
MRX



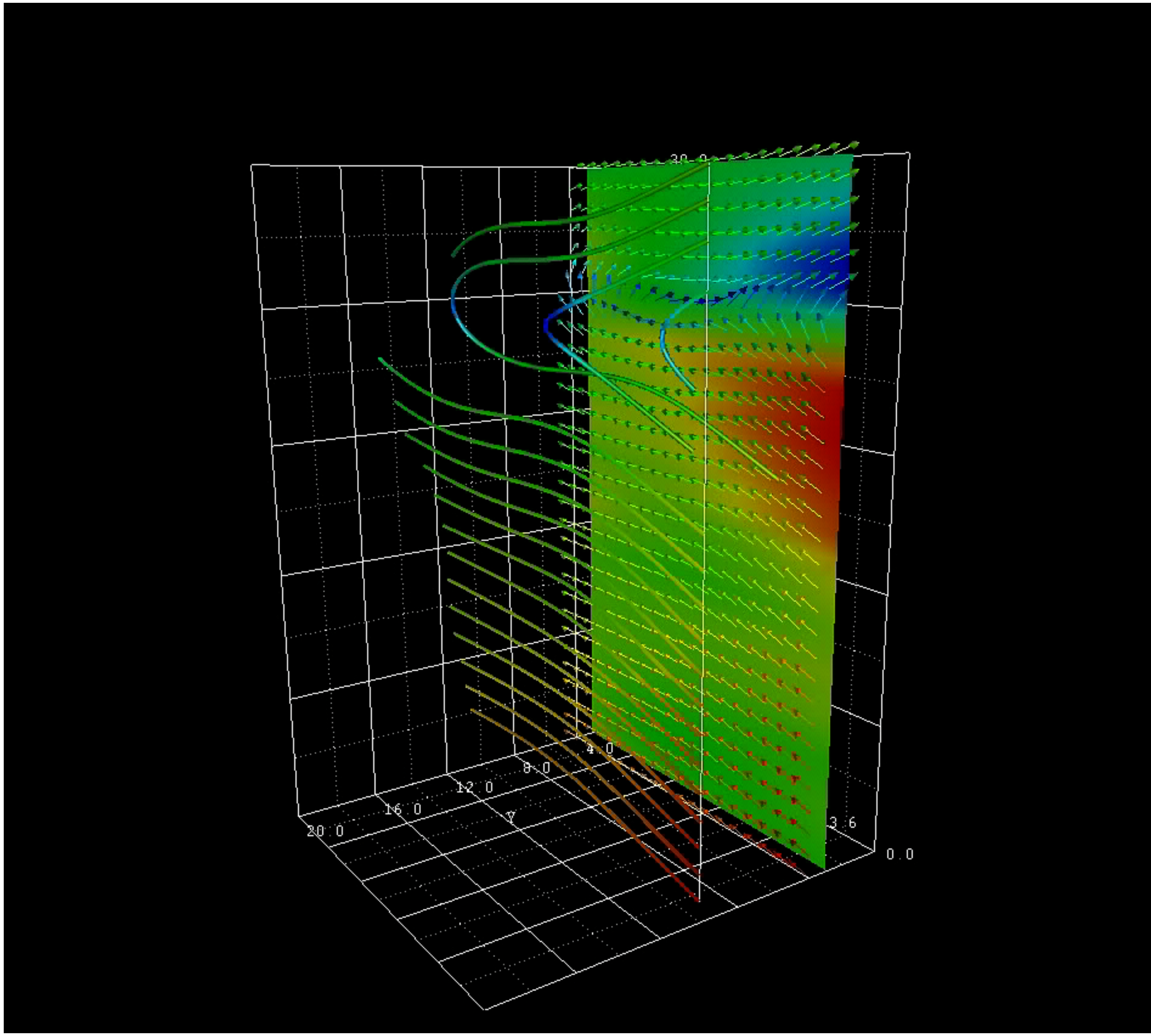
Ren, et al. PRL. 101,085003(2008)

- *Ion diffusion region with the width of ~ d_i*
- *Electron diffusion region with the width of ~ 8-12d_e*

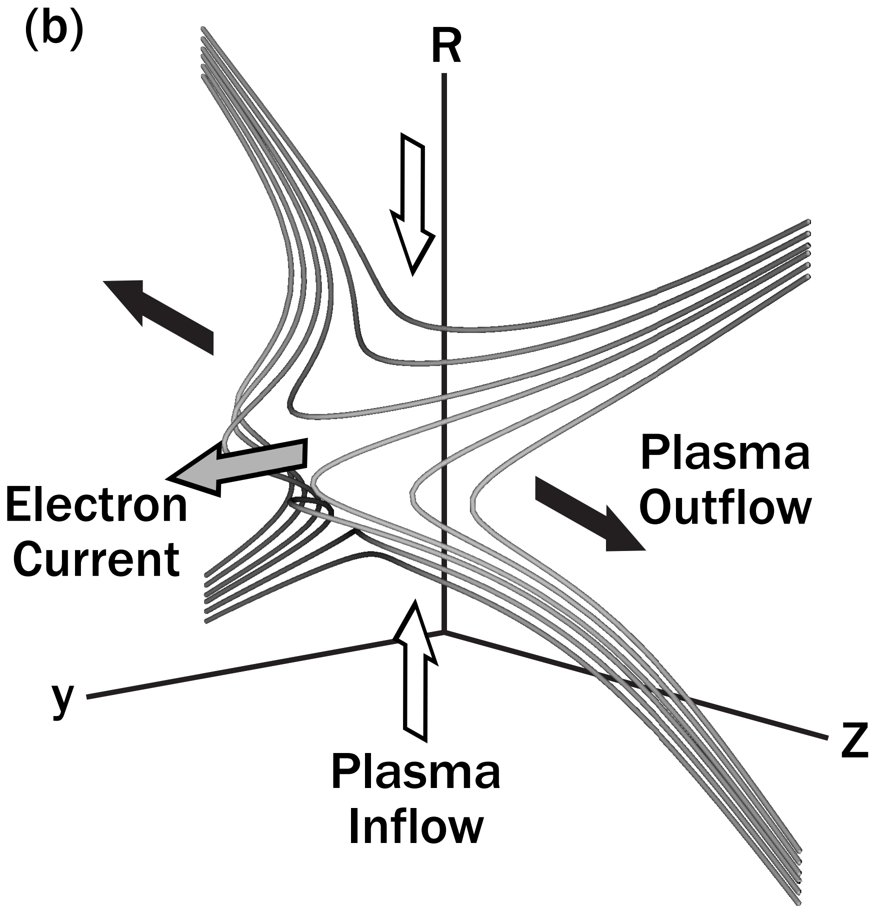
Evolution of magnetic field lines during reconnection in MRX



Measured region



Two-fluid physics dictates reconnection layer dynamics



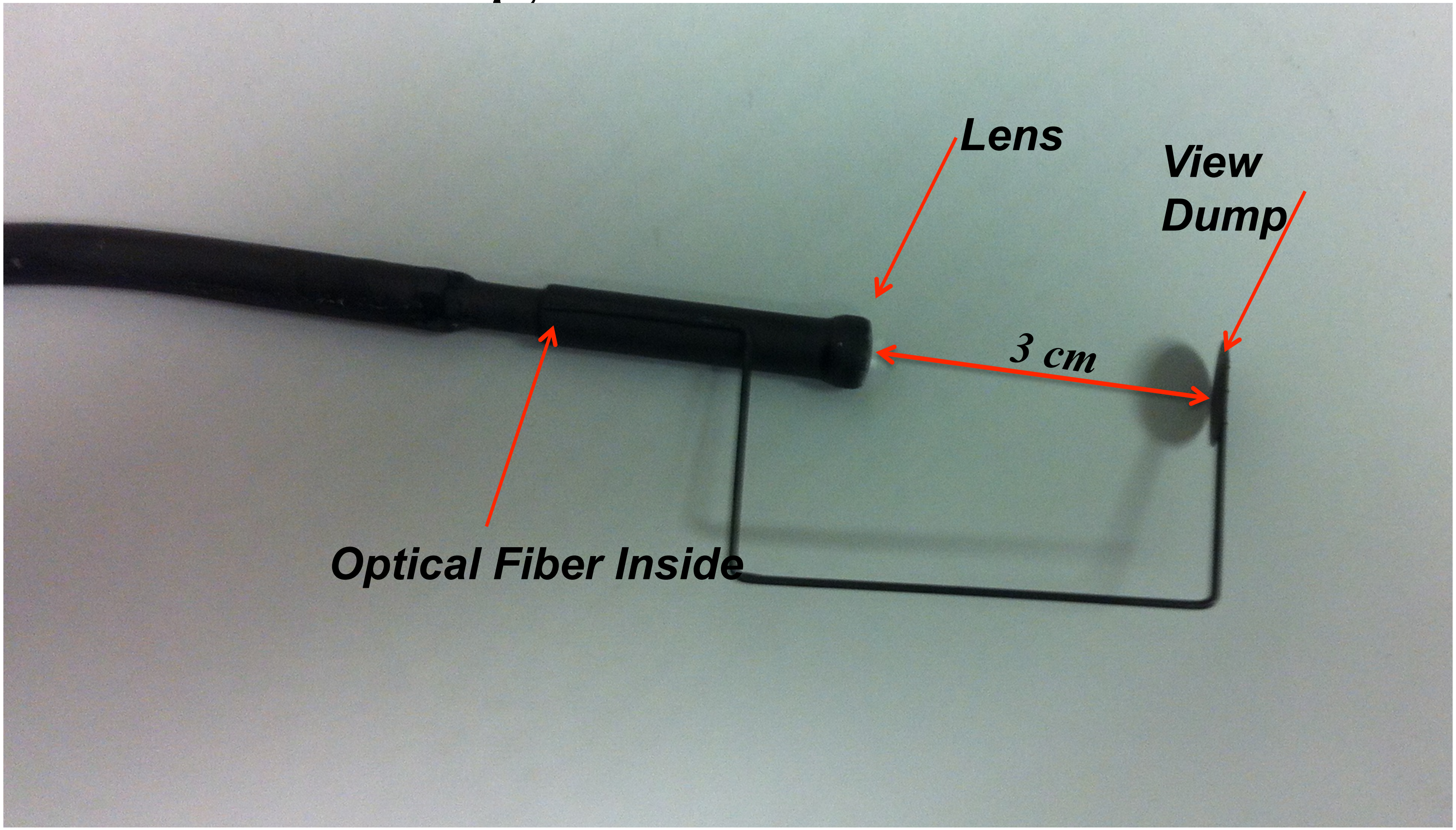
Sheath width ~ c/ω_{pi}

- Acceleration and heating of mirror trapped electrons.
- Out of plane magnetic field is generated during reconnection.
- Parallel electric conduction is expected to dictate potential profile before and after reconnection.

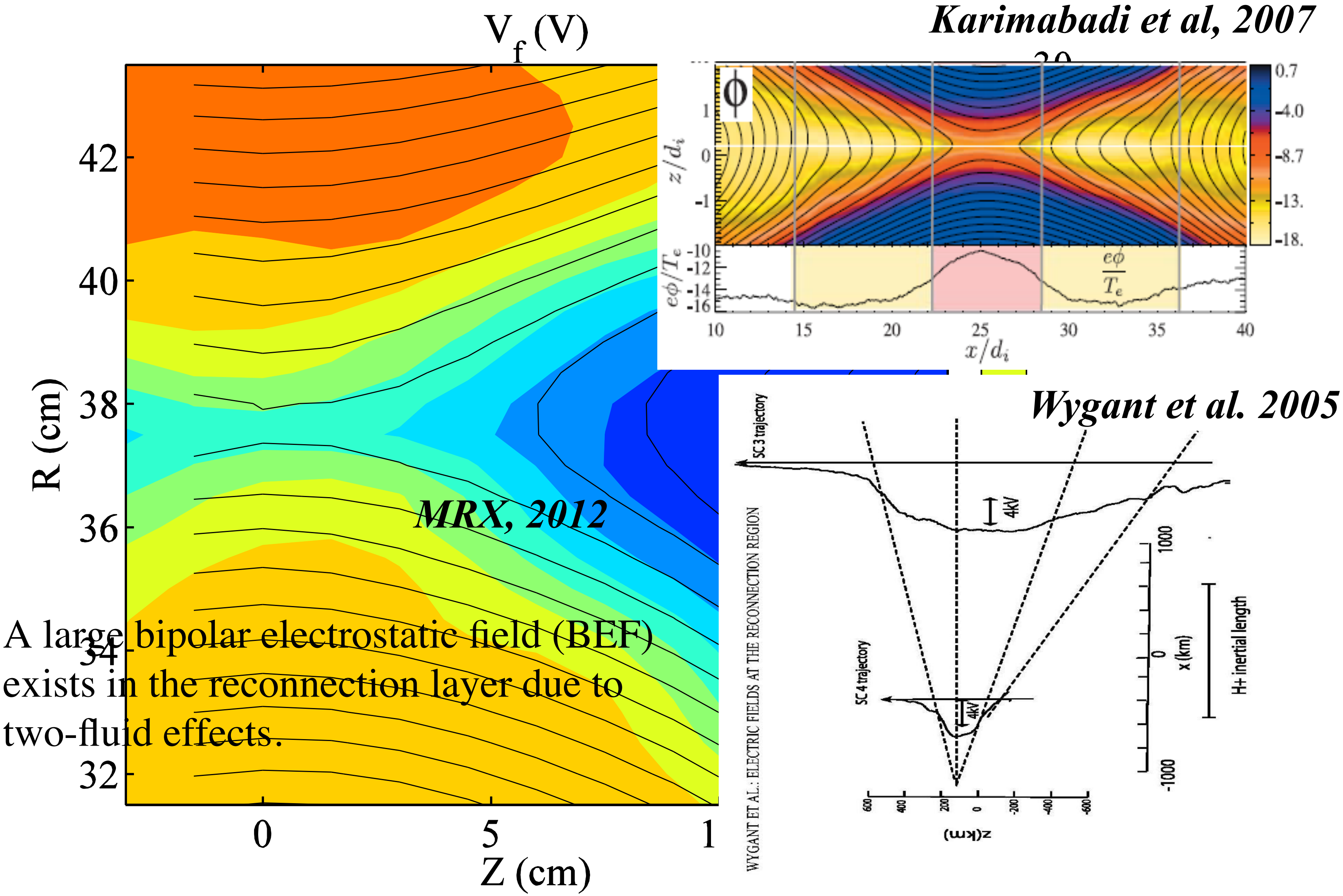
Recent MRX Results with New Diagnostics

- Magnetic probes
  - 7 probes placed every 3cm along Z, 6mm maximum radial resolution.
- Langmuir probes.
- **Mach probes.**
  - **Calibrated by spectroscopic data.**
- Floating potential probe array.
  - 17 radial measurement points, 7mm maximum radial resolution.
- High frequency fluctuation probes.
  - Fluctuations up to ~10MHz.
- **Ion Dynamics Spectroscopy Probes (IDSPs).**

Diagnostics - IDSP



In-plane potential profile



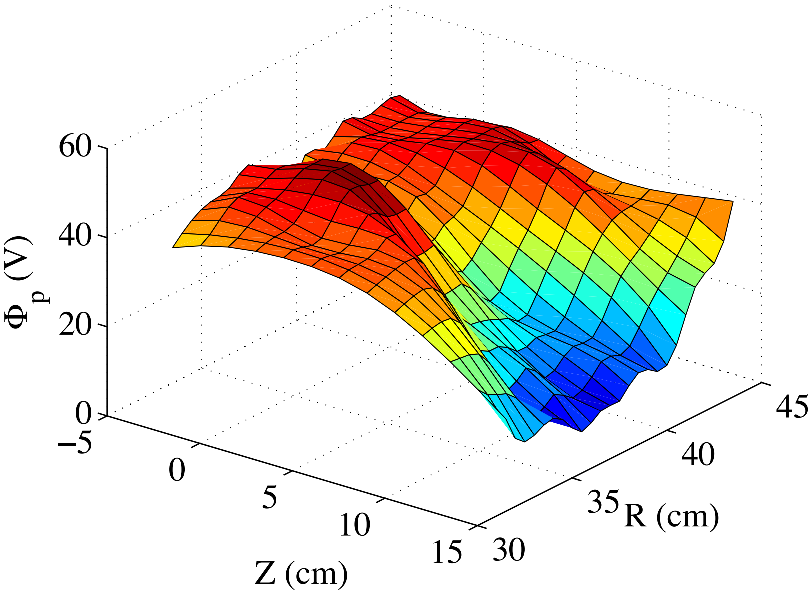
MRX, 2012

Karimabadi et al, 2007

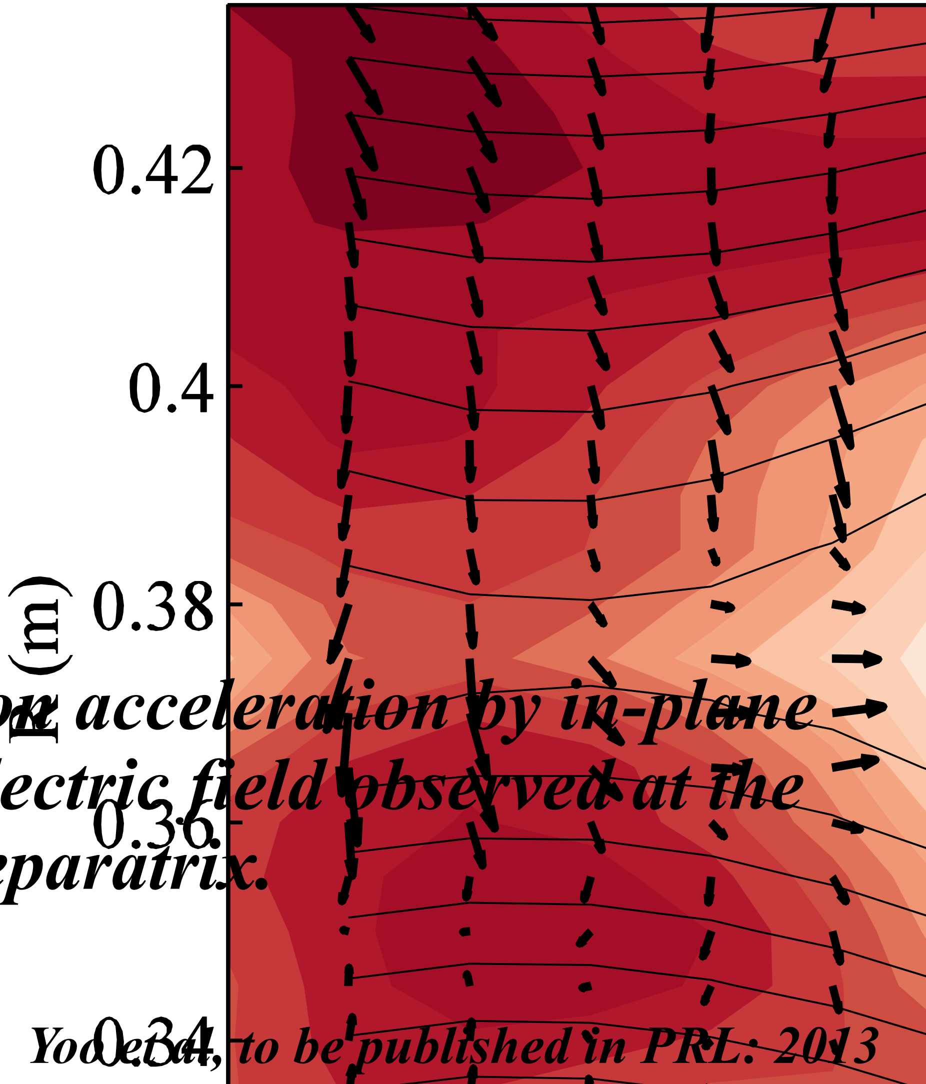
Wygant et al. 2005

- A large bipolar electrostatic field (BEF) exists in the reconnection layer due to two-fluid effects.

A saddle shape plasma potential profile is measured in MRX



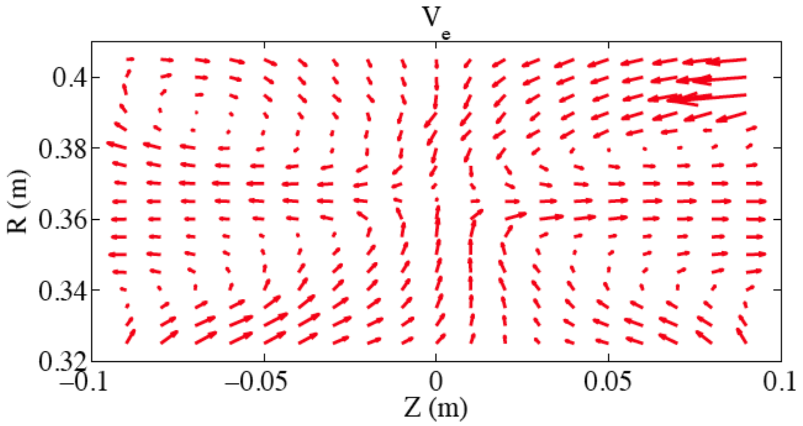
Potential profile on MRX

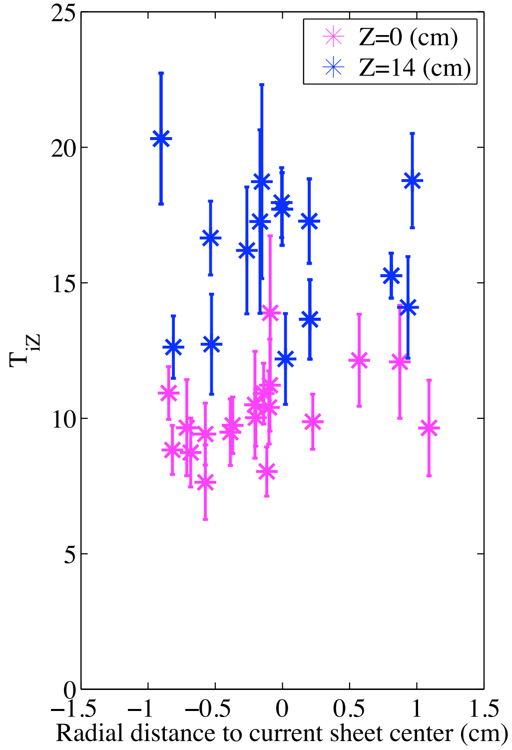


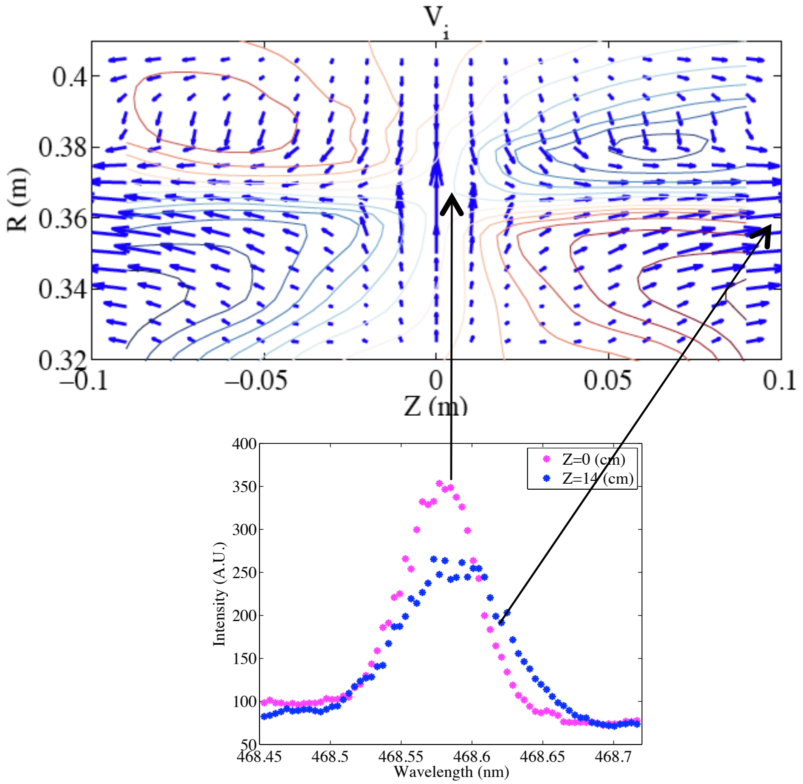
Ion acceleration by in-plane electric field observed at the separatrix.

Yoo et al., to be published in PRL: 2013

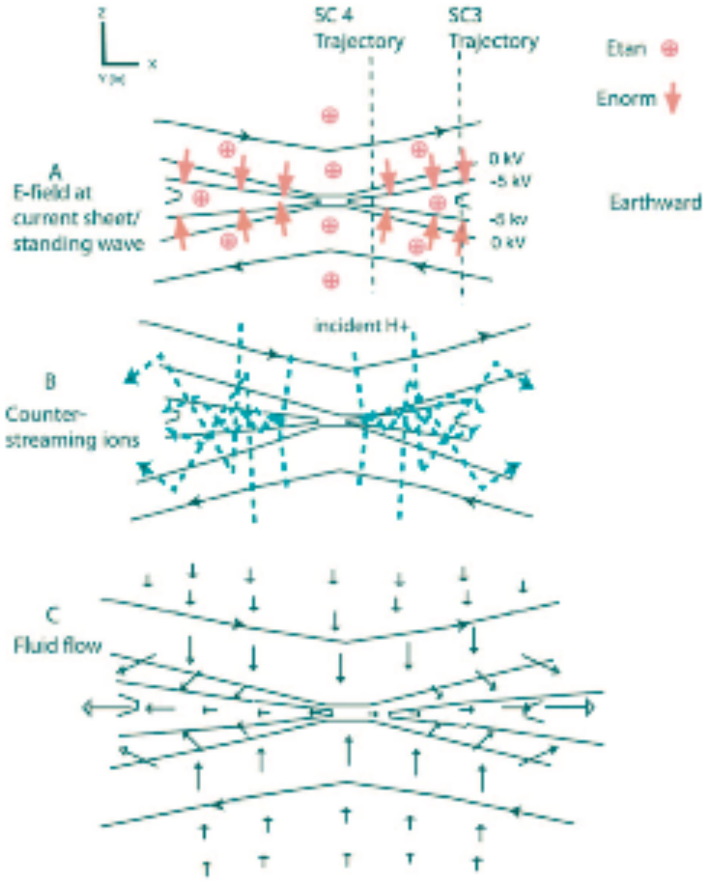
Measured dynamics of electron and ions



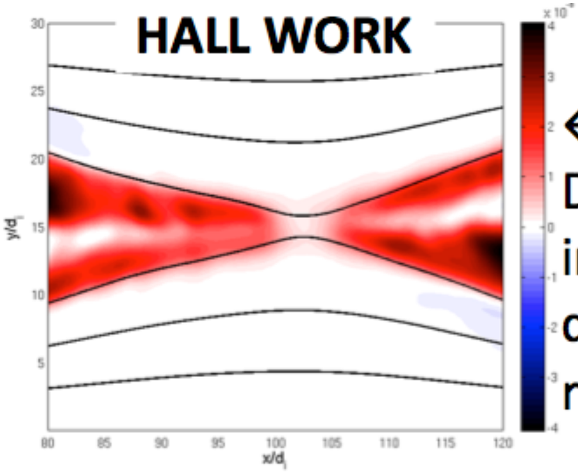




Ion acceleration data and simulation results

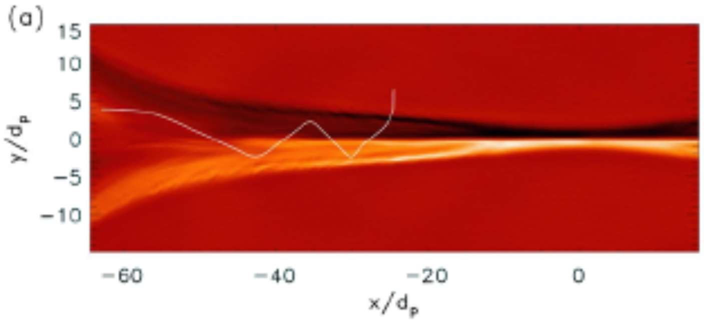


Wygant JGR 2005



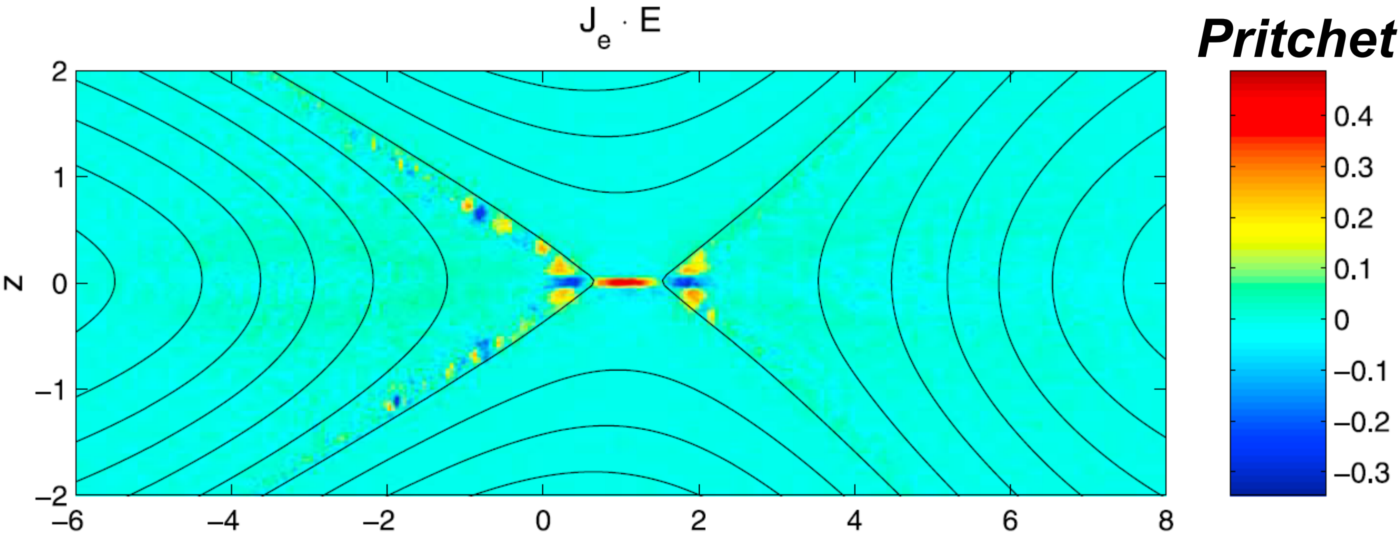
←$2{\cdot}10^{-8}$ Dominant in most of diffusion region

Goldman et al., 2012

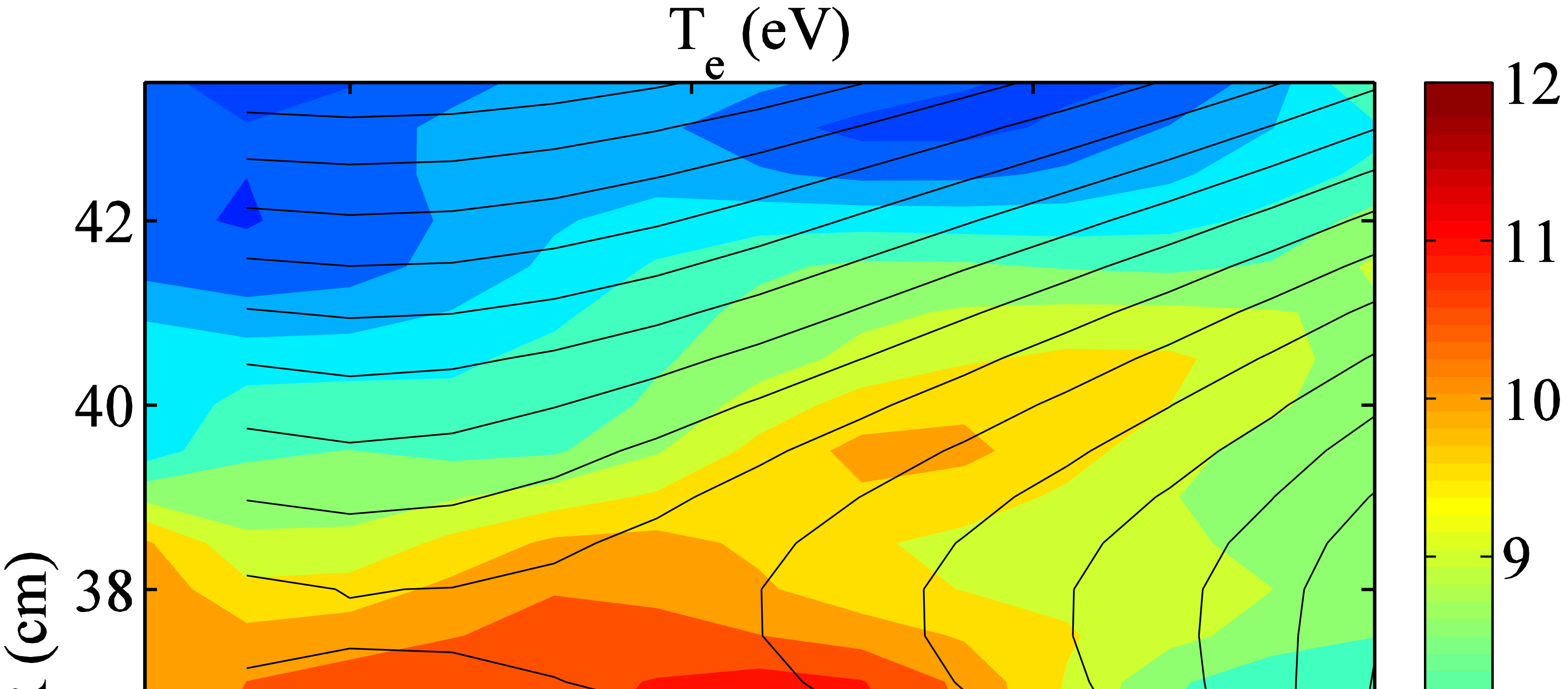


Drake et al., 2009

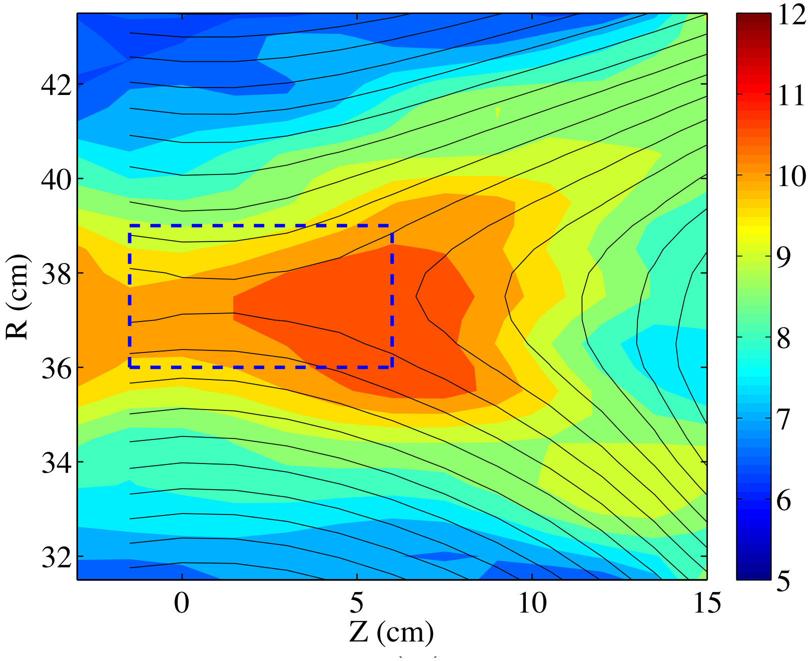
How are electron heated?

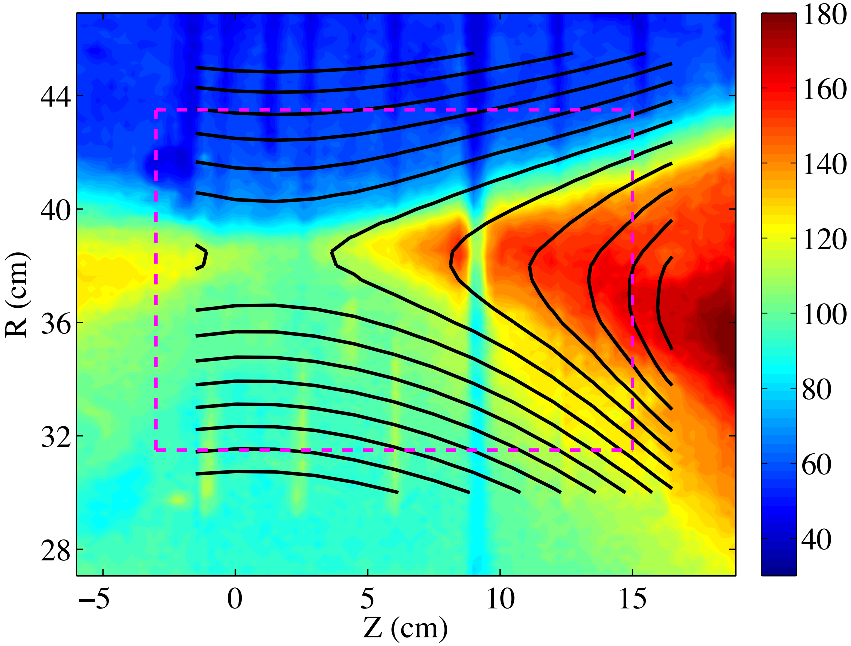


Pritchett 2010 JGR



How are electron heated?

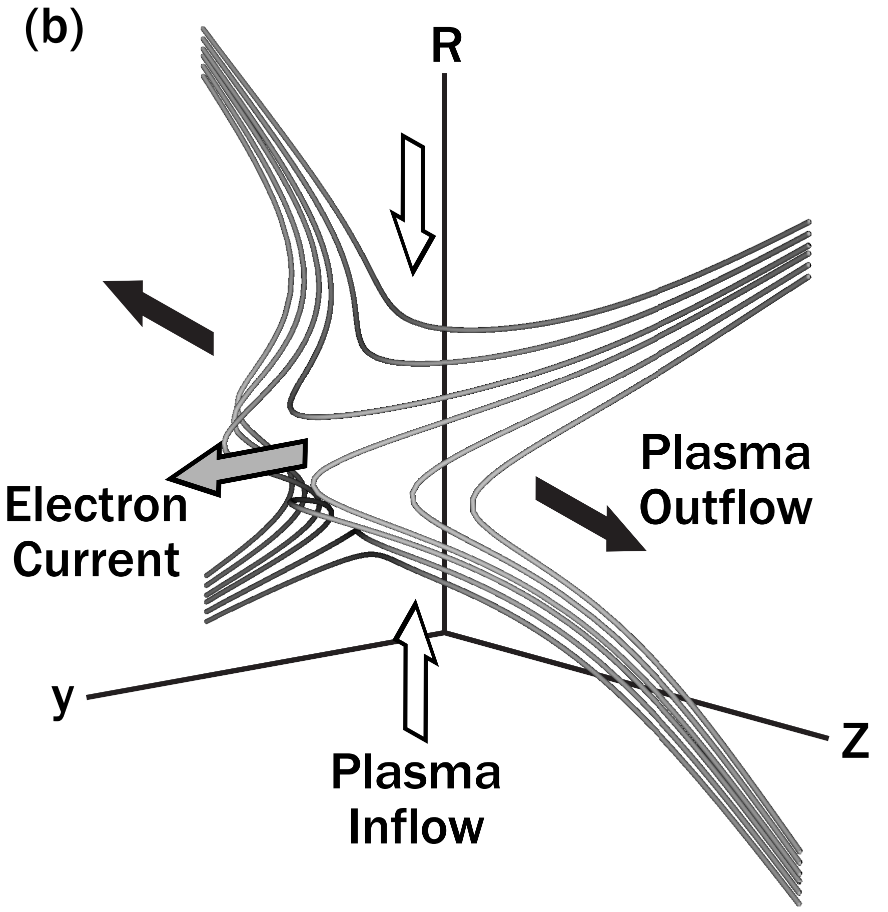




T_e (R, z) rom triple probes

- Light emission

Two-fluid physics dictates reconnection layer dynamics



Sheath width ~ c/ω_{pi}

- Acceleration and heating of mirror trapped electrons.
- Out of plane magnetic field is generated during reconnection.
- Parallel electric conduction verified even after reconnection.
- **Electron heating just outside the e-diffusion**
- **Ion acceleration and heating at the separatrices**

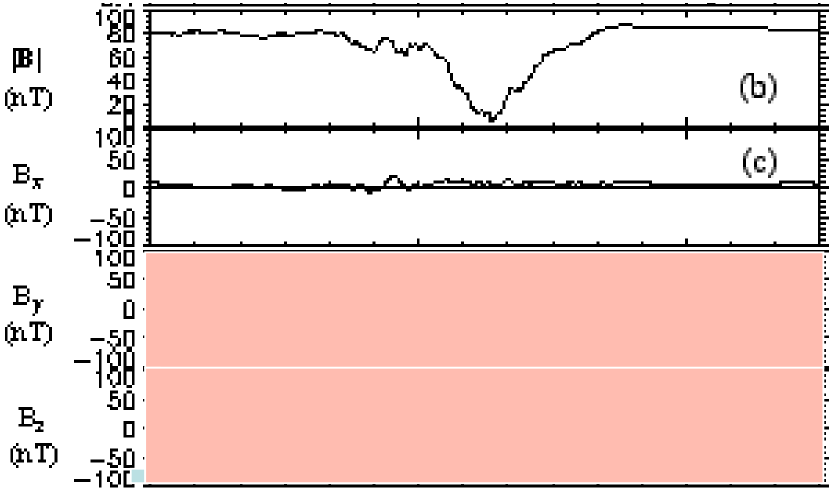
Collisionless Reconnection in the Magnetosphere

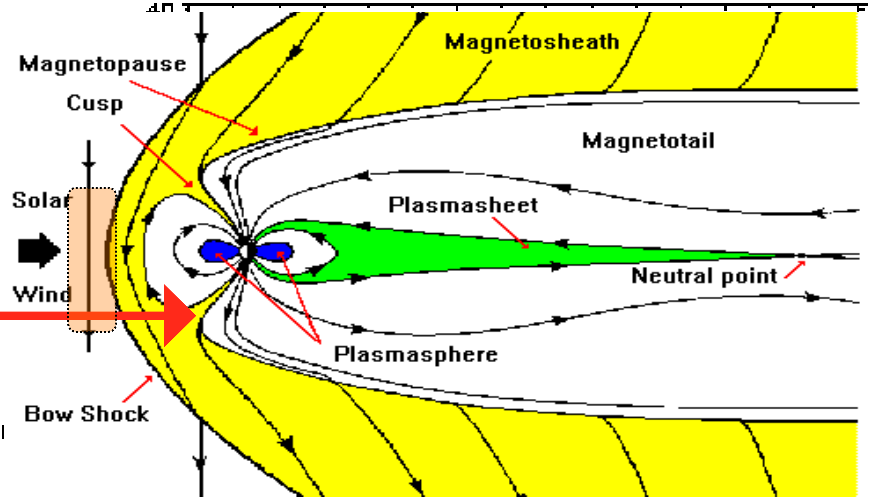
A reconnection layer has been documented in the magnetopause

$\delta \sim c/\omega_{pi}$

Measurements of Diffusion Region with a Hall effect signature

Mozer et al., PRL 2002

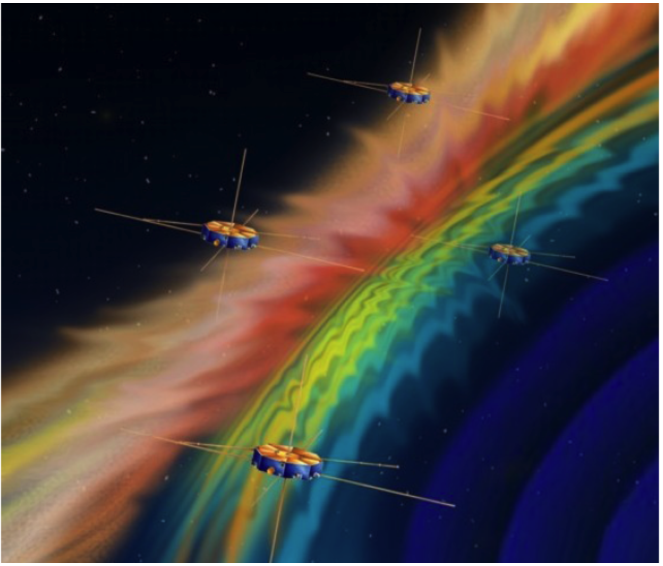


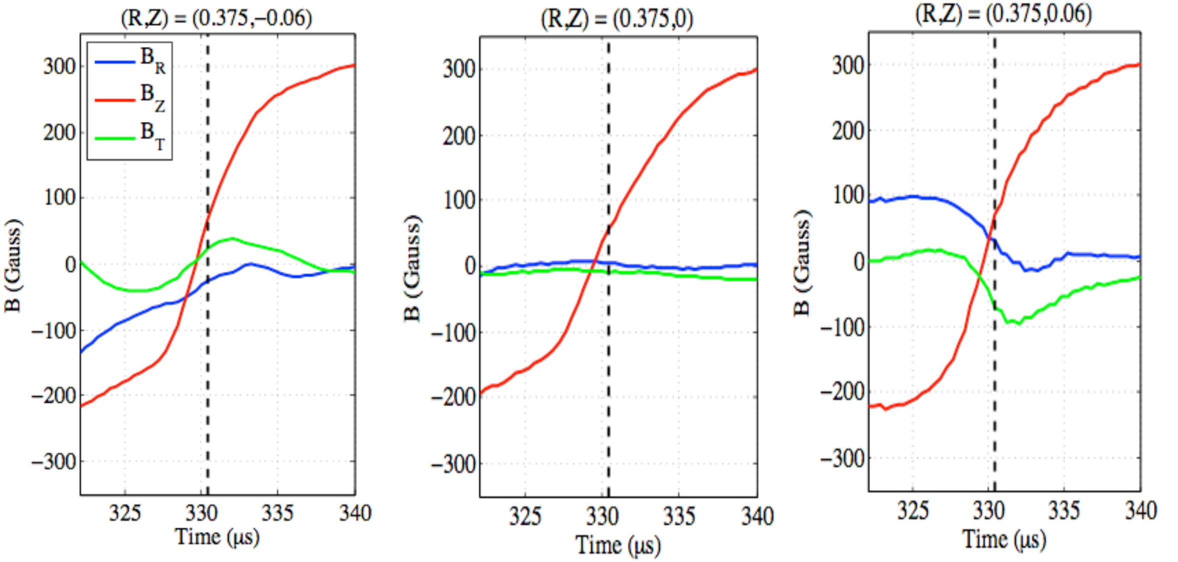


POLAR satellite

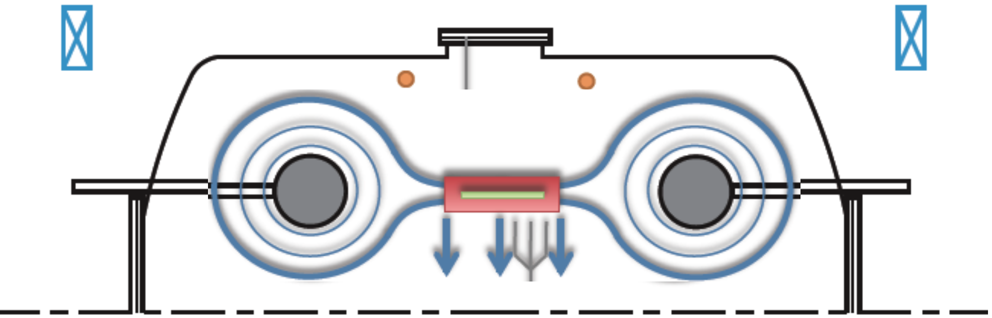
20

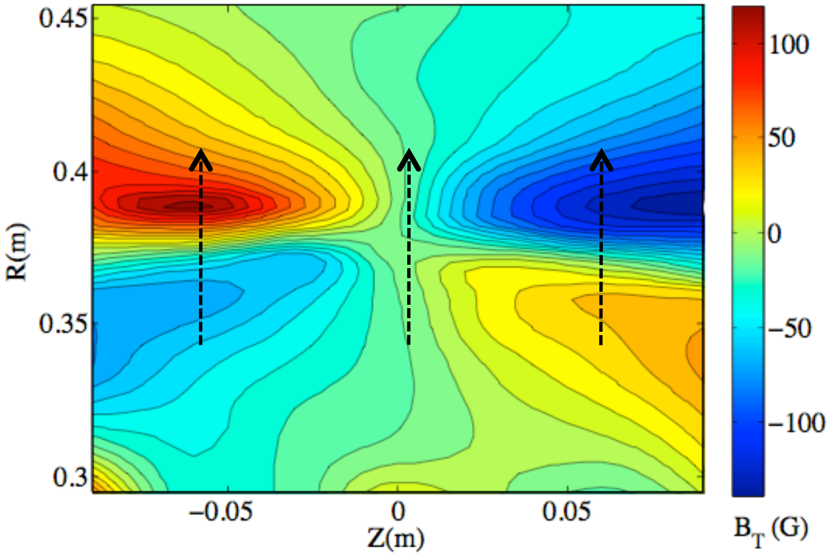
A jog experiment on MRX





MMS (Multi-scale Magnetosphere, Satellite)

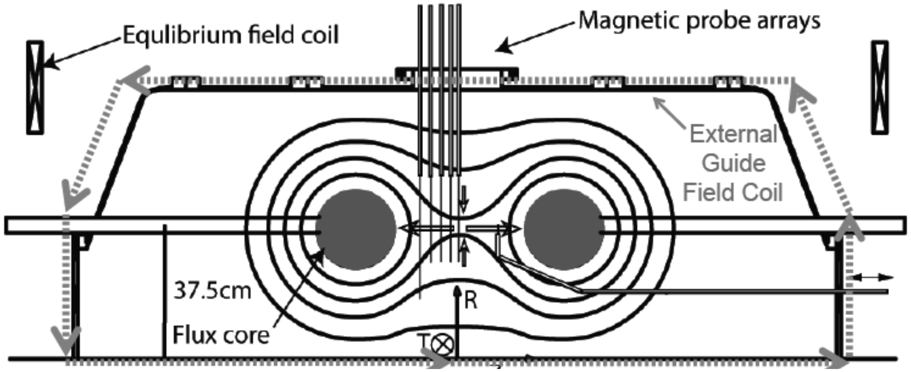




In collaboration with UNH, MMS, UC-Berkeley.

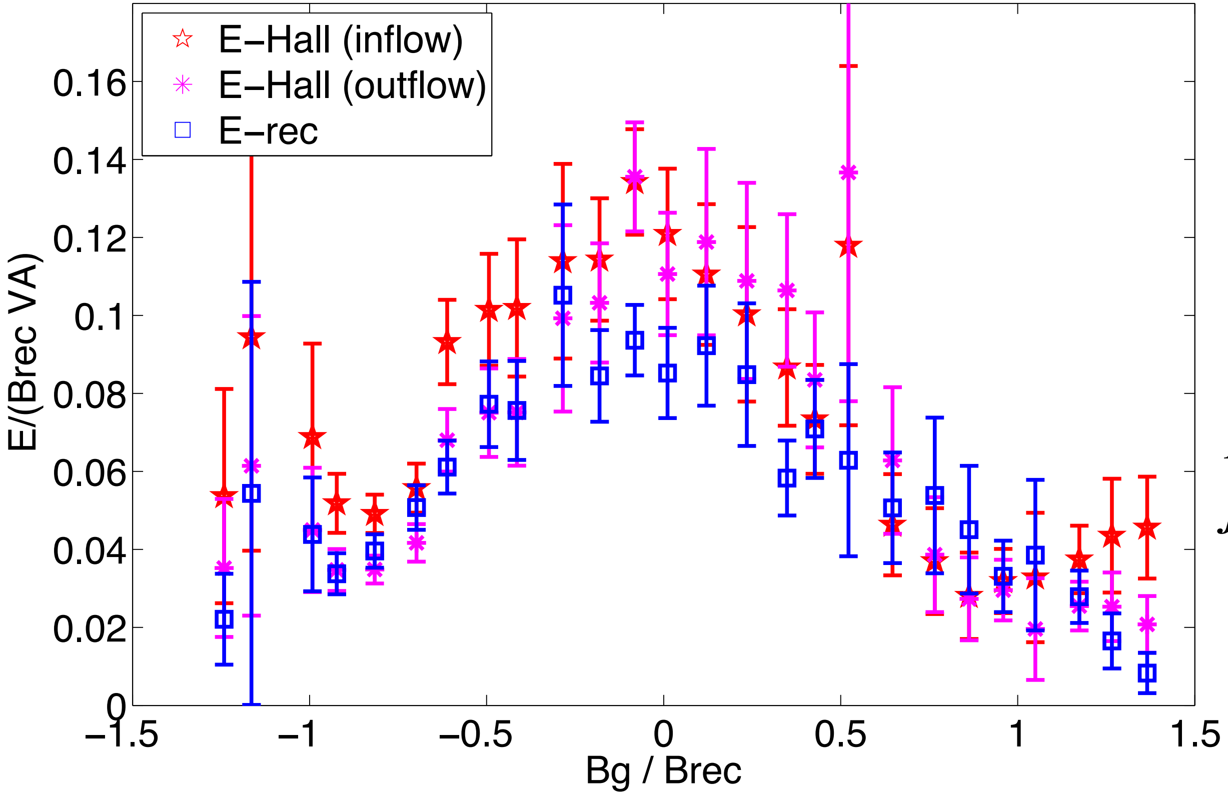
Example of Jogging Discharges – 2D Case

Hall Effects on Guide Field Reconnection in MRX



Effects of Guide Fields
on Collision-less Reconnection

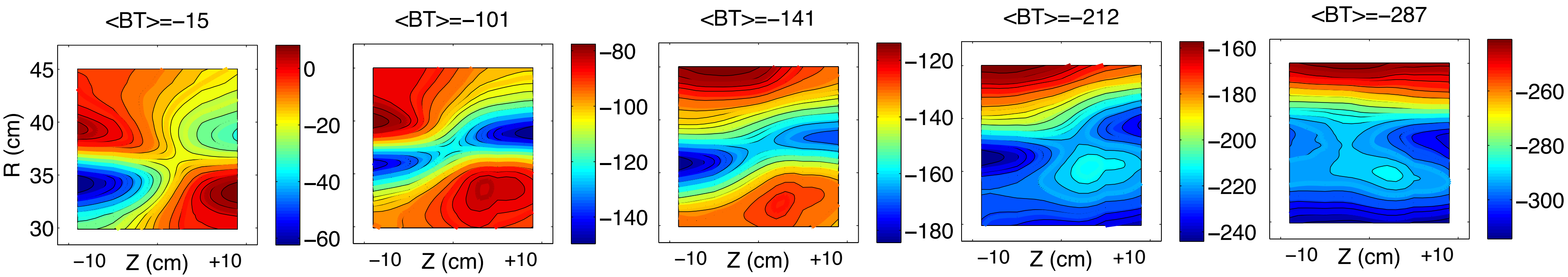
T. Tharp et al, PRL 2012

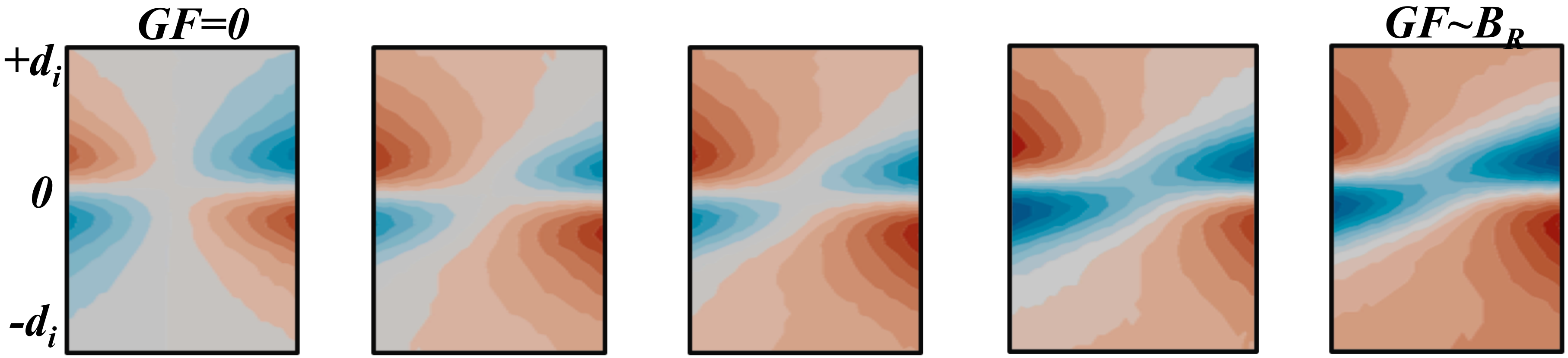


No comprehensive theory
for this observation yet!

Modified Quadrupole Field

There isn't a simple analytic model for this, but measurements qualitatively match two-fluid simulations



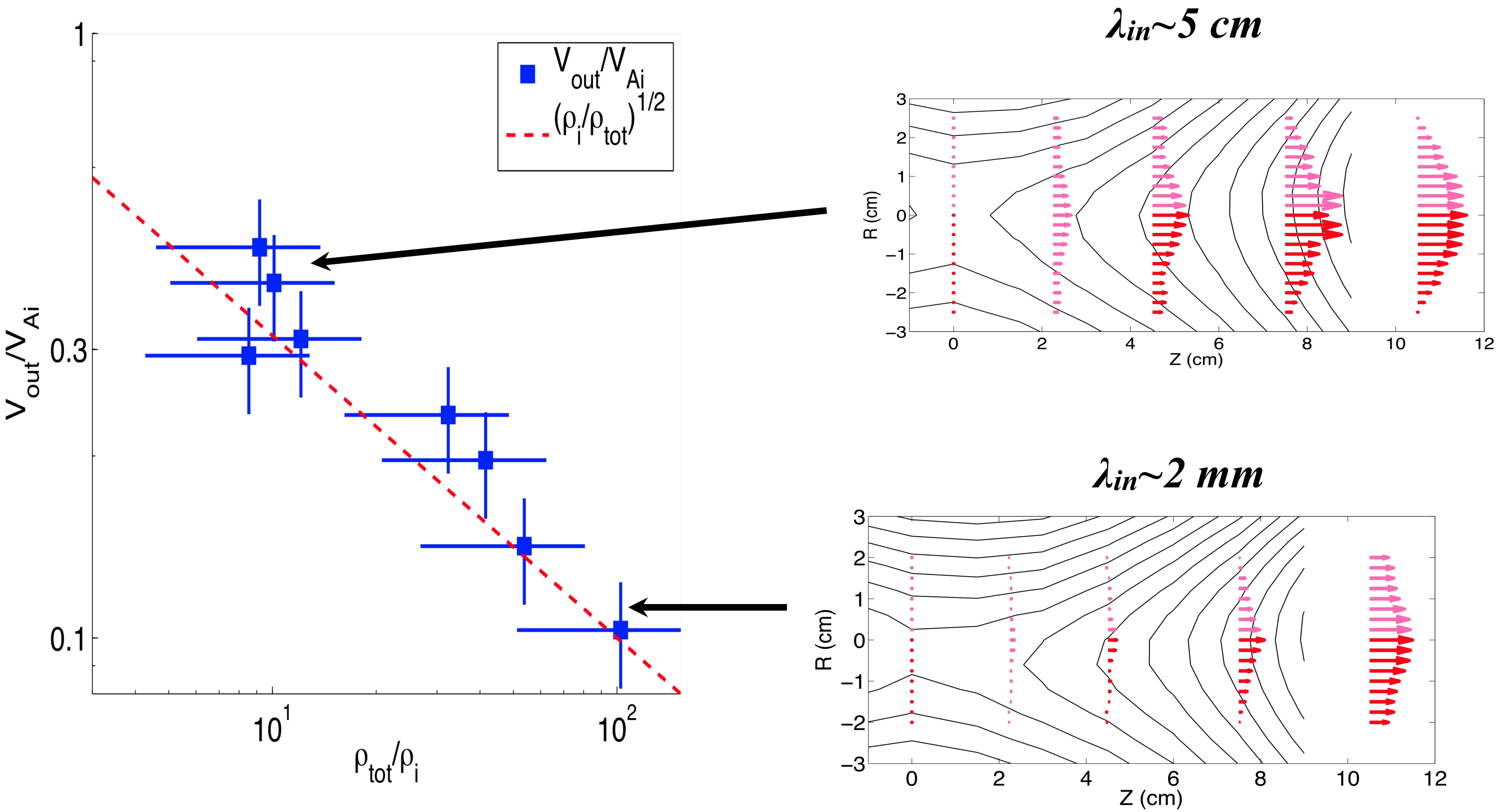


Simulations performed by A. Bhattacharjee, B. Sullivan, and Y. Huang.

Reconnection in Partially Ionized Plasmas

- Important in the solar chromosphere ($10^{-4} < \rho_i/\rho_n < 1$)
- Electron-neutral collisions increase classical resistivity
- Ion-neutral drag can effectively increase the ion mass: $V_A \rightarrow V_A\ (\rho_i/\rho_n)^{1/2}$; $c/\omega_{pi} \rightarrow c/\omega_{pi}(\rho_n/\rho_i)^{1/2}$
  - **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 will be needed to see all effects.

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

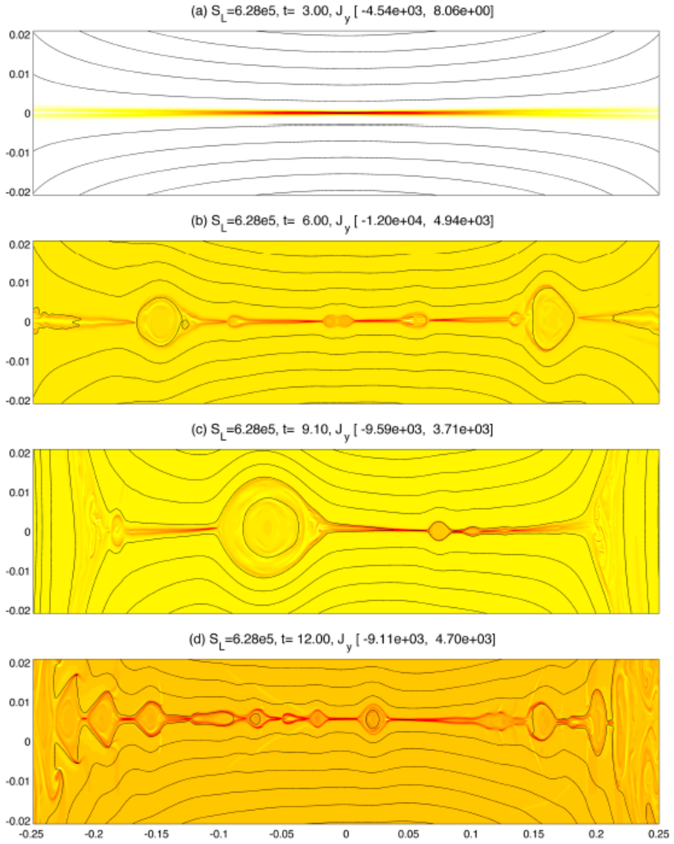

λ_{in}~5 cm

λ_{in}~2 mm

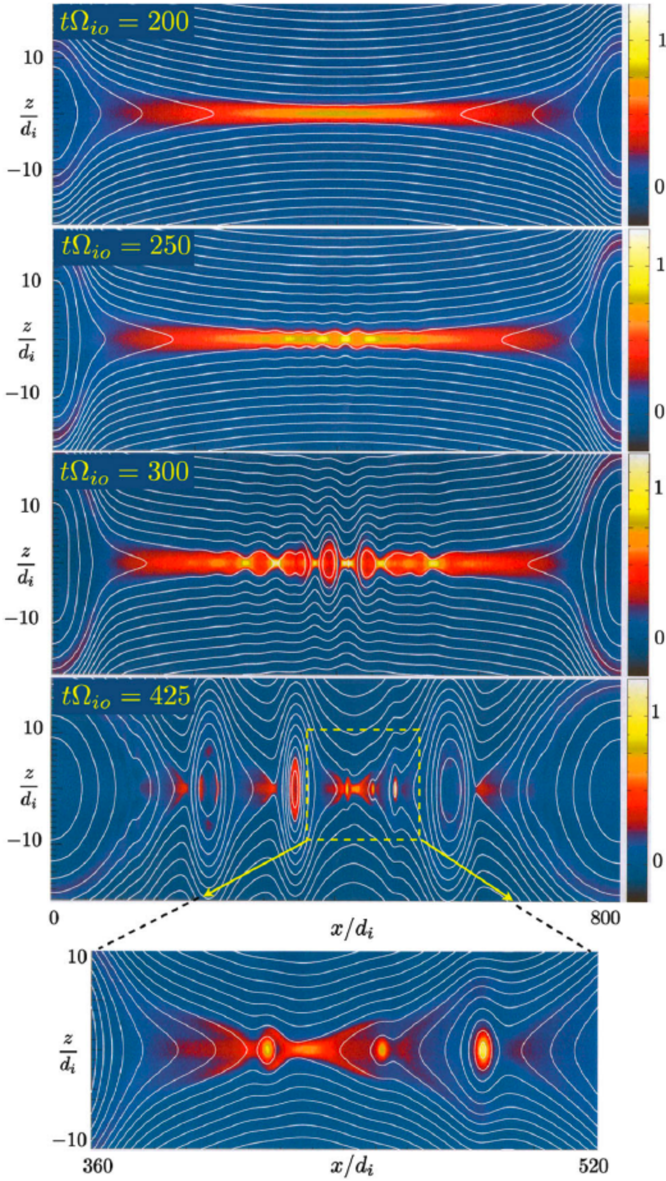
E. Lawrence et al PRL, (2013)

Recent (2D) Simulations Find Multiple Flux Ropes

Bhattacharjee et al. (2009):MHD



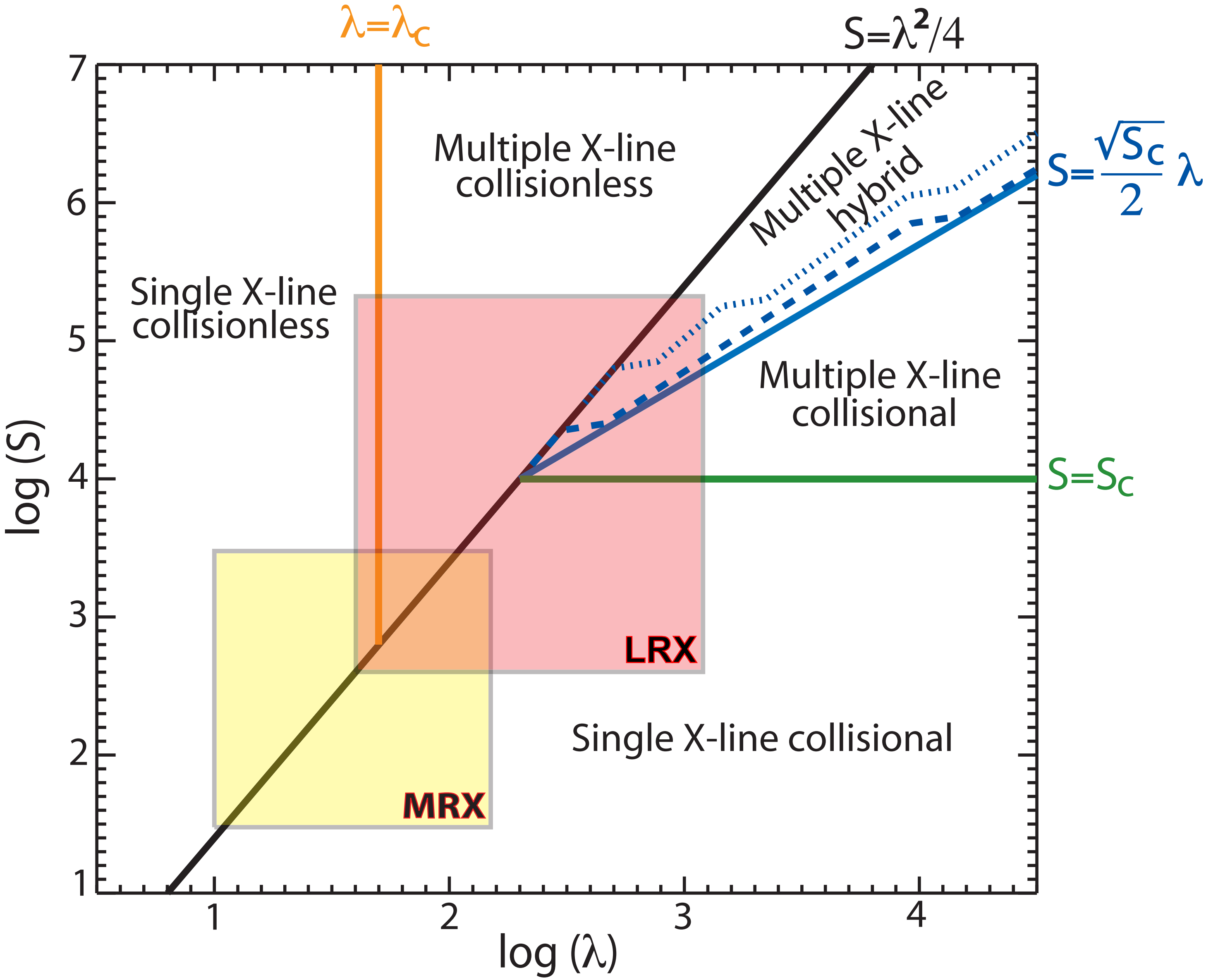
Daughton et al. (2009): PIC



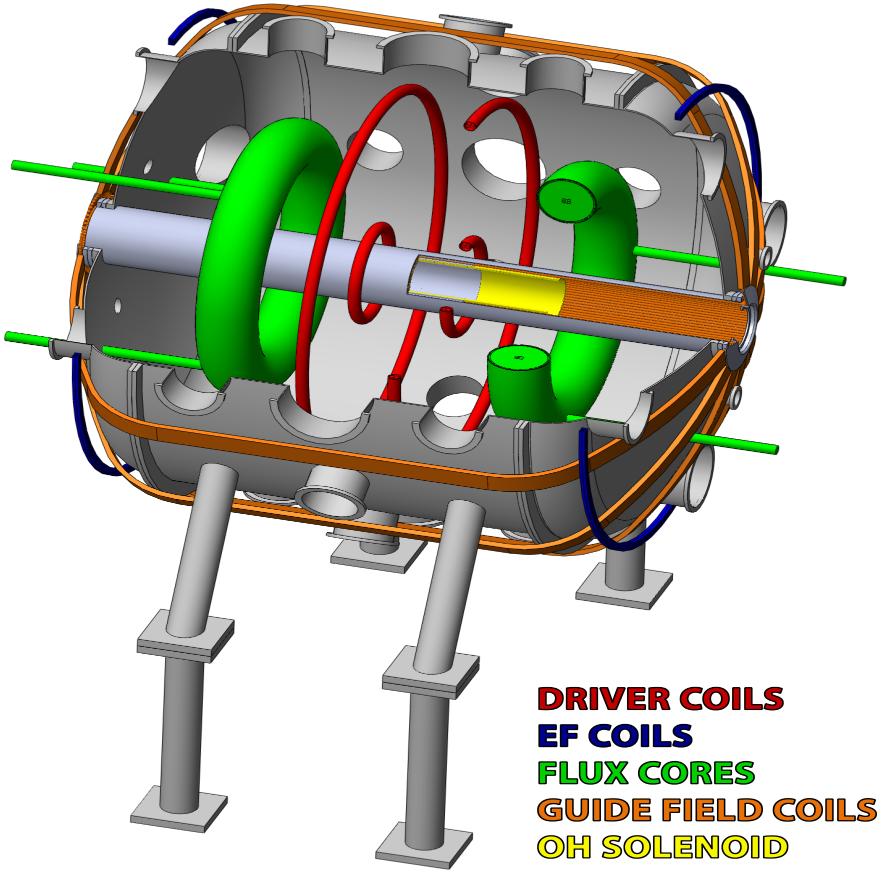
The Sweet-Parker layer breaks up to form plasmoids when $S > \sim 10^4$ => Turbulent reconnection?

Impulsive fast reconnection with multiple X points

New MRX phases provide access to broader issues of magnetic reconnection



New reconnection experiment proposed at PPPL



Proposed Large Reconnection Experiment (MRX-U)
[S=10^5, effective size=10^3]

Ji et al, 2013

Summary

- Notable progress made for identifying causes of fast reconnection
  - Two fluid MHD physics plays dominant role in the collisionless regime. Hall effects have been verified through a quadrupole field
  - Transition from collisional to collisionless regime documented
  - Impulsive reconnection (VTF, MRX)
  - Ion heating (SSX, VTF, MRX)

- Significant progress has been made both in laboratory and space astrophysical observations through cross-validation of experiments and modeling
  - Recent discoveries on MRX:

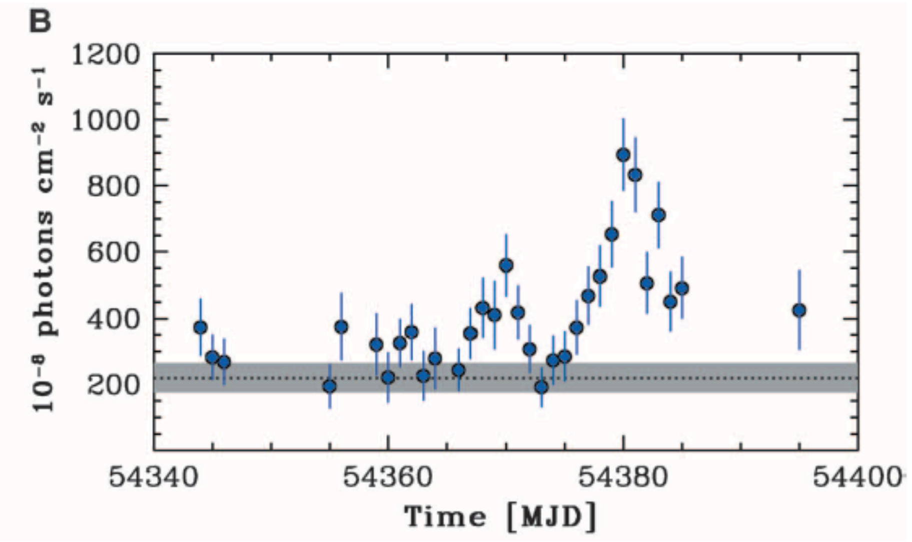
    Heating and acceleration of ions and electrons

    Effects of guide field

    Reconnection in partially ionized plasmas

- New findings on mechanisms of energy transfer to plasma particles
  - Acceleration
  - Heating

  Occur in much wider region than considered before



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