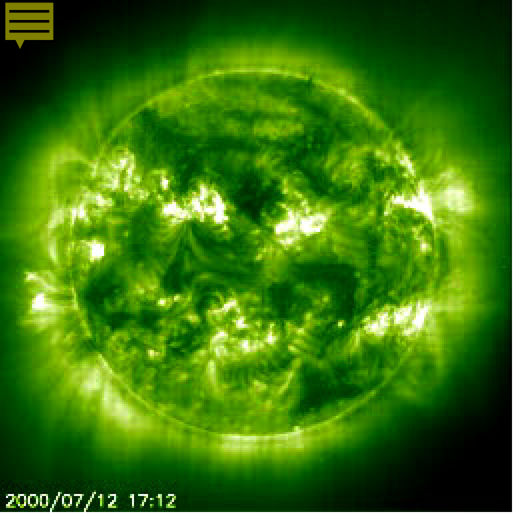
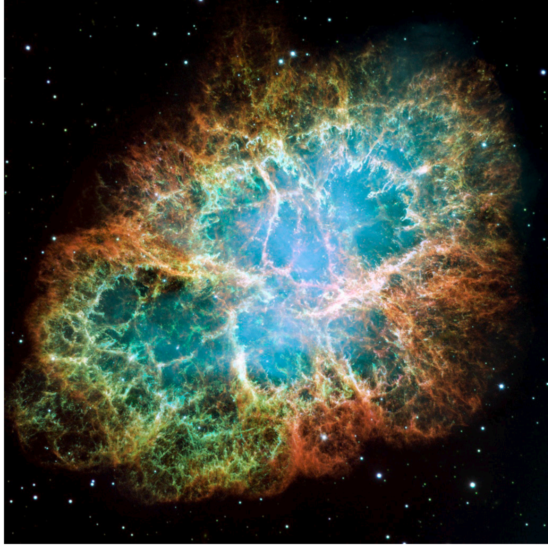




Magnetic reconnection, a key self-organization process in laboratory and astrophysical plasmas

Masaaki Yamada

In collaboration with MRX staff and CMSO members

Princeton Plasma Physics laboratory

Princeton University

Kyoto Conference on Non-Equilibrium Dynamics

In Astrophysics and Material Science

October 31-November 3, 2011

PPPL PRINCETON PLASMA PHYSICS LABORATORY

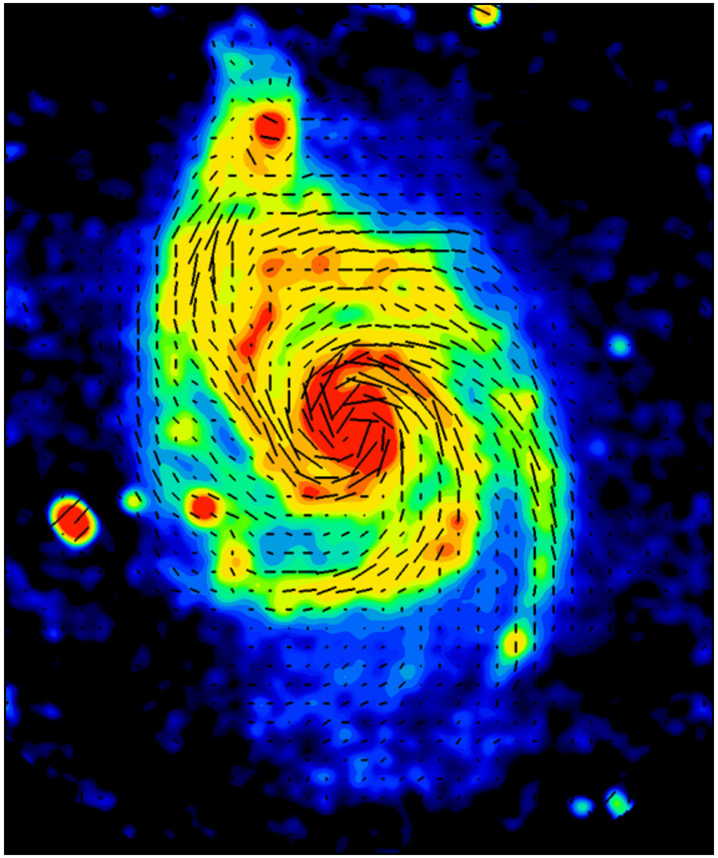
Outline

- **Magnetic reconnection**
  - Why does it occur so fast compared with the classical MHD theory?
- **Classical MHD (magneto-hydrodynamic) analysis**
  - Sweet-Parker model for reconnection layer and its generalization
  - Fast reconnection <=> Resistivity enhancement
- **Local analysis based on two-fluid physics**
  - **Lower collisionality => faster reconnection**
  - **Collision-free reconnection => an X-shaped neutral sheet**
  - **Hall effect and experimental verification**
  - **Identification of fluctuations (EM-LHDW)**
- **Global reconnection issues**

  Magnetic self-organization
  - **Sawtooth phenomena in tokamak**
- **A new scaling in transition from MHD to 2-fluid regime**

⇒ *M. Yamada, R. Kulsrud, H.Ji, Rev. Mod. Phys. v.82, 603 (2010)*
E. Zweibel & M. Yamada, Ann. Rev. AA, AA47-8, 291 (2009)

Plenty of B Field in the Universe <= Dynamos



Fields in M51; Beck 2000

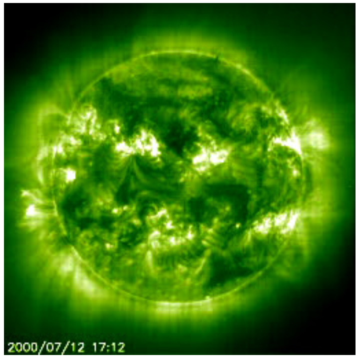
Polarization of 6cm emission. Indicates direction of B field.

- **Self-generation of magnetic field**
- **Kinetic Energy => Magnetic Energy**
- **How is magnetic field generated throughout the universe?**

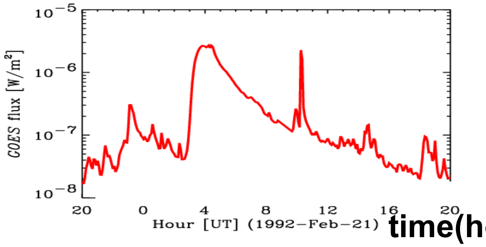
  (Earth, sun, stars, accretion disks, galaxies; lab plasmas)

Magnetic Reconnection: $B^2 \Rightarrow W_p$

Solar flare

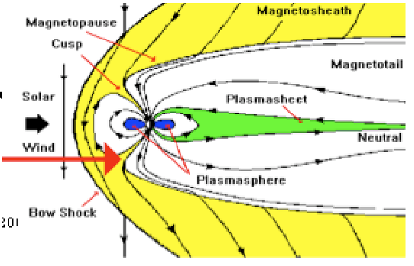


X-ray intensity

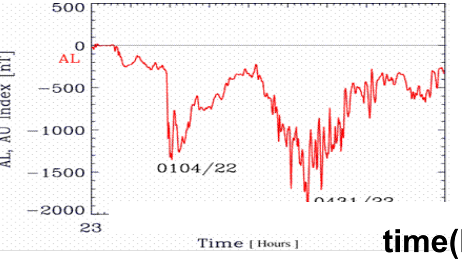


time(hour)

Magnetospheric Aurora-substorm

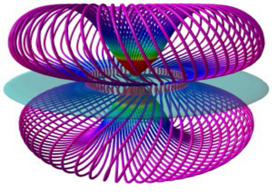


Magnetic Field strength

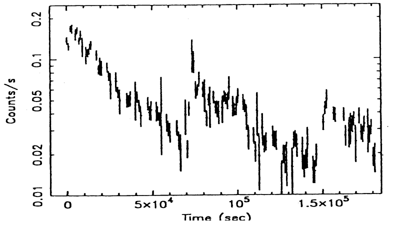


time(hour)

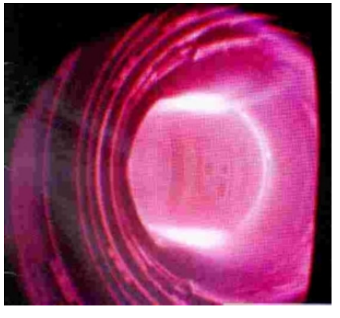
Protostellar flare



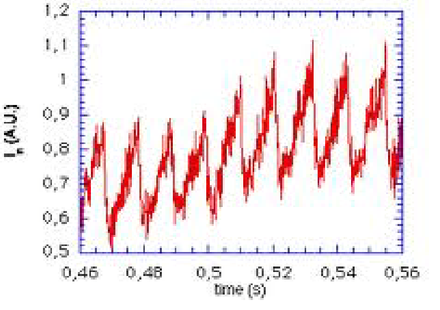
X-ray intensity



Tokamak disruption

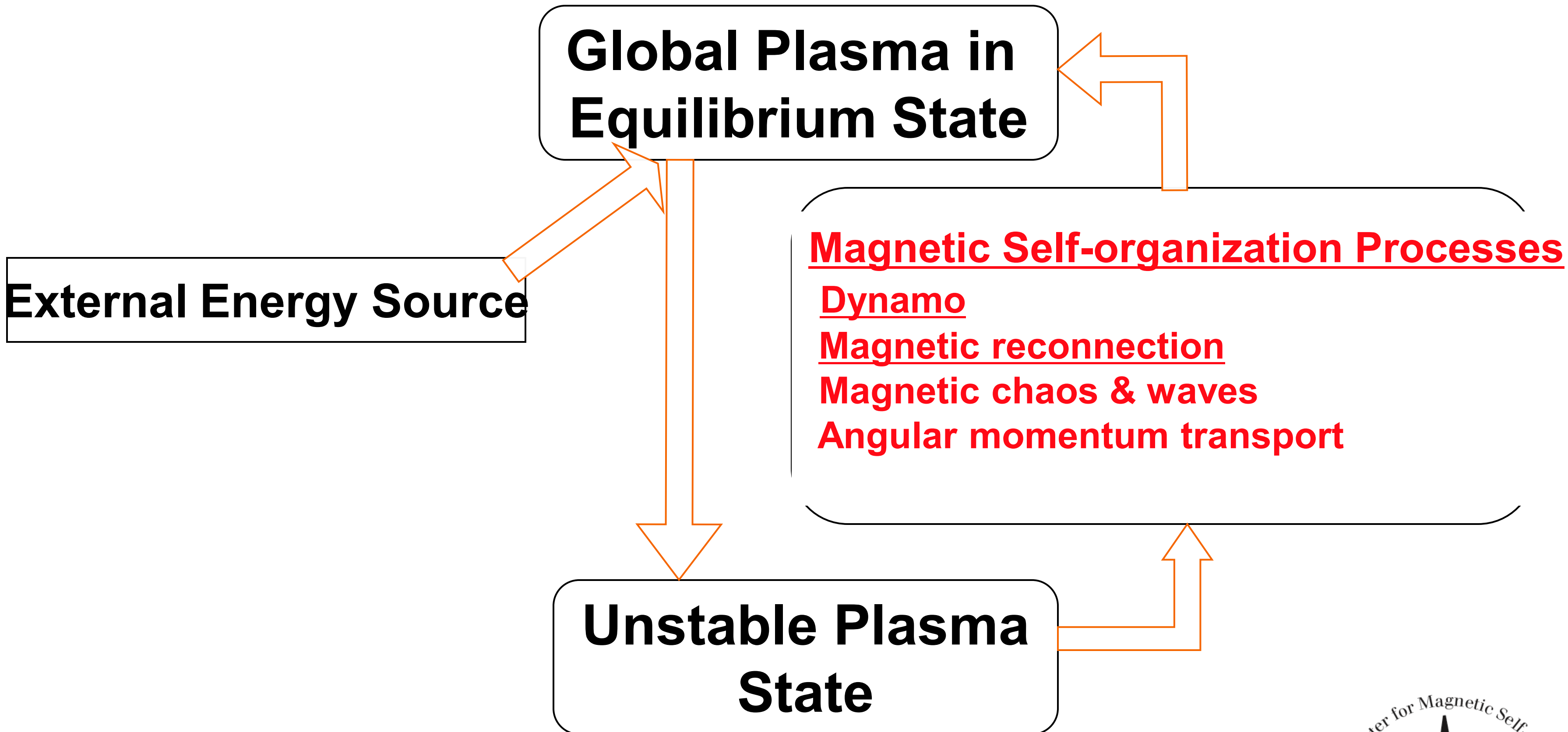


Electron temperature



Reconnection occurs very fast ($\tau_{reconn} \ll \tau_{SP}$)

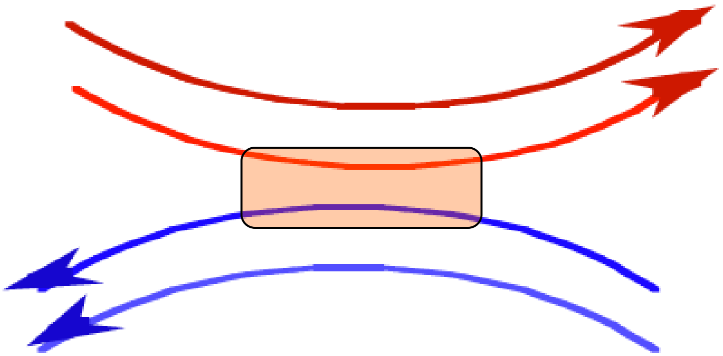
Magnetic Self-organization in Laboratory and Astrophysical plasmas



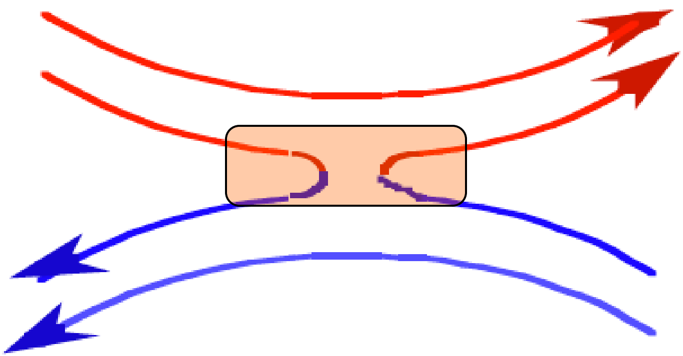
Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas

Magnetic Reconnection

- Topological rearrangement of magnetic field lines
- Magnetic energy => Kinetic energy
- Key to stellar flares, coronal heating, particle acceleration, star formation, energy loss in lab plasmas

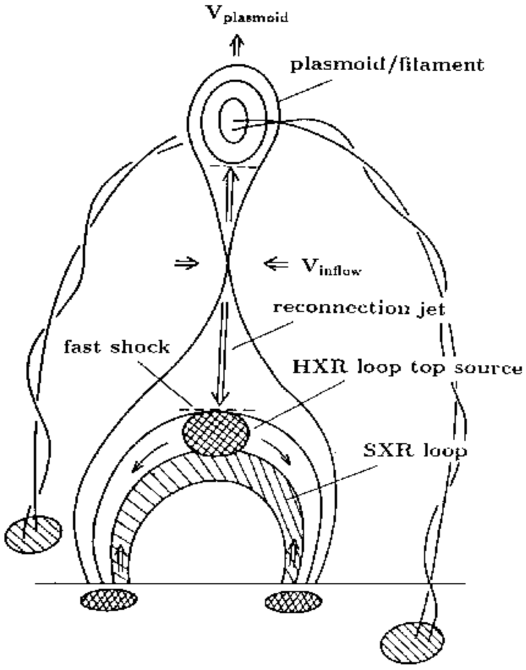


Before reconnection

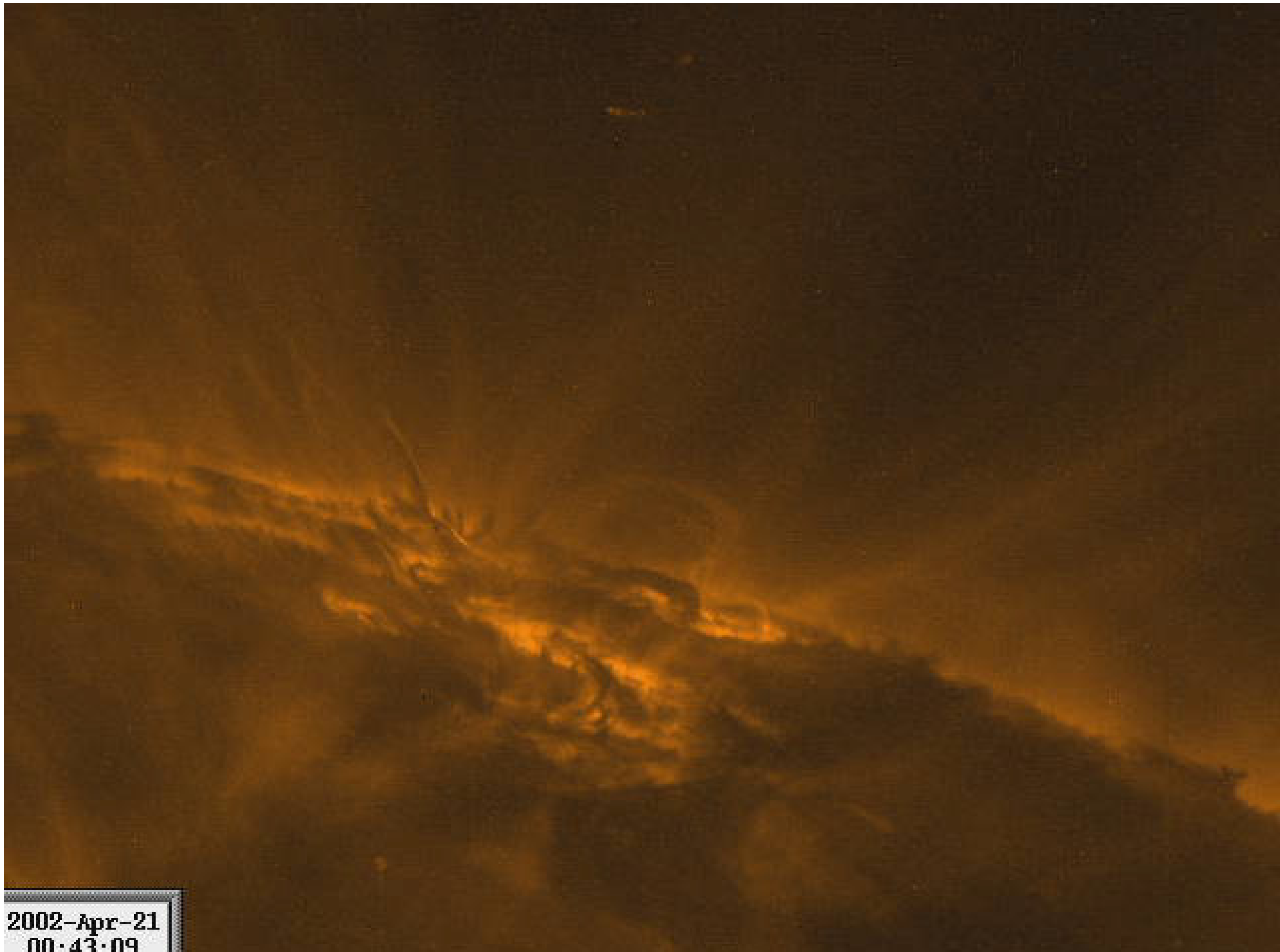


After reconnection

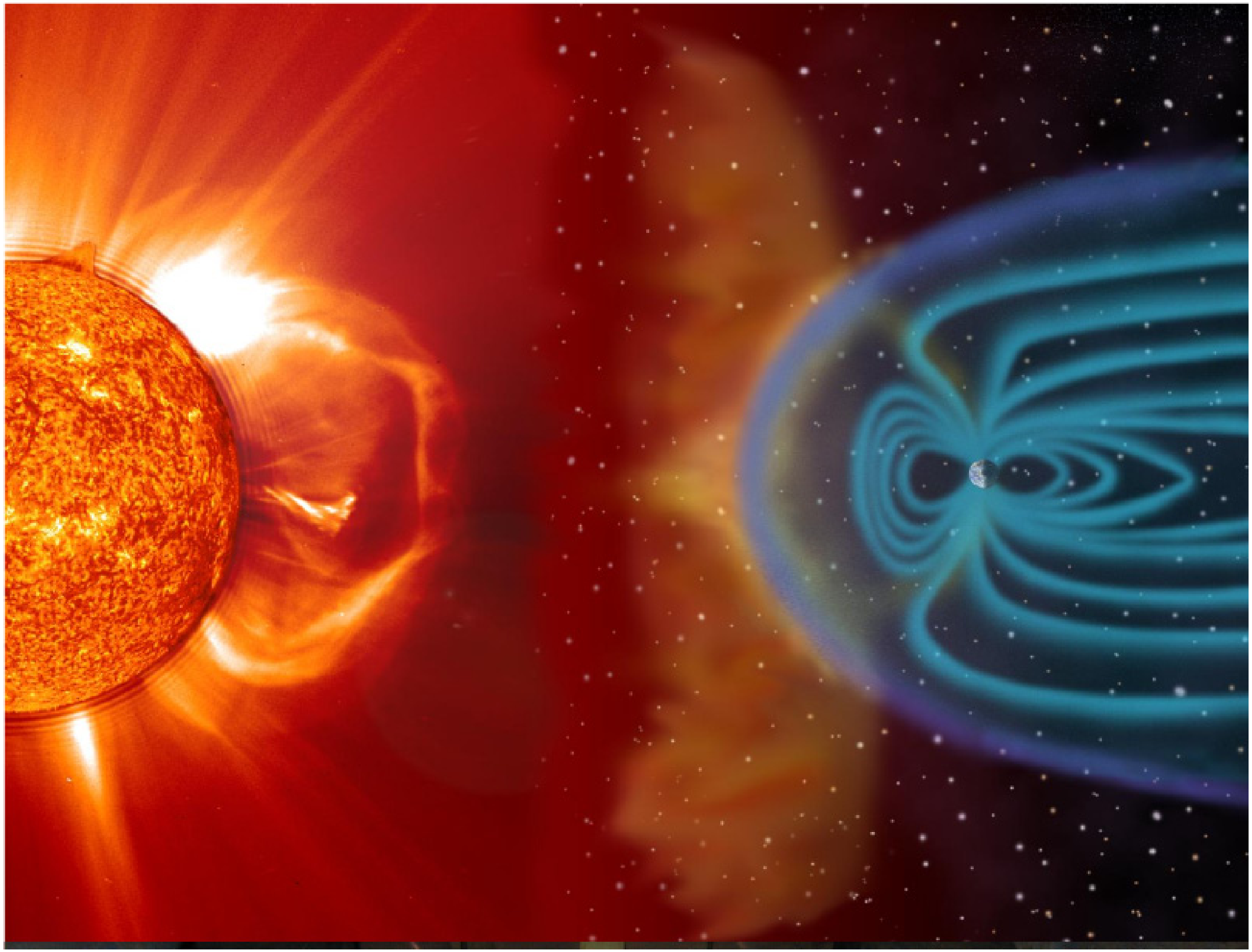
Reconnection in Coronal Mass Ejection



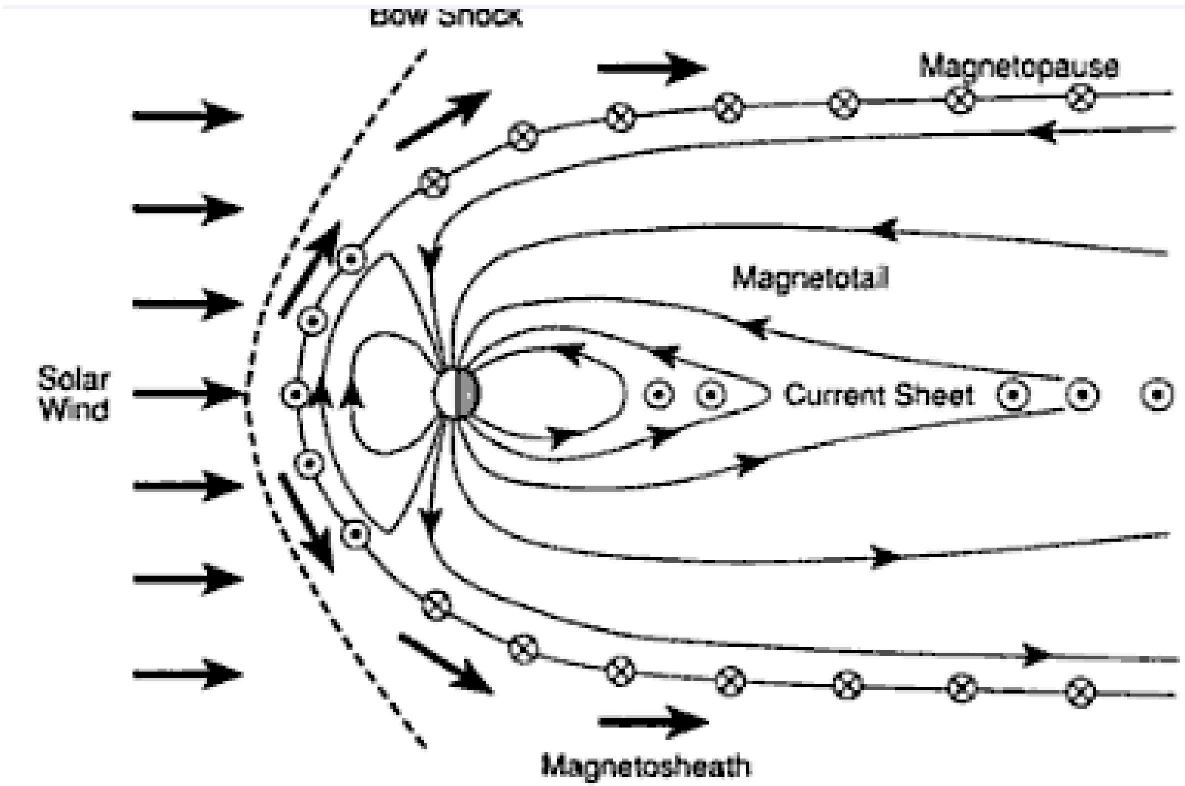
Shibata
Unified model

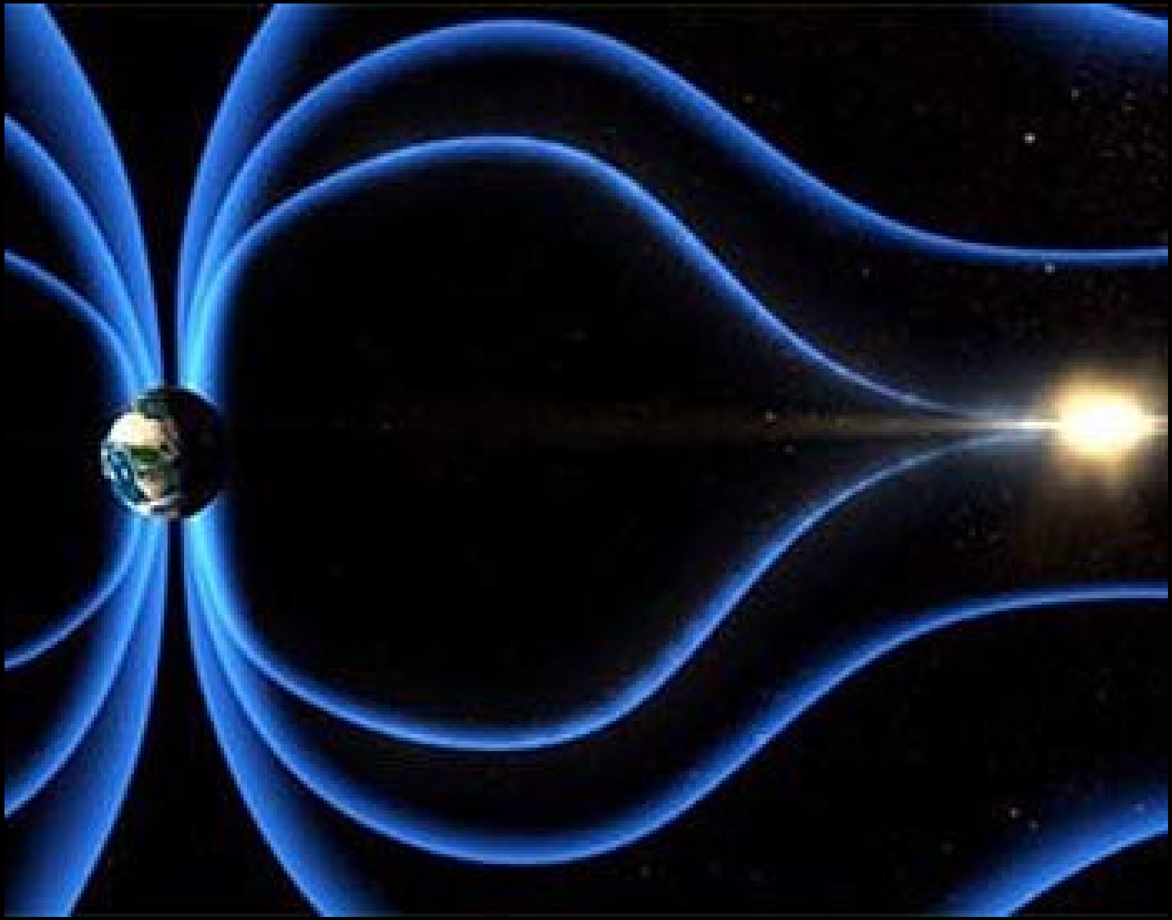


太陽風と地磁気の相互作用



地球磁気圏: Magnetosphere





Magneto-Rotational Instability: Anomalous Angular Momentum Transport

What: Redistribution of angular momentum through instabilities and turbulence.

Why important: Key to determine stellar evolution and accretion rates to power the brightest sources.

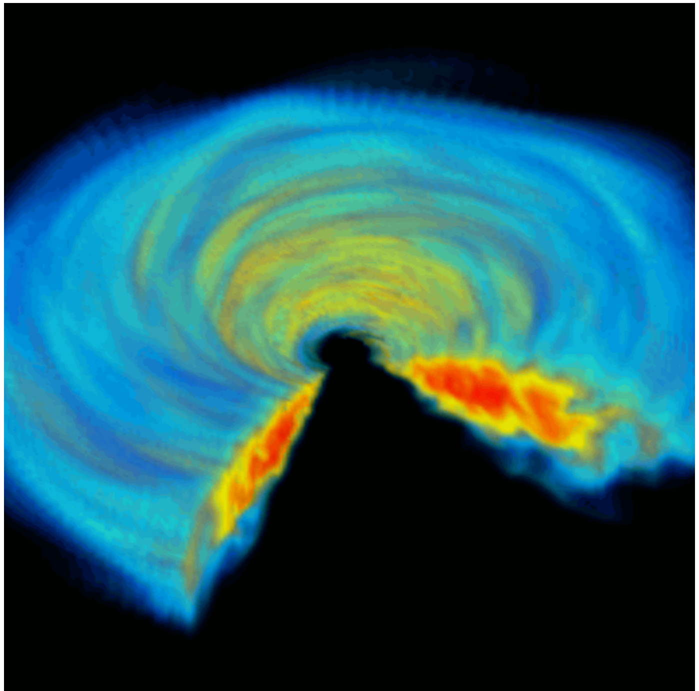
Challenge: Quantitative understanding of angular momentum transport based on plasma instabilities.

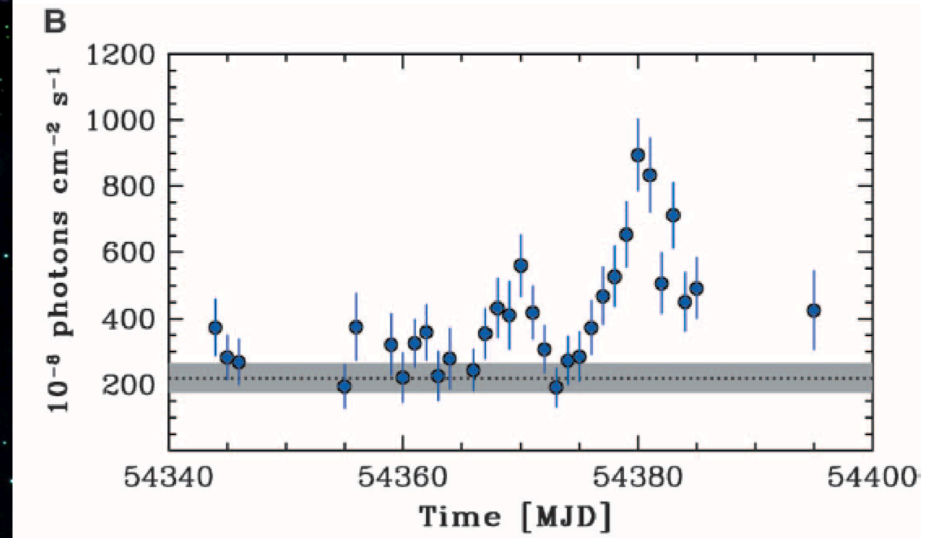
Does reconnection play a key role in MRI (Magneto-Rotational Instability)?

- Astro: Supermassive black holes are enormously bright because they accrete matter quickly. How to remove angular momentum?
- Plasma: Turbulence in shear flow, dissipation via heating and outflows together determine the transport efficiency. Lab experiments.

Light from a SMBH outshines its host galaxy

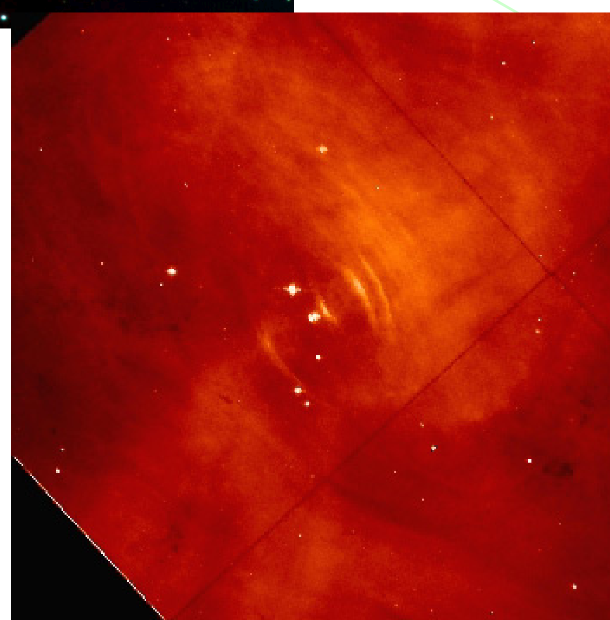
3D general relativistic MHD Simulation around a SMBH

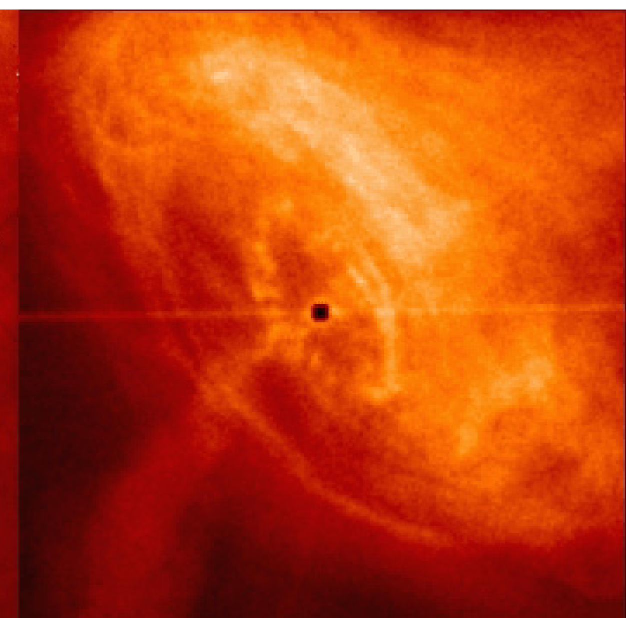




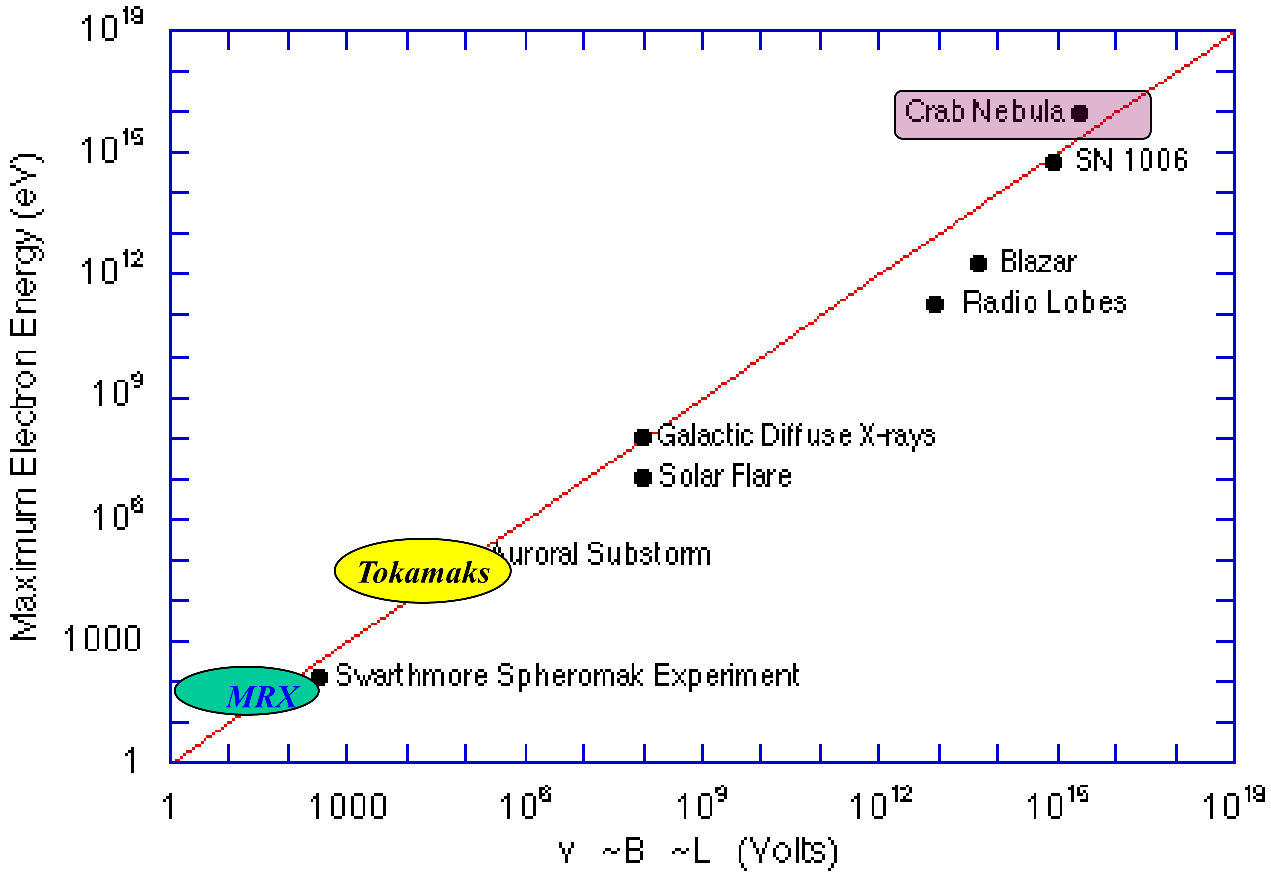
Gamma ray flares in Crab Nebura

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





Maximum particle energy in astrophysical and laboratory systems [by K. Makishima]



where v is the typical velocity, B is the typical magnetic field, and L is the typical system size

from K. Makishima, "Energy non-equipartition processes in the Universe."

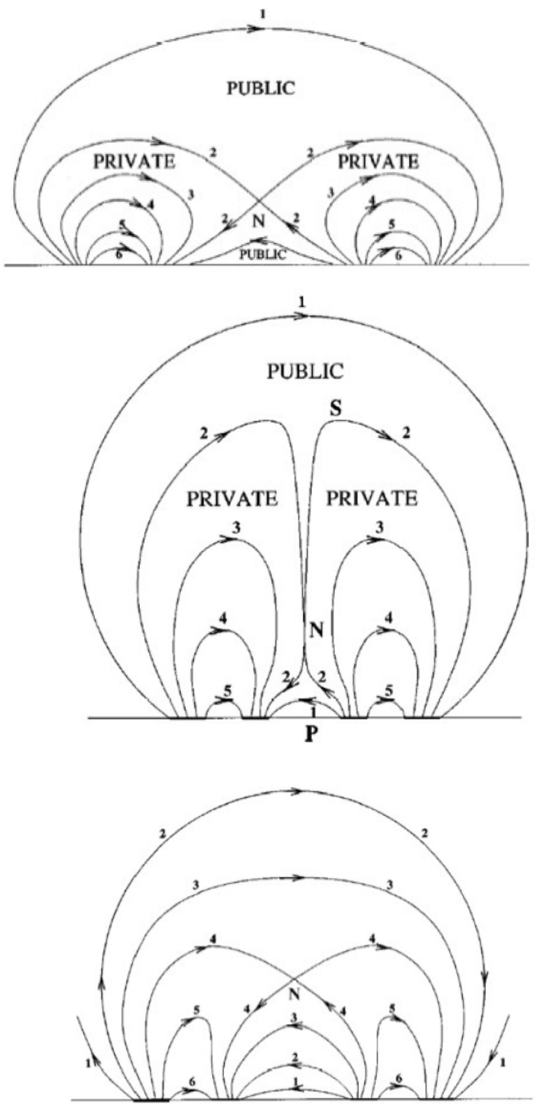
Magnetic Reconnection in the Sun

- Flux freezing makes storage of magnetic energy easy at the photo surface
- Magnetic reconnection occurs when flux freezing breaks
- Magnetic reconnection causes conversion of magnetic energy
  ＝＞radiation, particle acceleration, the kinetic energy of the solar wind.

A. Local Reconnection Physics

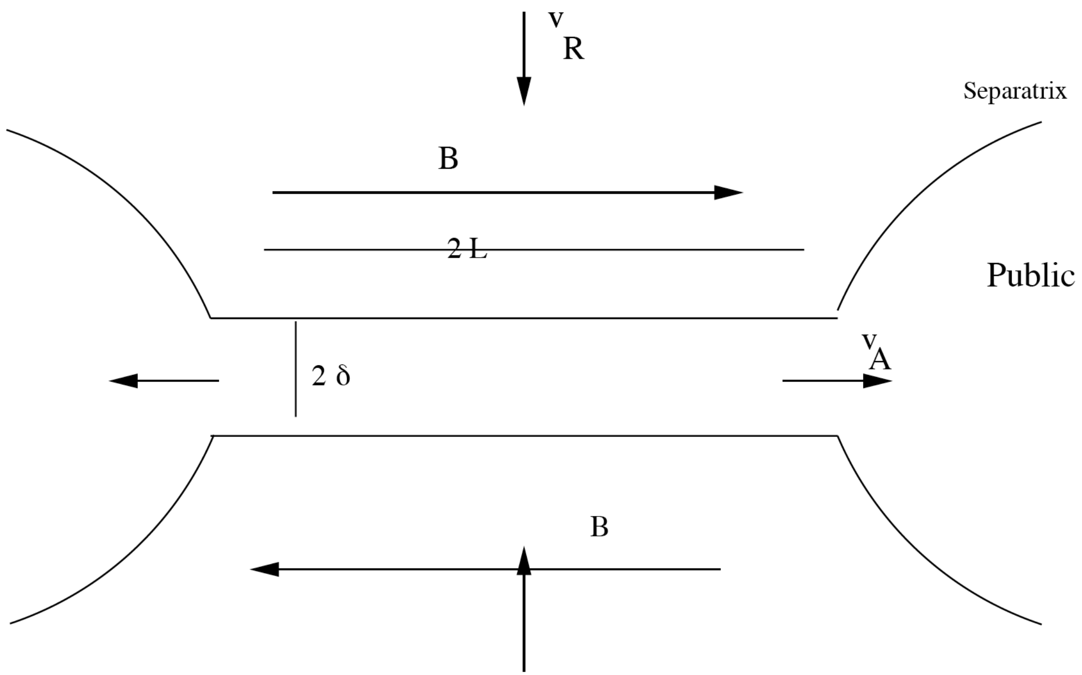
1. **MHD analysis**
2. Two-fluid analysis

Sweet Model



- Sweet considered magnetic reconnection in solar flares

Sweet-Parker Layer

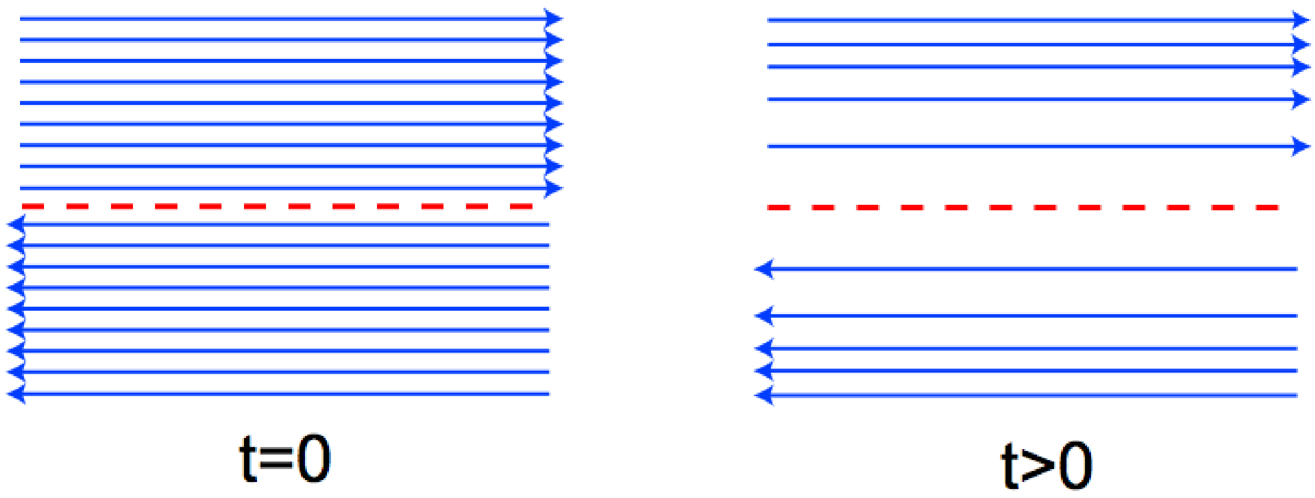


How do magnetic field line reconnect? (1)

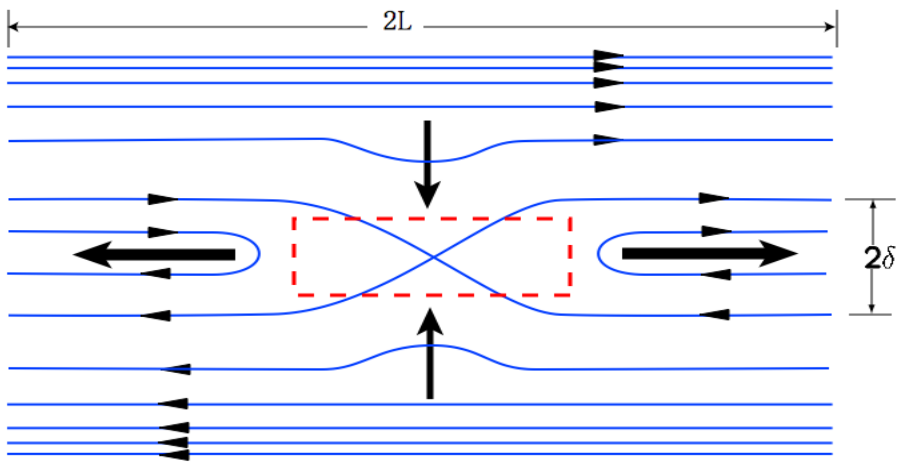
1-D Diffusion of Magnetic Field Lines

$$t_D \approx \frac{\mu_0 l^2}{\eta}$$

~10^6 years for solar coronae



How do magnetic field lines reconnect? (2D)



- In 2D picture, magnetic field lines should reconnect faster because newly reconnected field lines move out of the diffusion region quickly due to a tension force

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{j}$$

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

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$$

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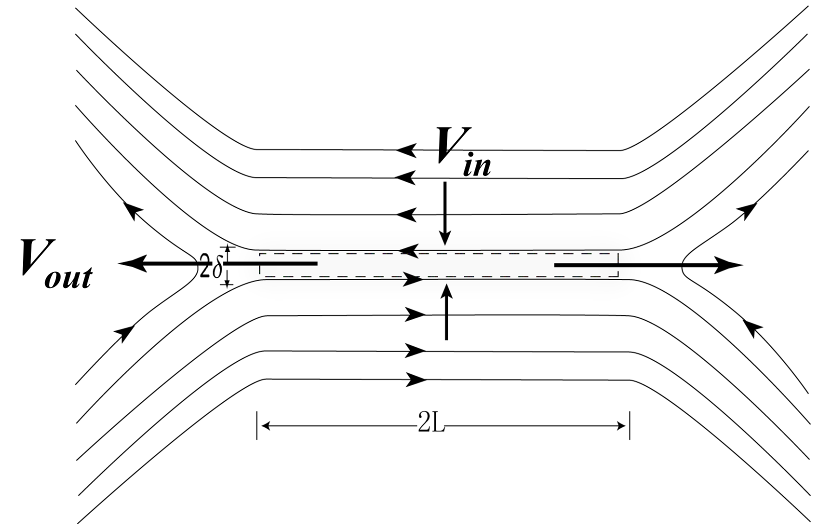
The Sweet-Parker 2-D Model for Magnetic Reconnection

Assumptions:

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



B is resistively annihilated in the sheet

τ_{reconn} << τ_{SP} ~ 6−9 months

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B} \quad \Rightarrow \quad V_{in} B = \frac{\eta_{Spitz}}{\mu_0} \frac{B}{\delta}$$

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

Mass conservation:

$$V_{in} L \approx V_{out} \delta$$

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

Pressure balance:

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

S=Lundquist number

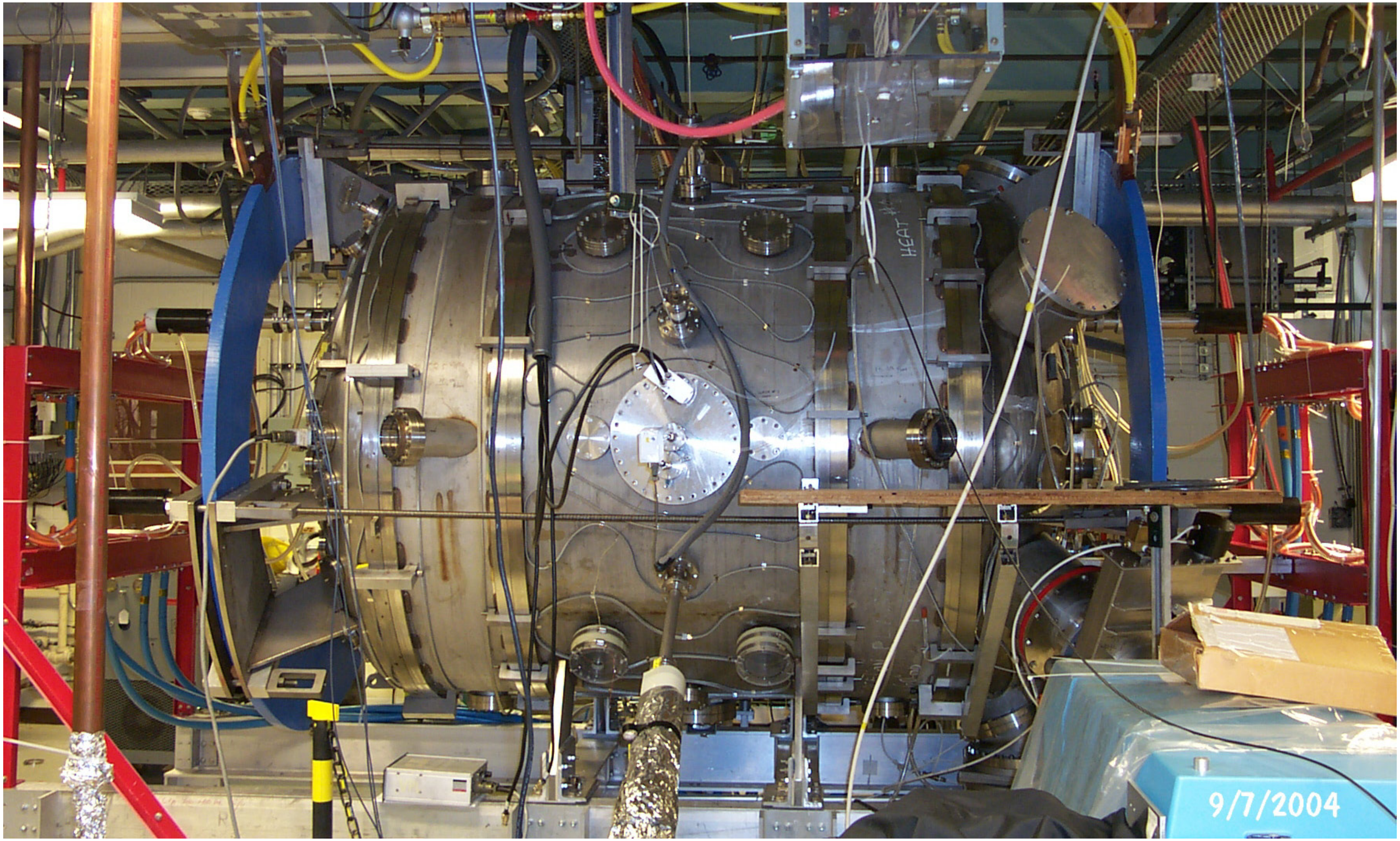
Magnetic Reconnection Experiments

What physics can we learn?

Dedicated Laboratory Experiments on Reconnection

Device	*Location*	*Start*	*Investigators*	*Geometry*	*Issues*
3D-CS	Russia	1970	Syrovatskii, Frank	Linear	3D, heating
LPD, LAPD	UCLA	1980	Stenzel, Gekelman	Linear	Heating, waves
TS-3/4	Tokyo	1990	Ono, Inomoto	Merging	Rate, heating
MRX	Princeton	1995	Yamada, Ji	Toroidal, merging	Rate, heating, scaling
SSX	Swarthmore	1996	Brown, Grey	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)



Objectives of Magnetic Reconnection Experiment

We learn from plasmas the fundamental physics of magnetic reconnection by generating **this elementary process in a controlled laboratory environment**

The primary issues;

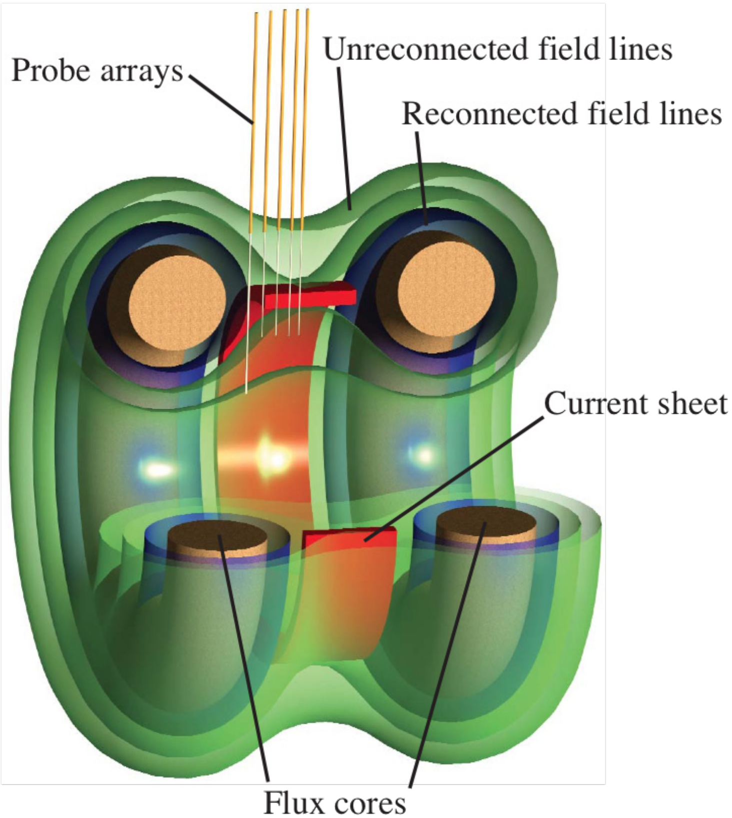
- **Study non-MHD effects in the reconnection layer; [two-fluid physics, turbulence, new physics]**
- **How magnetic energy is converted to plasma flows and thermal energy,**
- **How local reconnection determine global phenomena**

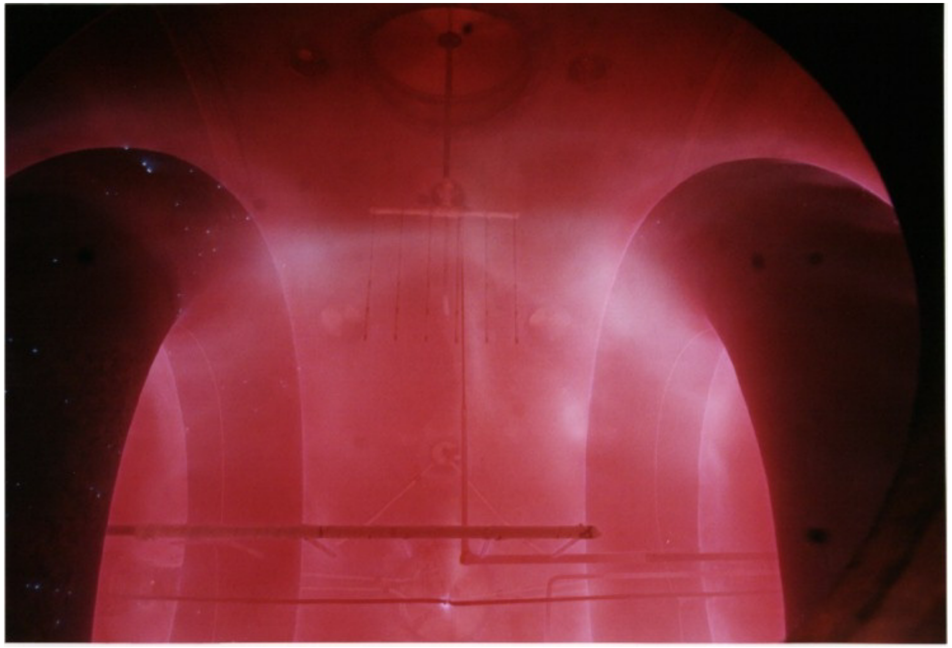
  - Global 2-D and 3-D MHD effects on reconnection

  - Effects of boundary

- **Why does reconnection occur so fast?**

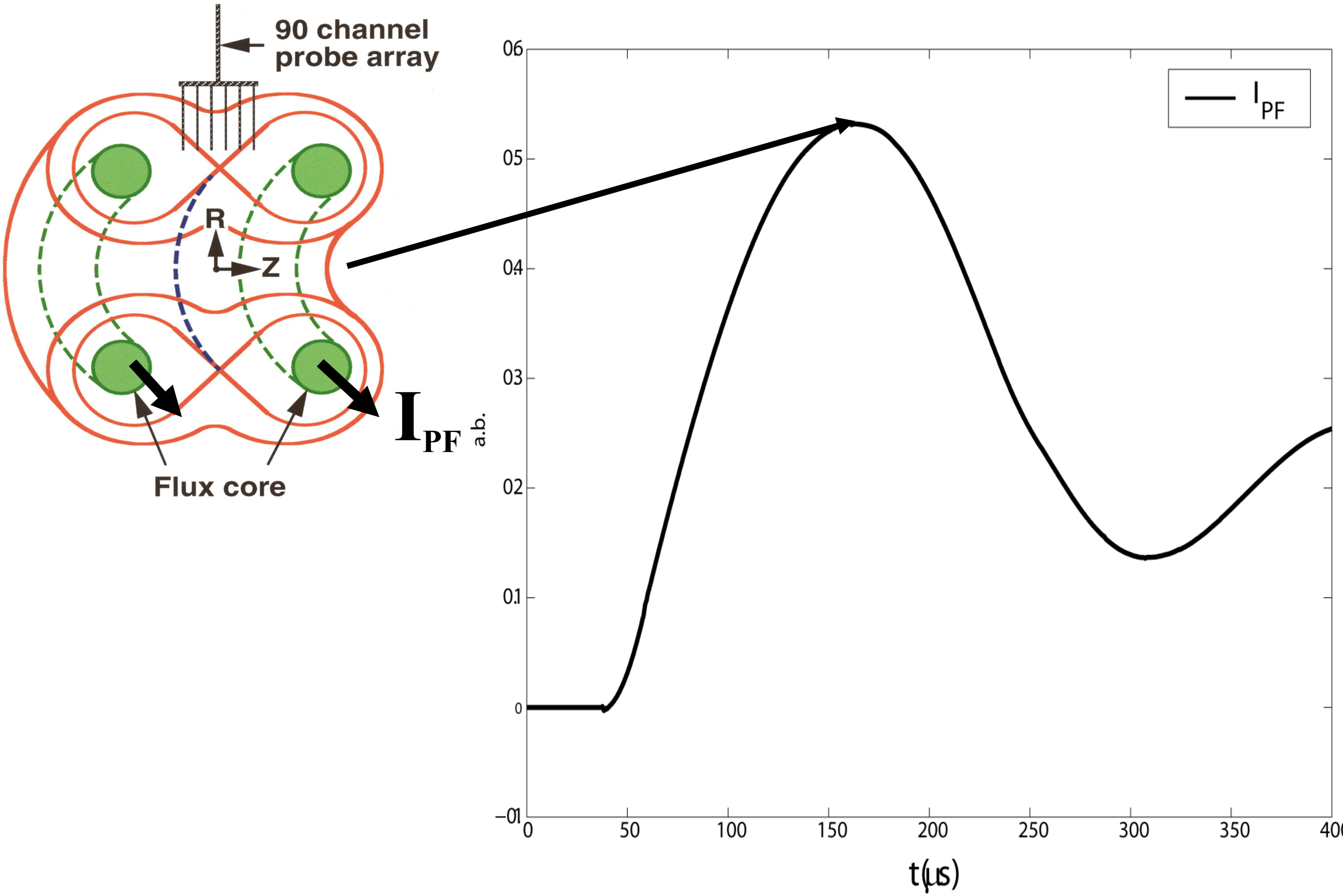
Plasma Production in MRX



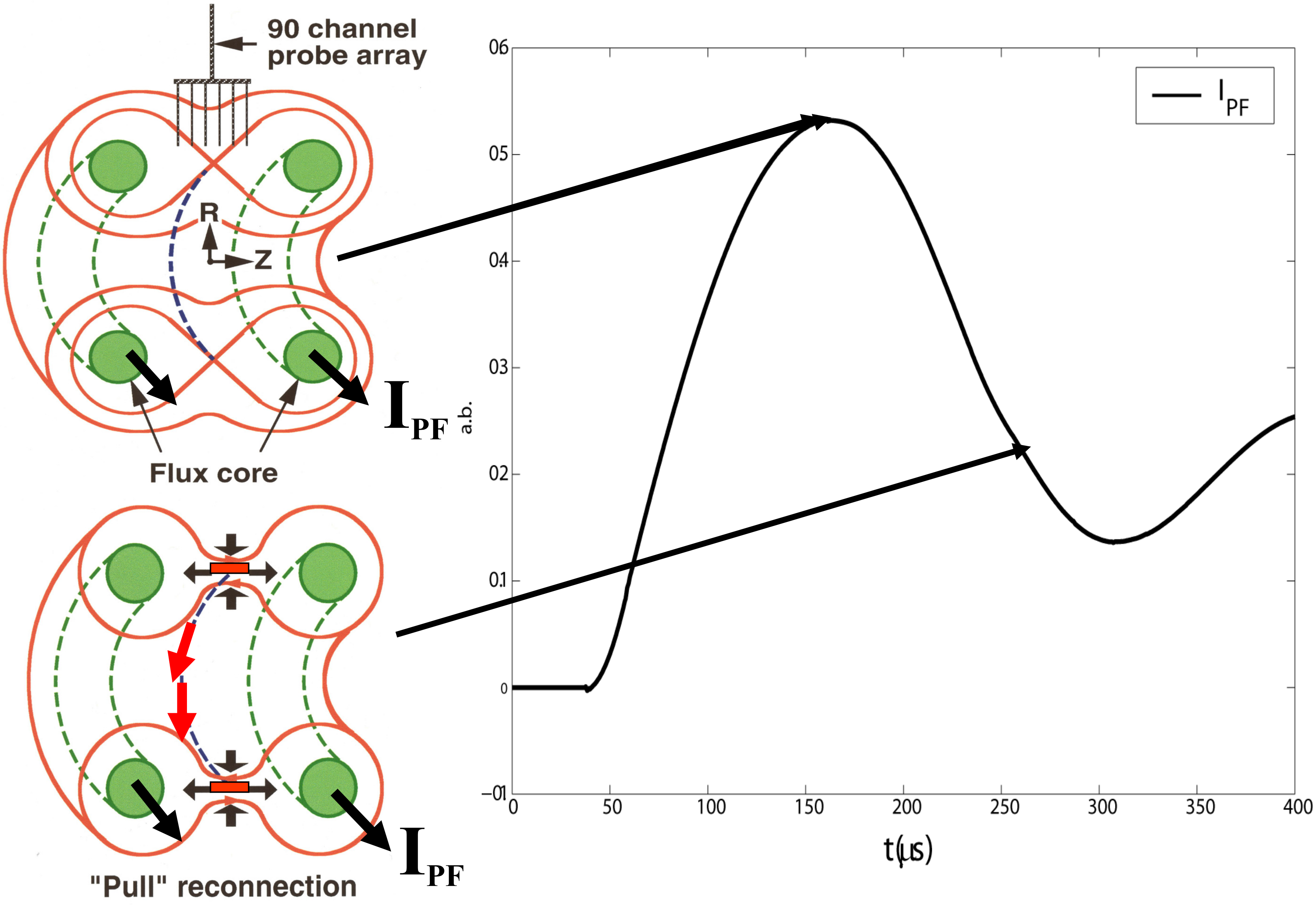


1) ***Gas is injected into the vacuum vessel.***
2) ***Currents through the "flux cores" ionize plasma and drive reconnection.***

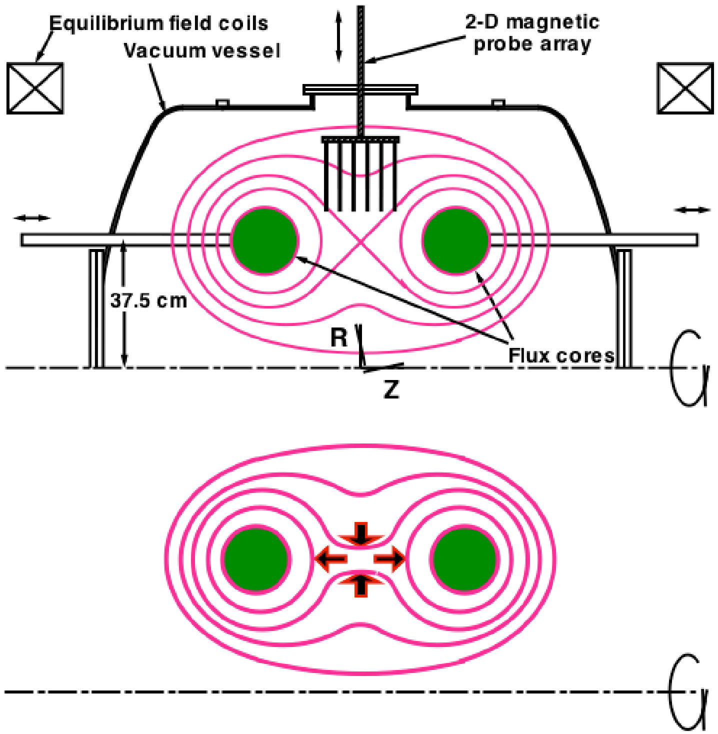
Pull Reconnection in MRX

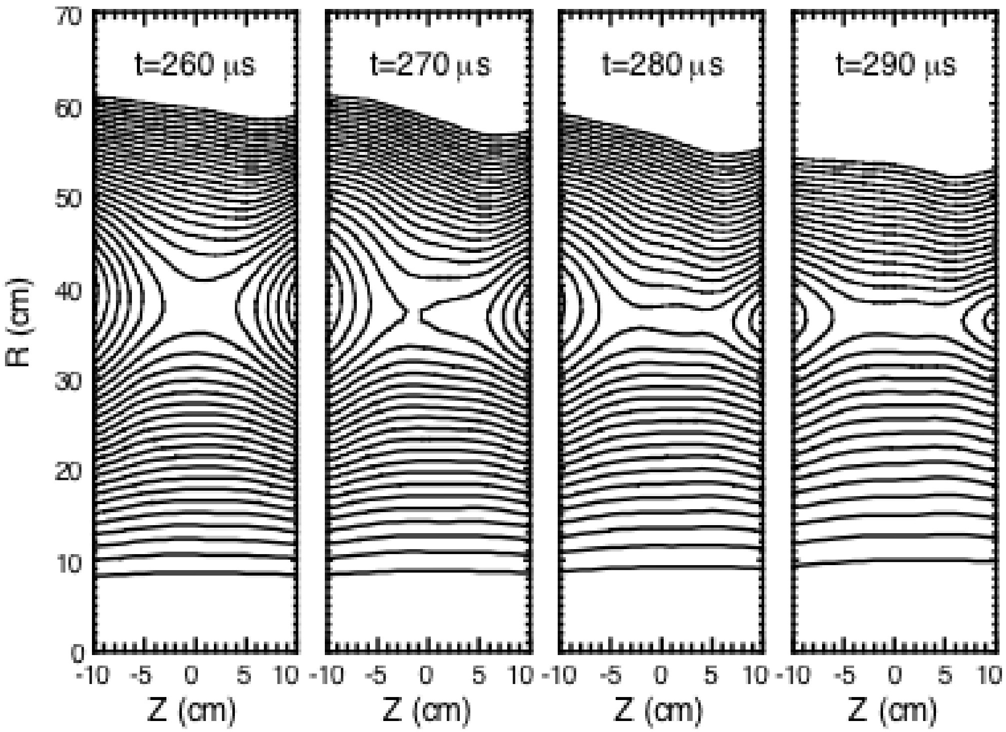


Pull Reconnection in MRX



Experimental Setup and Formation of Current Sheet





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

MRX

Magnetic
Reconnection
Experiment

Poloidal Flux Evolution

Null-helicity Reconnection

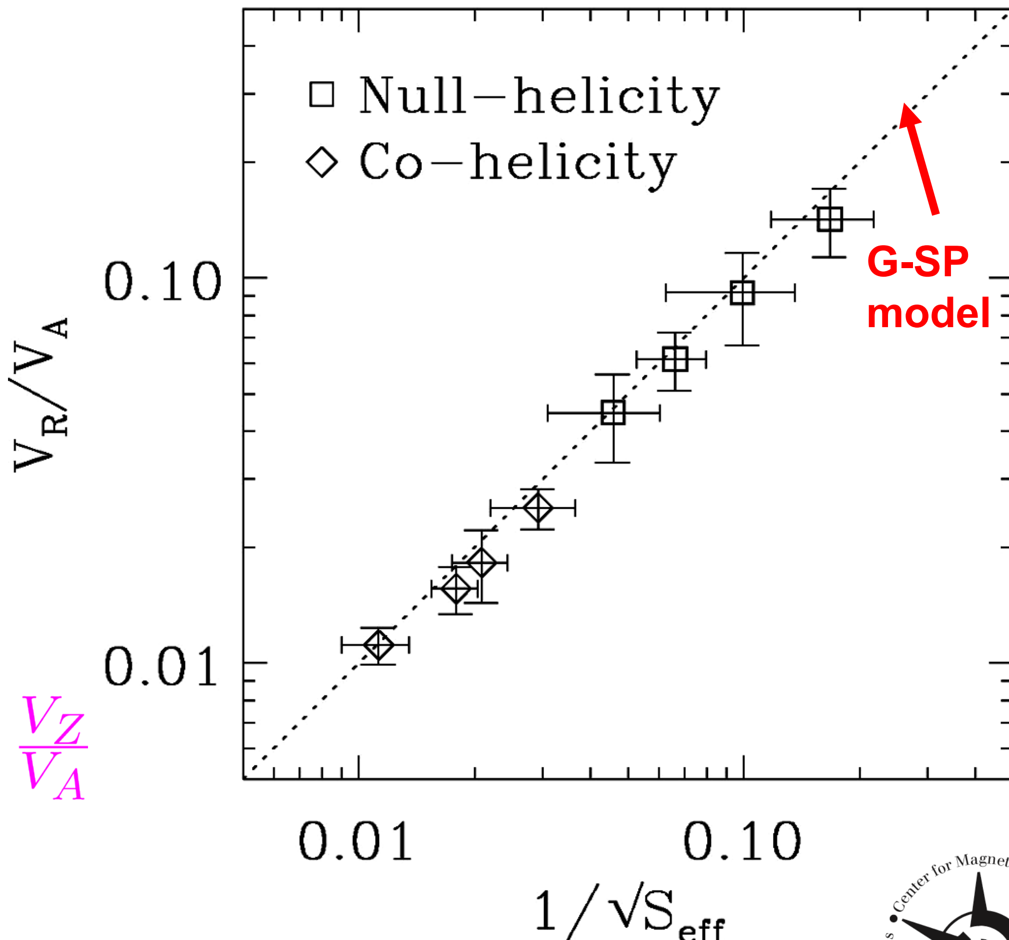
Princeton Plasma Physics Laboratory, Princeton University

Agreement with a Generalized Sweet-Parker Model

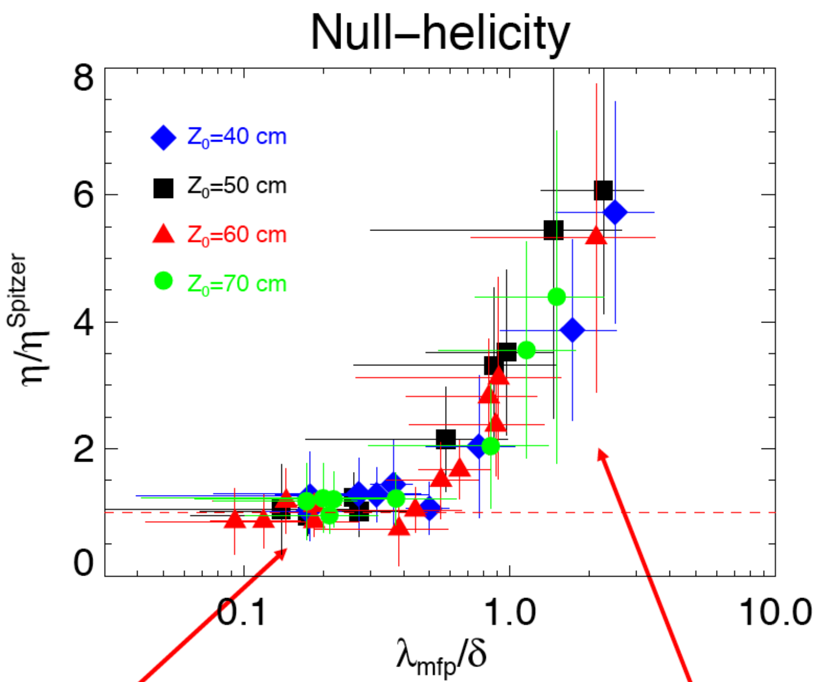
- **The model modified to take into account of**
  - **Measured enhanced resistivity**
  - Compressibility
  - High plasma pressure in downstream than upstream

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

(Ji et al. PoP '99)



Resistivity increases as collisionality is reduced in MRX



Effective resistivity

Close to classical Spitzer

$$\eta_\perp^{Spitzer} = 1.03 \times 10^{-4} T_e^{-3/2} Z \ln \Lambda$$

Enhanced in low collisional plasma

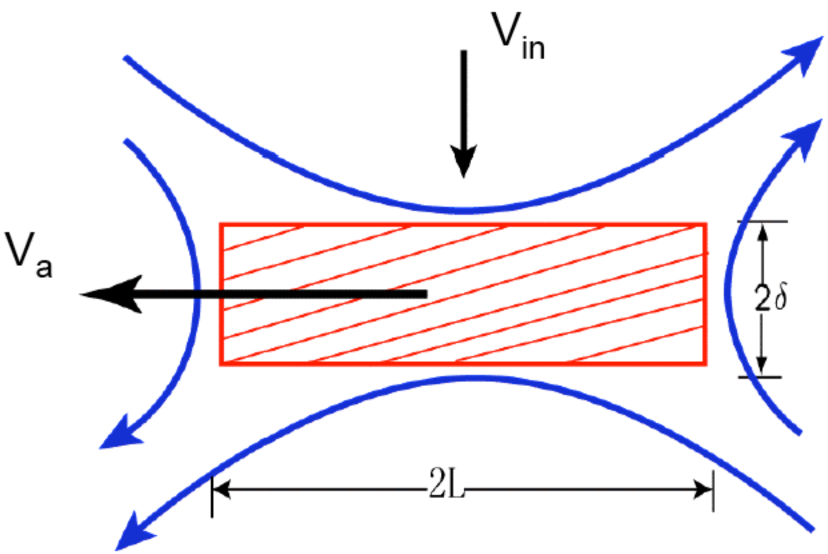
$$E_\theta + V_R \times B_Z = \eta j_\theta \qquad \eta^* \equiv \frac{E_\theta}{j_\theta}$$

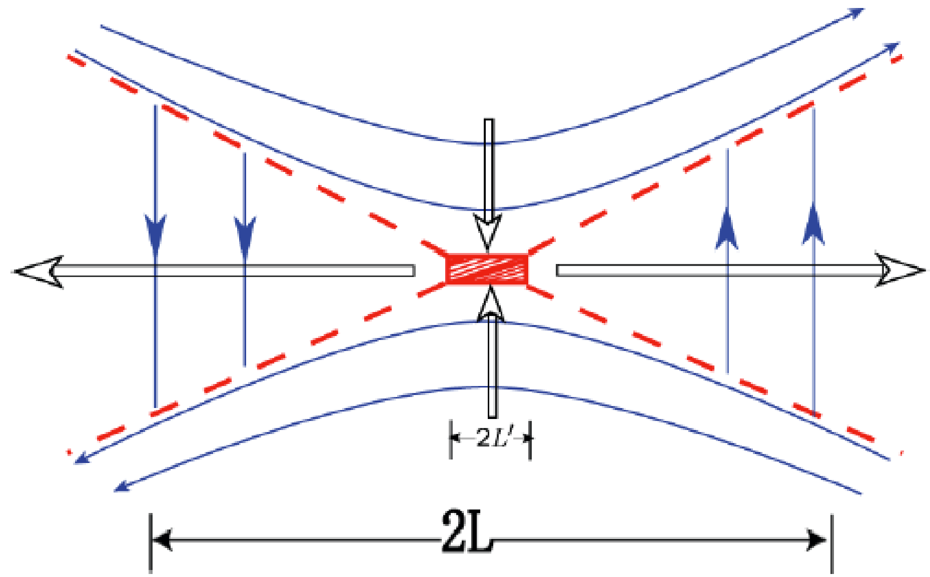
But the cause of enhanced η was unknown.

Local Reconnection Physics

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

Descriptions of Fast Reconnection





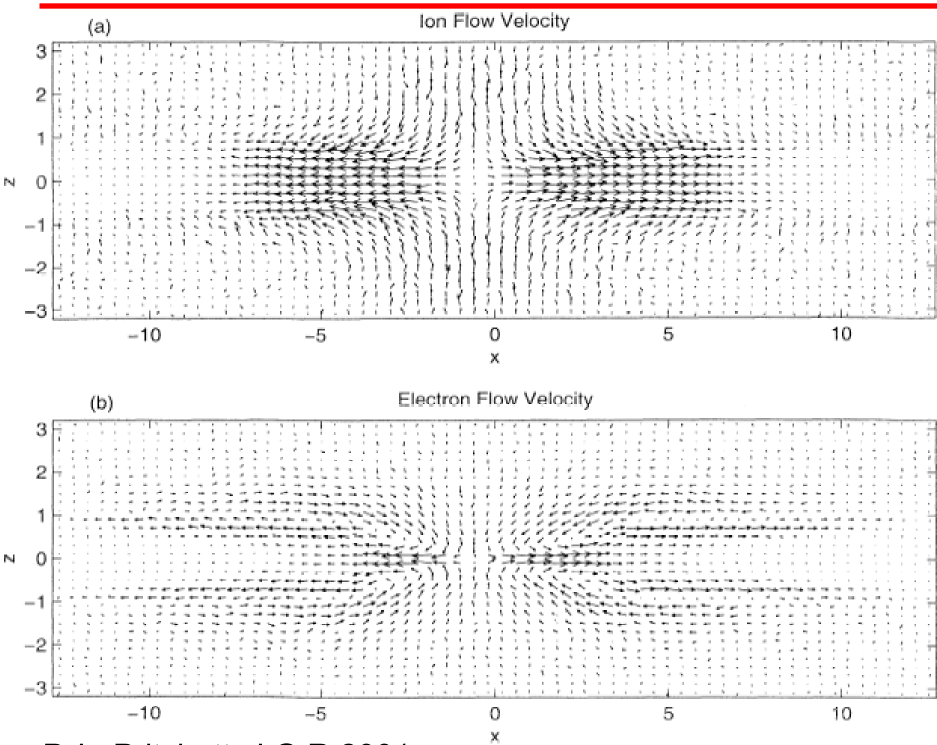
Generalized Sweet-Parker model with enhanced resistivity

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

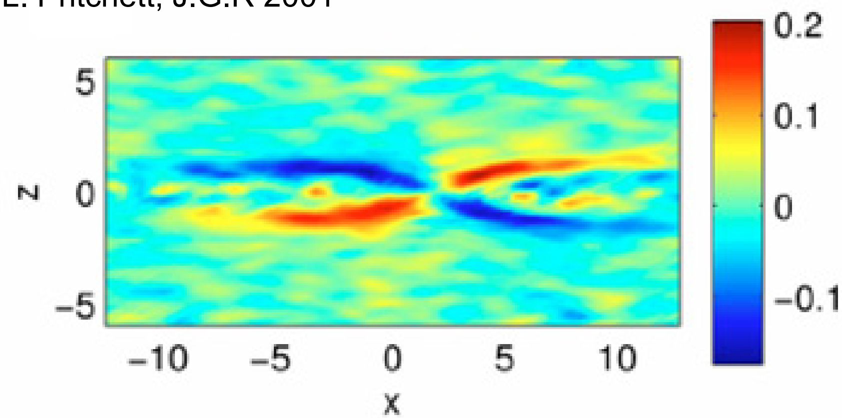
Two-fluid MHD model in which electrons and ions decouple in the diffusion region ($\sim c/\omega_{pi}$).

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

Extensive simulation work on two-fluid physics carried out in past 10 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,

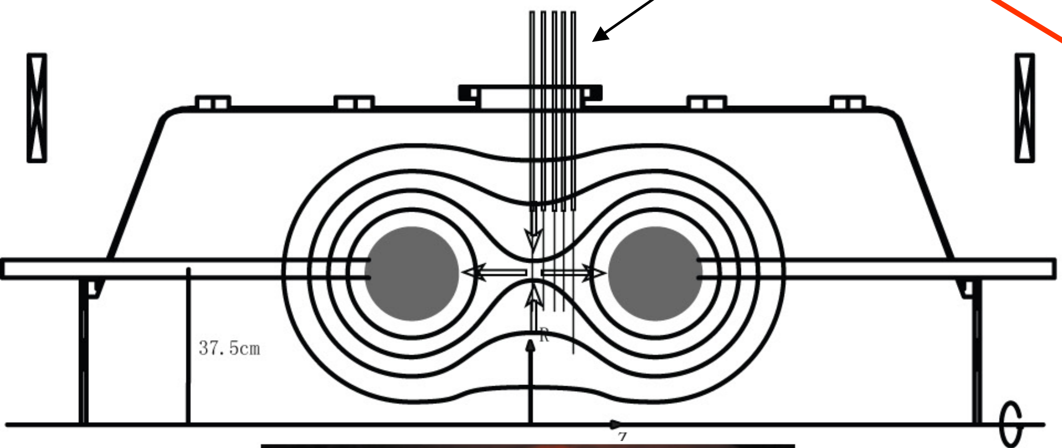
R. Horiuchi et al,

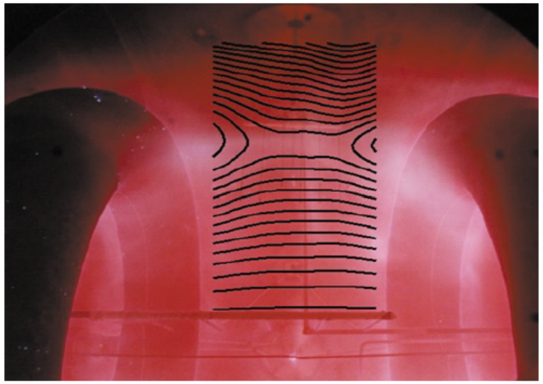
A. Bhattcharjee, M. Hesse, P. Pritchett, W. Daughton…

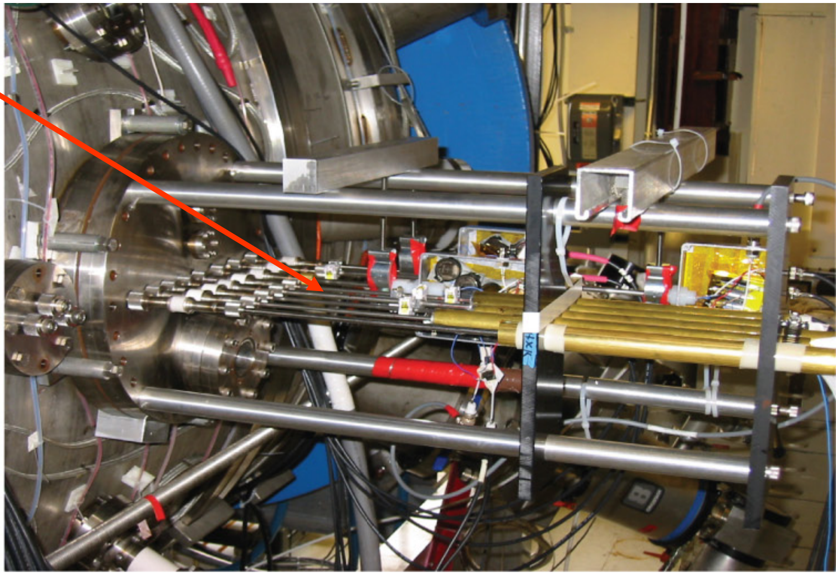
Out of plane magnetic field is generated during reconnection

MRX with fine probe arrays

Linear probe arrays

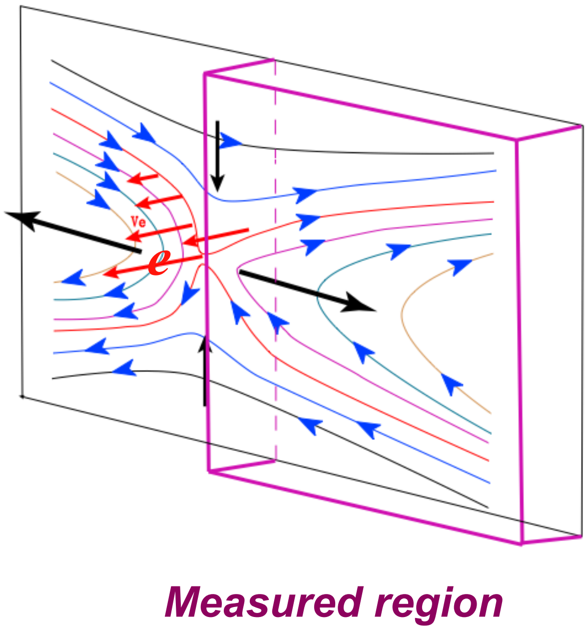


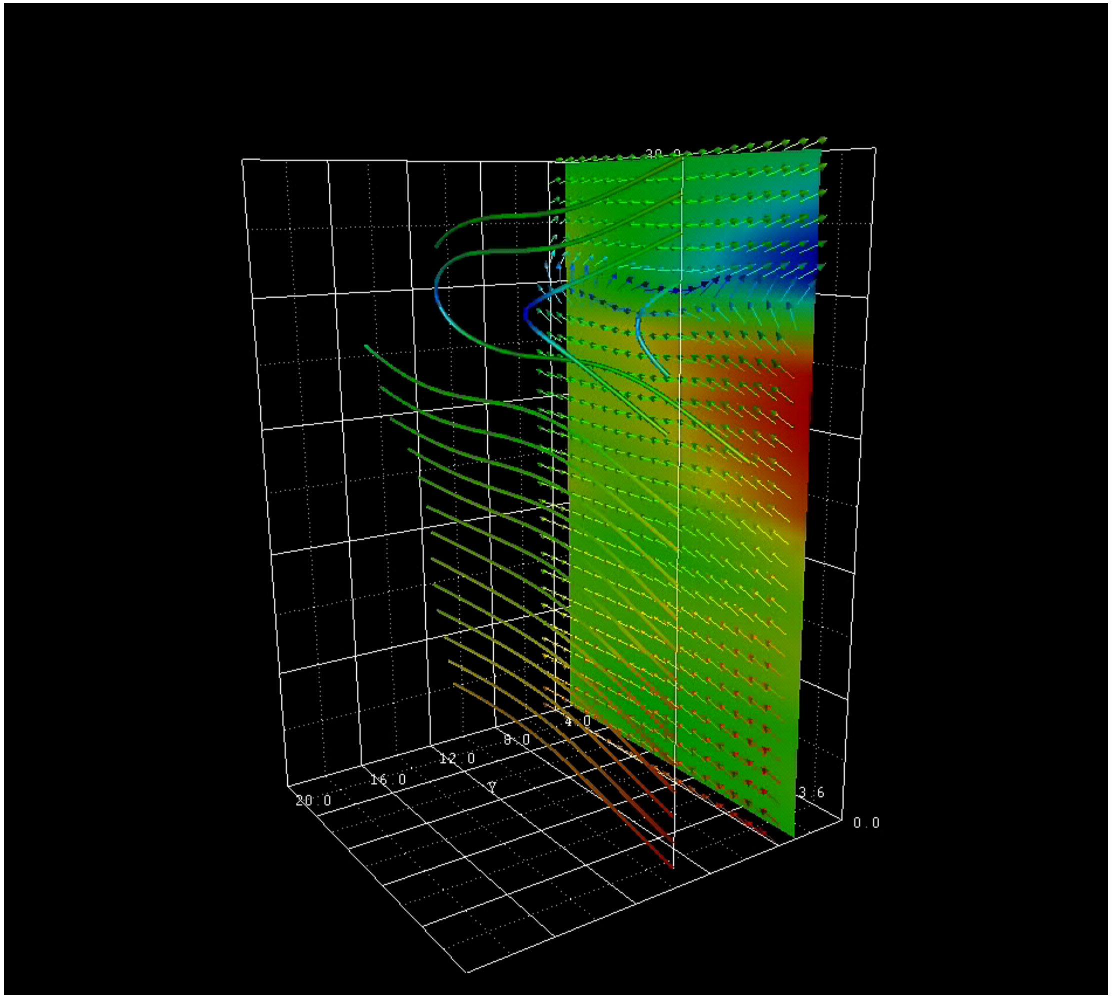




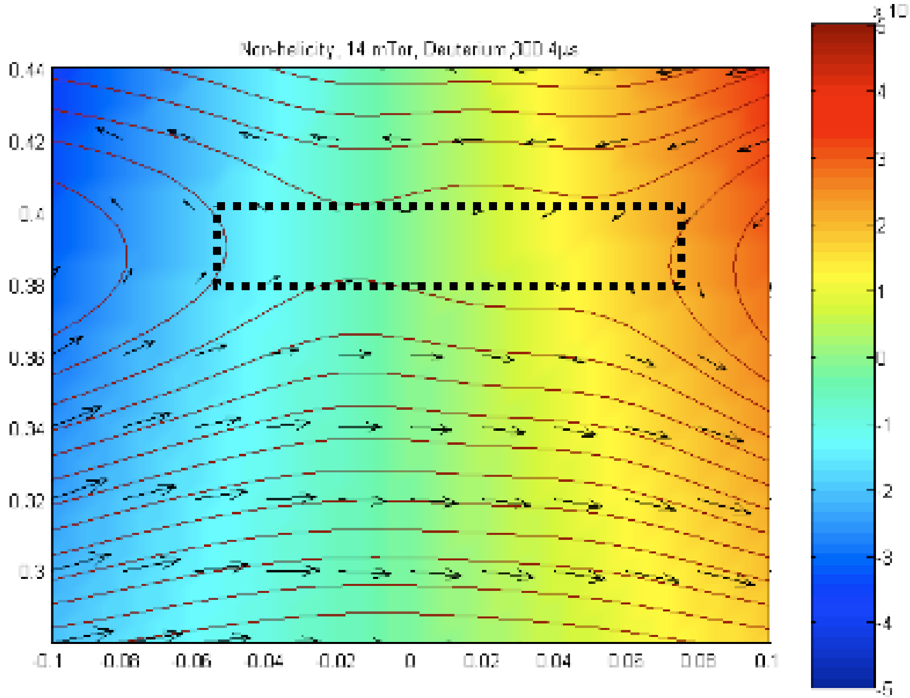
- Five fine structure probe arrays with resolution up to Δx= 2.5 mm in radial direction are placed with separation of Δz= 2-3 cm

Evolution of magnetic field lines during reconnection in MRX





Electrons pull field lines as they flow in the neutral sheet



Neutral sheet Shape in MRX

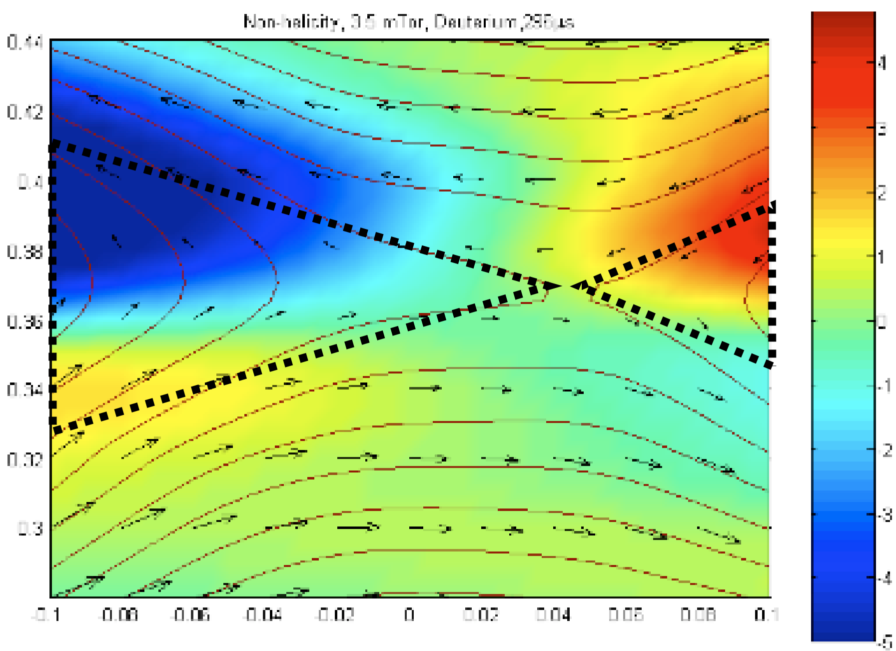
Changes from “Rectangular S-P” type to “Double edge X” shape as collisionality is reduced

Rectangular shape

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

Slow reconnection

No Q-P field



X-type shape

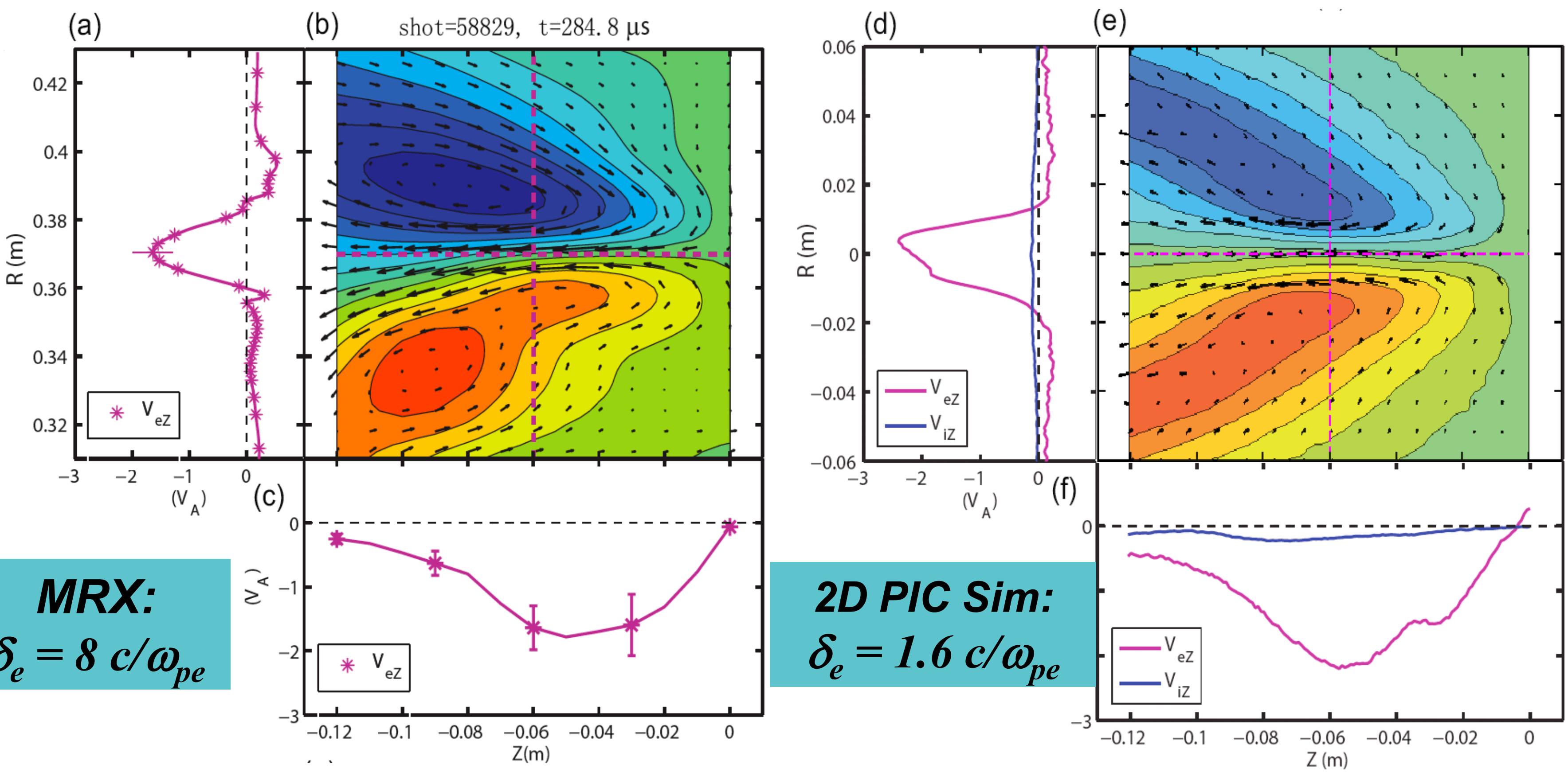
Collisionless regime: $\lambda_{mfp} > \delta$

Fast reconnection

Q-P field present

Yamada et al, PoP 2006

First Detection of Electron Diffusion Layer Made in MRX: Comparison with 2D PIC Simulations



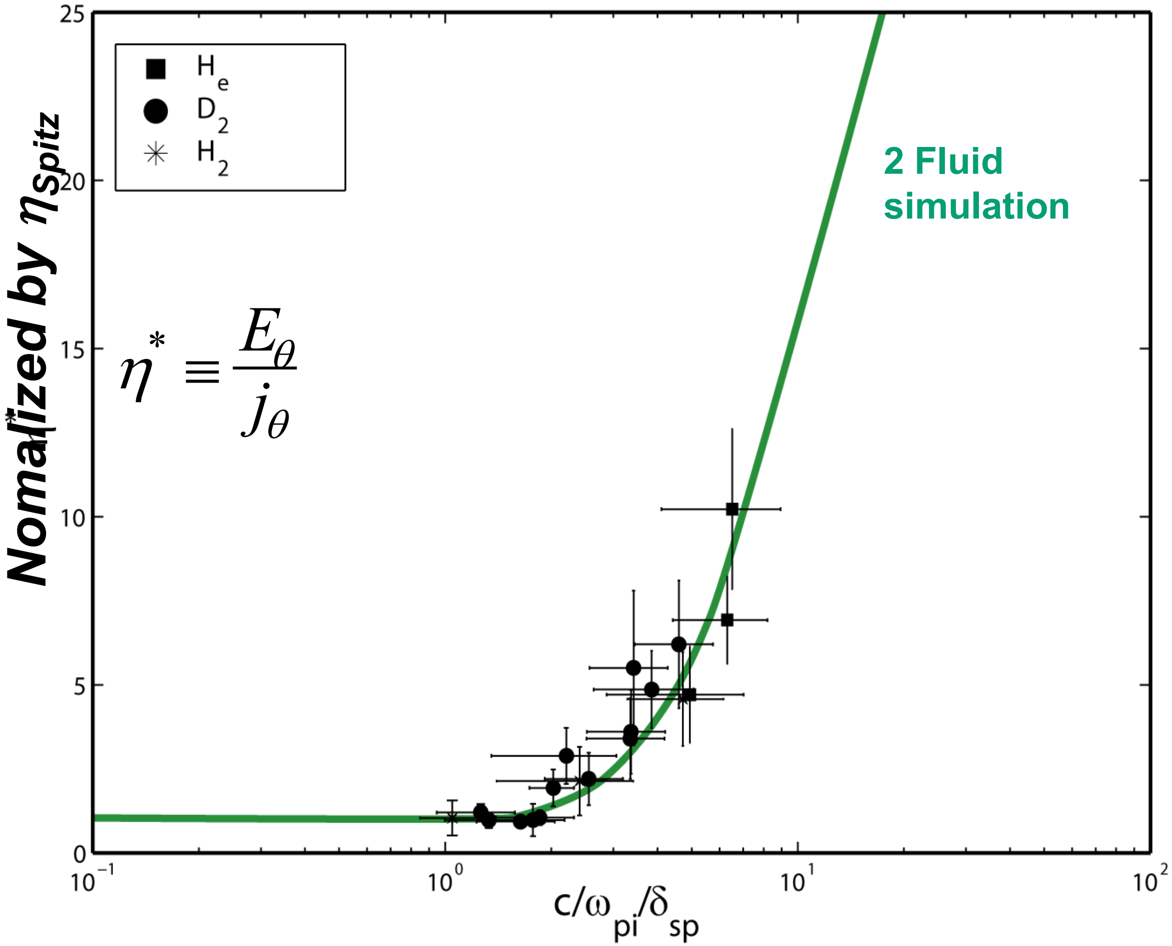
MRX:
$\delta_e = 8\ c/\omega_{pe}$

2D PIC Sim:
$\delta_e = 1.6\ c/\omega_{pe}$

All ion-scale features reproduced; but electron-layer is 5 times thicker in MRX Þ importance of 3D effects

Enhanced resistivity: MRX Scaling: η^* vs $(c/\omega_i)/\ \delta_{sp}$

A linkage between space and lab on reconnection



$(c/\omega_{pi})/\ \delta_{sp}$
$\sim 5(\ \lambda_{mfp}/L)^{1/2}$

Yamada et al, PoP, 2006

MRX scaling shows a transition from the MHD to 2 fluid regime based on $(c/\omega_{pi})/\ \delta_{sp}$

Linkages between space and lab on reconnection

System	L (cm)	B (G)	$d_i = c/\omega_{pi}$(cm)	δ_{sp} (cm)	d_i/δ_{sp}
MRX	10	100-500	1-5	0.1-5	.2-100
RFP/Tokamak	30/100	$10^3/10^4$	10	0.1	100
Magnetosphere	10^9	10^{-3}	10^7	10^4	1000
Solar flare	10^9	100	10^4	10^2	100
ISM	10^{18}	10^{-6}	10^7	10^{10}	0.001
Proto-star		$d_i/\delta_s >> 1$ or	$d_i/\delta_s << 1$		

$$d_i/\delta_{sp} \sim 5(\lambda_{mfp}/L)^{1/2}$$

Fast Reconnection
<=> Enhanced Electric Field

- Hall MHD Effects create a large E field (no dissipation)
- Electron Pressure Tensor
- Electrostatic Turbulence
- Electromagnetic Fluctuations (EM-LHW)

- Observed in space and laboratory plasmas

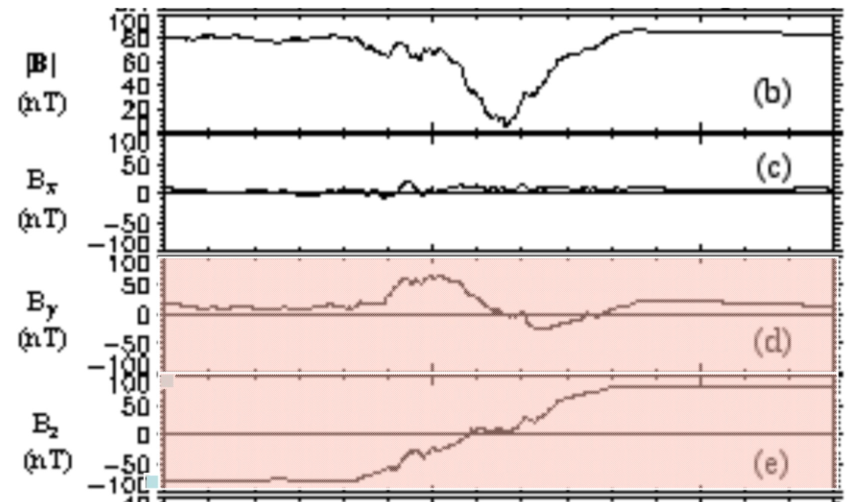
Magnetic Reconnection in the Magnetosphere

A reconnection layer has been documented in the magnetopause

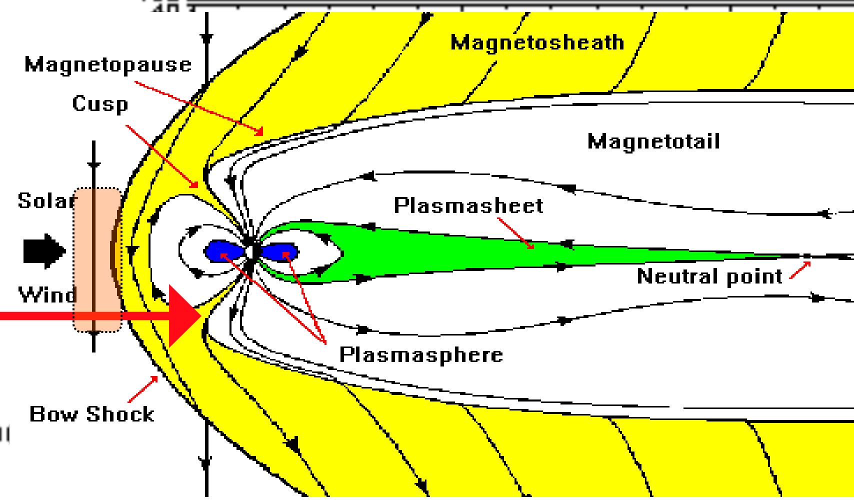
$\delta \sim c/\omega_{pi}$

Measurements of Diffusion Region with a Hall effect signature

Mozer et al., PRL 2002



POLAR satellite



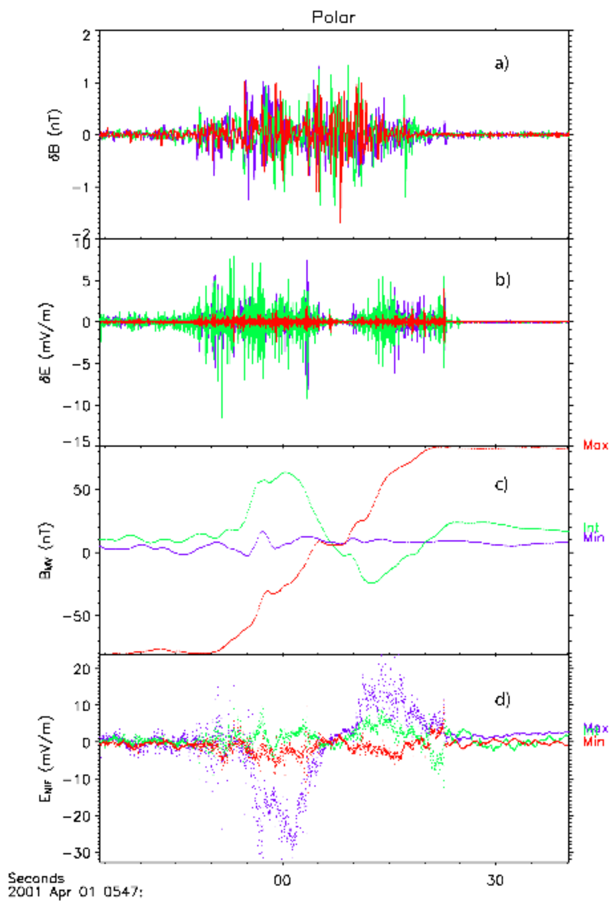
Similar Observations in Magnetopause and Lab Plasma

MRX

(a) **(Space:Bale et al. '04)**

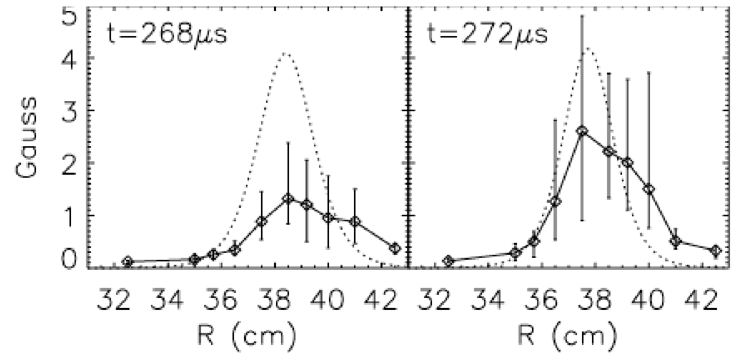
EM

ES

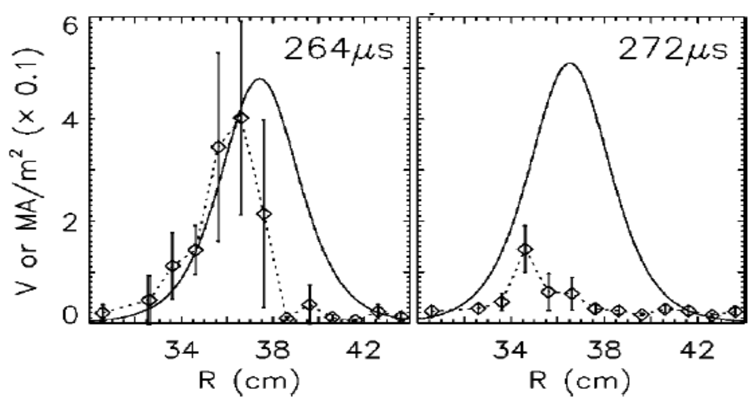


low β **high β** **low β**

(b) ***EM waves***



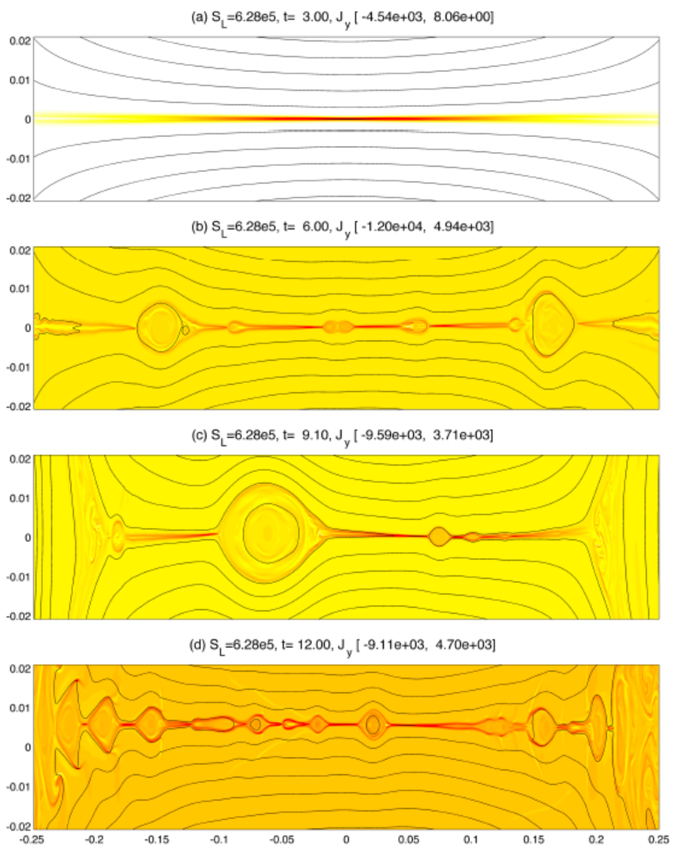
(c) ***ES waves***

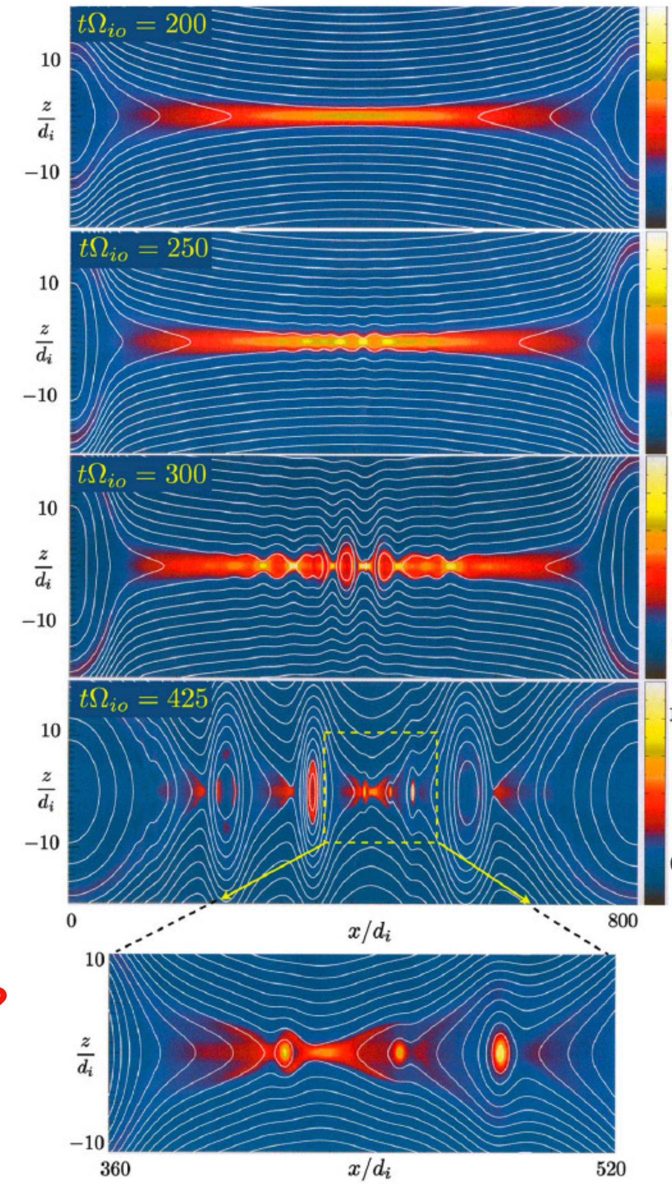


low β **high β**

Recent (2D) Simulations Find New Large S Phenomena

Bhattacharjee et al. (2009):MHD ***Daughton et al. (2009): PIC***

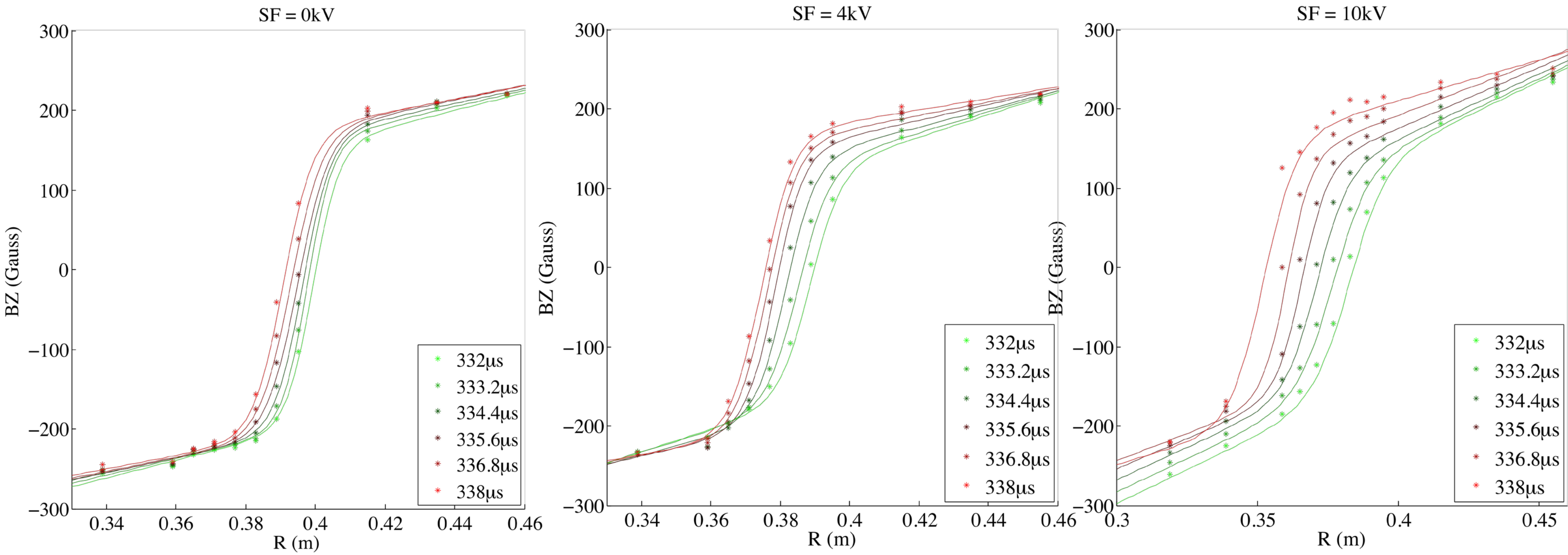


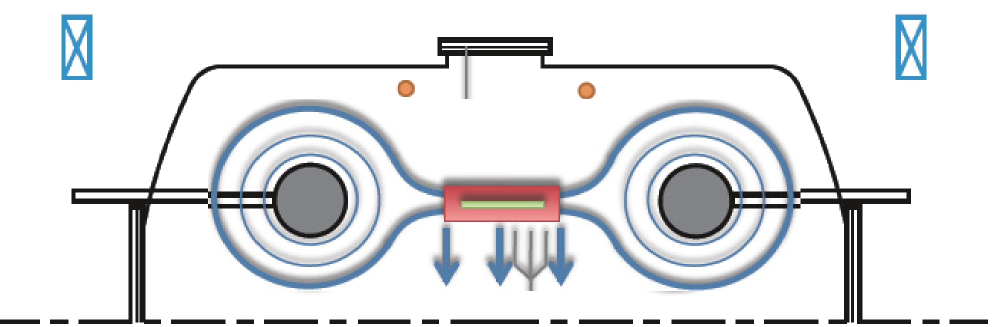


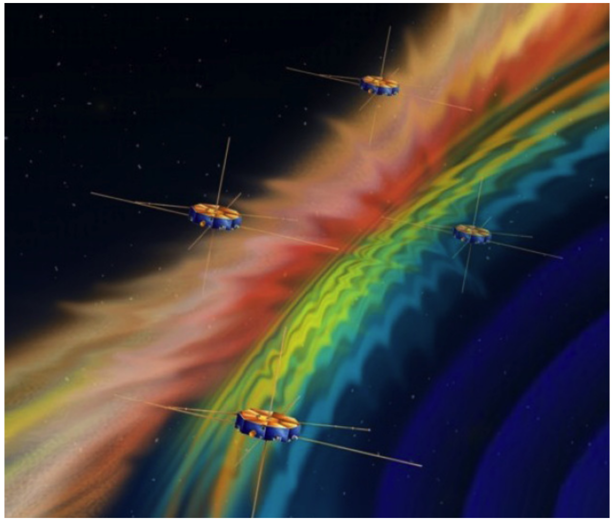
Sweet-Parker layers break up to form plasmoids when S > ~10⁴ ***=> Turbulent reconnection?***

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

A jog experiment on MRX (2011)

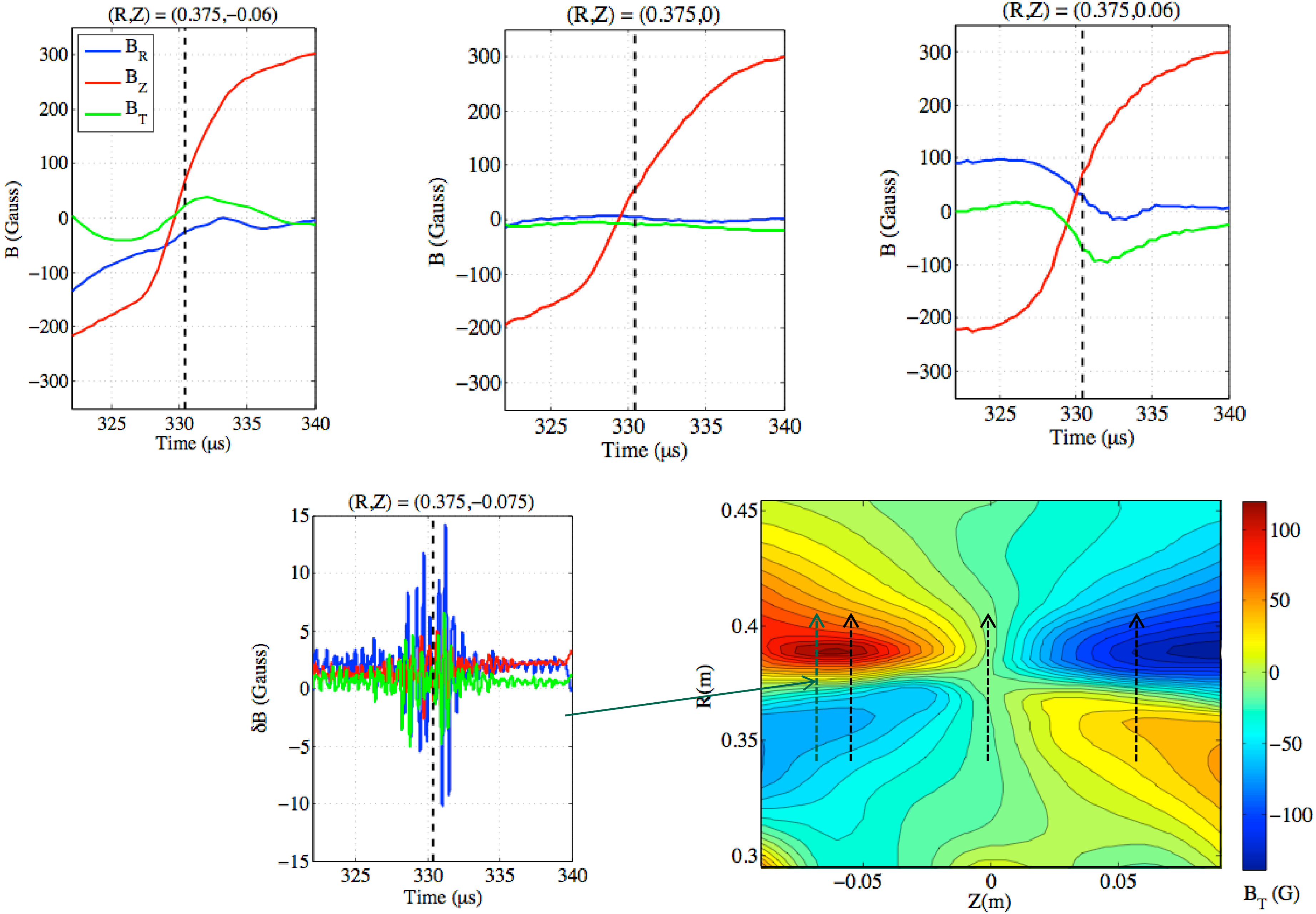






Collab. UNH, NASA, UC-Berkeley,

Jog experiment on MRX (2011)



PPPL
PRINCETON PLASMA PHYSICS LABORATORY

B. Global Reconnection Physics

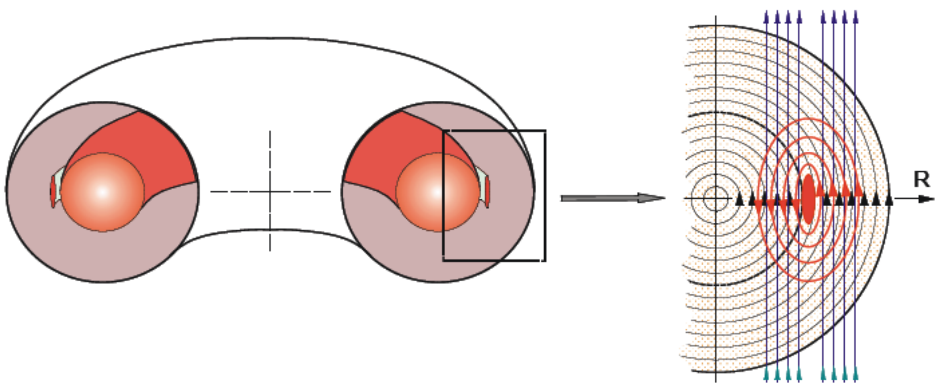
1. **Magnetic self-organization**
2. **Impulsive reconnection phenomena**
3. **Guide field effects**
4. **Particle acceleration**

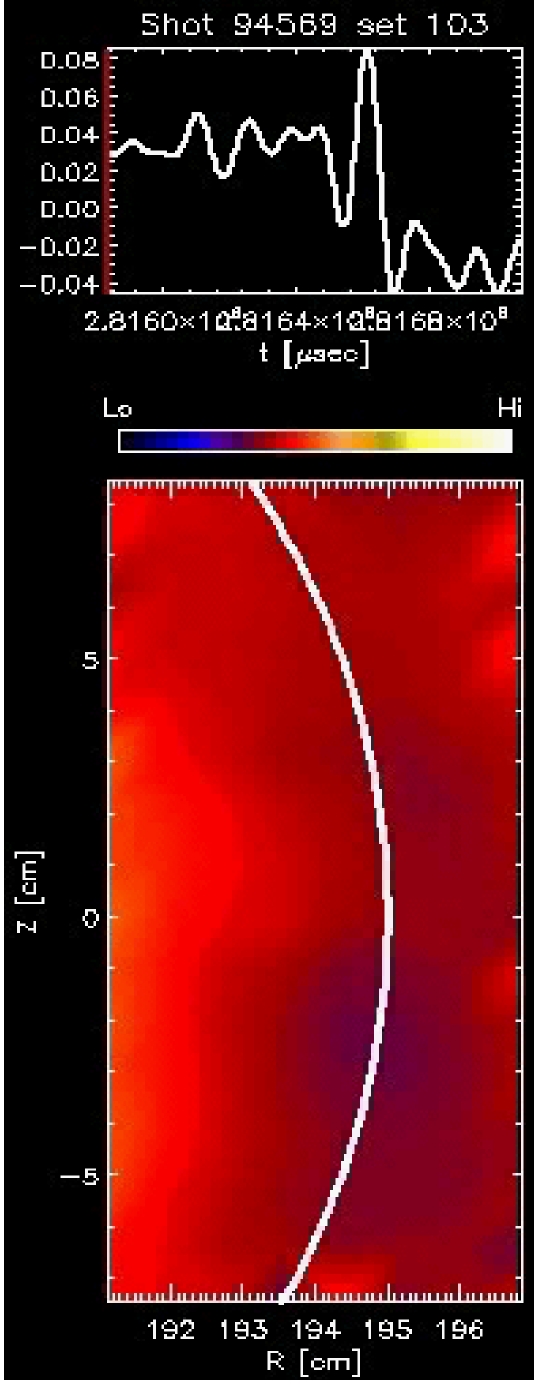
Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas

Sawtooth relaxation;
reconnection in a tokamak

H. Park et al (PRL-06) on Textor

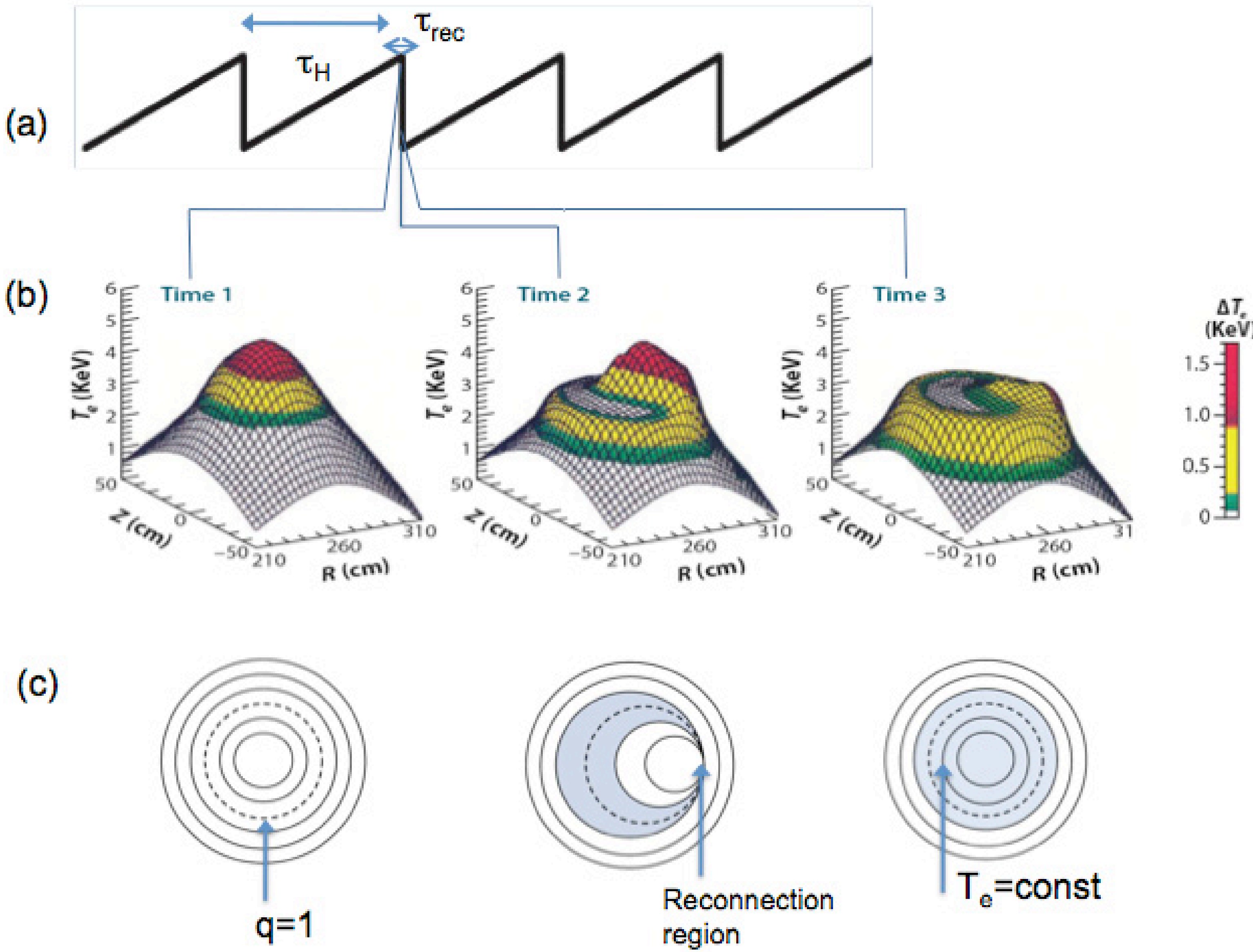
2-D T_e profiles obtained by measuring ECE (electron cyclotron emission) represent magnetic fluxes





Sawtooth crash (reconnection) occurs after a long flux build up phase

Particle acceleration into high energy regime



Summary

Good progress has been made in the research of magnetic reconnection <= collaboration between laboratory physics and astrophysics communities

- Transition from collisional to collisionless regime documented
- A scaling found on reconnection rate

- 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
  - Electron diffusion region identified.
  - Effects of turbulence
  - Causal relationship between these processes for fast reconnection is yet to be determined

- Universal principles yet to be found for mechanisms of particle acceleration and heating and for global reconnection phenomena
  - Magnetic self-organization
  - Global forcing
  - Impulsive reconnection