Frontiers for Laboratory Research of Magnetic Reconnection: Connections to Theory and Astrophysics

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Magnetic Field in the Universe V
October 5-9, 2015
Cargèse, Corsica, France

Magnetic Fields in the Universe

Yesterday:

What do they do? MRI, magnetized turbulence…

Today:

Where do they come from? Dynamo

Where do they go? Magnetic reconnection

> *Wherever there are magnetic fields, there will be magnetic reconnection.*

Magnetic *Reconnection* in the Universe: Throughout Heliophysical Plasmas

- Solar interior
  - Part of solar dynamo which requires changes in magnetic topology
- Solar chromosphere & corona
  - During solar flares; part of Coronal Mass Ejection; likely important for coronal heating
- Solar wind
  - Part of solar wind turbulence and current sheet dissipation
- Planetary interiors and magnetospheres
  - Part of planetary dynamos; part of plasma transport and magnetic storms; likely important for aurora activity
- Interface with local galactic plasma
  - Part of dissipation in heliospheric sheath and pause

Magnetic *Reconnection* in the Universe: Throughout Astrophysical Plasmas

Our galaxy:

- Star systems (100-400 billions of stars) mostly as our solar system
  - Also when they form from *molecular clouds*; when they explode through *supernova*; *flares and winds* from compact objects, e.g. Crab Nebula or magnetars; *gamma-ray bursts* during compact object merging
- Accretion disks
  - Protostellar disks and jets; X-ray binary disks (interiors and coronae)
- Interstellar medium
  - Part of ISM turbulence and current sheet dissipation; galactic magnetic field topology; galactic wind
- Galactic center
  - Maybe during Sagittarius A* flares

Extra-galactic:

- Galaxies (100-500 billions) mostly as our galaxy
- Active Galactic Nuclei (AGN) disks (interiors and coronae), e.g. quasars, blazers
- Dynamics of radio jets and lobes
- Heating or cooling of galaxy clusters

Magnetic *Reconnection* in the Universe: Throughout Laboratory Fusion Plasmas

- **Magnetic fusion plasmas**
  - Sawtooth oscillations in tokamaks
  - (Neoclassic) tearing mode growth
  - Disruptive activity such as major disruptions, possibly edge-localized modes
  - Magnetic self-organization (relaxation) events in low-field systems as in reversed field pinches and spheromaks
  - Formation of field reversed configurations via theta-pinch or plasma merging
- **Inertial fusion plasmas**
  - Possibly in Z-pinch plasmas, in which magnetic drive dominates
  - Possible even in laser-driven plasmas, in which magnetic field is applied to improve the energy confinement, or magnetic fields could spontaneously arise by Biermann battery effects, and then saturate by reconnection

Magnetic reconnection is a fundamental plasma process throughout the Universe and important for laboratory fusion.

… summarized in a reconnection "phase diagram" by Ji & Daughton (2011)

Major Questions for Magnetic Reconnection

1. **How is reconnection rate determined?** ***(The rate problem)***
2. **How does reconnection take place in 3D?** ***(The 3D problem)***
3. **How does reconnection start?** ***(The onset problem)***
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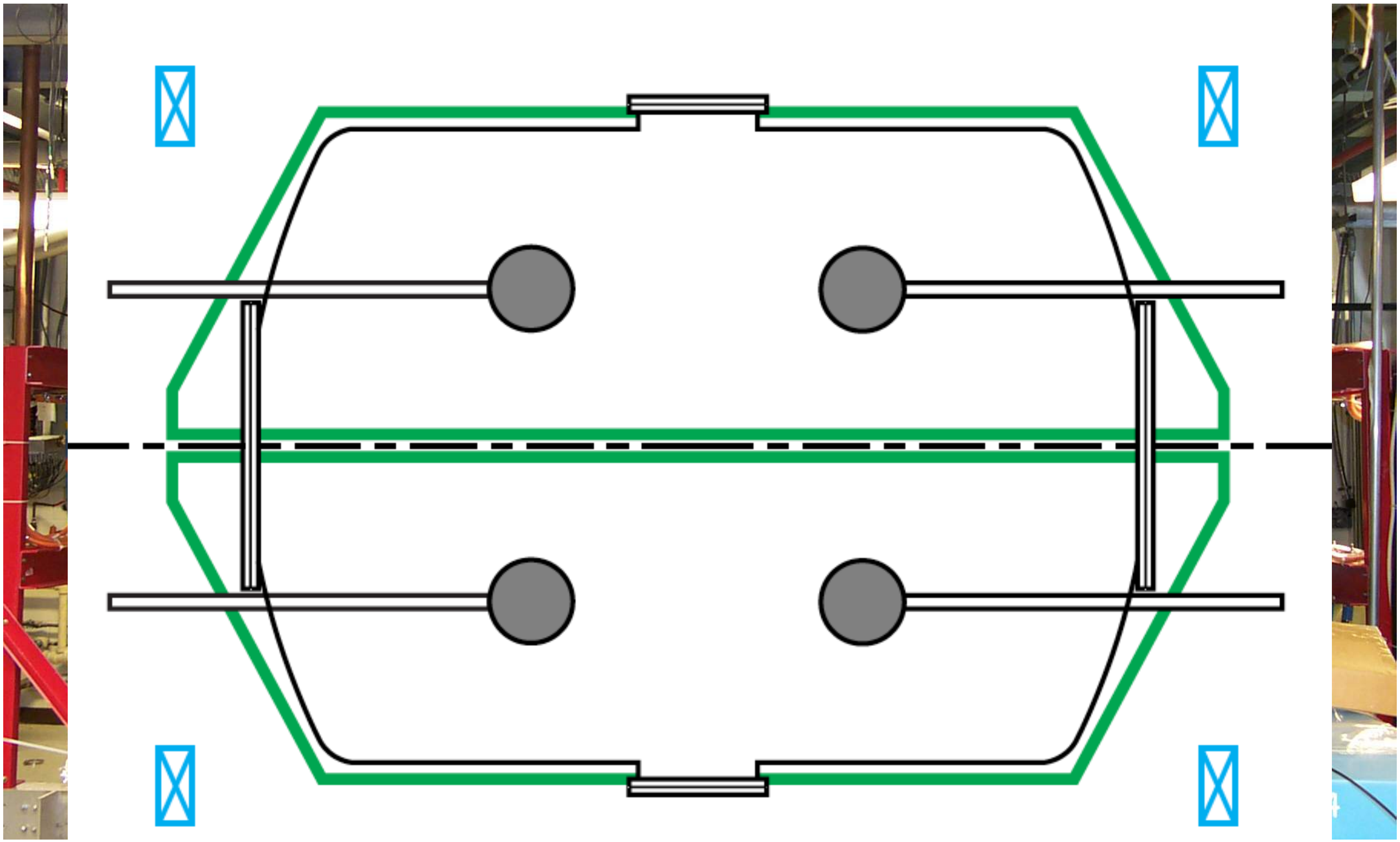
7. **What roles reconnection plays in flow-driven systems (The *flow-driven* problem)**
8. **How does reconnection take place under extreme conditions? (*The extreme problem*)**
9. **How to apply local reconnection physics to a large system?** ***(The multi-scale problem)***

Can we study these problems in the lab?

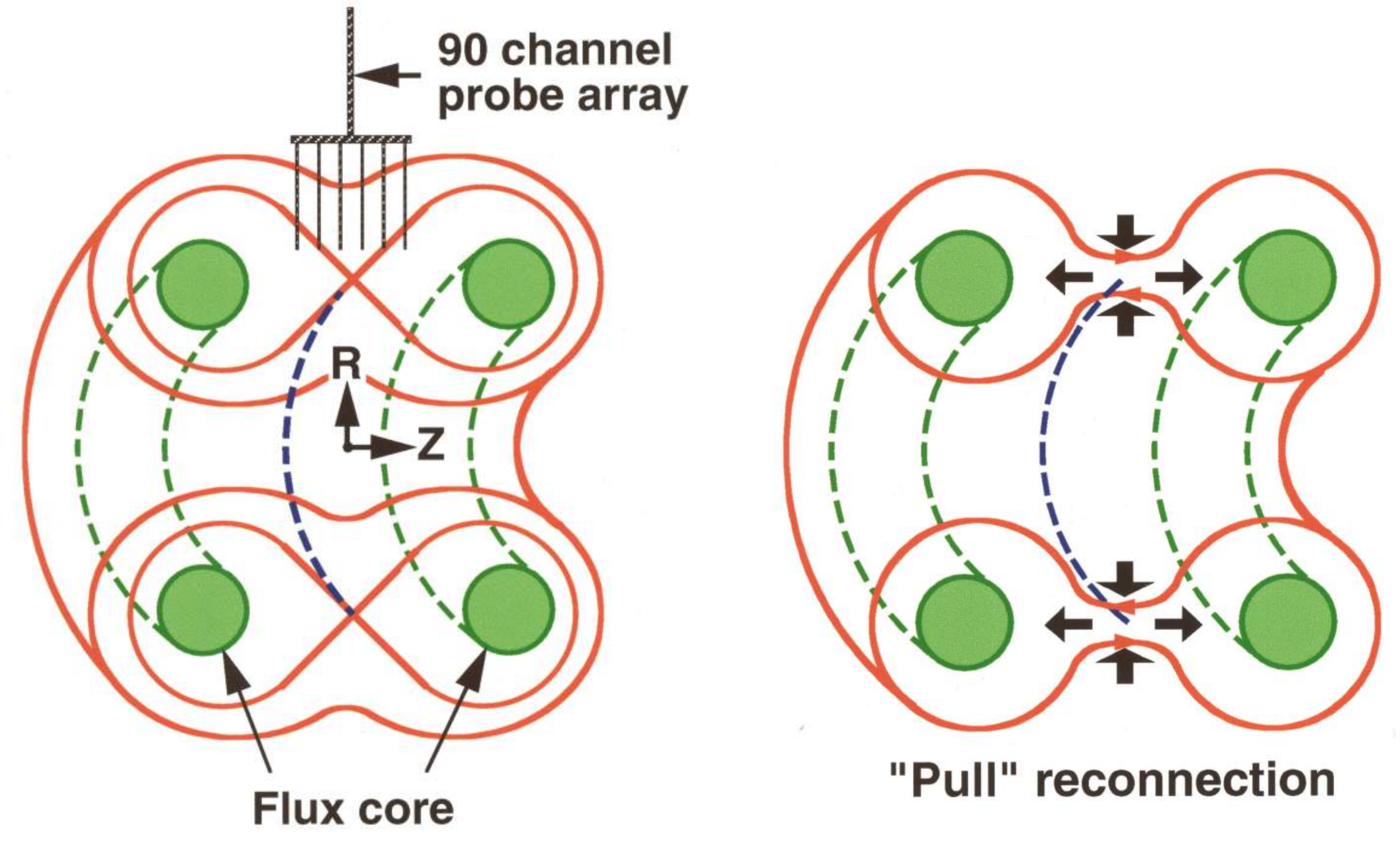
Dedicated Laboratory Experiments on Reconnection

Device	*Where*	*Since*	*Who*	*Geometry*	*Focus*
3D-CS	Moscow	1970	Syrovatskii, Frank	Linear	3D, energy
LPD, LAPD	UCLA	1980	Stenzel, Gekelman, Carter	Linear	Energy, 3D
TS-3/4, MAST	Tokyo	1990	Katsurai, Ono	Merging	Rate, energy
MRX	Princeton	1995	Yamada, Ji	Toroidal, merging	Rate, 3D, energy, partial ionization, boundary, onset
SSX	Swarthmore	1996	Brown	Merging	Energy, 3D
VTF	MIT	1998	Fasoli, Egedal	Toroidal	Onset, 3D
Caltech exp	Caltech	1998	Bellan	Planar	Onset, 3D
RSX	Los Alamos	2002	Intrator	Linear	Boundary, 3D
RWX	Wisconsin	2002	Forest	Linear	Boundary
Laser plasmas	UK, China, Rochester	2006	Nilson, Li, Zhong, Dong, Fox, Fiksel	Planar	Flow-driven, extreme
VINETA II	Max-Planck	2012	Grulke, Klinger	Linear	3D
TREX	Wisconsin	2013	Egedal, Forest	Toroidal	Energy
FLARE	Princeton	2013	Ji +	Toroidal	All
HRX	Harbin,China	2015	Ren +	3D	3D, energy

Magnetic Reconnection Experiment (MRX)
(since 1995; mrx.pppl.gov)



The Basic Experimental Setup in MRX

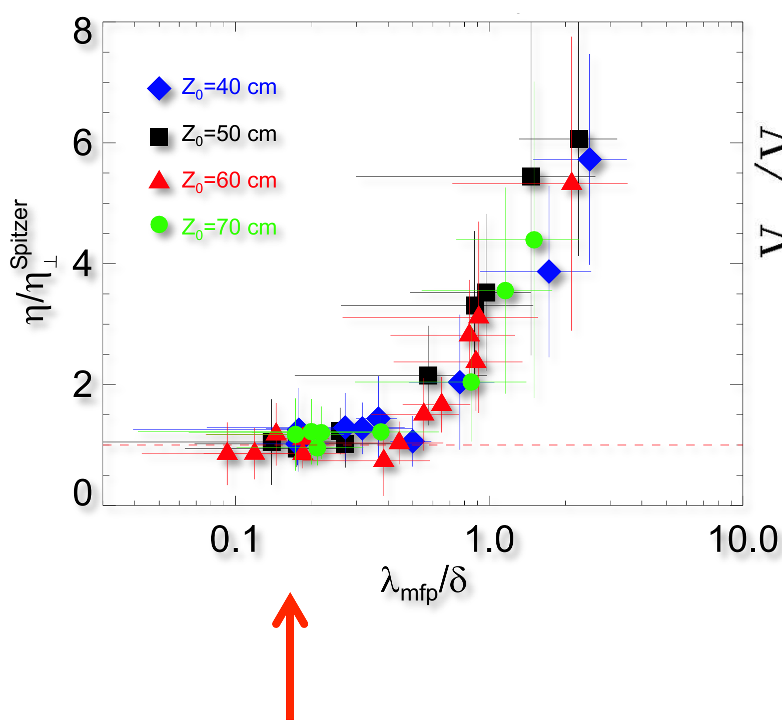


Key: Control + Diagnostics

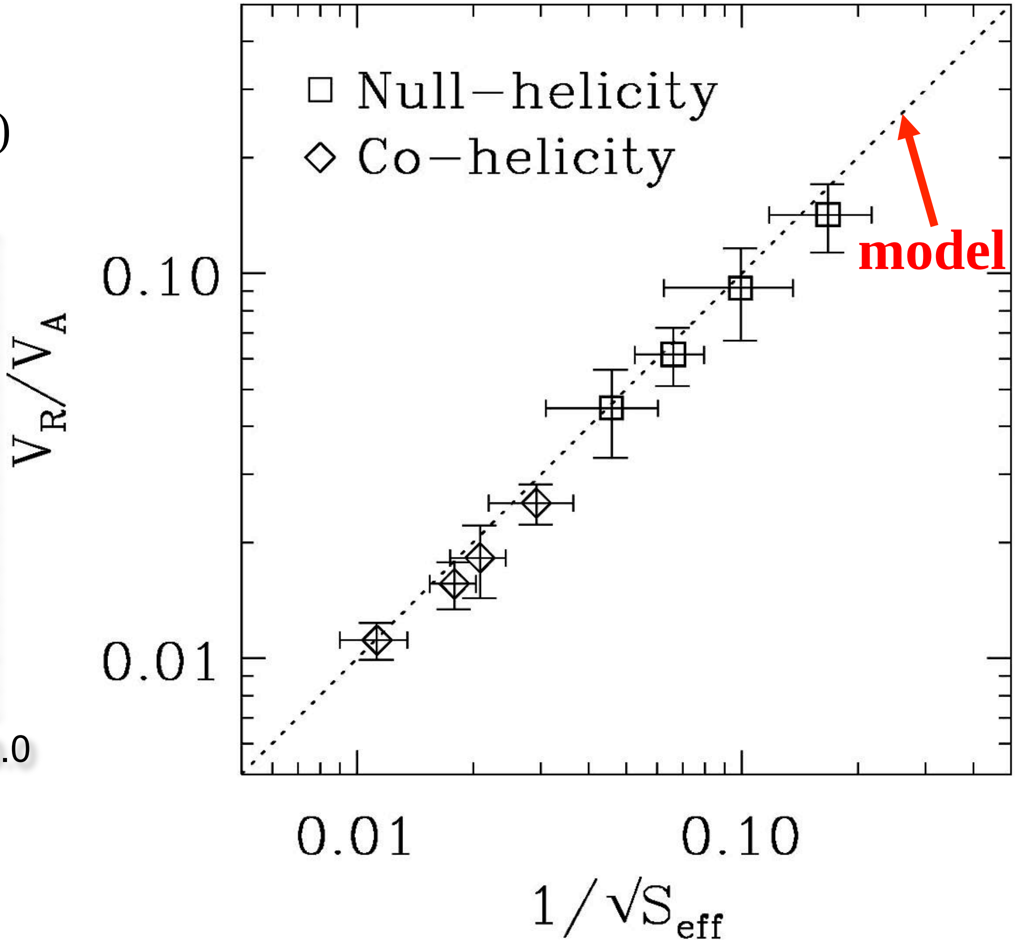
Sweet-Parker Model Works in *Collisional Plasmas*

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

- **When collisional, the apparent resistivity (*E*/*j*) agrees with Spitzer values** (slow reconnection)



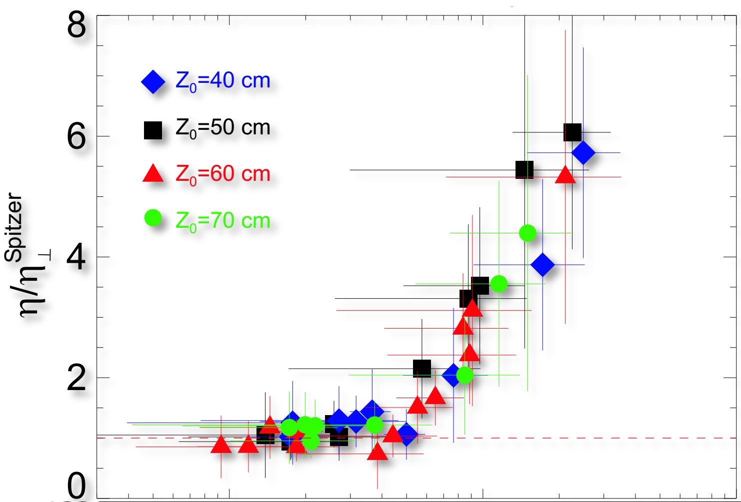
collisional

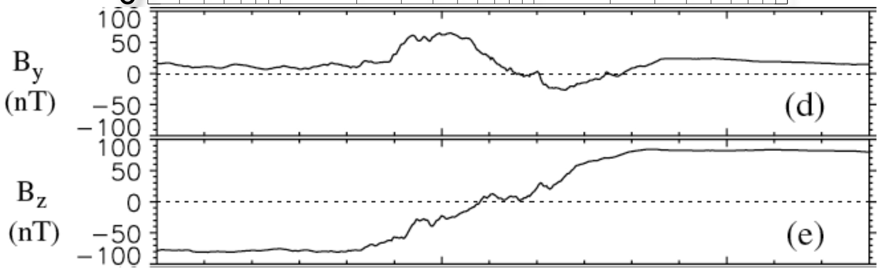


Two-fluid Model Works in *Collisionless Plasmas*

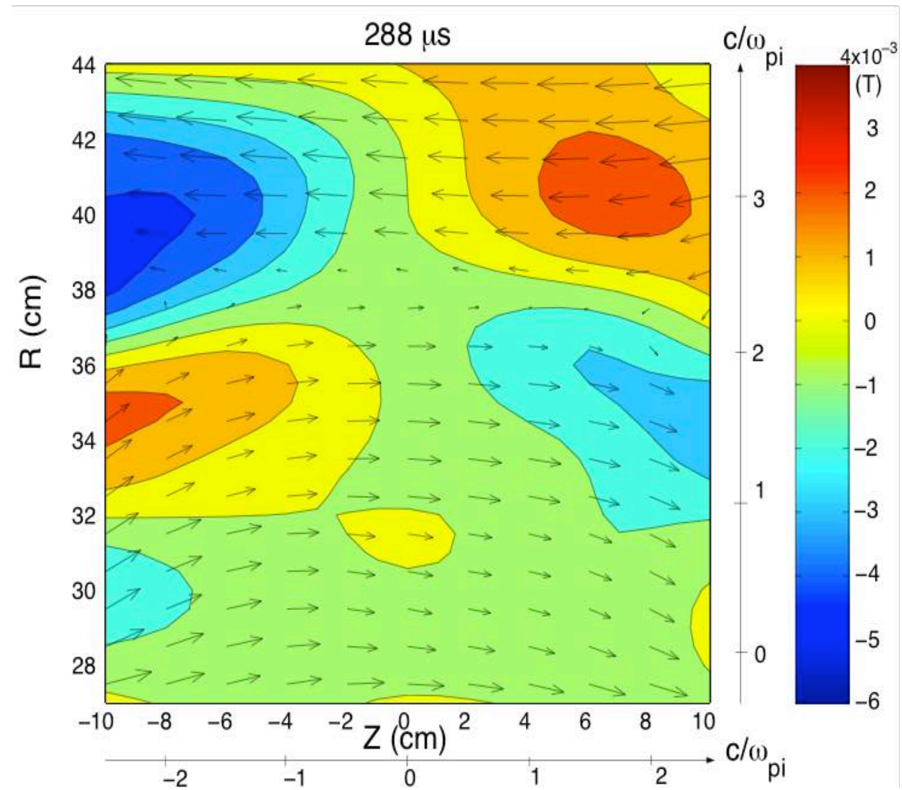
Ren et al., PRL (2005)
Yamada et al., PoP (2006)

- **When collisionless, the apparent resistivity (*E*/*j*) increases beyond Spitzer values** (fast reconnection)





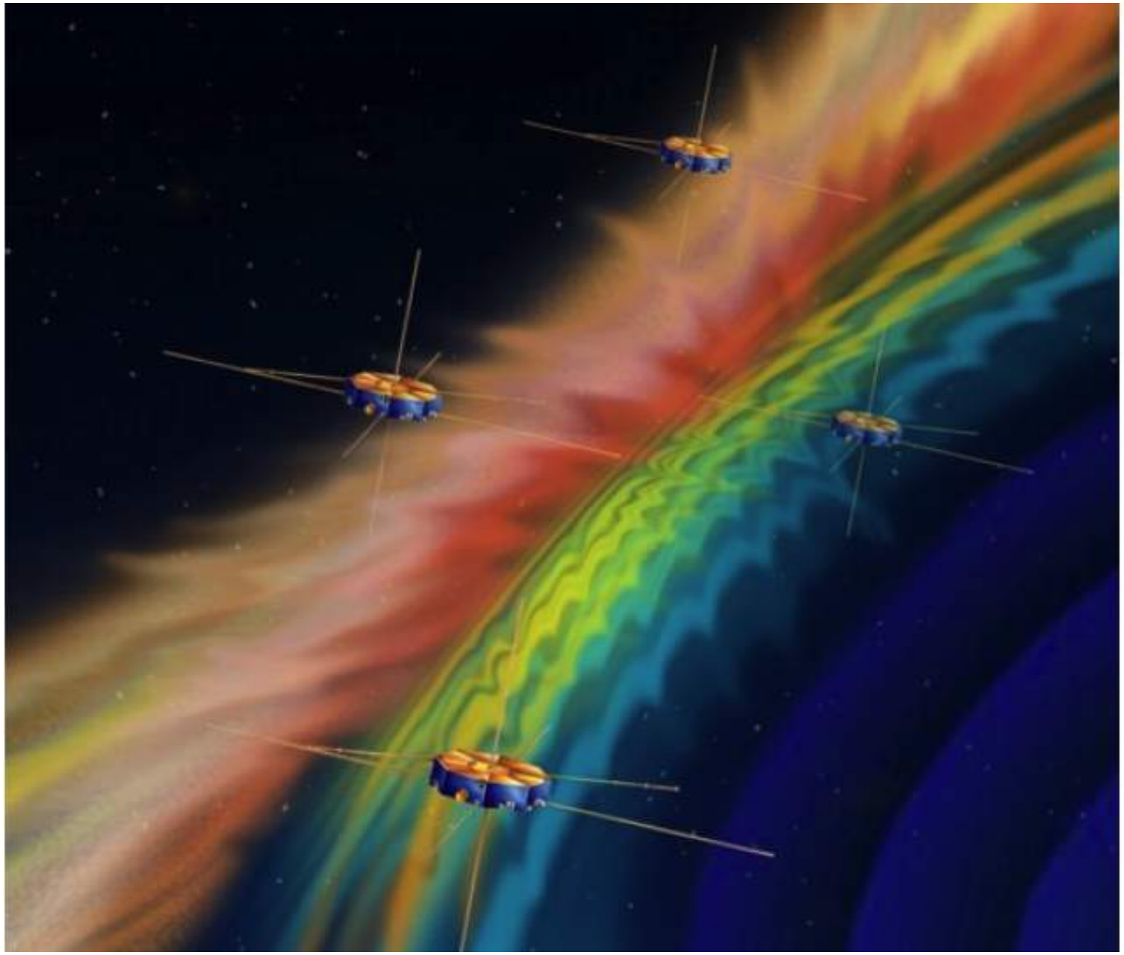
POLAR satellite: Mozer et al. (2001)



- Predicted quadrupole out-of-plane field detected on the ion scale

Next frontier: Electron diffusion regions

- **Goals of the $1.4B Magnetospheric Multi-Scale (MMS) mission launched on March 12, 2015**



Next frontier: Electron diffusion regions

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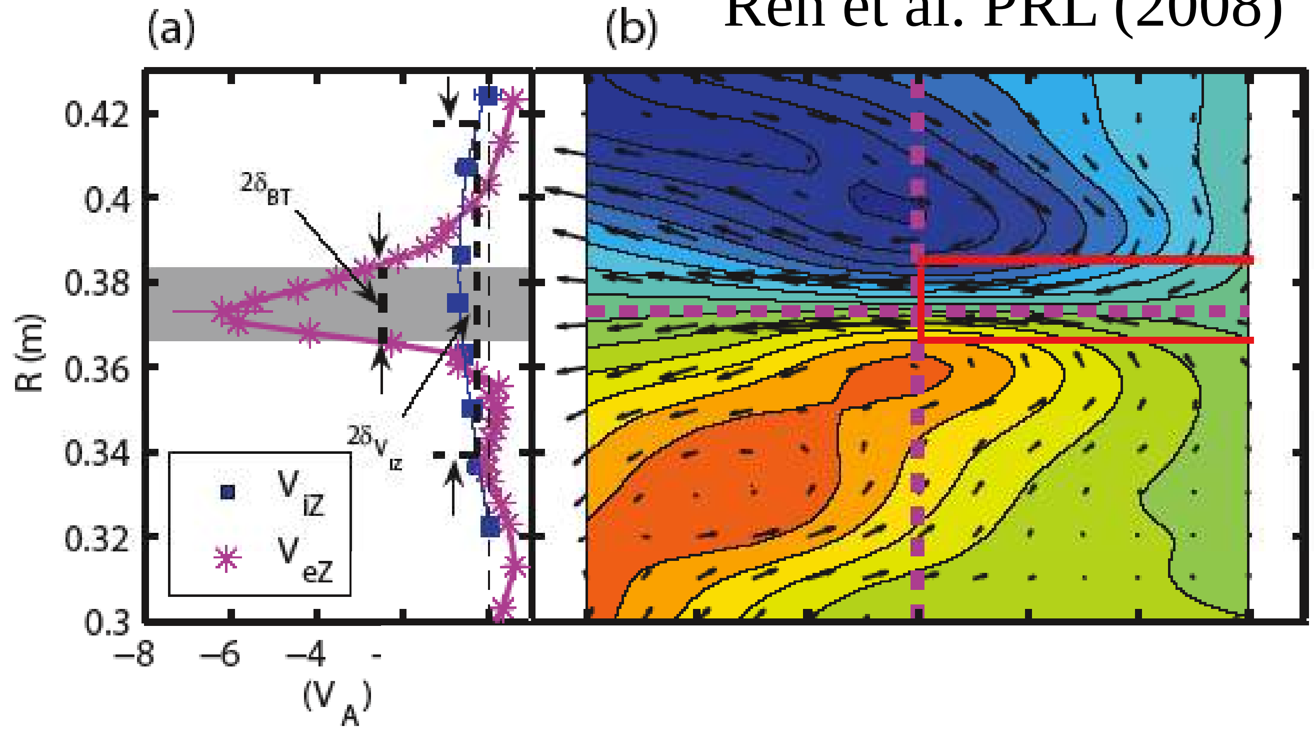
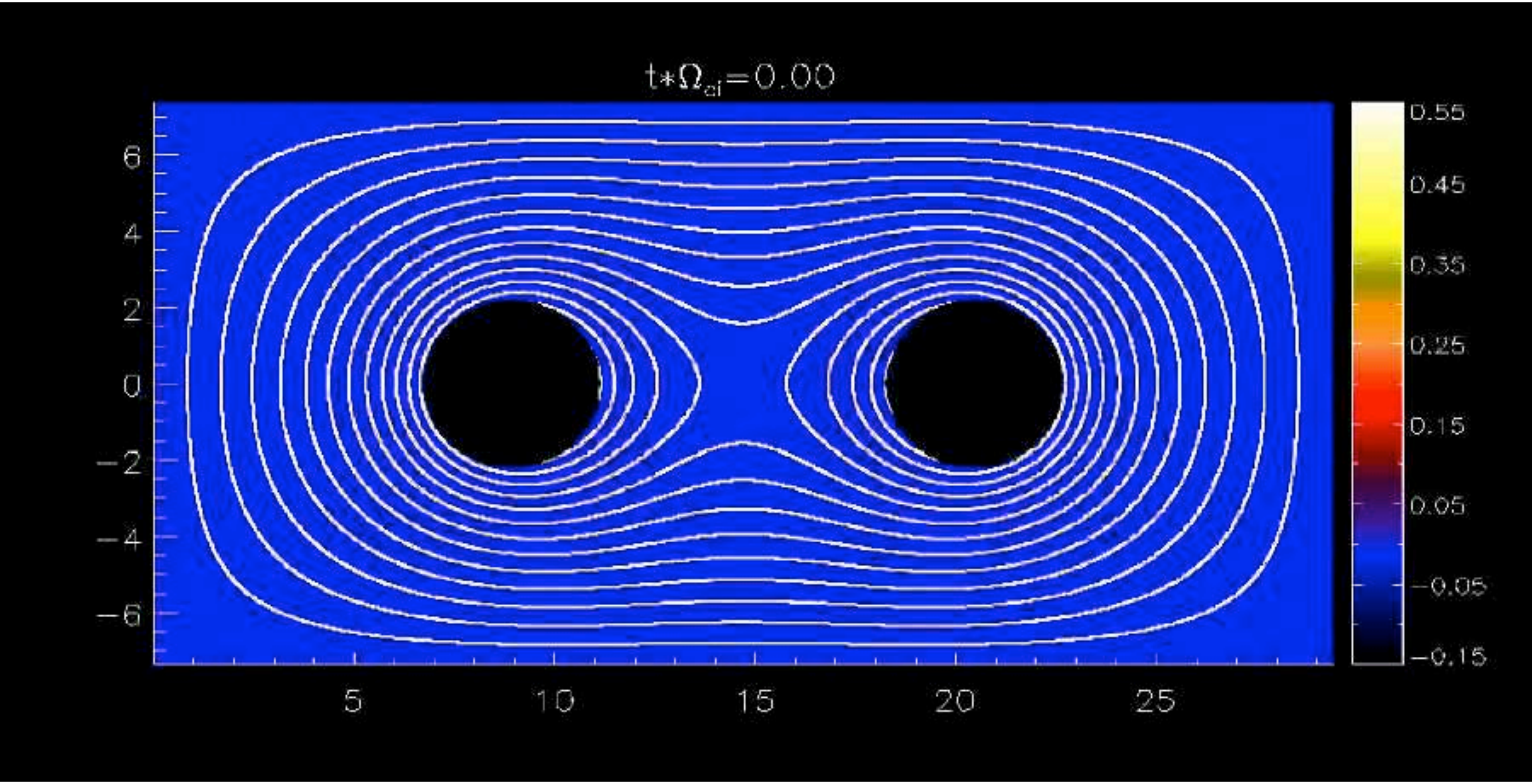


First detection of electron layer in lab!

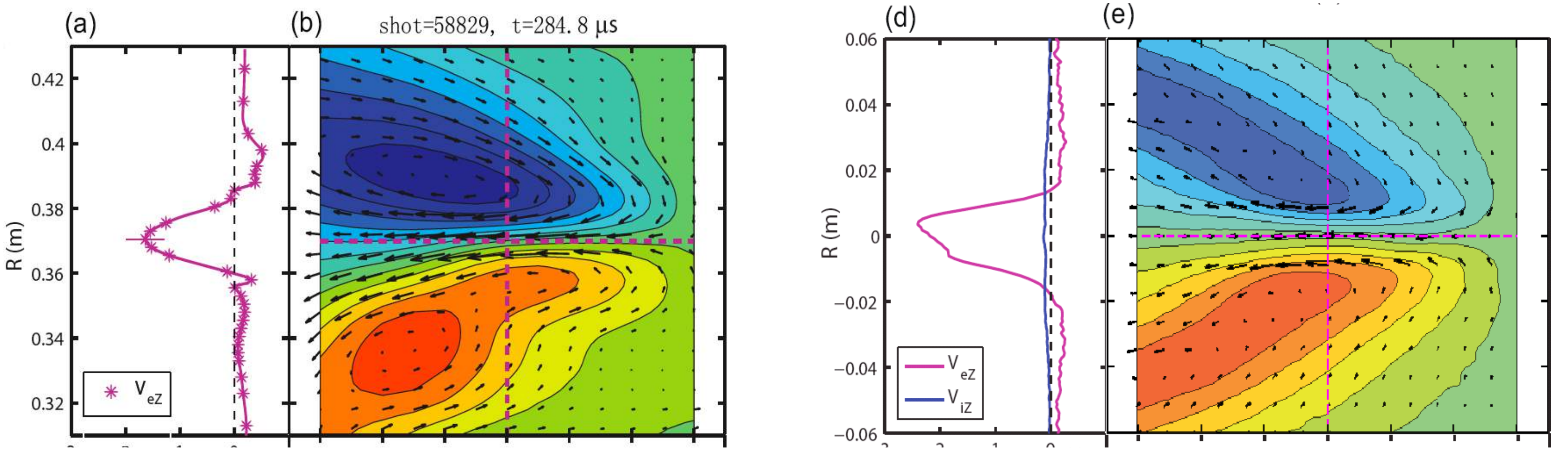
2D PIC Simulation in MRX Setup

Dorfman et al., PoP (2008)



All ion-scale features are reproduced by 2D PIC simulations…

Ji et al. GRL (2008); Dorfman et al. PoP (2008); Roytershteyn et al. PoP (2010)



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

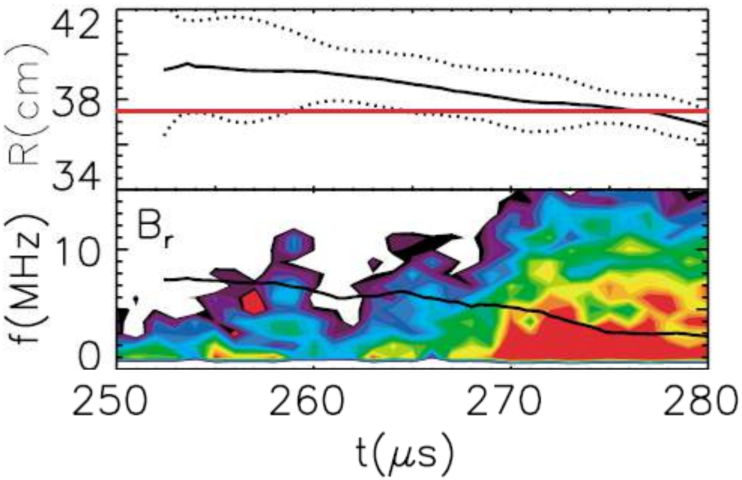
2D PIC Sim:
$\delta_e = 1.6\ c/\omega_{pe}$

… but not on electron scales!

How can 3-D dynamics affect the reconnection process?

Waves and Turbulence

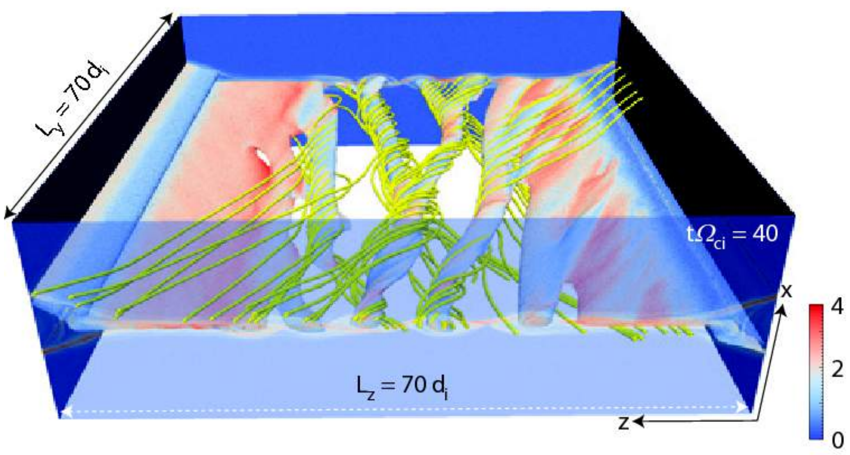
- 3-D variation allows for a large class of waves: Can these waves generate anomalous resistivity that speeds up reconnection?



(Ji et. al., PRL, 2004)

Flux Rope Structures

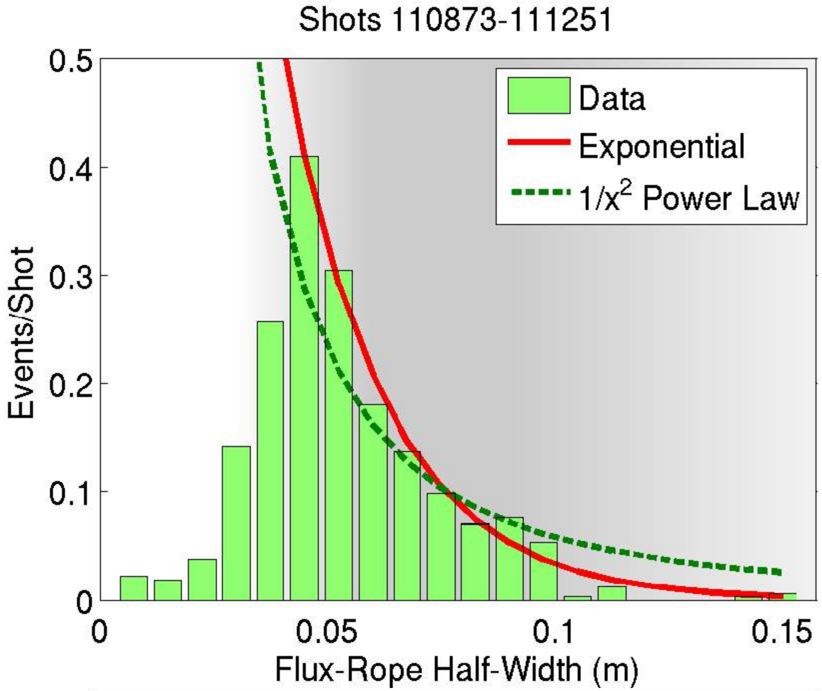
- Islands in 2.5-D are analogous to flux ropes in 3-D

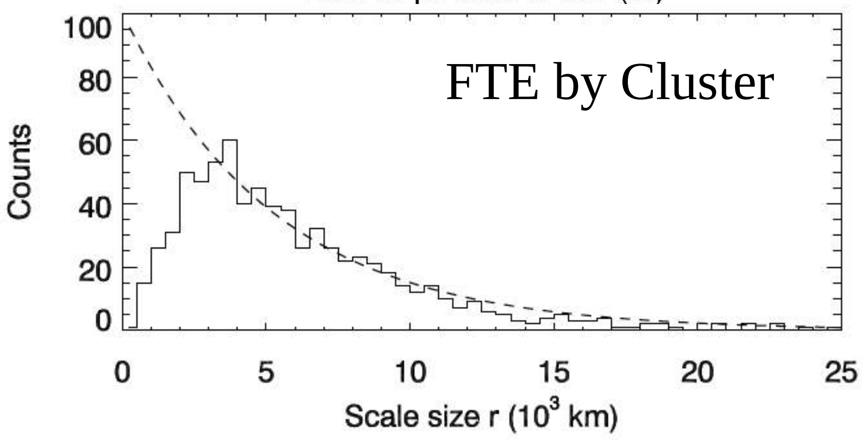


(Daughton et. al., Nature Physics, 2011)

Statistics of flux rope sizes

Dorfman et al. (2014)

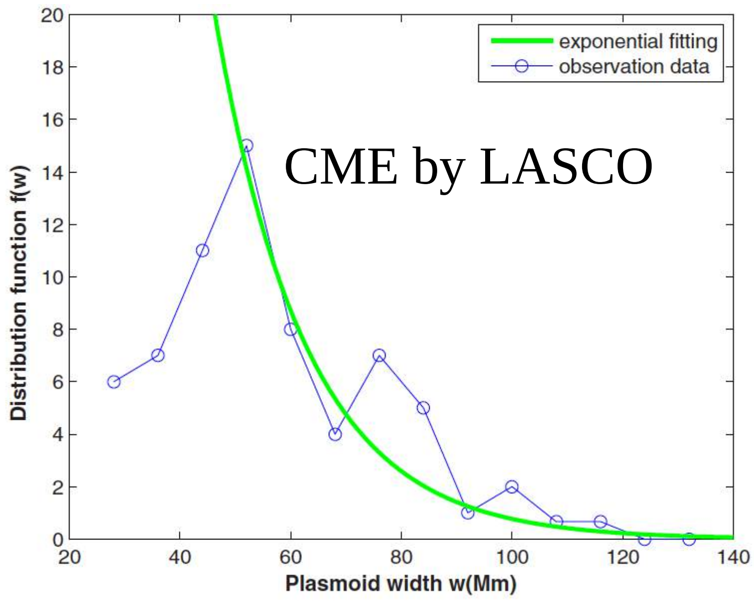




Fermo et al. (2011)

Theory/simulation:

- 1/x^2 in MHD [Uzdensky et al. (2010); Loureiro et al. (2012)]
- exp(-x) in Hall-MHD [Fermo et al. (2010); Fermo et al. (2011)]
- 1/x followed by an exp(-x) tail in MHD [Huang & Bhattacharjee (2012); Guo et al. (2013)]



Guo et al. (2013)

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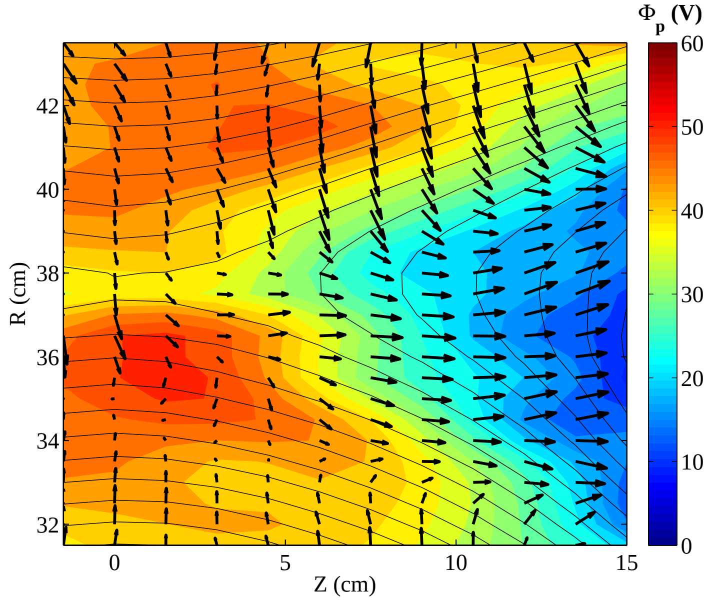
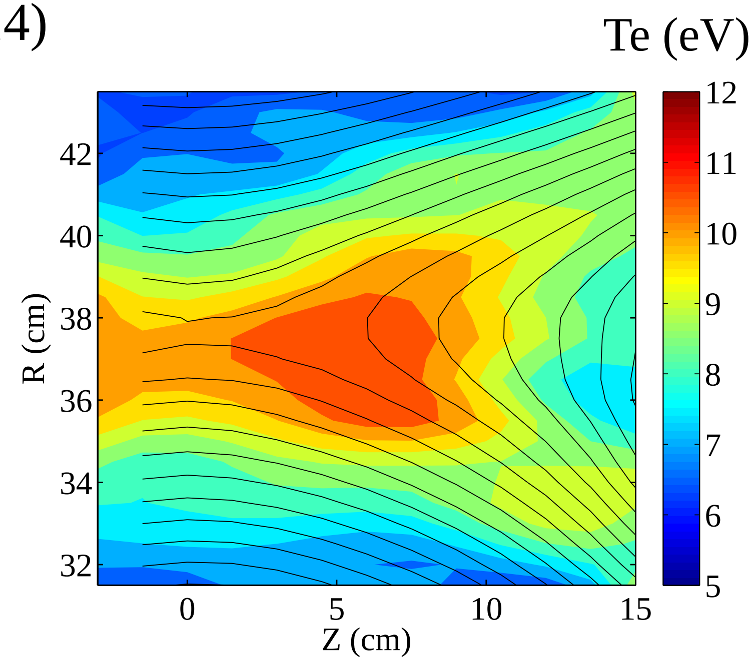
Energy converted from magnetic field to plasma: ion flow acceleration, ion and electron heating

Yoo et al. PRL (2013)
Yamada et al. Nature Communications (2014)

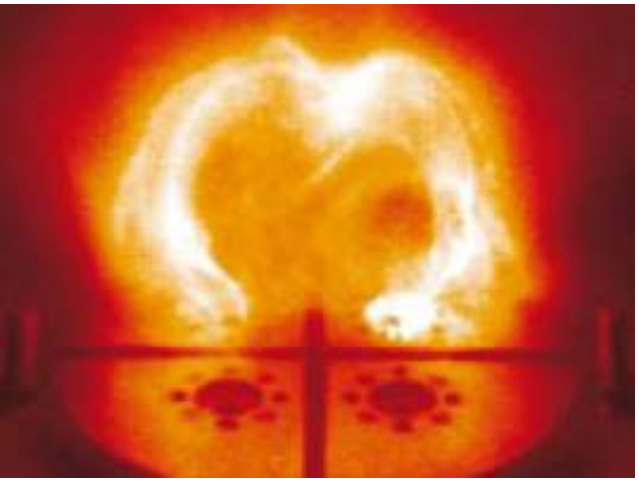




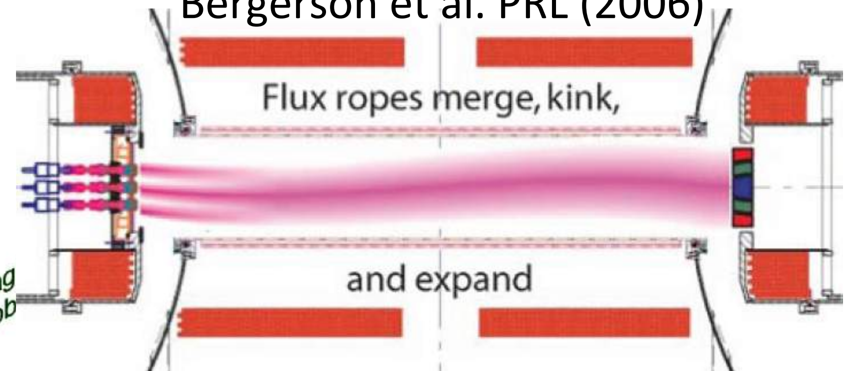
- 1/2 of magnetic energy goes to plasma
  - 2/3 to ion flow energy and heating
  - 1/3 to electron heating
- Consistent with Earth's magnetospheric data by Eastwood et al. (2013)

The Boundary Problem: Line-tied or Free-end for Flux Rope Dynamics

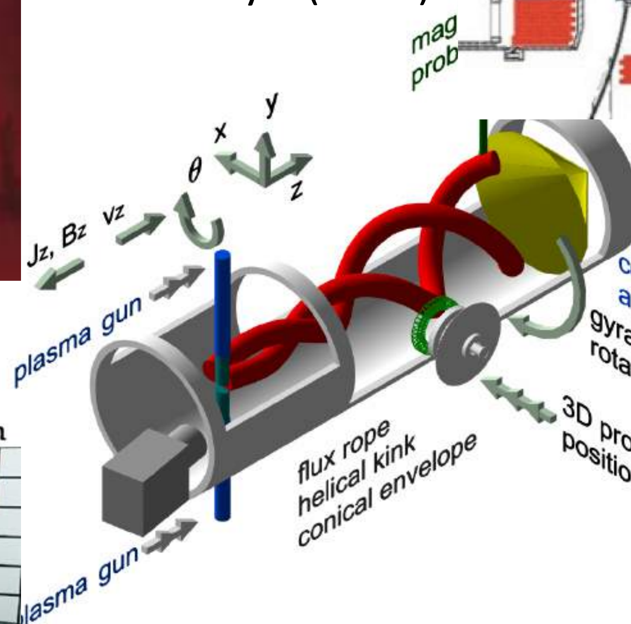
Hansen & Bellan ApJ (2004)



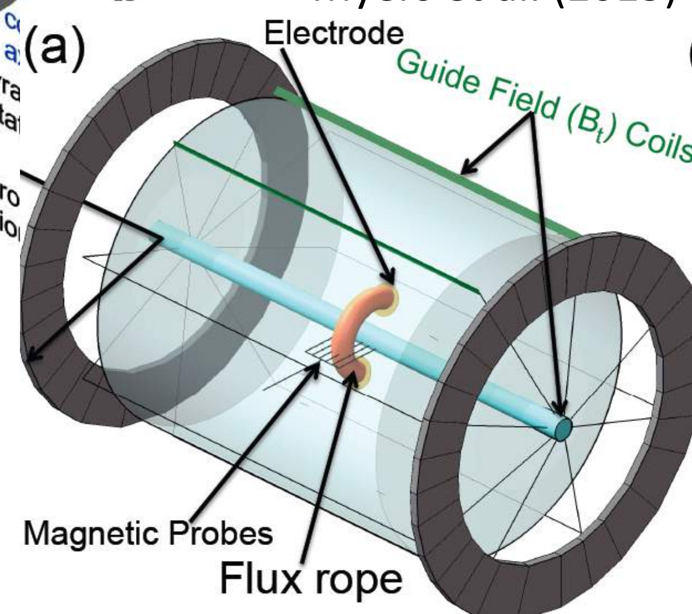
Bergerson et al. PRL (2006)

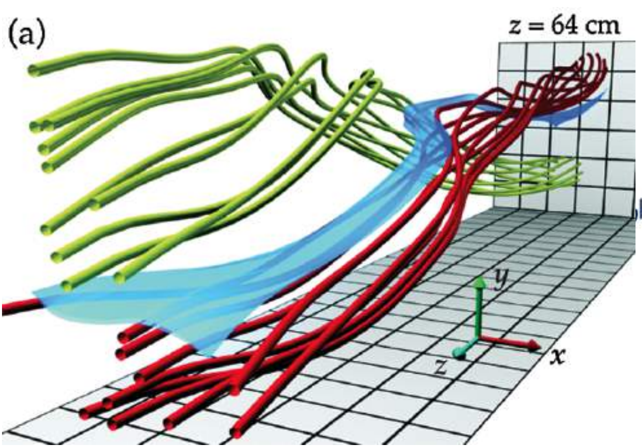


Intrator et al.
Nature Phys. (2009)



Oz et al. (2010)
Myers et al. (2015)





Lawrence & Gekelman
PRL (2009)

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Advanced Ongoing Beginning

The Multi-Scale Problem:

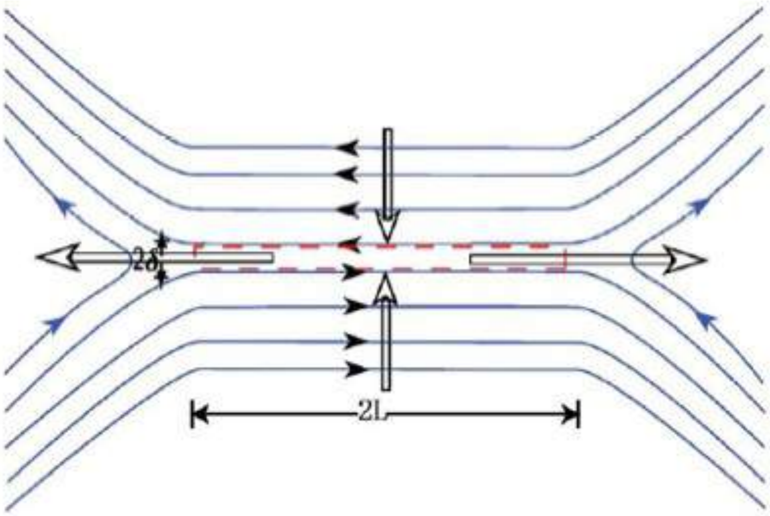
How to apply local reconnection physics to heliophysical and astrophysical plasmas with large sizes and high S?

➔ A reconnection phase diagram

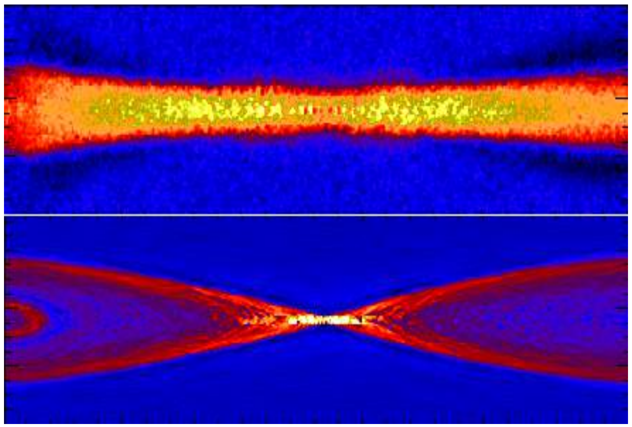
➔ A next generation reconnection experiment: FLARE

Two Broad Categories of Reconnection Models: Collisional MHD versus Collisionless Kinetic

e.g. Sweet-Parker Model



e.g. Kinetic Model



Valid for large plasmas but predicts slow reconnection

$$\frac{V_R}{V_A} = \frac{1}{\sqrt{S}} \qquad S = \frac{\mu_0 L V_A}{\eta}$$

Predicts fast reconnection but practical only for small plasmas

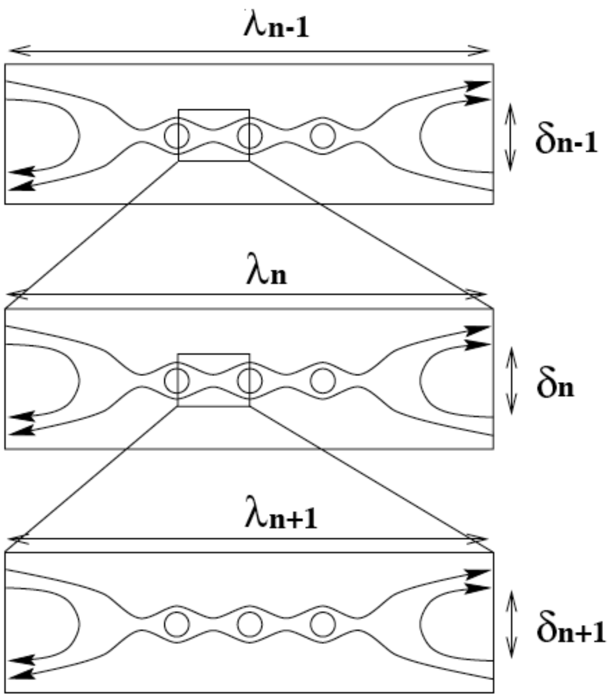
$$\frac{V_R}{V_A} \sim 0.1$$

How to combine these to explain fast reconnection in large plasmas?

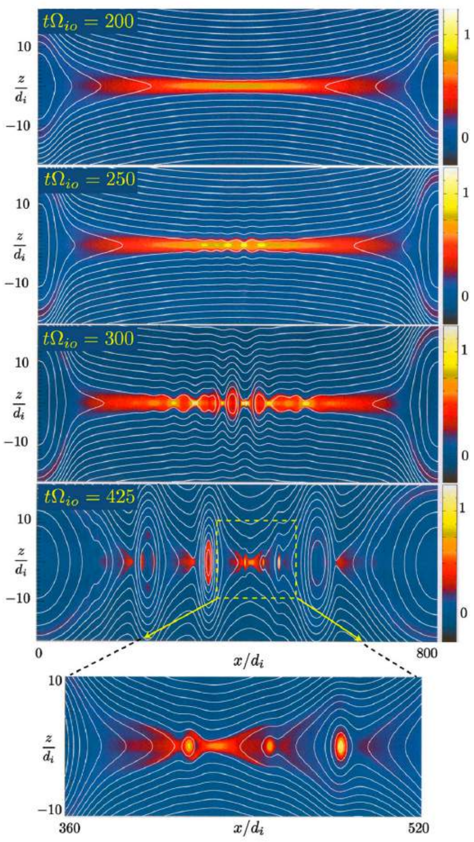
➔A multiple scale challenge!

Plasmoid Dynamics May Solve Scale Separation Problem

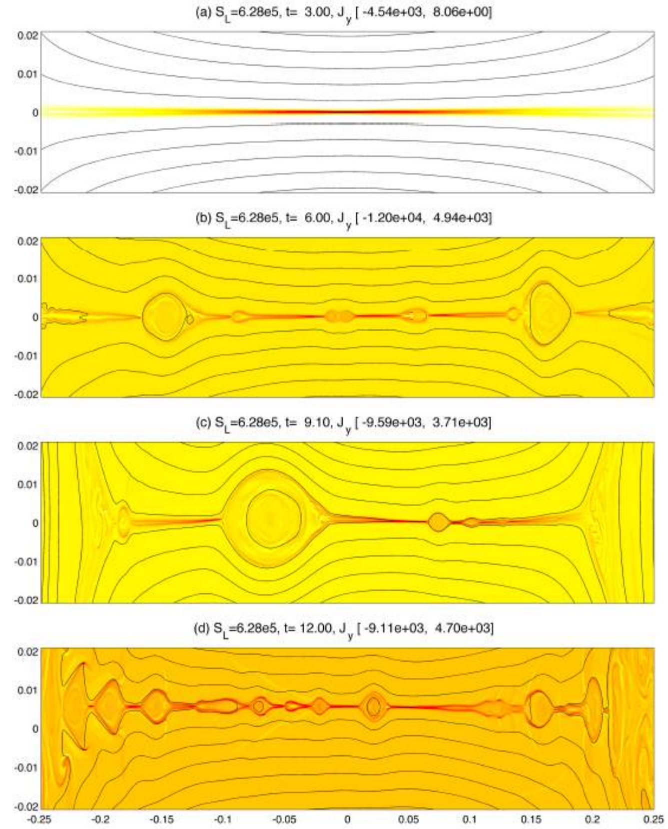
Shibata & Tanuma (2001)



Daughton et al. (2009)



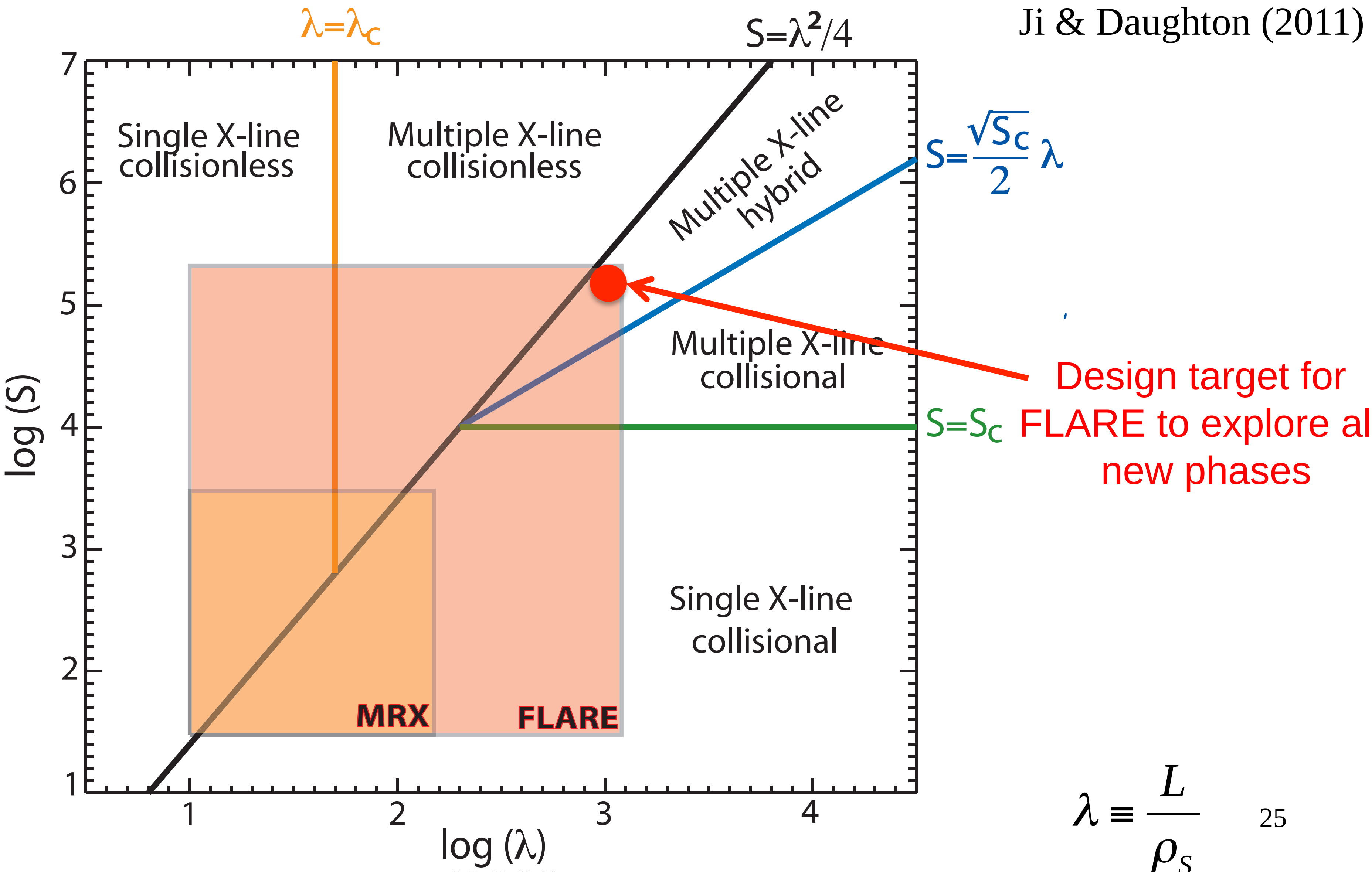
Bhattacharjee et al. (2009)



Many theoretical works: Loureiro et al. (2007); Cassak et al. (2009); Uzdensky et al. (2010) ….

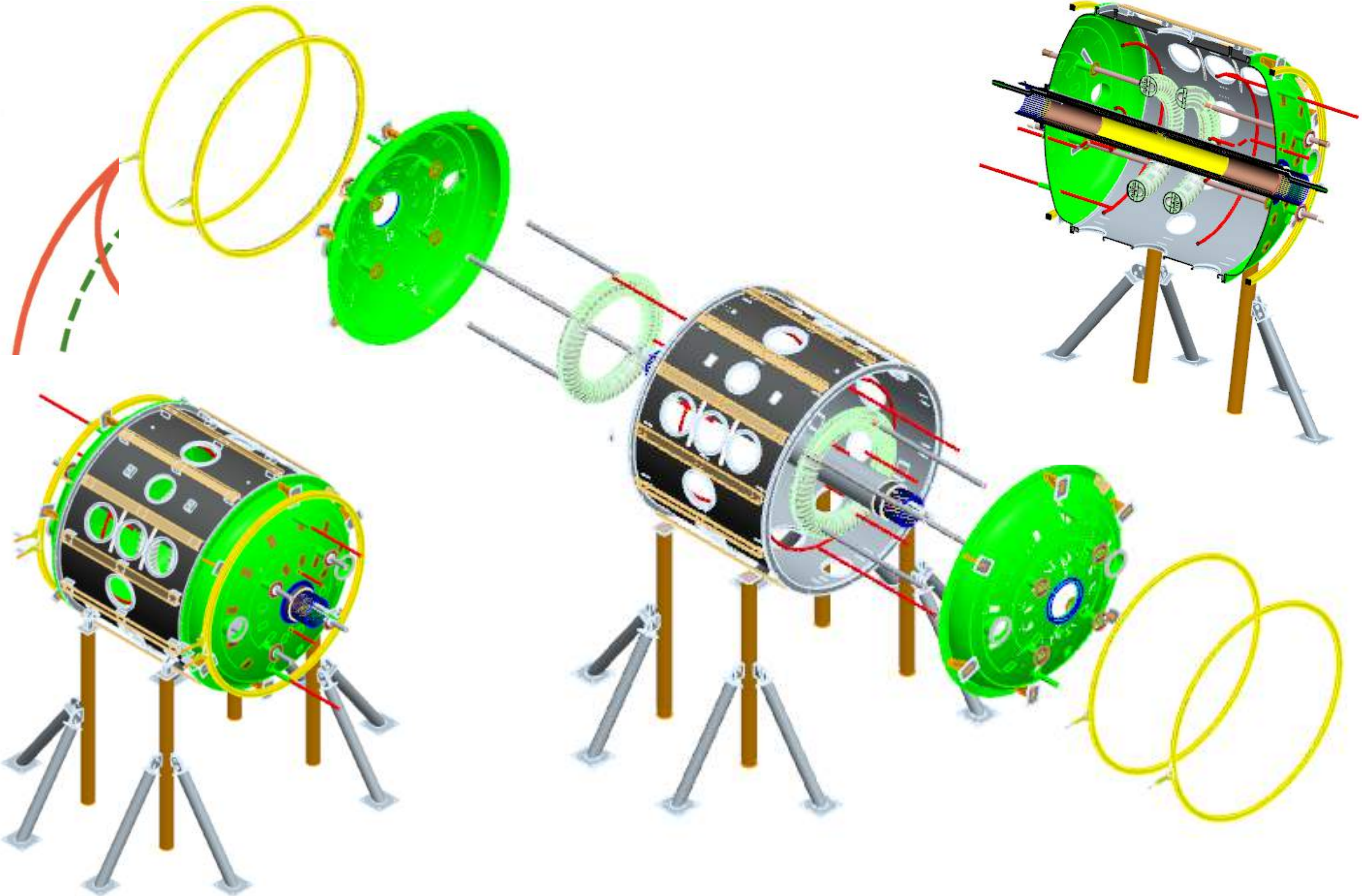
"Phases Diagram" for Different Coupling Mechanisms during Reconnection in Large Plasmas

Ji & Daughton (2011)



$$\lambda \equiv \frac{L}{\rho_S}$$

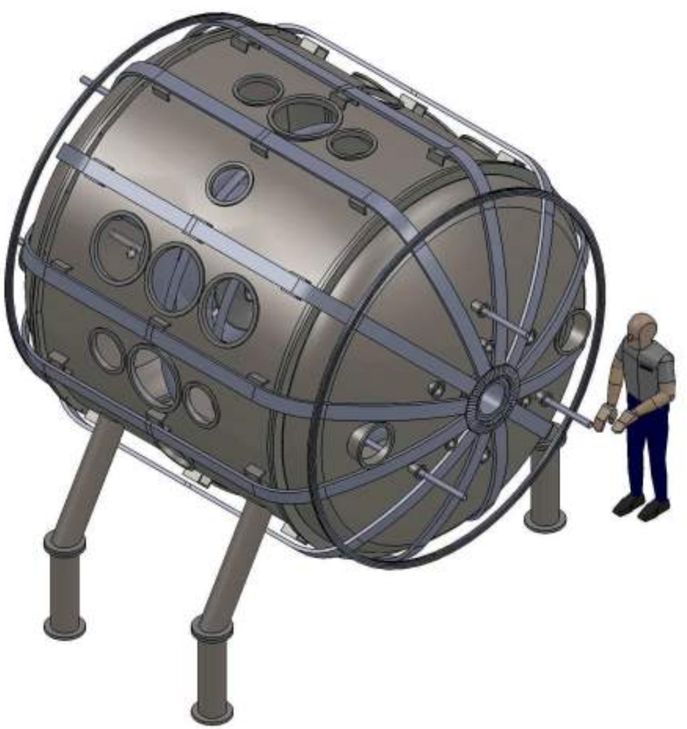
FLARE (Facility for Laboratory Reconnection Experiments) project (since 2013; flare.pppl.gov)



FLARE Parameters & Project Status

Parameters	MRX	FLARE
Device diameter	1.5 m	3 m
Device length	2 m	3.6 m
Flux core major diameters	0.75 m	1.5 m
Flux core minor diameter	0.2 m	0.3 m
Stored energy	25 kJ	4 MJ
Ohmic heating/ drive	No	0.3 V-s
Outer driving coil	Yes	Yes
Inner driving coil	No	Yes
S (anti-parallel)	600-1,400	5,000-16,000
$\lambda=(Z/\delta_i)$	35-10	100-30
S (guide field)	2900	100,000
$\lambda=(Z/\varrho_S)$	180	1,000

Phase 1 (Optimization): complete
Phase 1 (Design): complete
Phase 2 (Procurement): ongoing
Phase 2 (Manufacturing): ongoing
Phase 2 (Assembly): FY2016
Phase 2 (Installation): FY2016
Operation and Research: FY2017



FLARE will be a user facility, open to everyone from space, solar, astro and fusion. Sample Topics:

- Multiple-scale
  - Plasmoid instability in MHD
  - Scaling multiple MHD X-lines
  - Transition from MHD to kinetic
  - Scaling of kinetic X-lines
  - Guide field dependence of multiple-scale reconnection
- Reconnection rate
  - Reconnection rate for multiple MHD X-lines
  - Reconnection rate for multiple MHD and kinetic X-lines
  - Upstream asymmetry + guide field effects on reconnection
- Reconnection onset
  - Is reconnection onset local or global?
  - Is reconnection onset 2D or 3D?
- 3D effects
  - Plasmoid inst. in 3D: flux ropes?
  - Third dimension scaling: towards turbulent reconnection?
  - Externally drive tearing recon.
  - Interaction of multiple tearing modes: magnetic stochasity?
  - Line-tied effects in 3rd direction
- Particle heating and acceleration
  - Ion energization in large system
  - Electron energization in large system
  - Scaling of ion energization
  - Scaling of electron energization
- Partial ionization
  - Modification of multiple-scale reconnection by neutral particles
  - Neutral particle energization

Any Ideas and Collaborations are Welcome!

Summary: Frontiers for Laboratory Reconnection Research

- Resolve electron-scale physics (comparisons w/ MMS, THOR)
- Particle energization, especially for non-thermal tails & anisotropy (in competition with shocks and turbulence)
- Realistic 3D geometries (Earth's magnetosphere etc.)
- Onset (key to predict space weather & disruptions)
- Partial ionization (application to solar chromosphere, molecular clouds, & protostellar disks)
- Boundary condition (line-tied flux ropes)
- Flow-driven systems (part of turbulence, dynamo saturation)
- Extreme conditions (radiation, strong B)
- Multi-scale (application to helio/astrophysical reconnection)