LA-UR-11-12054

Approved for public release; distribution is unlimited.

Title: Flux ropes, current sheets, islands and turbulence

Author(s): Intrator, TP

Intended for: DOE
the APS Division of Plasma Physics, 2011-11-14/2011-11-18 (Salt Lake City, Utah, United States)
Environmental monitoring and surveillance
Reading Room
RCRA

Flux ropes, current sheets, islands and turbulence

T. P. Intrator[1],
J. A. Sears[1], T. E. Weber[1], D. Liu[1], D.R. Pulliam[1]
A. Lazarian[2]
[1] P-24 Plasma Physics Group, Los Alamos National Laboratory
[2] Dept Astronomy, Univ Wisconsin, Madison

53rd Annual Meeting of the APS Division of Plasma Physics
November 14-18, 2011
Salt Lake City, Utah
USA

Laboratory astrophysics at LANL

- Links between turbulence and reconnection
  - Sweet – Parker, unstable current sheets are plasmoid unstable
  - RSX access to unstable current sheets

Abstract

We describe earth bound laboratory experiment investigations of patchy, unsteady, bursty, magnetic field structures that are unifying features of magnetic reconnection and turbulence in helio, space and astro physics. Flux ropes are ubiquitous structures on the sun and the rest of the heliosphere. We use experimental probes inside the the flux ropes to macroscopic magnetic field lines, unsteady wandering characteristics, and dynamic objects with structure down to the dissipation scale length. We also show some theta pinch data that appear to be in the plasmoid formation regime for magnetic reconnection. Computational approaches are finally able to tackle simple 3D systems and we sketch some intriguing simulation results that are consistent with experimental data for magnetic reconnection and turbulence.

*Supported by NASA grant NNH10A0441, NSF-OFES Center for Magnetic Self Organization, LANS DE-AC52-06NA25396

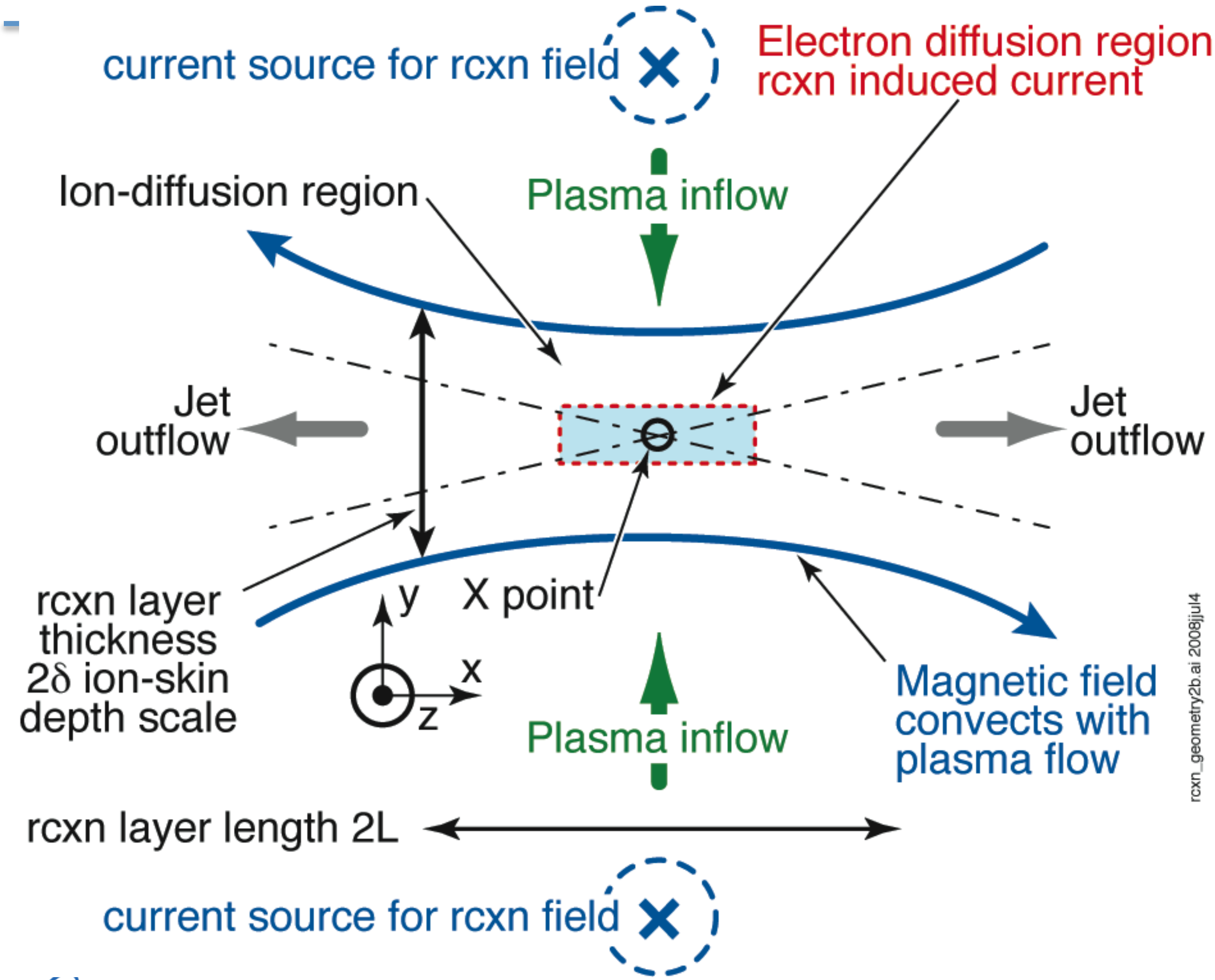
Outline

- Sweet – Parker, unstable current sheets
- Islands exist! Magnetosphere data
- Islands link reconnection to turbulence
- Simulations
- RSX data

Magnetic reconnection forms current sheets

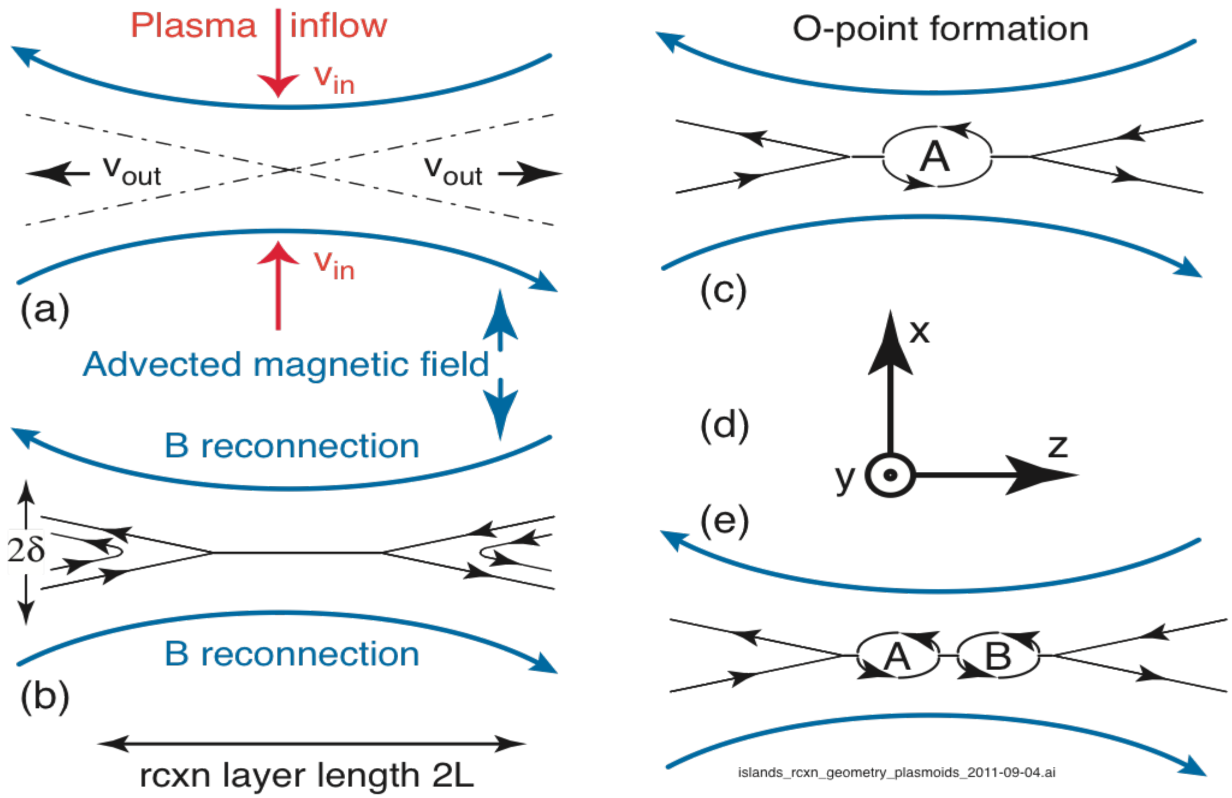
- Sweet-Parker assumes stable current sheets
  - predicts “slow” Sweet-Parker reconnection, rate ≈ $S^{-1/2}$
  - Observed reconnection rates (nature, lab) are too fast
- Fatal flaw: What if current sheets are unstable?
  - 3D micro structure different from external macro-structure
  - Small size ⇔ fast reconnection rate
  - reconnection ⇔ turbulence
- FRC data (from FRX-L and worldwide database) in regime of island-plasmoid-flux rope formation.
- Experimental platform for astrophysics at $S > 10^6$

Sweet-Parker reconnection geometry



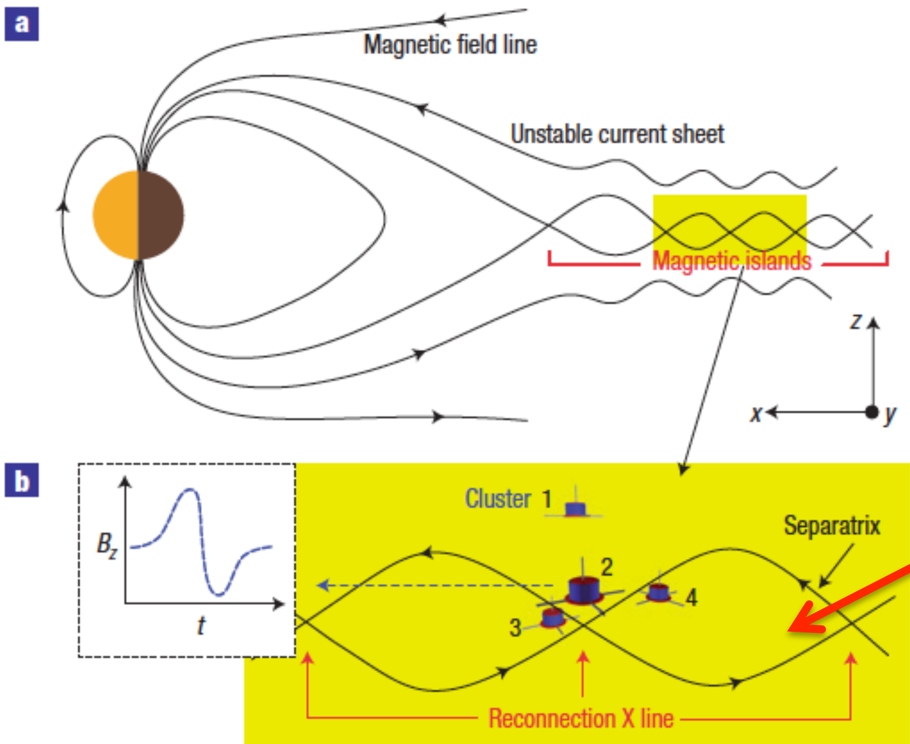
- X-point locates induced reconnection current
- X-line extends in out of plane direction

Sweet-Parker current sheets => islands



Theory: Number of islands, plasmoids, flux ropes ... scale as $N_p \approx S^a$, 0<a<1, S = Lundquist number

Magnetic islands exist in magnetosphere



Chen et. al., CLUSTER data in magnetotail, Nature 2007

Magnetotail spacecraft observe magnetic field reversal characteristic of islands/flux ropes.

Collisionless reconnection in nature is much faster than Sweet-Parker

Flux ropes are present in a wide variety of cosmic phenomena.

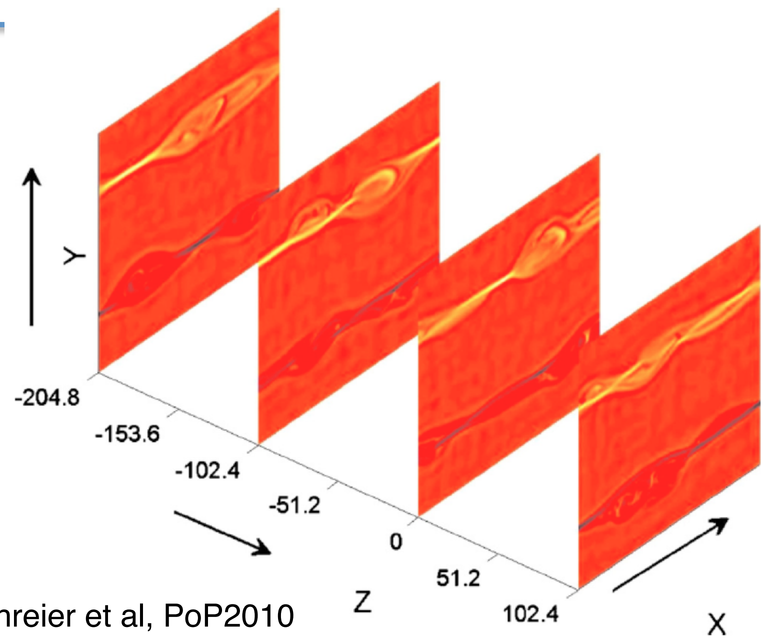
Flux rope

Filamentation and island formation observed:

- Magnetosphere
- Solar atmosphere
- Heliosphere
- Galactic structure
- Cosmological structure

Los Alamos NATIONAL LABORATORY EST. 1943

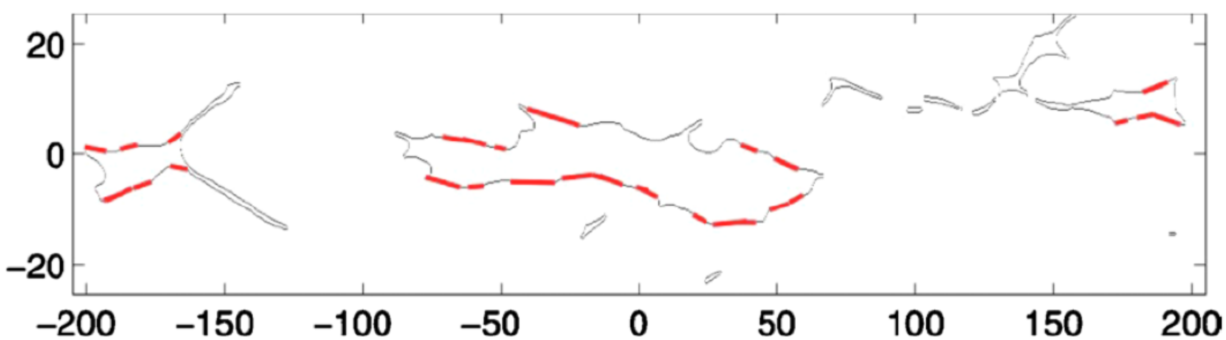
Spacecraft data can be ambiguous



Schreier et al, PoP2010

New models of reconnection, coupled with increasing experimental and numerical data can determine the "signatures" of reconnection and flux rope dynamics, enabling smart trigger algorithms.

(top left) Slices in the x-y plane reveal island formation and reconnection.



(bottom left) Slice of x-z plane reveals discontinuous x-lines. A small sampling of this field would be confusing to algorithms interpreting spacecraft data.

Los Alamos NATIONAL LABORATORY EST. 1943

Reconnection current sheet simulations

- Schreier et al, PoP2010 (but look at RSX data slides 38,39!?)

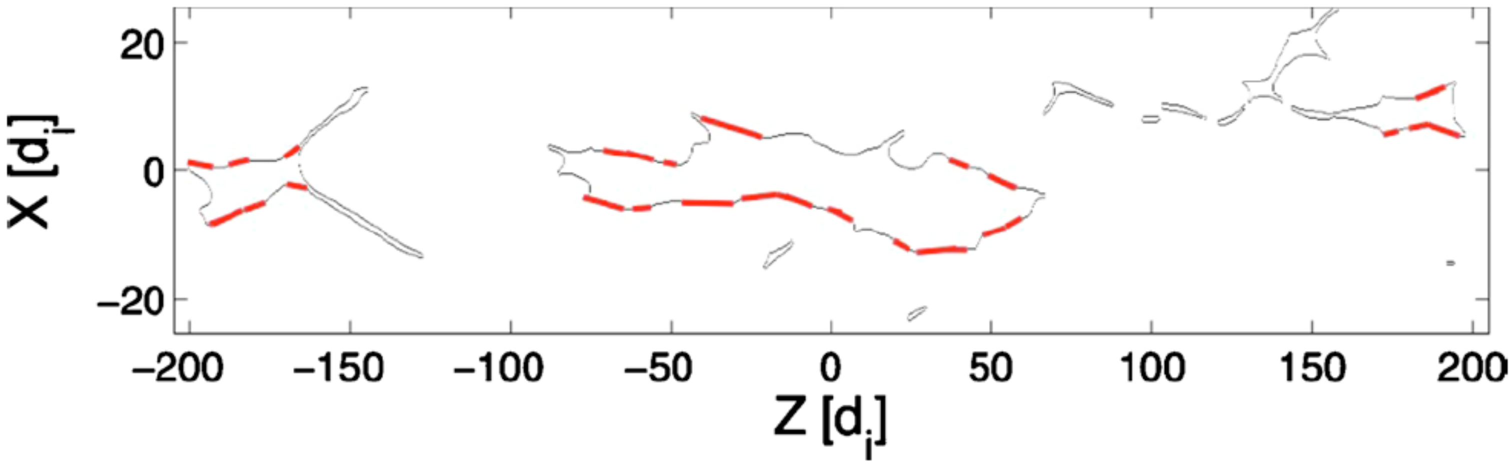


FIG. 5. (Color online) Edges of the projection of the strong current density at $t=201$ on the x-z plane and detected by the Canny method are shown in black. The thicker (red) lines are the result of the Hough transform.

- Projection onto x-z plane shows 3D structure!
- Discontinuous X-lines in the out of plane direction

Reconnection current sheet simulations

- Schreier et al, PoP2010 (but look at RSX data slides 6,10!?)

What would a spacecraft trajectory through this see?

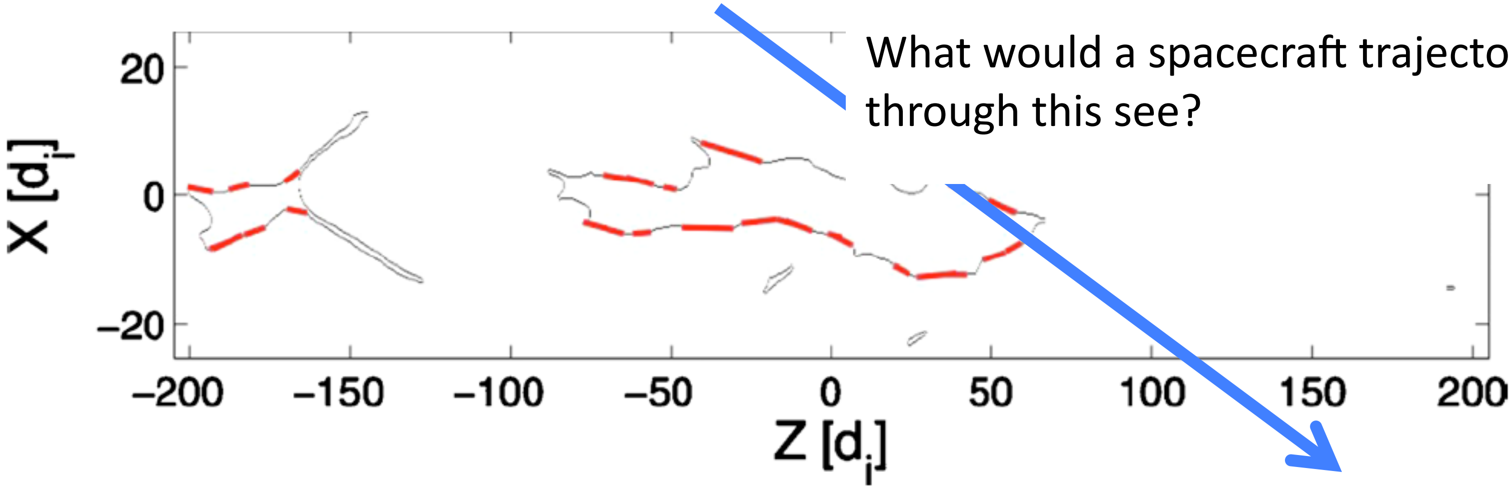
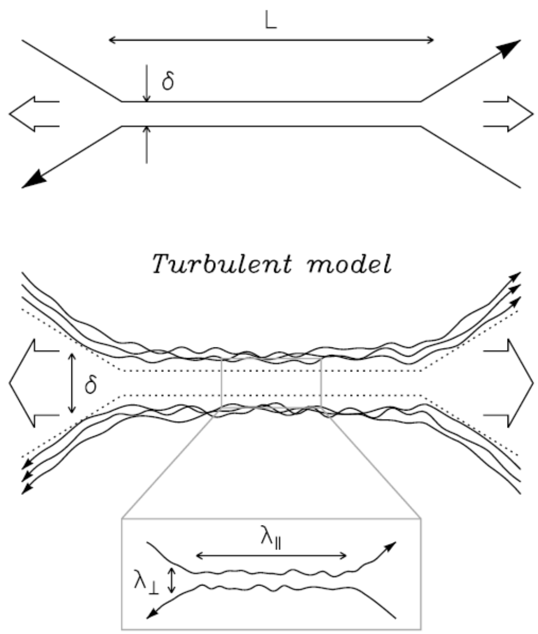


FIG. 5. (Color online) Edges of the projection of the strong current density at $t=201$ on the x-z plane and detected by the Canny method are shown in black. The thicker (red) lines are the result of the Hough transform.

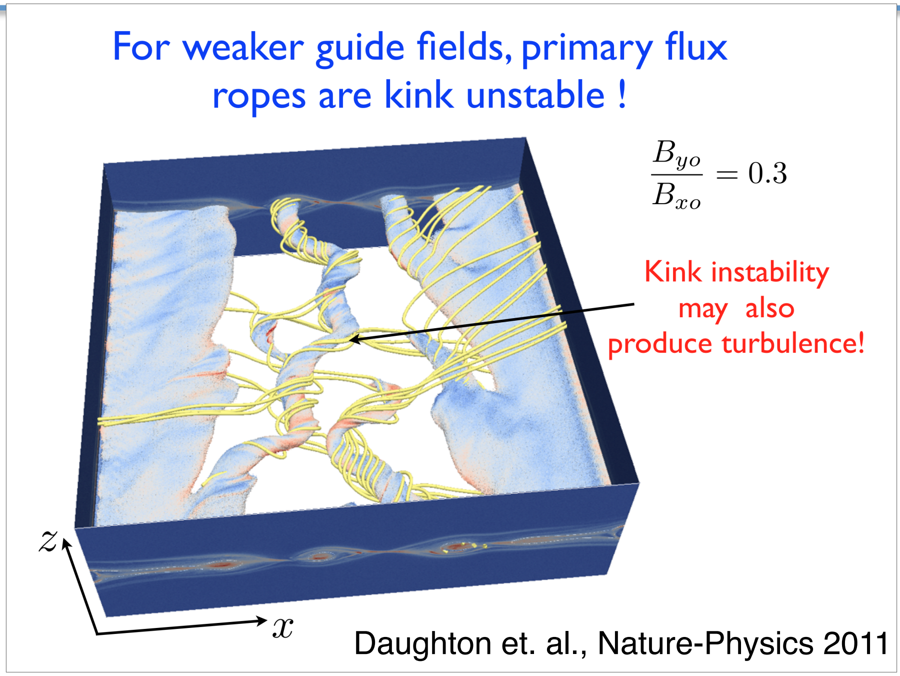
- Projection onto x-z plane shows 3D structure!
- Discontinuous X-lines in the out of plane direction

Magnetic island formation = flux ropes.



Lazarian, Vishniac ApJ 1999, Kowal 1999

Field line perturbations cause reconnection to take place in localized regions, and are unstable to break-up, cascade to smaller length-scales and turbulence ensues.

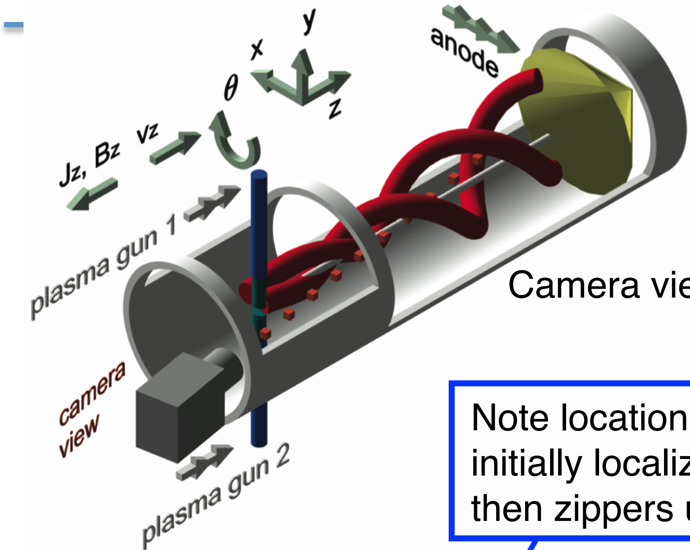


Same RSX dynamics seen in large scale PIC simulations.

Current sheet breaks up into flux ropes which then interact.

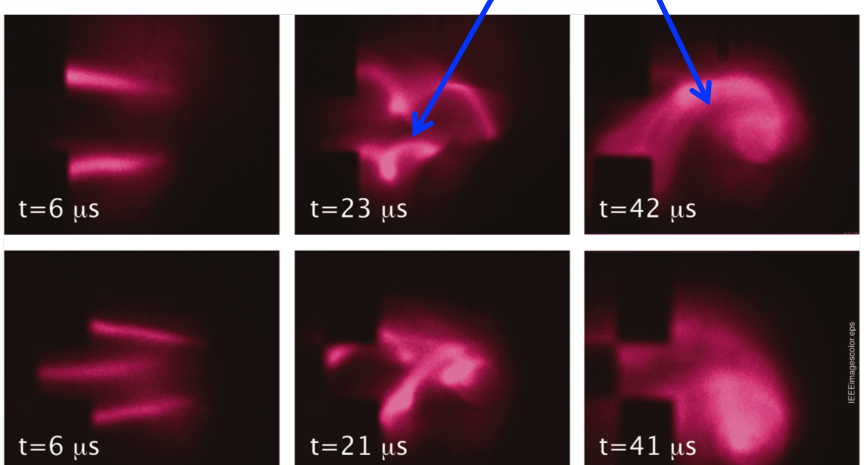
Produces discontinuous x-lines, 3d structure, multi-scale cascade.

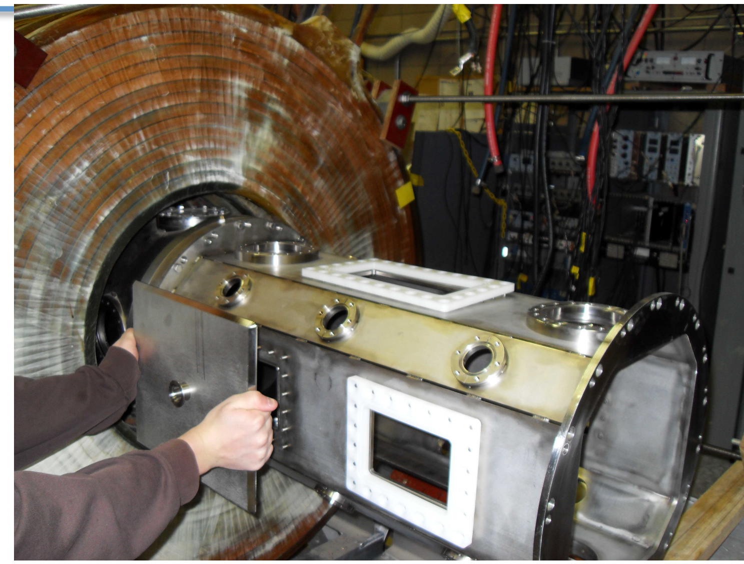
RSX experiment: flux ropes interact in 3d.



Camera views end-on.

Note location of "x-line": initially localized axially, then zippers upstream.





3d positioning ports allow unique diagnostic access.

Kinked flux ropes interact at discrete patch.

Knob physics from 2d to 3d by reducing guide field.

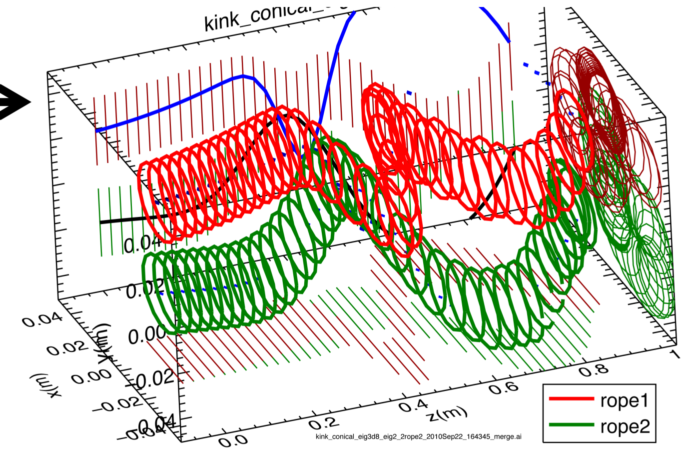
MHD building blocks: Flux Ropes

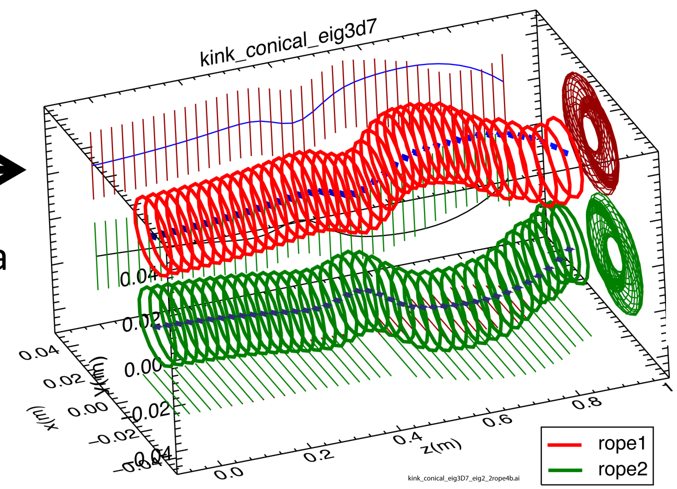
RSX plasma guns + 3D magnetics + model reconstruction

Kinked flux ropes gyrate, parallel currents attract → reconnection [Intrator et al, Nature Physics (2009)]

→ Or bounce! [Sun, et al, "Flux Rope Dynamics: Experimental Study of Bouncing and Merging," Physical Review Letters **105**, 255001 (2010).] + PRL highlights

Dynamics, statistics: turbulence & rcxn?

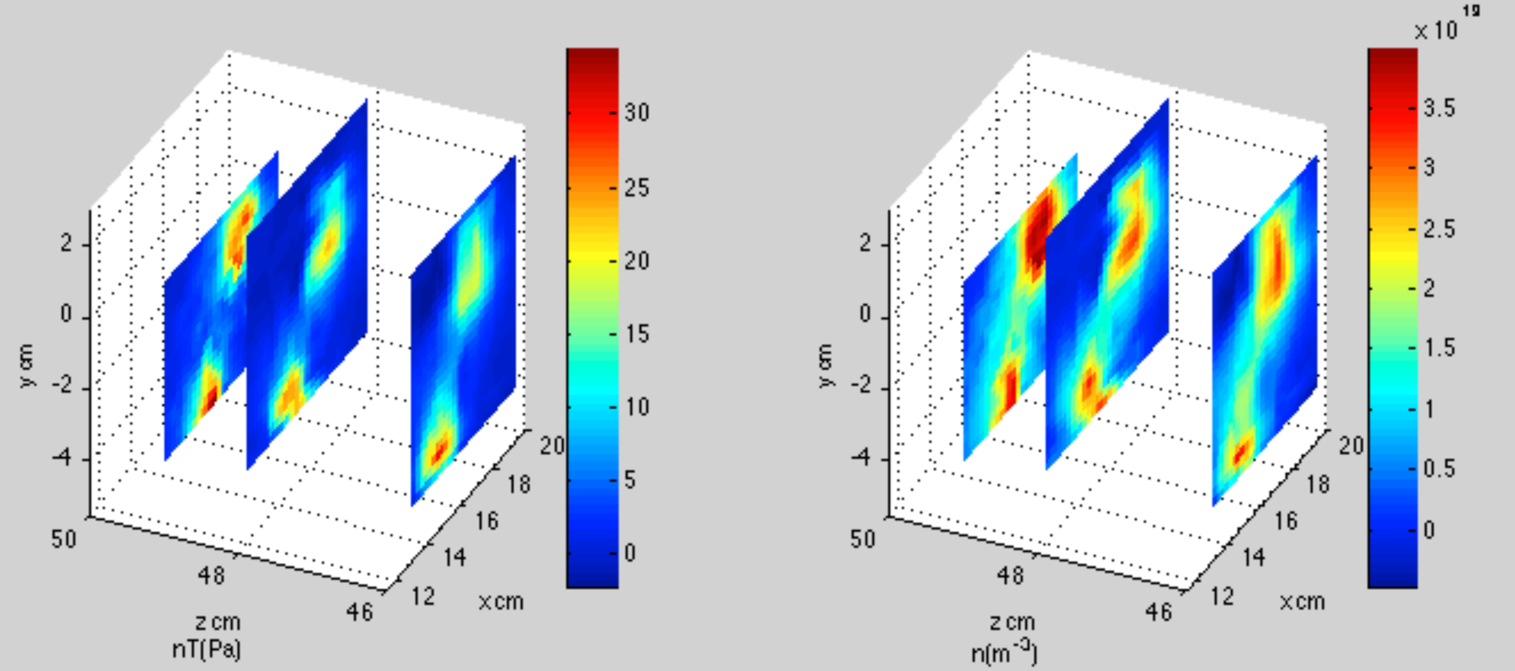




Plasma guns

External anode

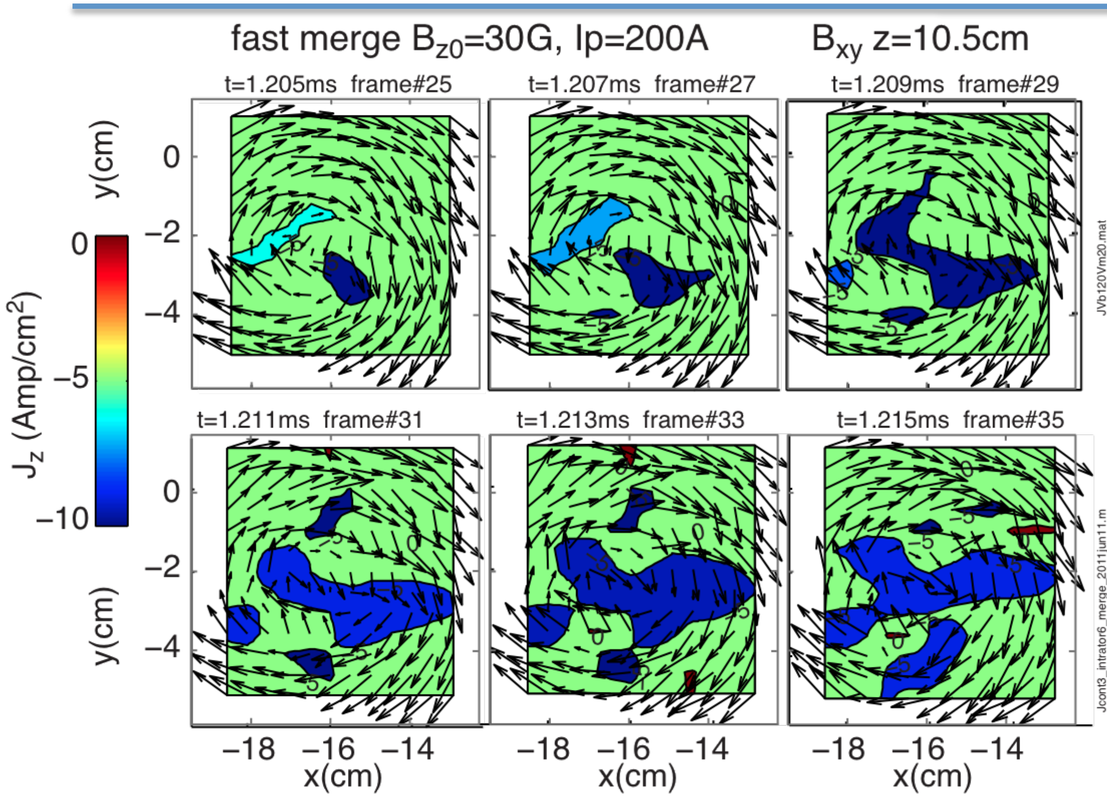
RSX 3D data n, p=nT



t=1.216ms, all in SI units
Pressure and Density plots
PN_xy3z_3D_Intrator3.m

- Data taken with 3D probe positioner
- can resolve electron skin depth

New flux rope dynamics identified.



(Above) Transverse slices of data showing two flux ropes initially merging, then shredding into several flux ropes. (Right) Potential as a function of seperation of two flux ropes accounting for magnetic attraction (red) and angular momentum (black).

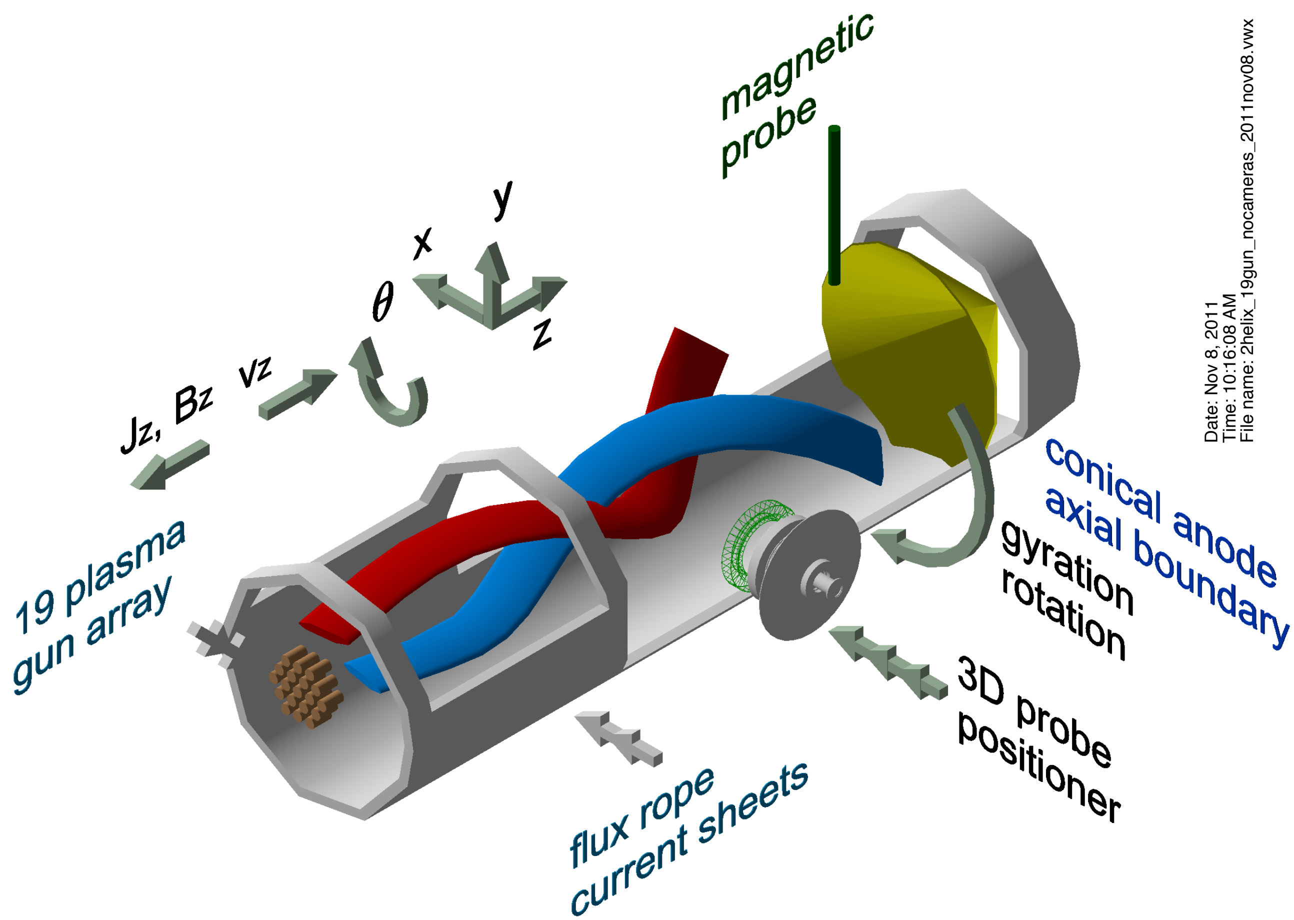
Flux rope dynamics studied, several effects contribute to dynamics:

- Magnetic attraction
- Kinking
- Pressure pileup
- Angular momentum & orbits

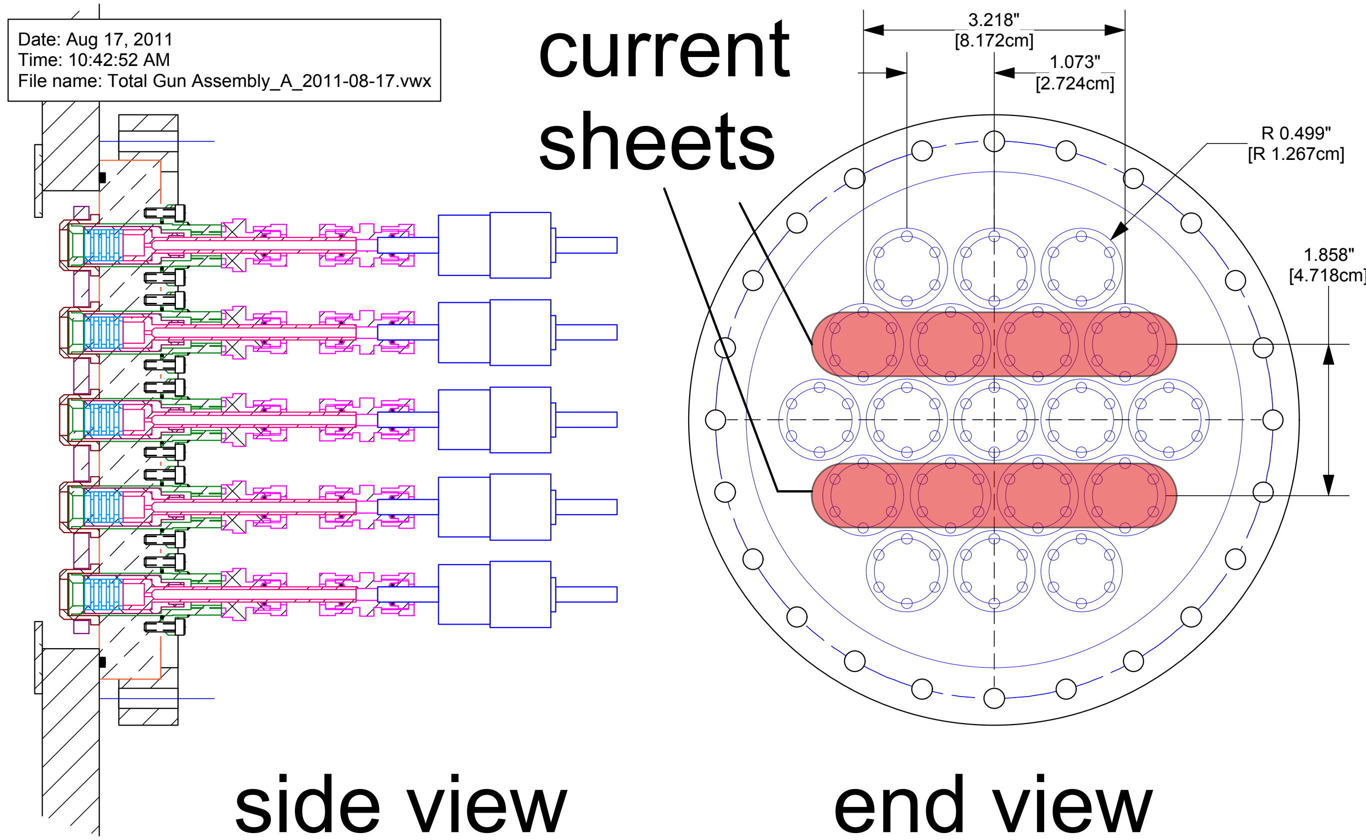
Effect: Flux ropes sometimes merge, bounce, or shred.

Dynamics vary over space – 3d process.

Current sheet plasmoid instabilities: RSX



Current sheet plasmoid instabilities: RSX



Current sheet plasmoid instabilities: RSX

Table 1: Survey of plasma characteristics accessible in RSX experiment, $d_i = c/\omega_{pi}$, $T_i \approx 1eV$ [Dorf *et al.* , 2010], flux ropes ohmically heat. B_{z0}, $B_\perp$ refer to guide and reconnecting field, H^+ plasma, T_e can be heated with RF antenna to $60 - 80eV$.

type	ref	etc	n	B_{z0}	$B_\perp$	T_e	L_{SP}	ρ_i	L_{SP}/ρ_i	L_{SP}/d_i	$S_\perp$
			cm^{-3}	G	G	eV	cm	cm		$d_i = c/\omega_{pi}$	
2 rope	[Intrator *et al.* , 2009]	Fig. 14	1×10^{13}	100	12	15	3.5	1.0	3.5	0.5	17
2 rope	[Sun *et al.* , 2010]	Fig. 9	1×10^{13}	50	12	12	1.8	1.9	1.8	0.5	13
2 rope	year 1	first data	2×10^{13}	400	50	20	3.5	0.25	14	0.7	70
2 sheet	year 2		4×10^{13}	400	60	20	6.0	0.25	22	1.6	105
2 sheet	year 2	RF heat	4×10^{13}	400	100	50	6.0	0.25	25	1.7	670
2 sheet	year 3	RF heat	2×10^{14}	1000	250	50	6.0	0.25	61	3.7	800

Summary

- Sweet-Parker reconnection picture can be modified to include unstable current sheets
- We measure in the laboratory flux ropes that “shred” down to electron skin depth dissipation scales
- Propose experiment to study unstable current sheets in RSX