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Flux ropes, current sheets, islands and turbulence

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abstract

- We describe earth bound laboratory experiment investigations of patchy, unsteady, bursty, patchy magnetic field structures that are unifying features of magnetic reconnection and turbulence in helio, space and astro physics. Macroscopic field lines occupy cross sectional areas, fill up three dimensional (3D) volumes as flux tubes. They contain mass with Newtonian dynamics that follow magneto-hydro-dynamic (MHD) equations of motion. Flux rope geometry can be ubiquitous in laminar reconnection sheet geometries that are themselves unstable to formation of secondary “islands” that in 3D are really flux ropes. Flux ropes are ubiquitous structures on the sun and the rest of the heliosphere. Understanding the dynamics of flux ropes and their mutual interactions offers the key to many important astrophysical phenomena, including magnetic reconnection and turbulence. We describe laboratory investigations on RSX, where 3D interaction of flux ropes can be studied in great detail. We use experimental probes inside the the flux ropes to measure the magnetic and electric fields, current density, density, temperatures, pressure, and electrostatic and vector plasma potentials. Macroscopic magnetic field lines, unsteady wandering characteristics, and dynamic objects with structure down to the dissipation scale length can be traced from data sets in a 3D volume. Computational approaches are finally able to tackle simple 3D systems and we sketch some intriguing simulation results that are consistent with 3D extensions of typical 2D cartoons for magnetic reconnection and turbulence.

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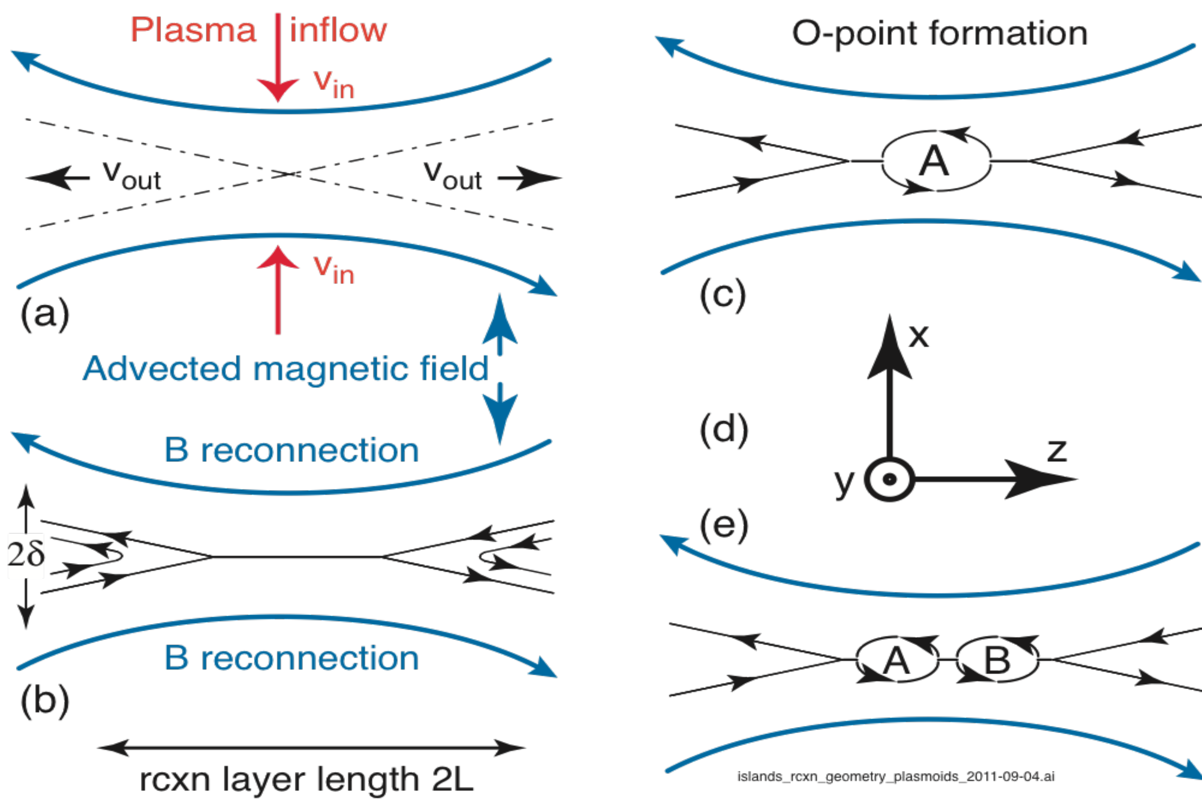
Laboratory astrophysics at LANL

- Links between turbulence and reconnection
  - Sweet – Parker, unstable current sheets are plasmoid unstable
  - Plasmoids - islands link reconnection to turbulence
  - Islands in 3D are flux ropes
  - Simulations, RSX data
- RSX access to unstable current sheets

Magnetic reconnection forms current sheets

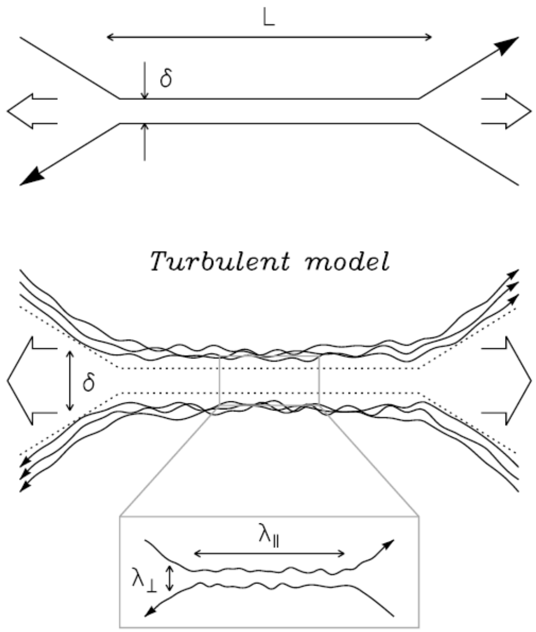
- Sweet-Parker assumes stable current sheets
  - predicts "slow" Sweet-Parker reconnection, rate ≈ $S^{-1/2}$
  - Observed reconnection rates (nature, lab) are too fast
- Fatal flaw: What if current sheets are unstable?
  - 3D micro structure different from external macro-structure
  - Small size ⇔ fast reconnection rate
  - reconnection ⇔ turbulence

Sweet-Parker current sheets => islands

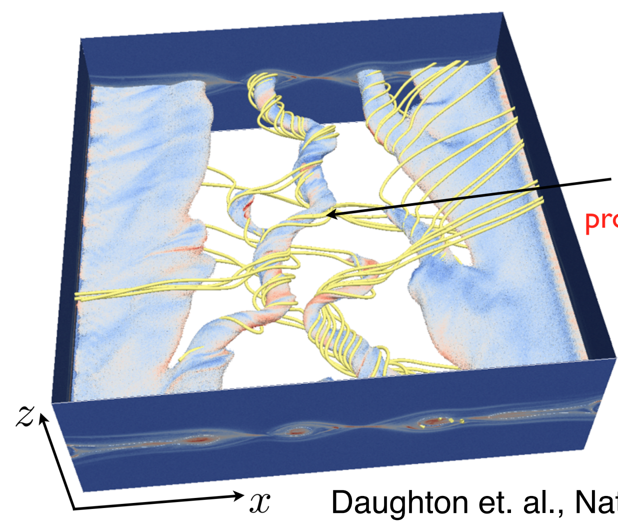


Theory: Number of islands, plasmoids, flux ropes ... scale as
$N_p \approx S^a$, $0<a<1$, S = Lundquist number

Magnetic island formation = flux ropes.



Lazarian, Vishniac ApJ 1999, Kowal 1999

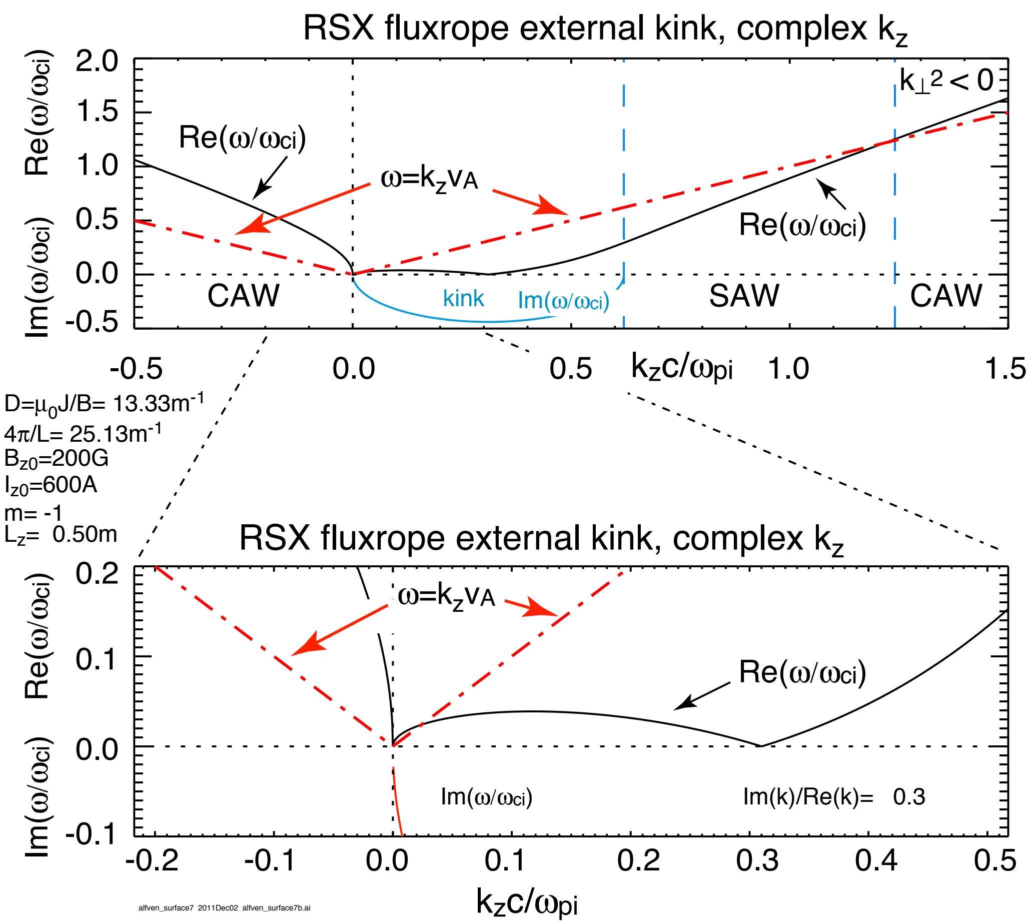


Daughton et. al., Nature-Physics 2011

Dynamics seen in large scale VPIC simulations resemble RSX data.

Current sheet break up ⬄ flux ropes ⬄ 3D interactions ⬄ discontinuous X-lines ⬄ reconnection ⬄ turbulence

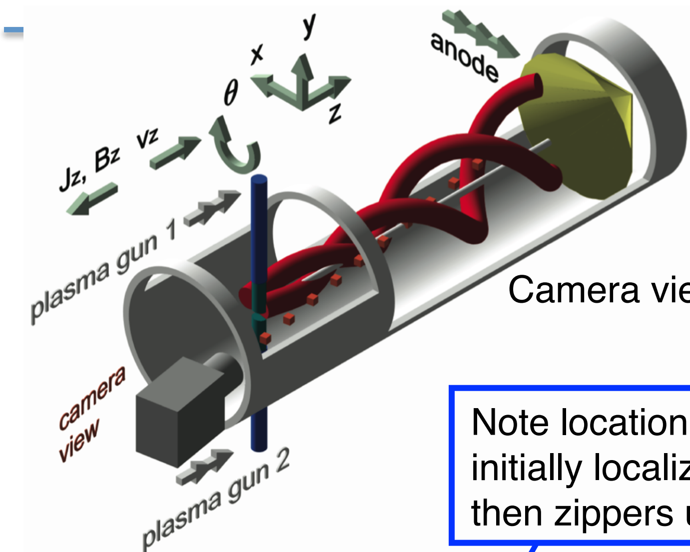
Finite J•B → background helicity → different parallel vs anti parallel waves



How does this affect turbulence models?

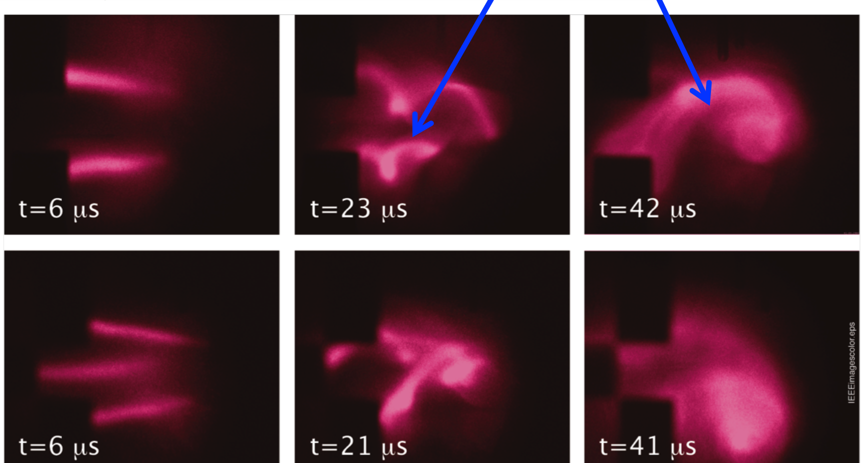
- Alfven waves are exact solutions to incompressible MHD equations
- Elsasser variables: $Z_{\pm} = v \pm b/(\rho\mu_0)^{1/2}$
- What if $Z_{\pm}$ are no longer symmetric??
- Goldreich-Sridhar model supposes that oppositely propagating wave packets pass through each other without velocity of magnetic disturbances, but rather “shear” each other at long wavelength (small k_z)

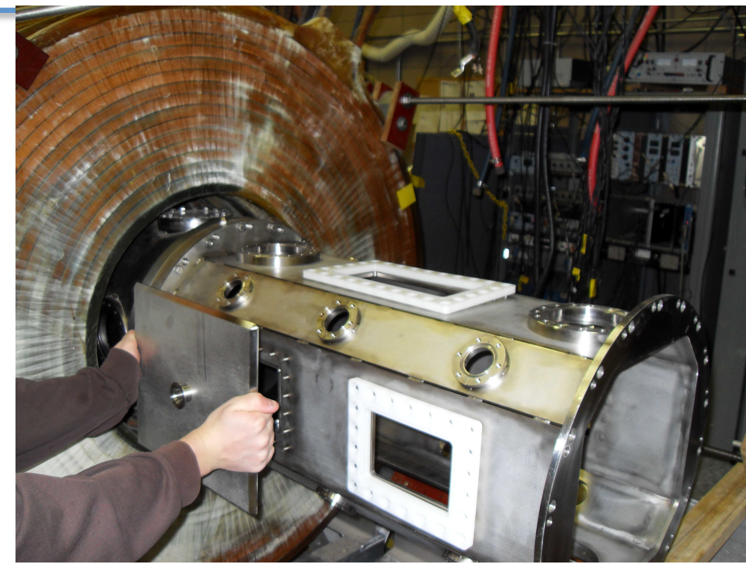
RSX experiment: 3D flux rope interactions



Camera views end-on.

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



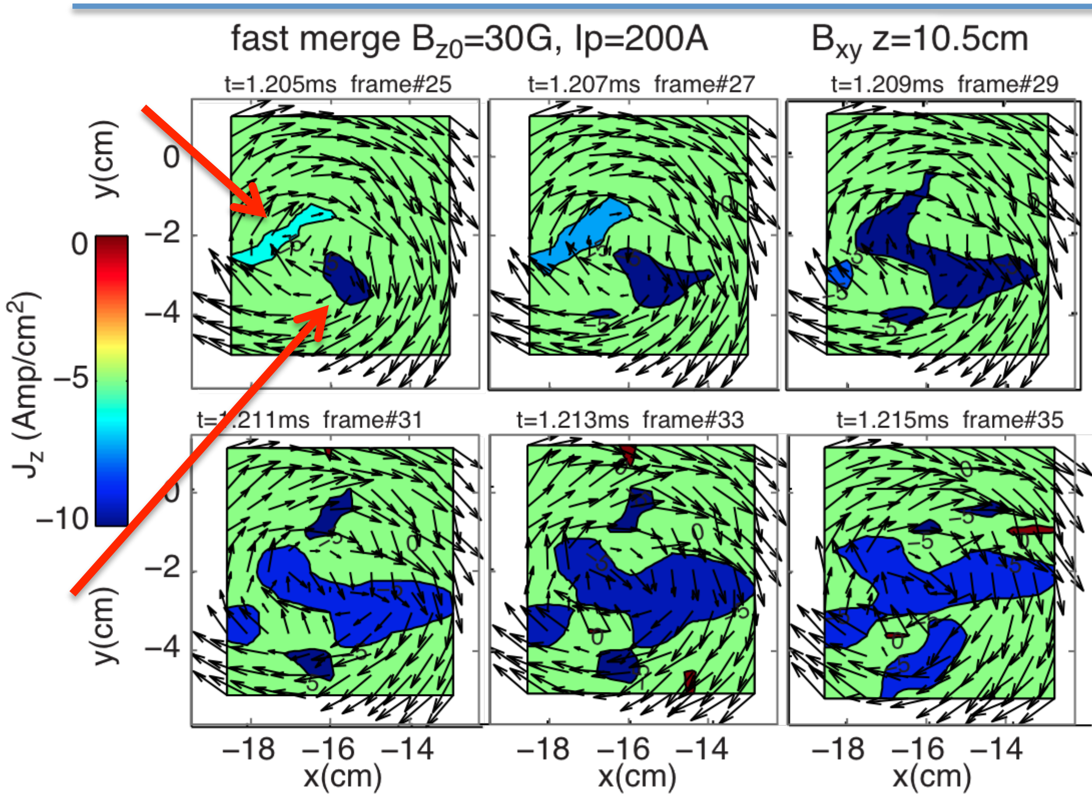


3d positioning ports allow unique diagnostic access.

Kinked flux ropes interact at discrete patch.

Reduce guide field: Knob physics from 2D to 3D

New flux rope dynamics identified.



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.

x-y cutplane data: two flux ropes initially fast merge, then "shred" into several smaller flux ropes.

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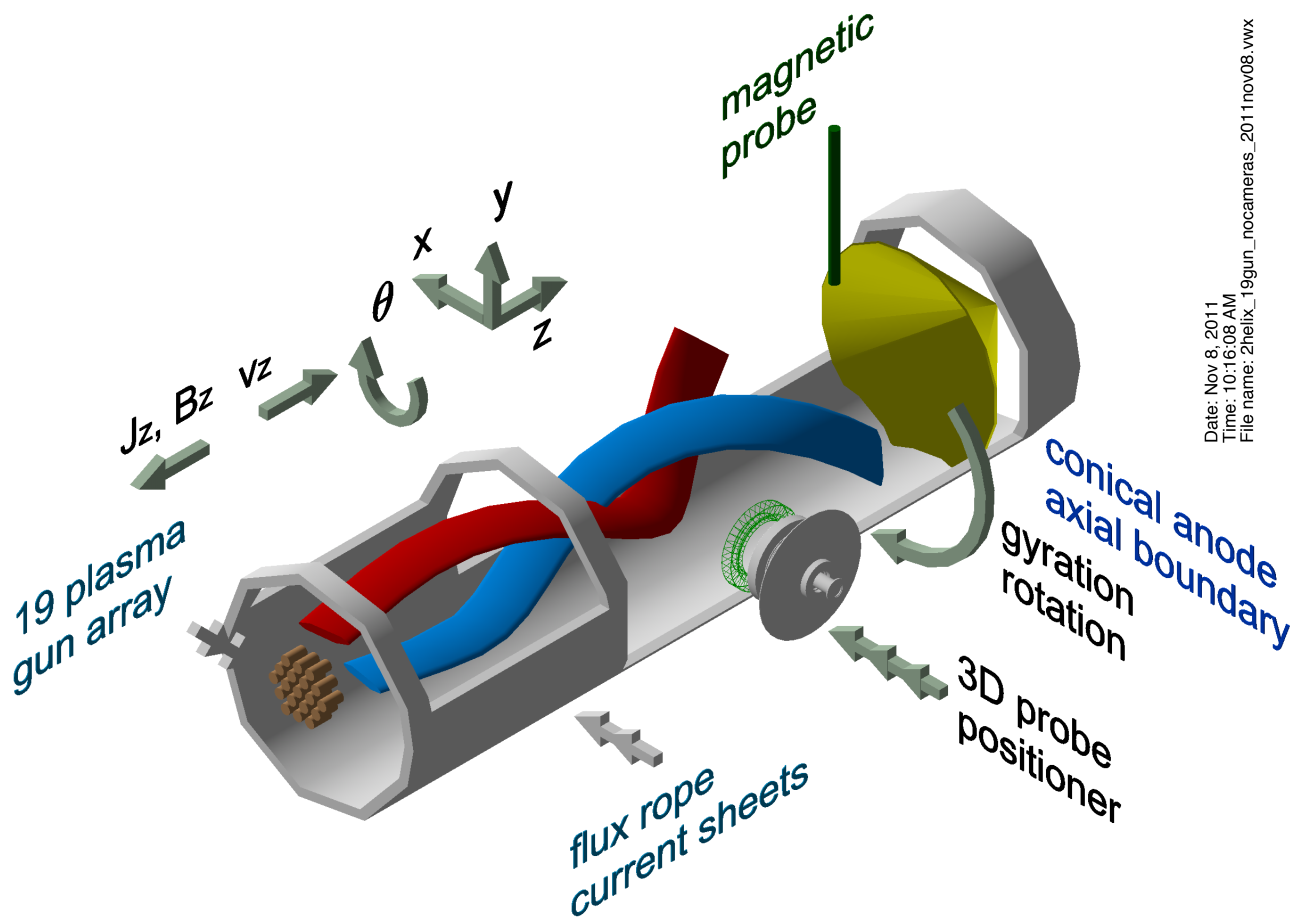
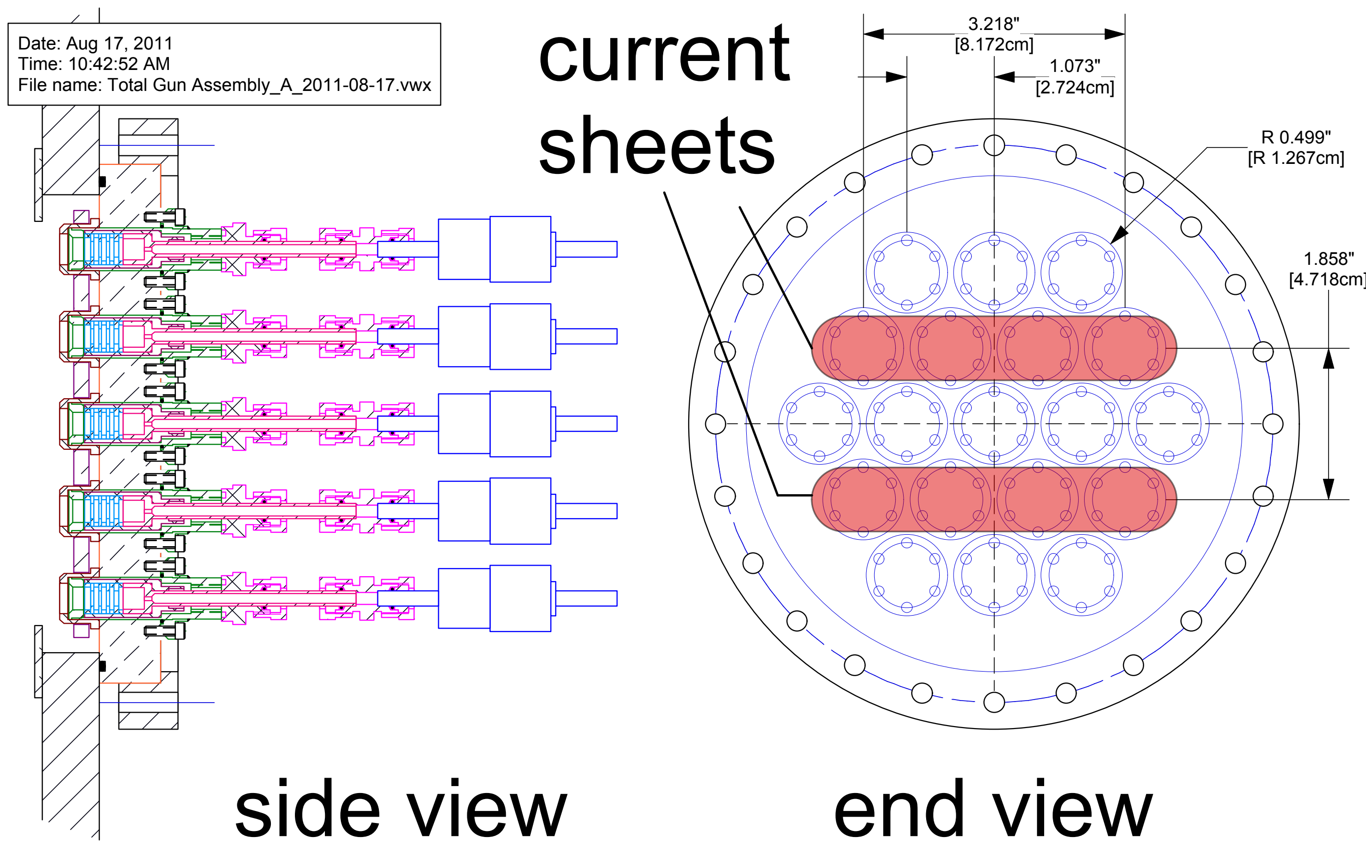
Proposed RSX current sheet plasmoid instabilities



Hardware current sheet implementation



Attainable current sheet parameters

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

Current sheet width/ion gyro radius

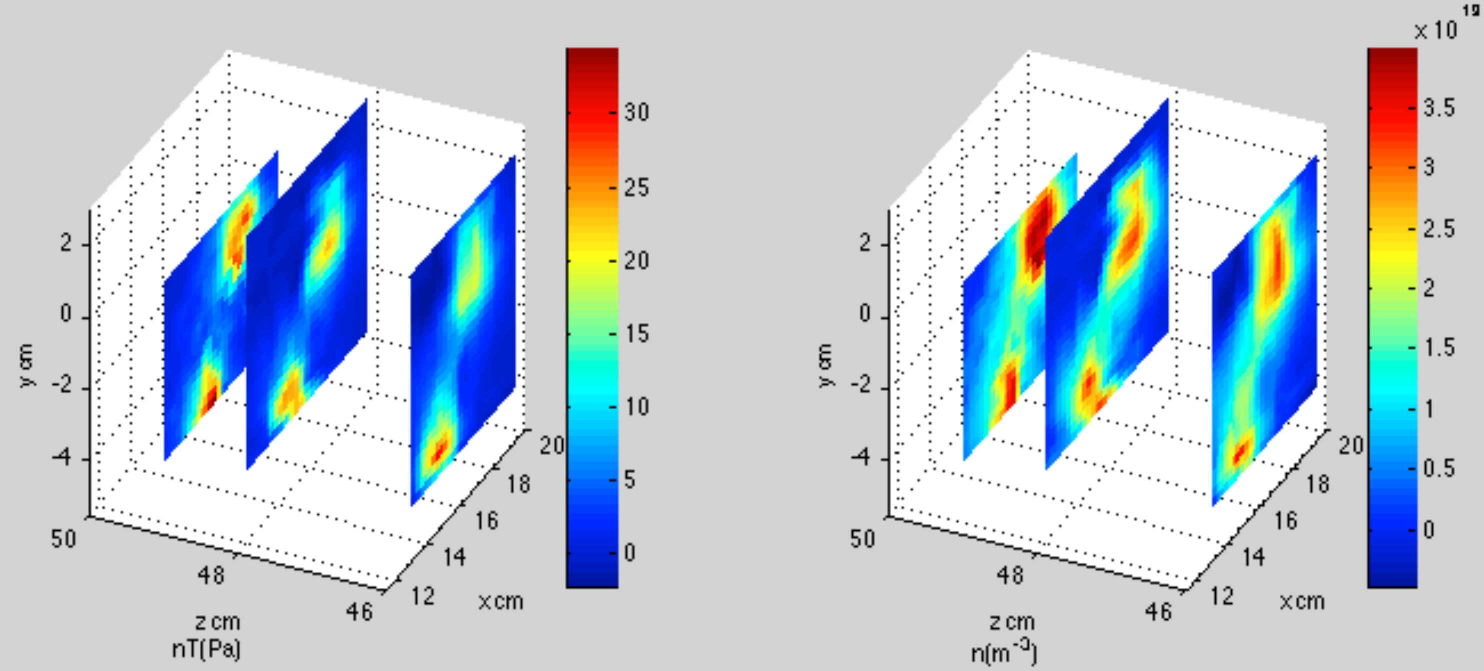
Width/ion skin depth

Lundquist #

Summary

- Sweet-Parker reconnection picture should include unstable current sheets
- Plasmoids or islands ↔ flux ropes ↔ significant J•B ↔ helicity ↔ non symmetric “Elsasser” variables
- Laboratory flux ropes “shred” down to ≈ electron skin depth dissipation scales
- Proposed RSX implementation: unstable current sheets

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

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