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Title: Two LANL laboratory astrophysics experiments!

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Two LANL laboratory astrophysics experiments

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NASA Geospace - NNHIOA044I

Abstract

Two LANL laboratory astrophysics experiments

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Two laboratory experiments are described that have been built at Los Alamos (LANL) to gain access to a wide range of fundamental plasma physics issues germane to astro, space, and fusion plasmas. The over arching theme is magnetized plasma dynamics which includes significant currents, MHD forces and instabilities, magnetic field creation and annihilation, sheared flows and shocks.

The Relaxation Scaling Experiment (RSX) creates current sheets and flux ropes that exhibit fully 3D dynamics, and can kink, bounce, merge and reconnect, shred, and reform in complicated ways. Recent movies from a large data set describe the 3D magnetic structure of a driven and dissipative single flux rope that spontaneously self saturates a kink instability. Examples of a coherent shear flow dynamo driven by colliding flux ropes will also be shown.

The Magnetized Shock Experiment (MSX) uses Field reversed configuration (FRC) experimental hardware that forms and ejects FRCs at 150km/sec. This is sufficient to drive a collision less magnetized shock when stagnated into a mirror stopping field region with Alfven Mach number MA=3 so that super critical shocks can be studied. We are building a plasmoid accelerator to drive Mach numbers MA >> 3 to access solar wind and more exotic astrophysical regimes. Unique features of this experiment include access to parallel, oblique and perpendicular shocks, shock region much larger than ion gyro radii and ion inertial length, room for turbulence, and large magnetic and fluid Reynolds numbers.

*DOE Office of Fusion Energy Sciences under LANS contract DE-AC52-06NA25396, NASA Geospace NNHIOA044I, Basic

Magnetized plasma dynamics beyond fluids

A tale of two lab-astro experiments

- RSX: Flux ropes in 3D at kinetic scales
  - Non linearly saturated kink
  - Shear flows & dynamo
- MSX: Magnetized shocks at $M_A > 3$
  - Magnetic bubble smashes onto a stopping mirror
  - Large enough for diffusive shock acceleration
  - Breakthrough diagnostic: pulsed polarimeter

Why laboratory experiments?

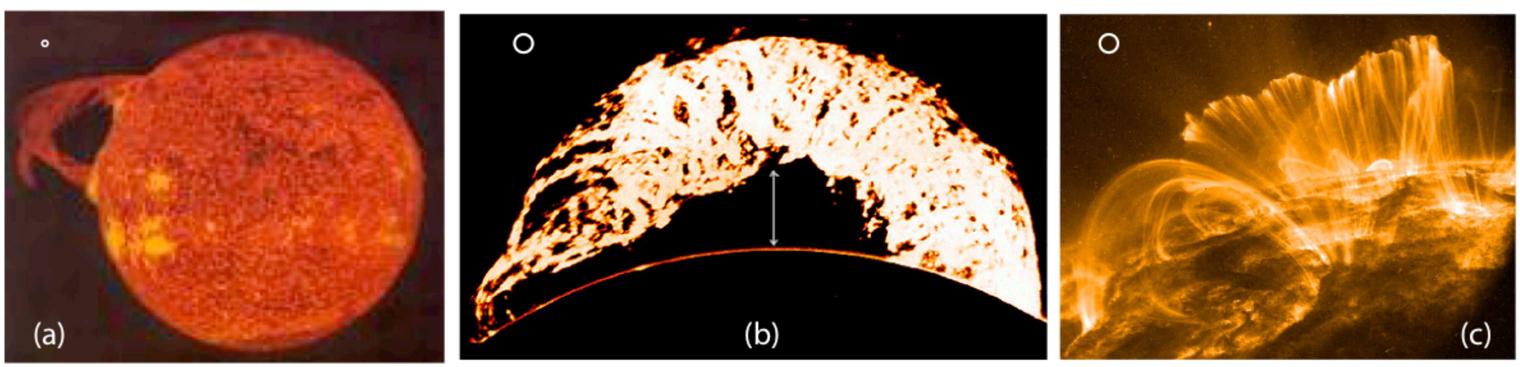
Complement spacecraft, astrophysical data & simulations

- MHD has no intrinsic scale
  - 100s Light Years vs 50 cm
- dimensionless parameters → distill physics features
- Spacecraft provide in-situ data BUT few locations, ambiguous reference frame
- Remote observations use surrogate quantities (eg spectroscopy) to infer the physics
- 3D laboratory data → window on nature

Flux ropes are everywhere in the universe

There is universal tendency to develop filaments of electric current and tubes of magnetic field lines that helically wrap around a magnetic axis. These flux ropes are twisted along their own axis and writhe or gyrate …

Solar eruptions



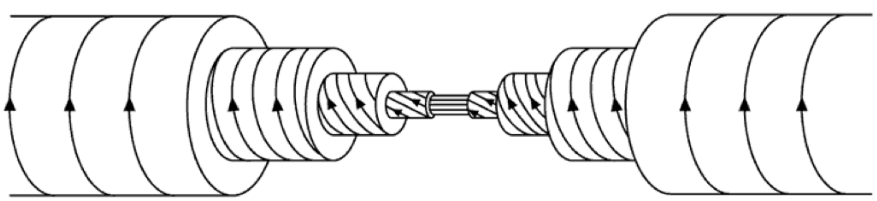
NOAA

Grandaddy, HAO 1945, visible

TRACE in xray

What is a flux rope?

- Flux rope ⇔ Bundle of magnetic field lines wrapped around a magnetic axis → Flux tube threaded with electric current
- Plasma + mass → inertia, Newtonian mechanics
  - Transport significant energy, mass, momentum
  - Helicity

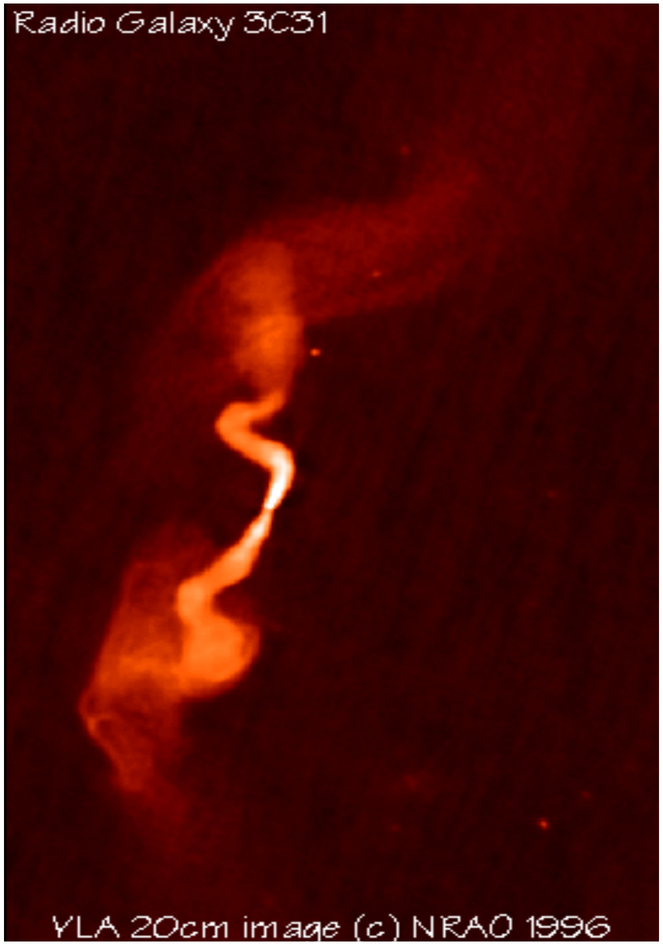


Interior Structure of Flux Rope

Russell & Elphic

Flux ropes: building blocks of MHD

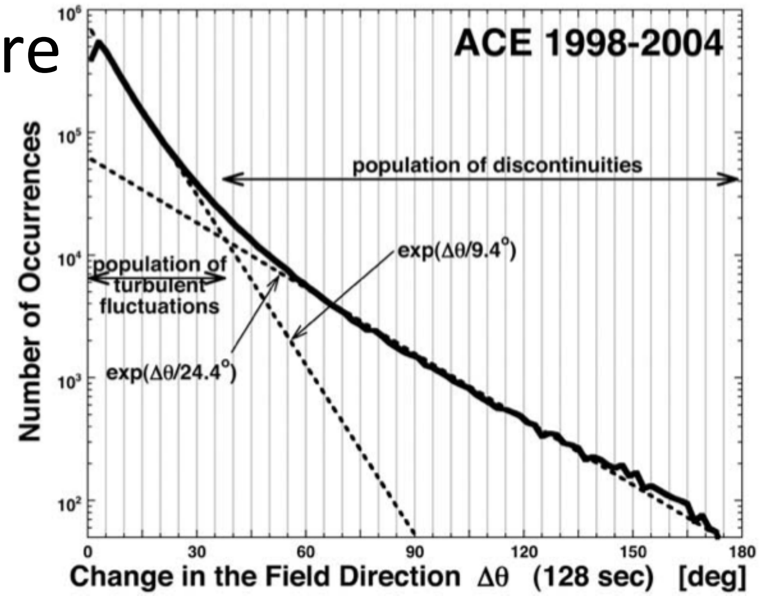
IR image, Near center of Milky Way, ≈ 80 LY long, Morris et al. Nature, 2007



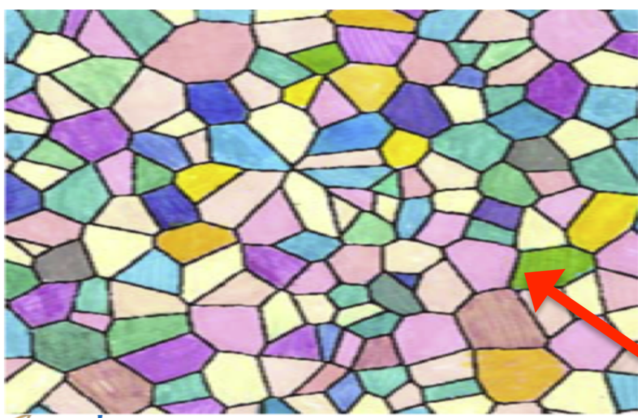
NGC383, 209MLY away, ≈300kpc length

Solar wind is likely packed with flux ropes

Solar wind has flux rope structure



tangled about the Parker spiral



Sketch of the flux tube texture of the solar-wind plasma. Each flux tube contains a different plasma, move independently, with fast parallel flow.

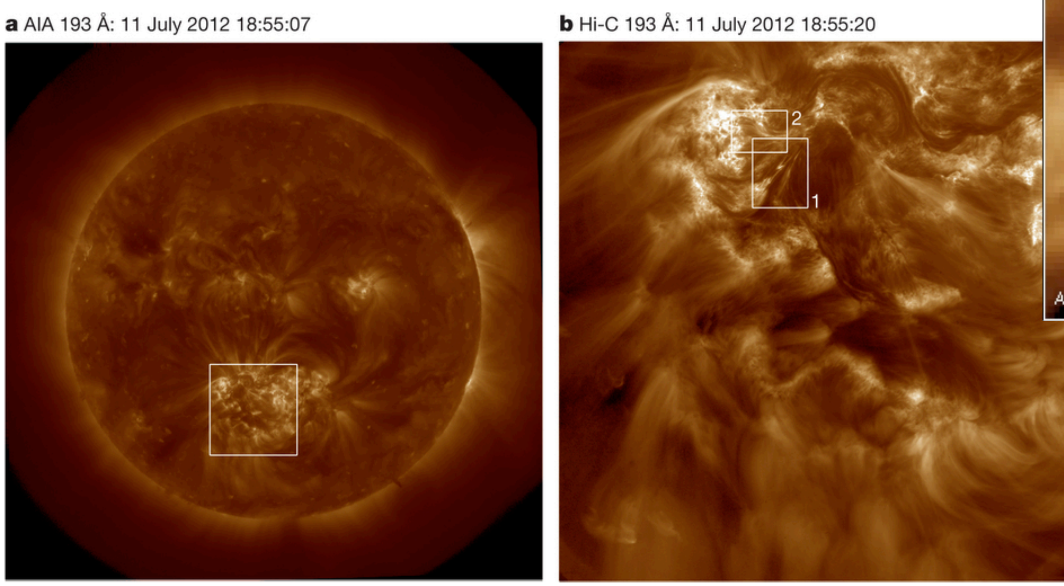
J. Borovsky, Flux tube texture of the solar wind: Strands of the magnetic carpet at 1 AU? JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, A08110, 4, 2008

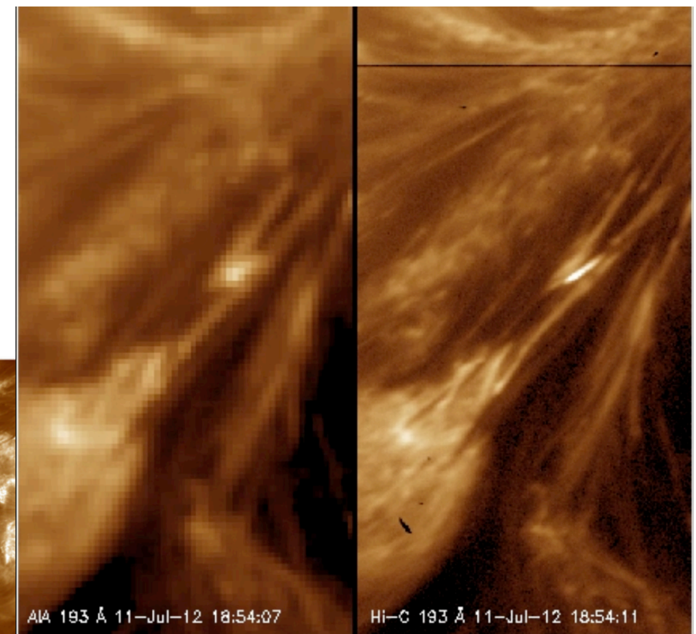
Cross sections of the network of tubes

Big Bear Observatory movie

Flux ropes in solar corona (not photosphere)

- Soft X-ray emission from the corona is shown by a sounding rocket 1- arcsec-resolution AIA full-sun image (11 July 2012, 18:55 UT) at 193 Å with a further zoom in level (Cirtain2013).



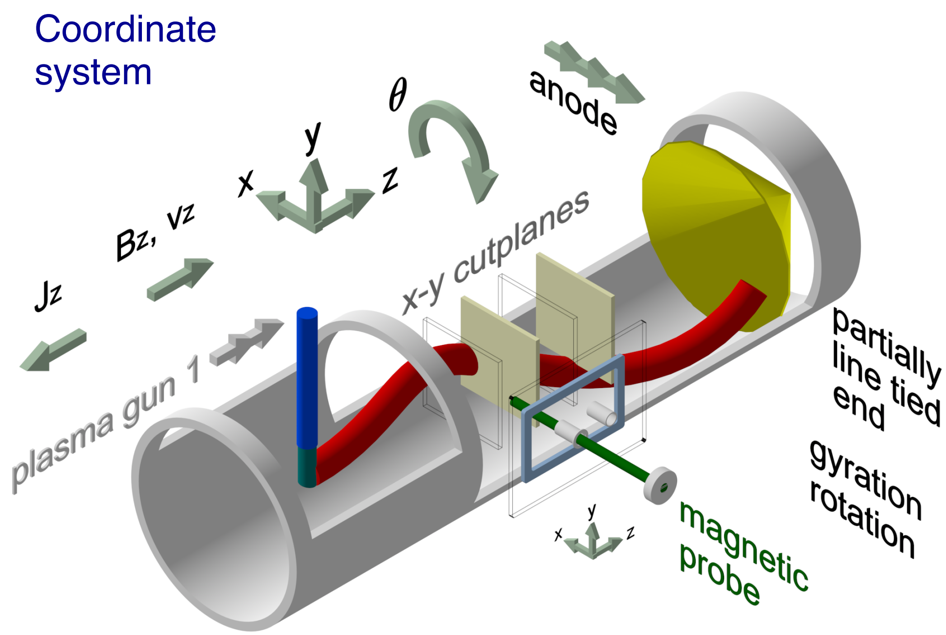


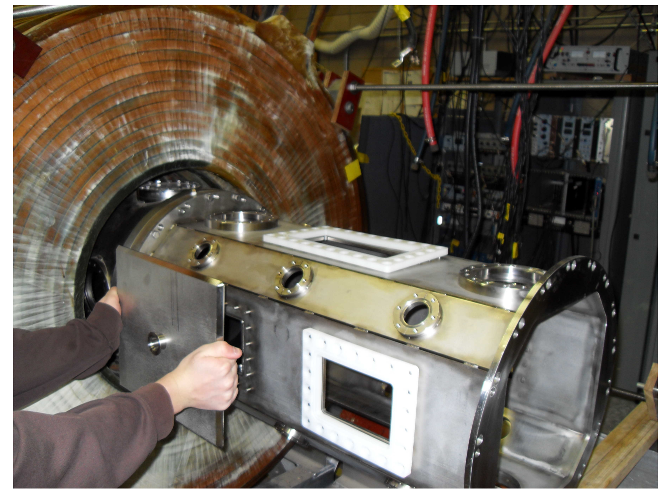
A Hi-C rocket flight image at high 0.2 arc-sec (150km) resolution (right) com-pared to the AIA 1 arc-sec resolved image on the left, at at 193 Å , for the field of view in- dicated by the boxes in Fig. 1. Braided and twisted features are believed to be magnetic flux ropes (Cirtain et al. , 2013).

Relaxation Scaling Experiment

- Single flux rope kinks when J/B becomes large
- Rope becomes helical and gyrates
- It should explode on an Alfven time (1usec)
- But the flux rope gyrates forever, living in a metastable, non linearly stabilized state

RSX experiment: single 3D flux rope kink + gyration, apparently stable

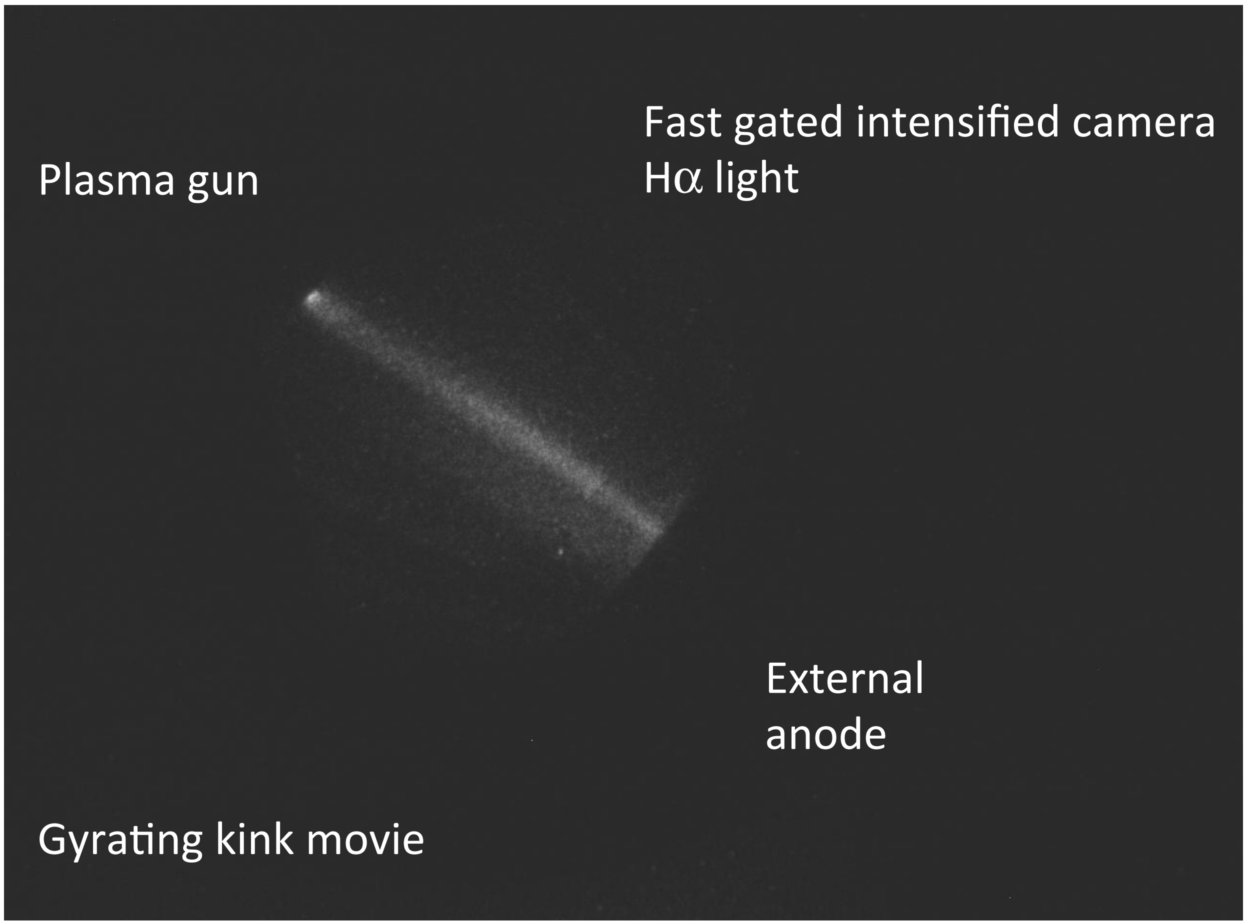




3D positioning ports allow unique diagnostic access.

Kink goes unstable

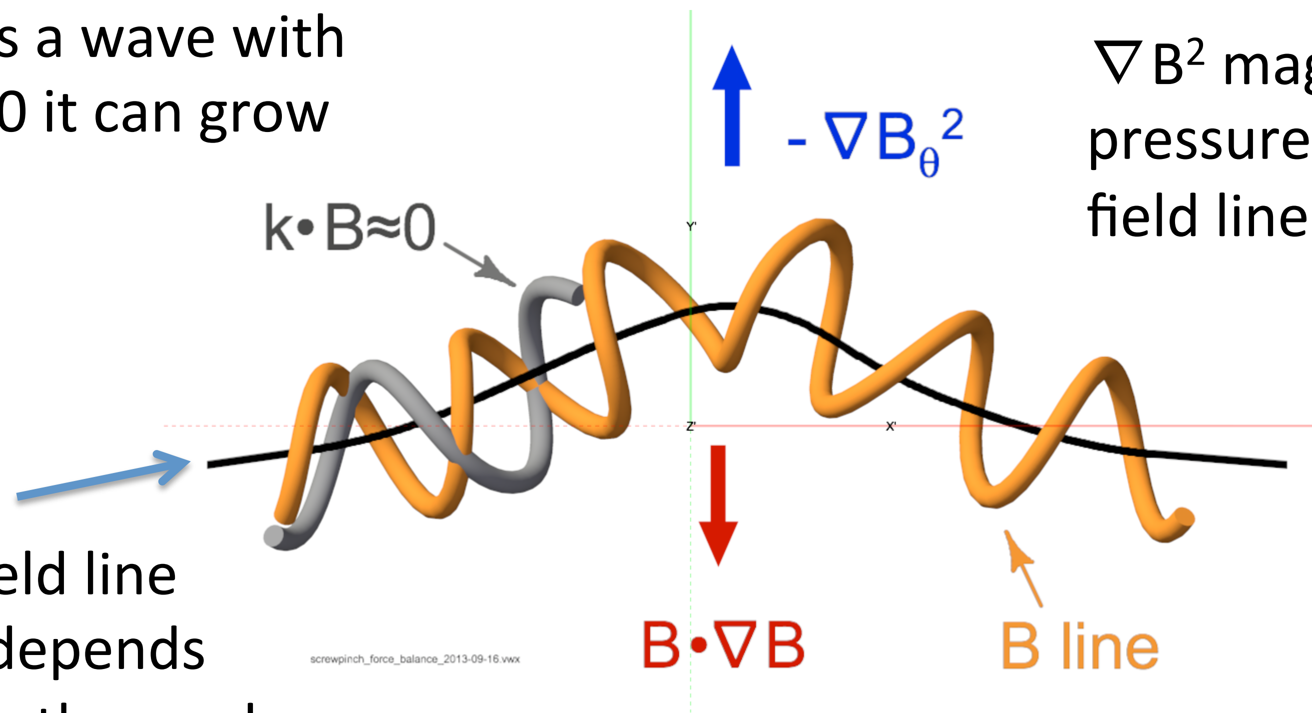
but does not explode on the Alfven time



BC changes kink force balance

If there is a wave with $k \bullet \nabla B \approx 0$ it can grow

∇B^2 magnetic pressure pushes field line away



$B \bullet \nabla B$ field line tension depends upon whether ends are clamped or not

Single flux rope non linearly self stabilizes its kink behavior

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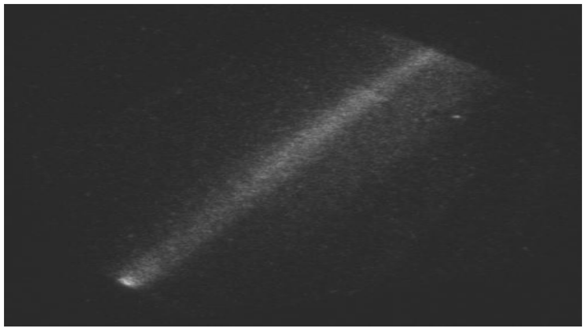
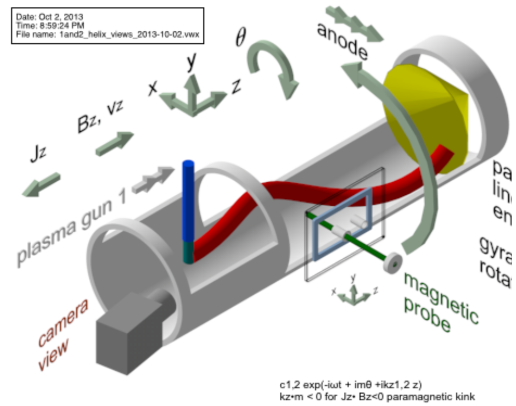
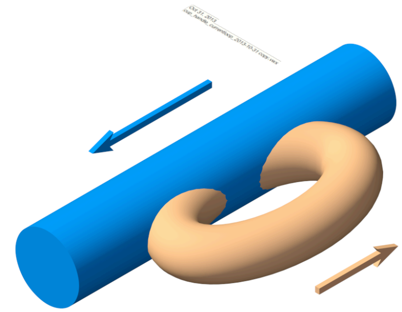
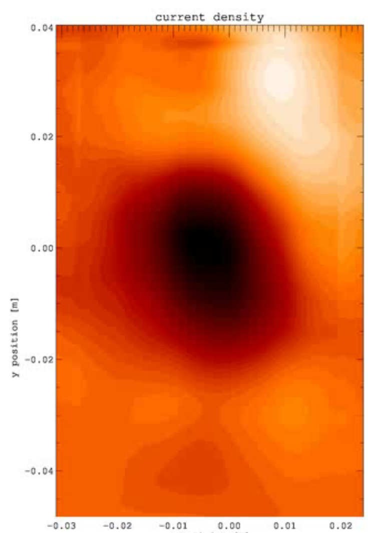


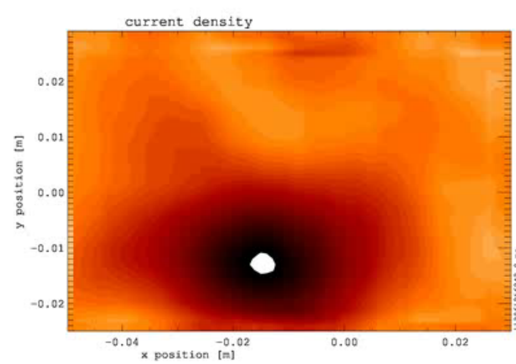




Z=25cm from plasma gun Jz(x,y)

flux rope (black) & reversed (white)

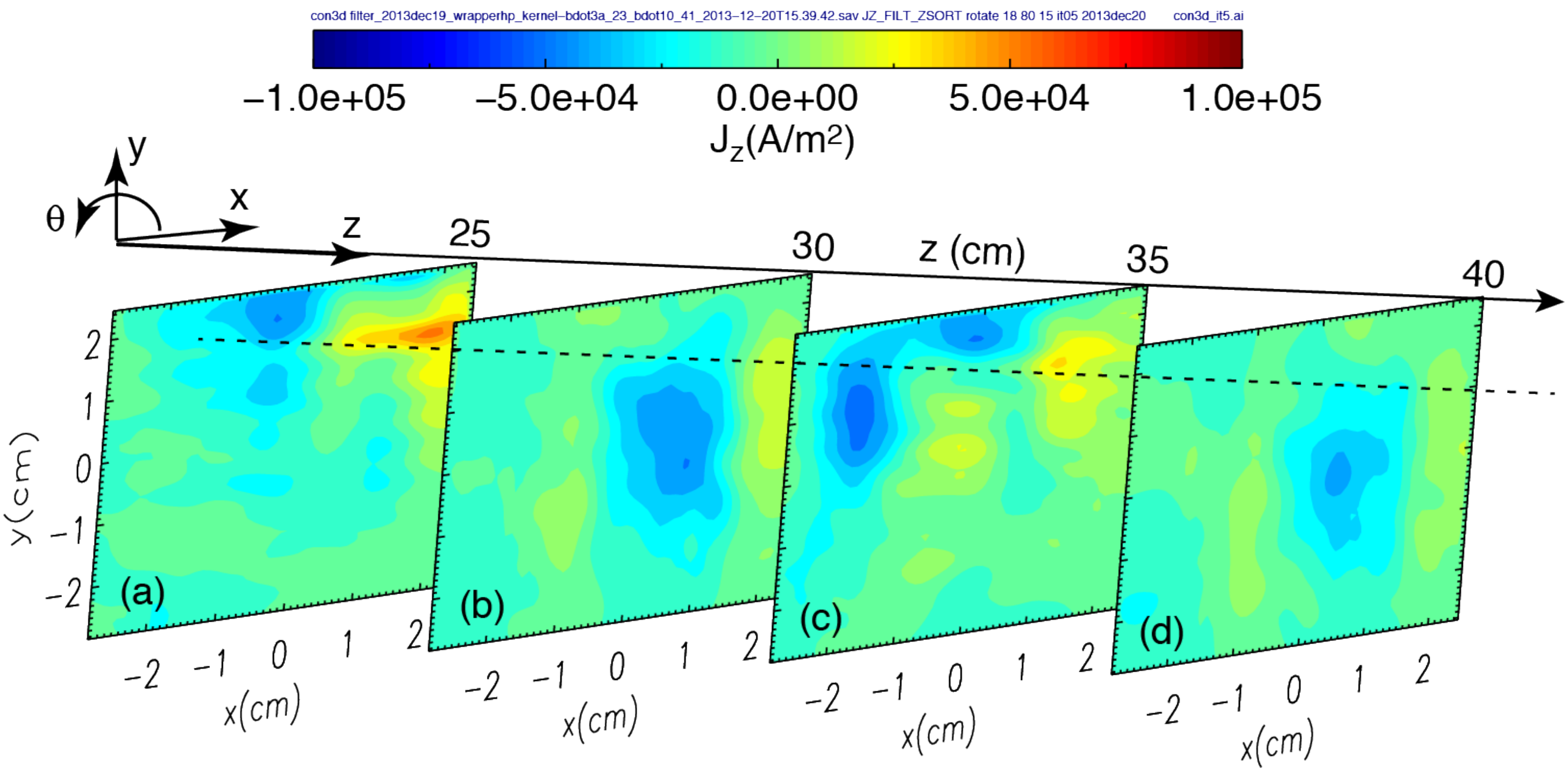




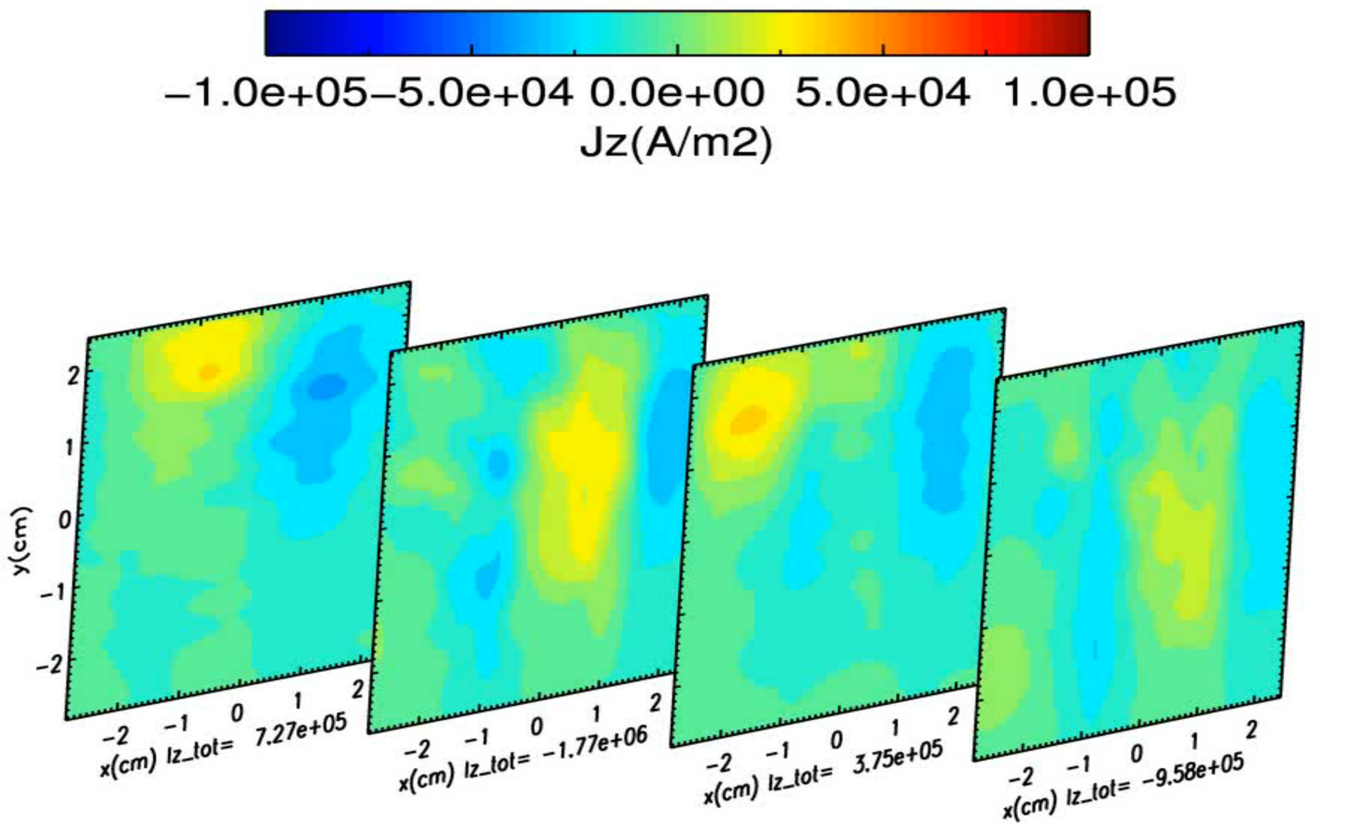
Z=40cm from plasma gun

No obvious induced -Jz

3D data coordinate system



3D data movie

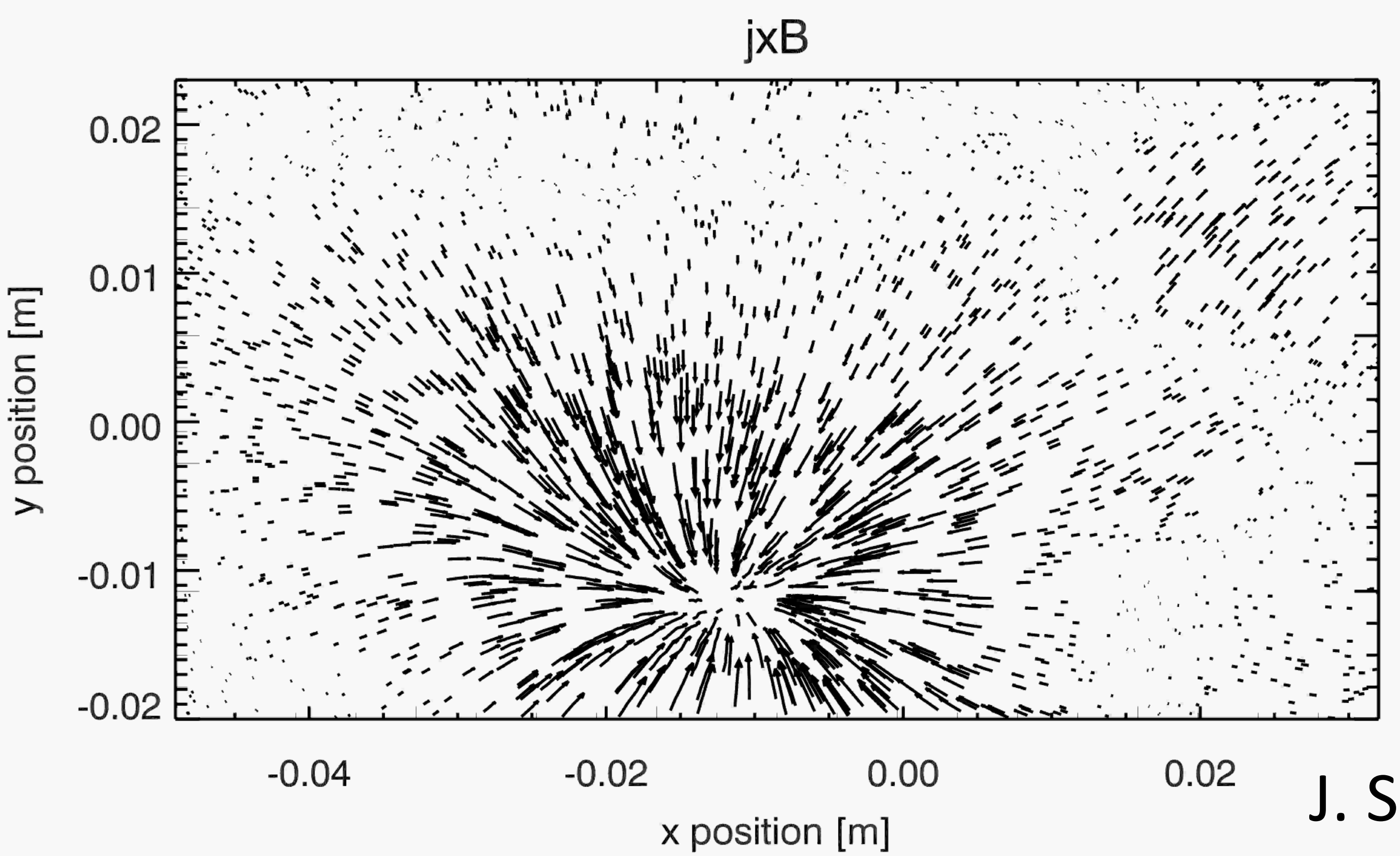


Blue = flux rope

Yellow = return current inside plasma

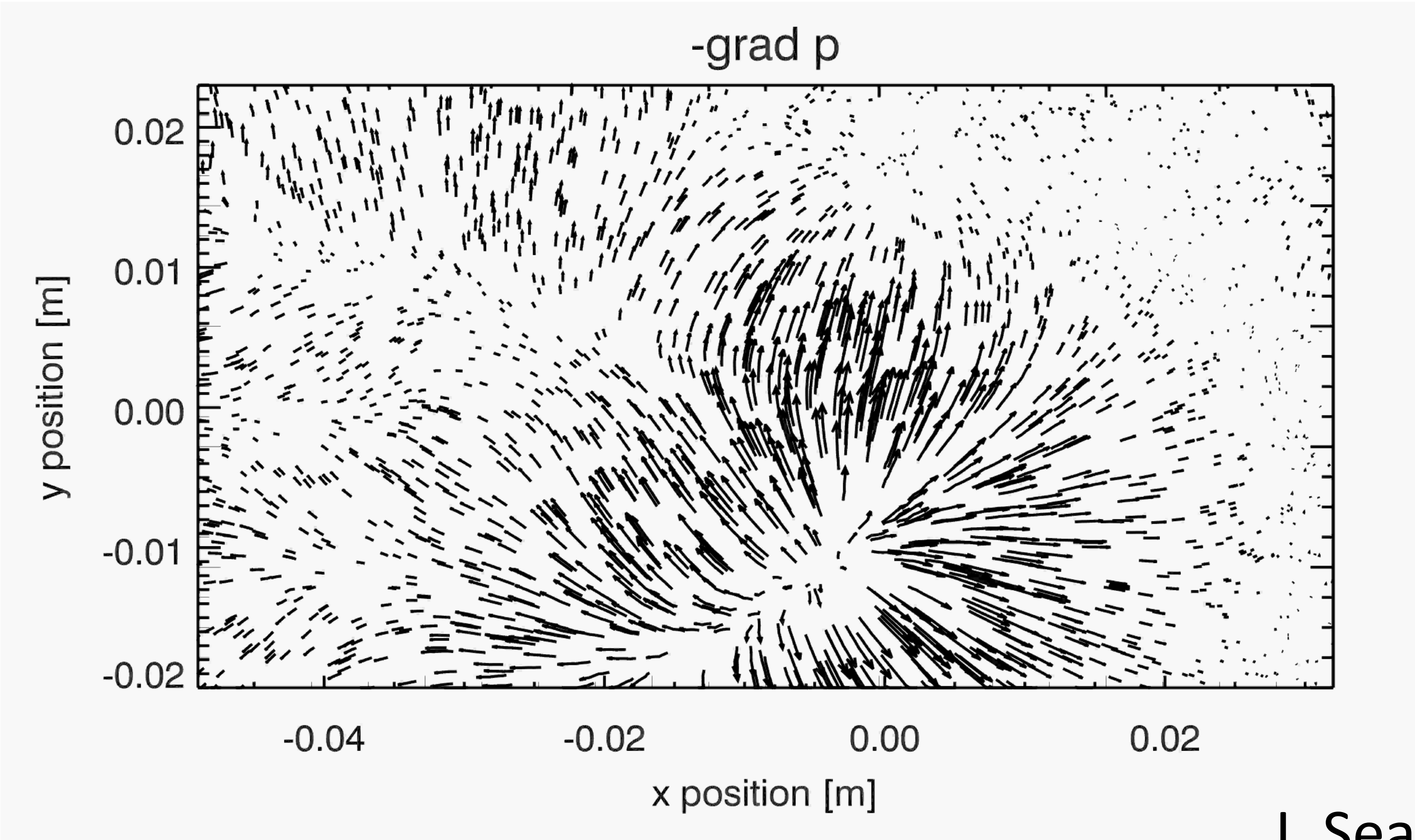
Los Alamos NATIONAL LABORATORY EST. 1943

JxB movie in x-y cutplane



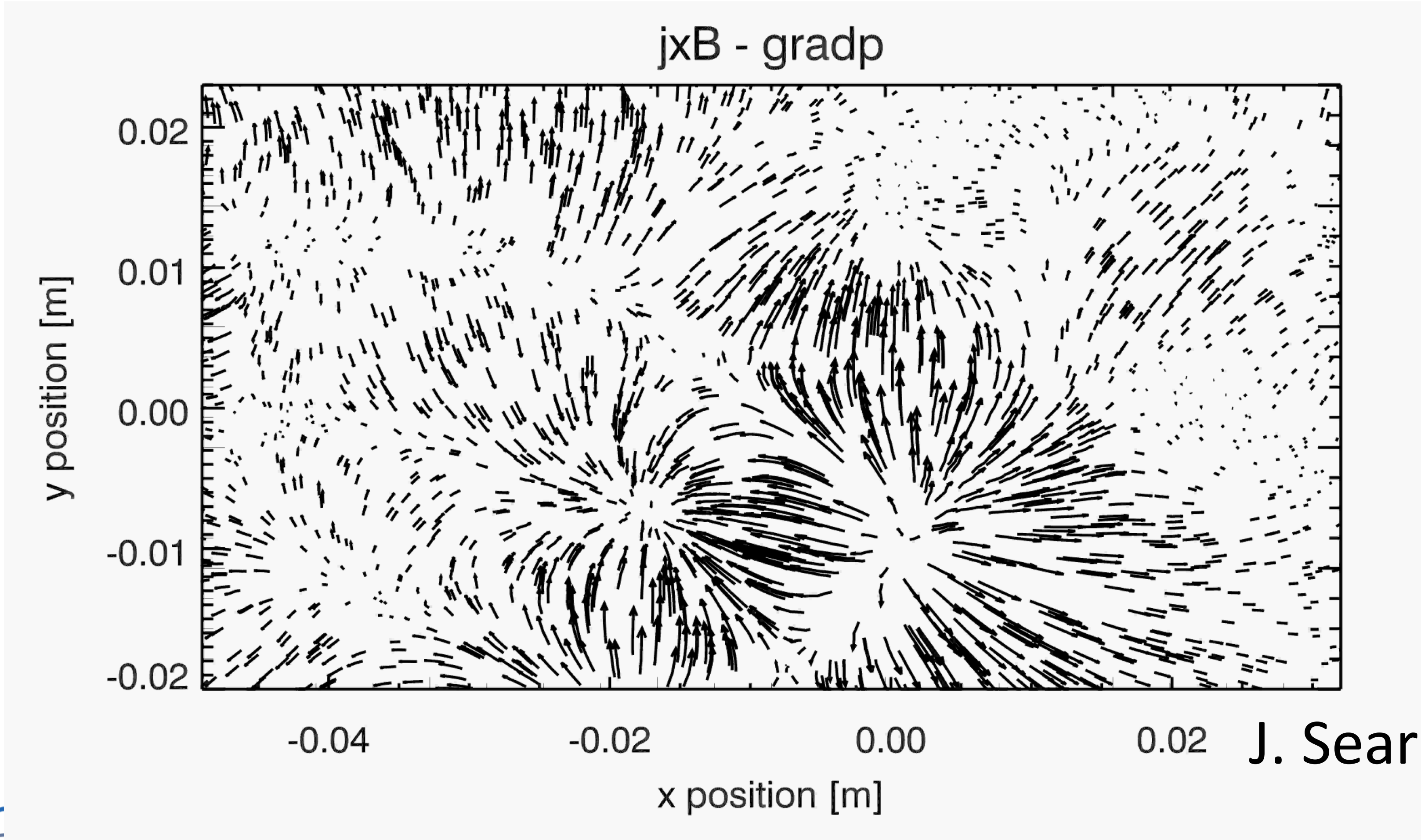
J. Sears

-∇p movie in x-y cutplane



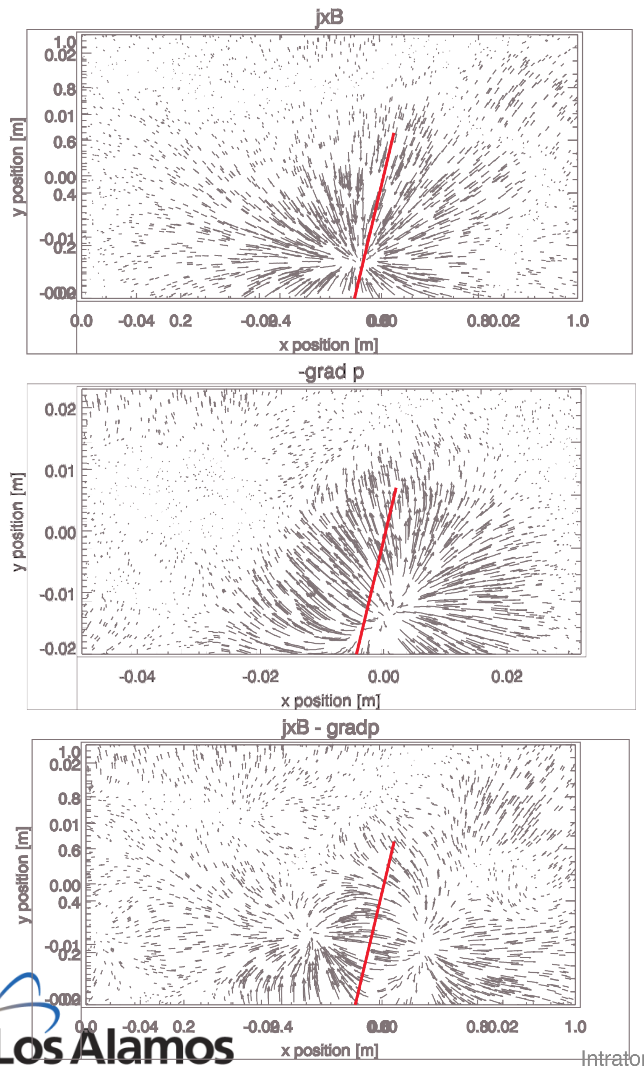
J. Sears

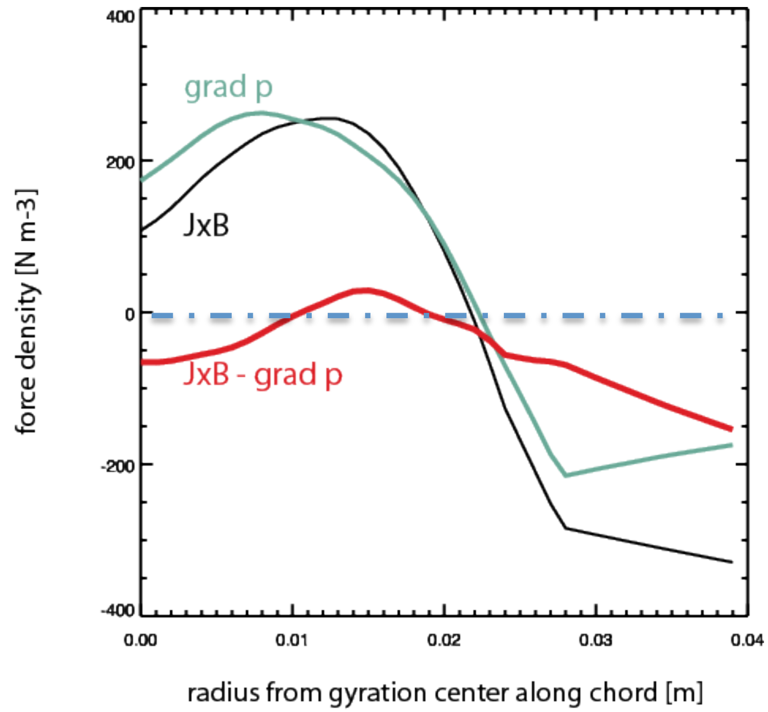
JxB-∇p ≠ 0 ?!? movie



J. Sears

Look along a gyration radius geodesic:
In plane forces have 30% discrepancies





J. Sears

$$\rho\, dv/dt = JxB - \nabla p \approx ?$$

Sheared rotation & gyration flow, Coriolis force v$\times\Omega$, d/dt → v•∇v, ∇x∇p≠0??

Evolution of a single flux rope in 3D

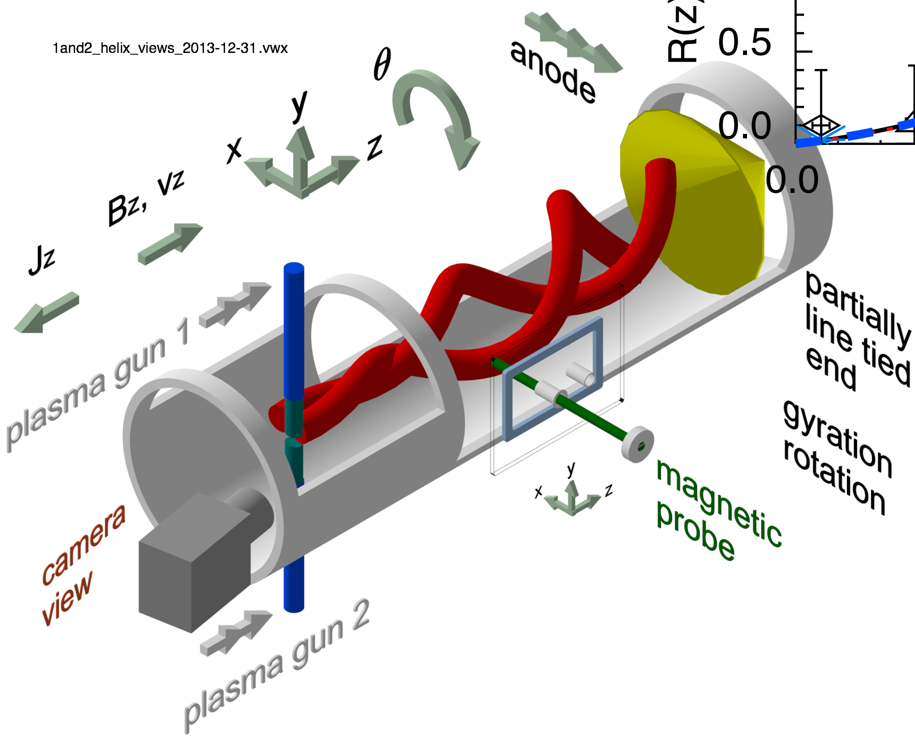
- Kink unstable when J•B > Kruskal Shafranov threshold
- Axial plasma flow doppler $k_z \cdot v_z$ ⇔ W(gyration) WRITHE
- Flux rope spins on its own axis w TWIST
- BUT the kink helix is apparently non linearly stable
- Experimental data down to electron kinetic scales
- *What is the force balance in 3D?*

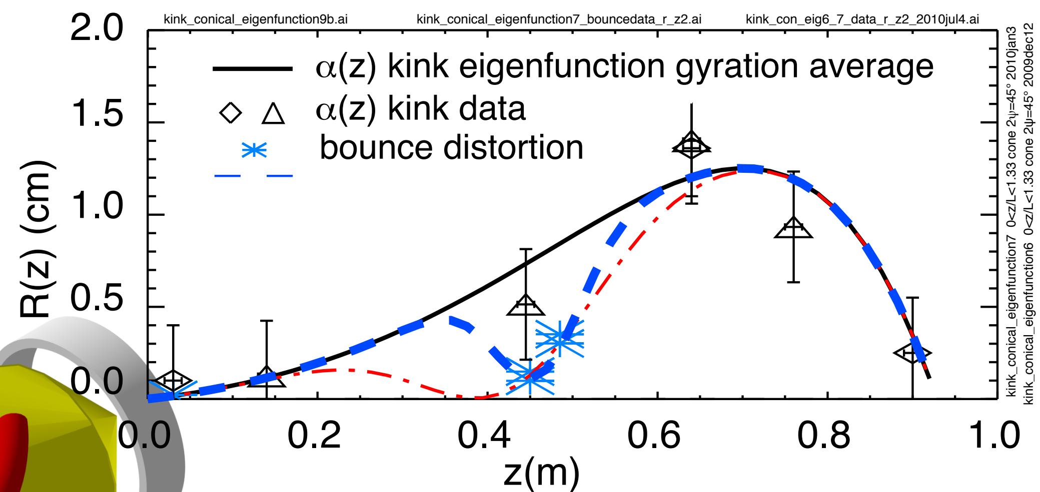
- Data show that $J \times B - \nabla p \neq 0$
- Which forces can we measure?
- $\rho \, dv/dt = J \times B - \nabla p + qnE + \Omega \times v + \ldots$?

RSX: two flux ropes

- Twin flux ropes kink, become helical and gyrate
- Parallel currents attract
- Flux ropes collide and bounce instead of reconecting
- Between the flux ropes in what ought to be a reconnection region, a quadrupole out of plane magnetic field forms
- Why?

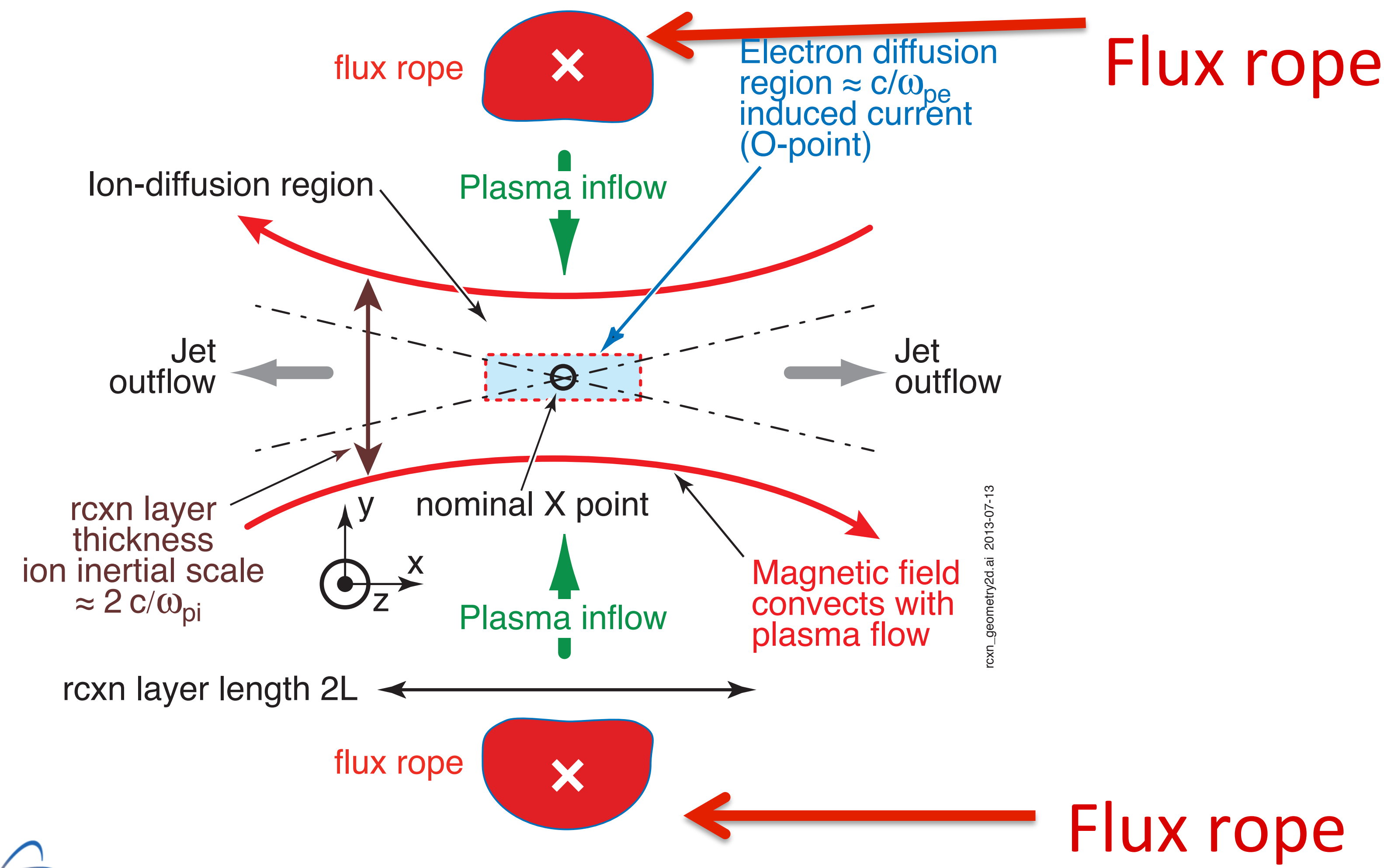
Two flux ropes bounce without reconnecting



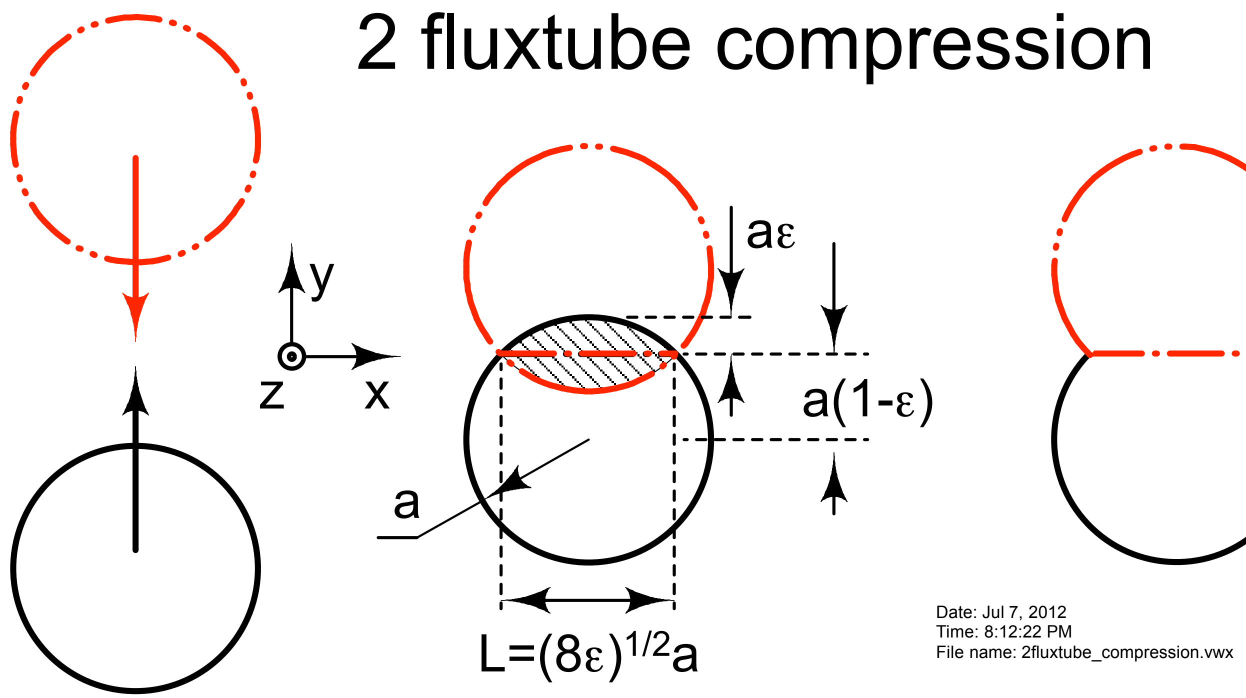


Flux ropes bump into each other and bounce often

Reconnection geometry is supported by plasma currents (colliding flux ropes)



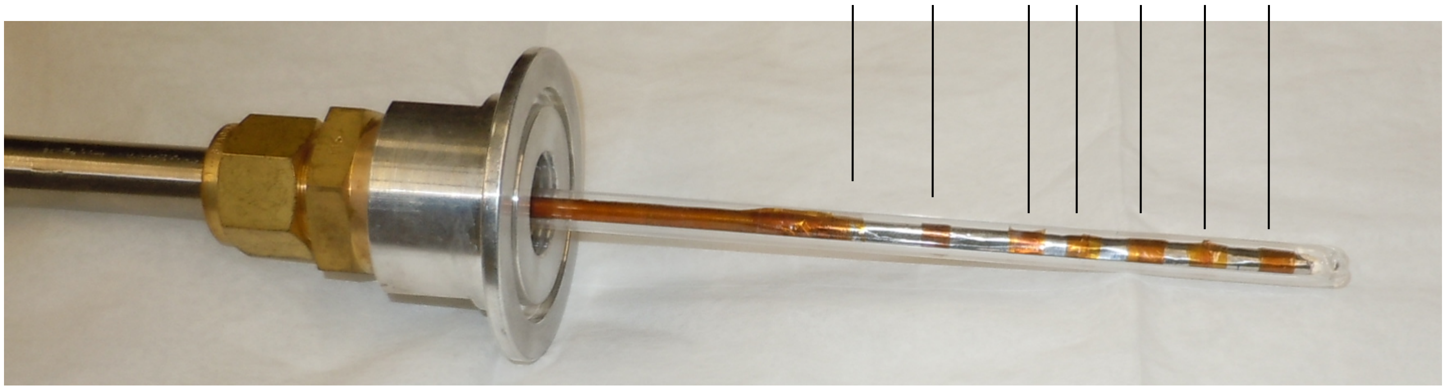
Simple model for flux rope *collision & compression*



Two flux ropes approach each other, collide, and compress their mutual facing volumes, with the common face length denoted by L. v_y = (half) the collision speed.

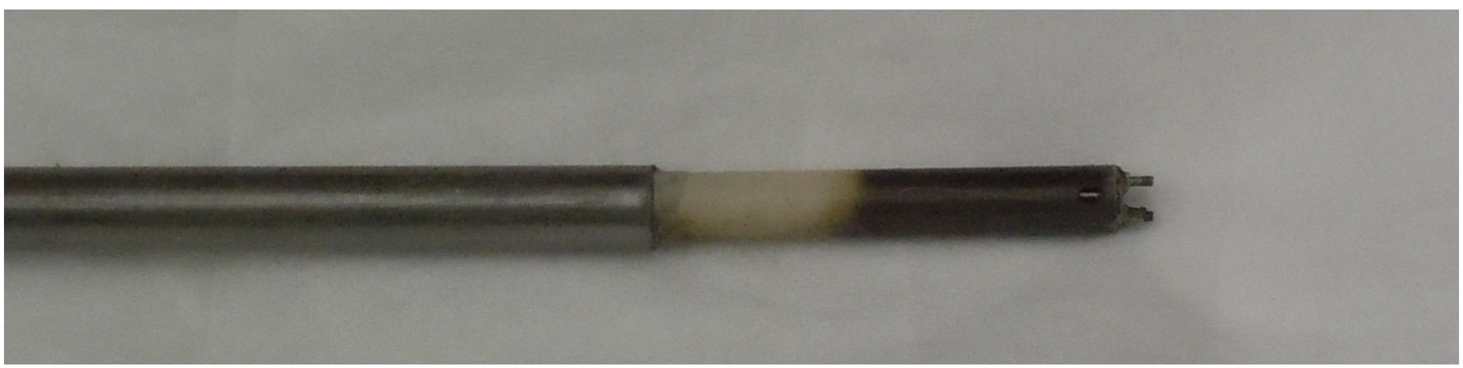
3D scannable probes

magnetic probe with multiple sensors



6 mm

mach probe with extra floating tip



3 mm

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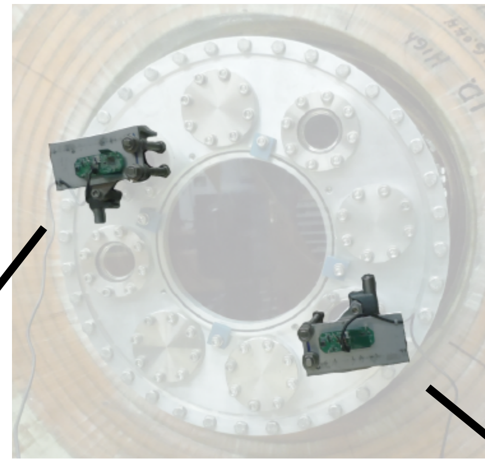
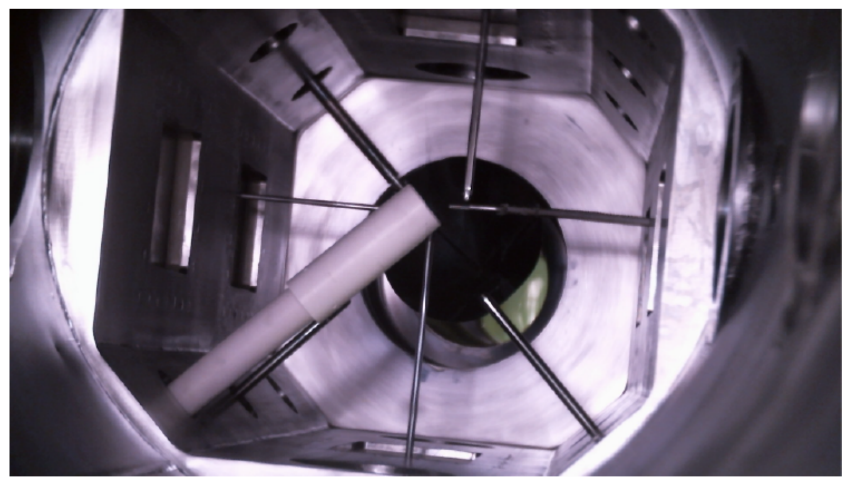
CMSO

the two cameras view at different angles to triangulate





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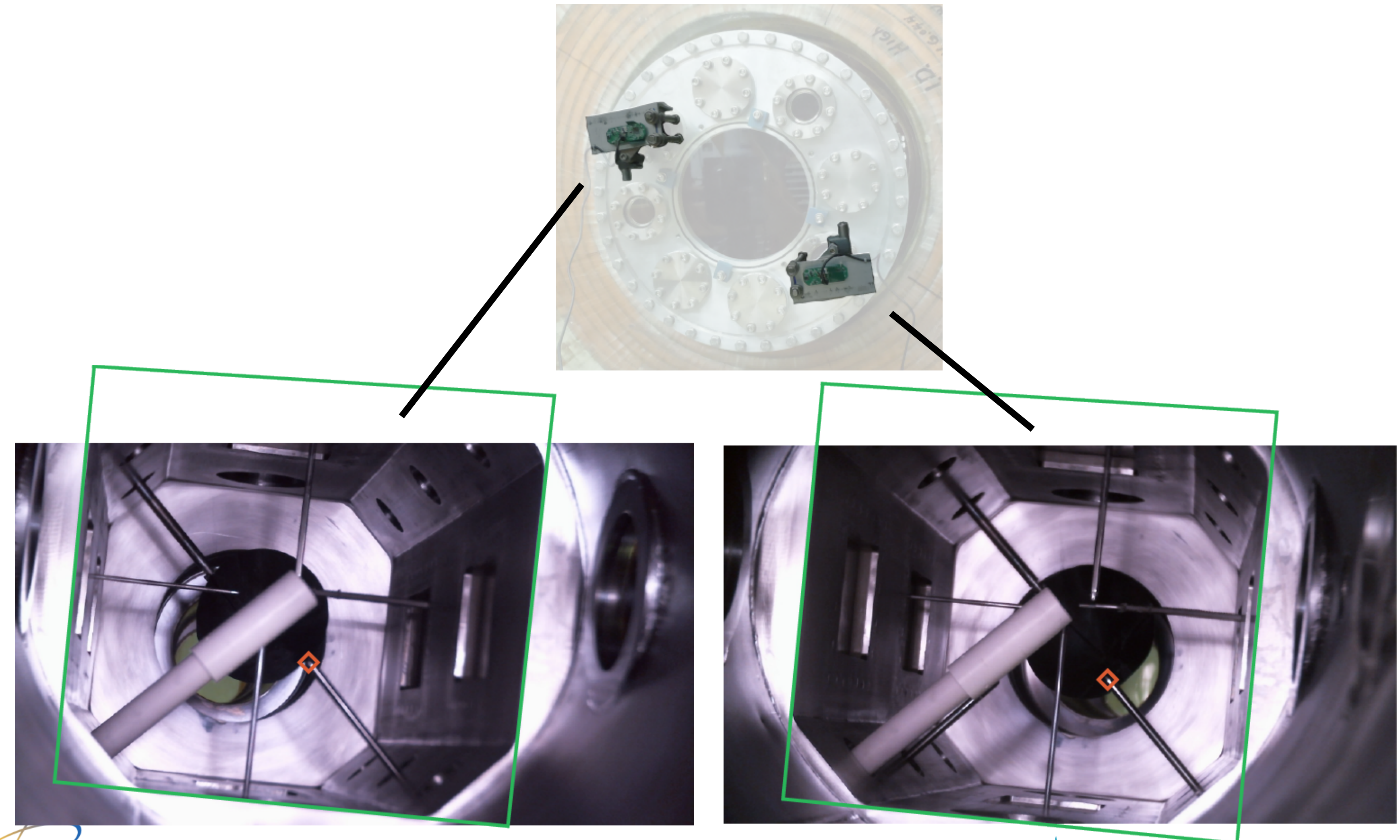
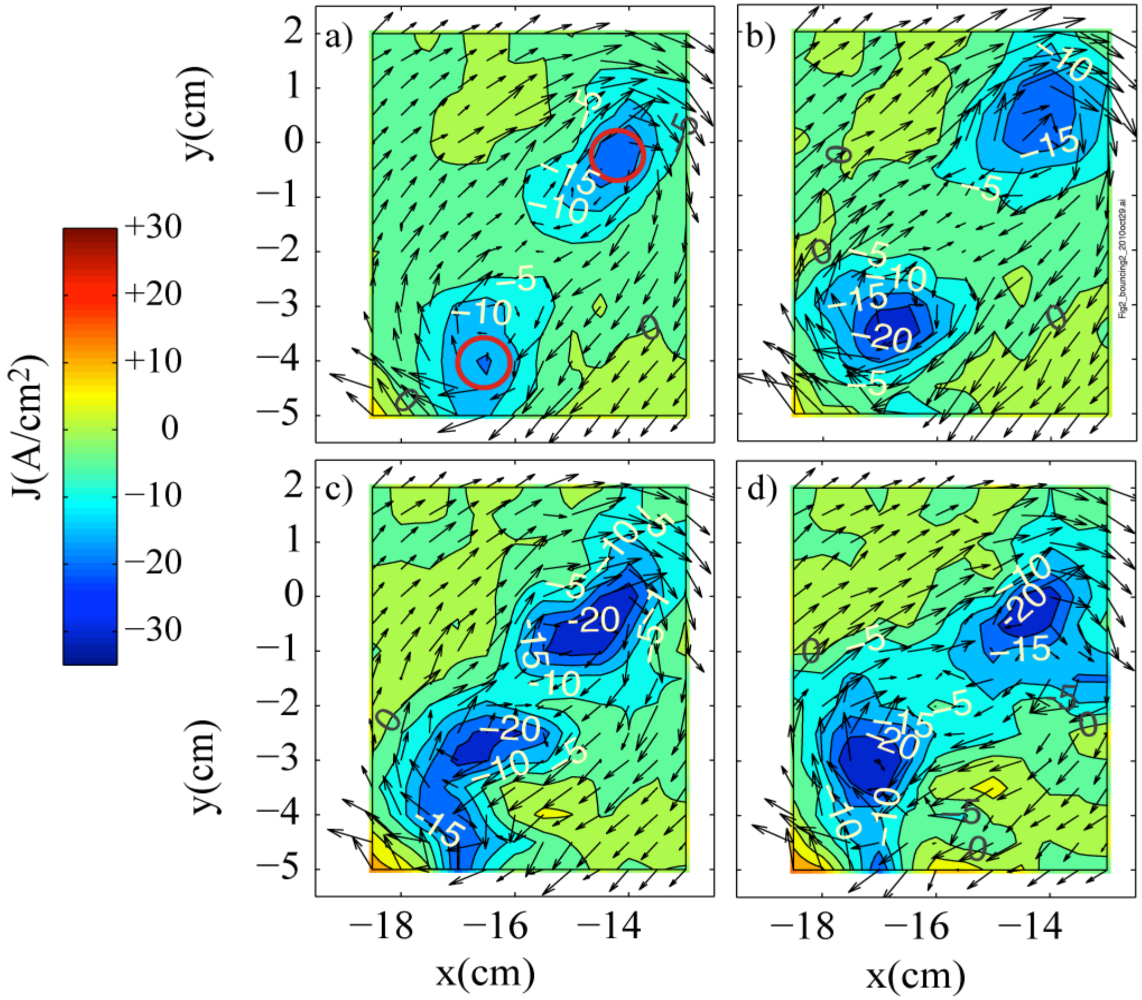
CMSO

1. vessel edges are recognized by algorithm to find camera orientation

2. user selects probe whose location is to be calculated



RSX data: bouncing flux ropes & sheared plasma flow

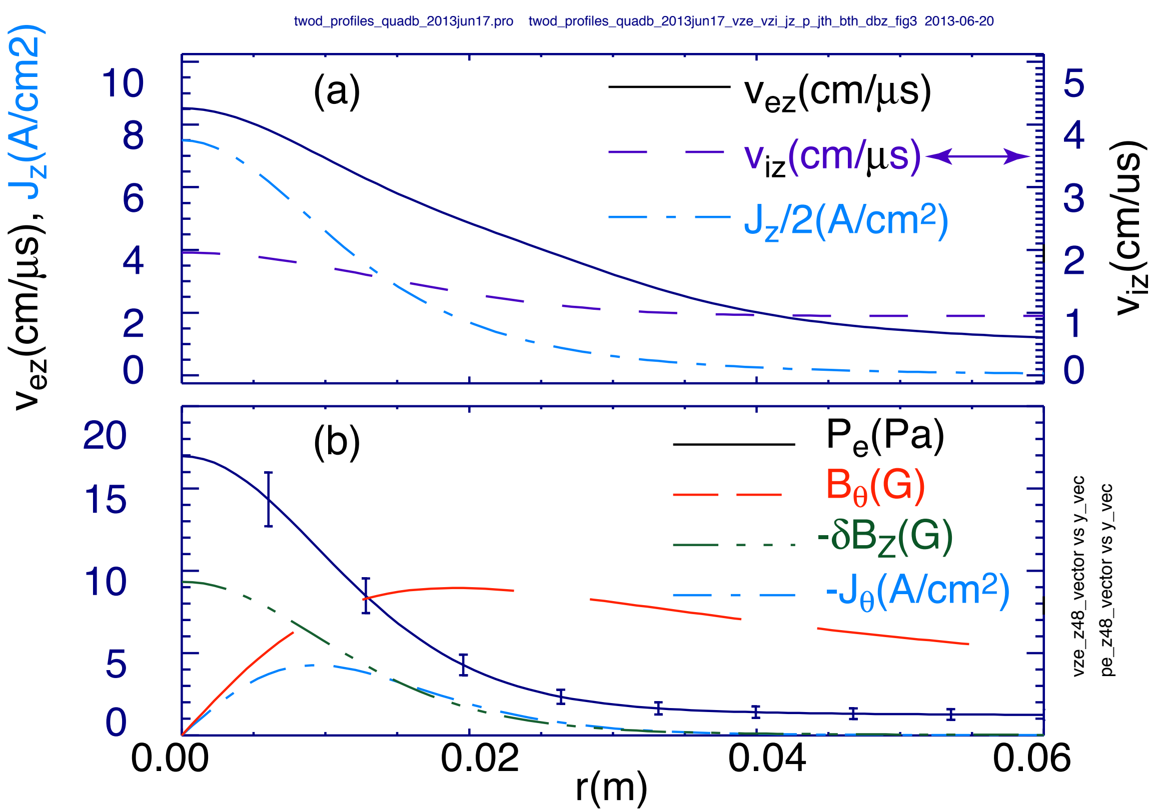


Magnetic data,
vector B shown by arrows
(Sun et al. , PRL2010)

Contours of current
density out of plane
$J_z = \nabla x B_\perp / \mu_0$

Since $J=en(v_i - v_e)$,
We will use magnetic J +
flow data v_i to back out
electron flow
$v_e = v_i - J/en$

Flux rope profiles match *screw pinch* model

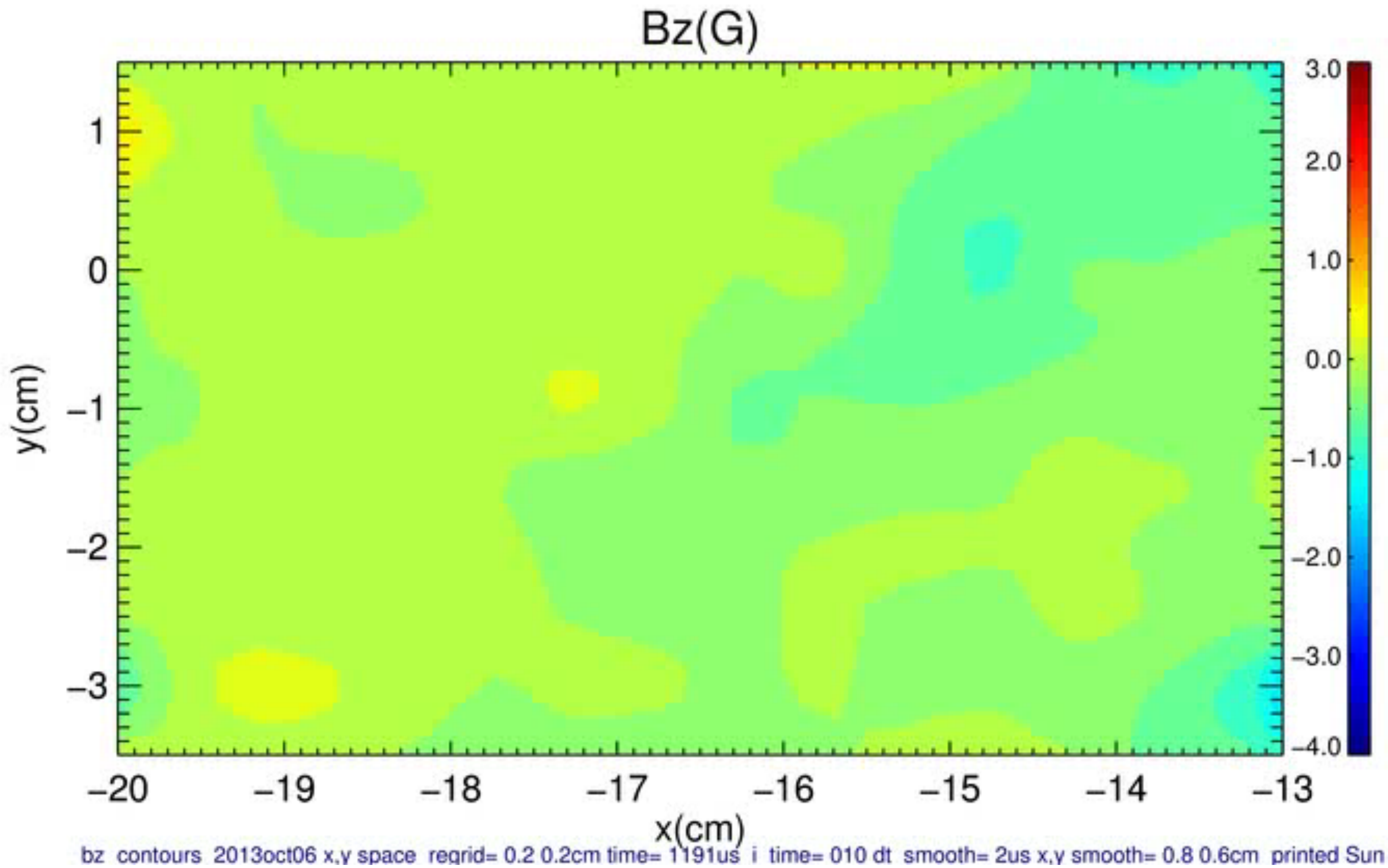


Radial force density balance

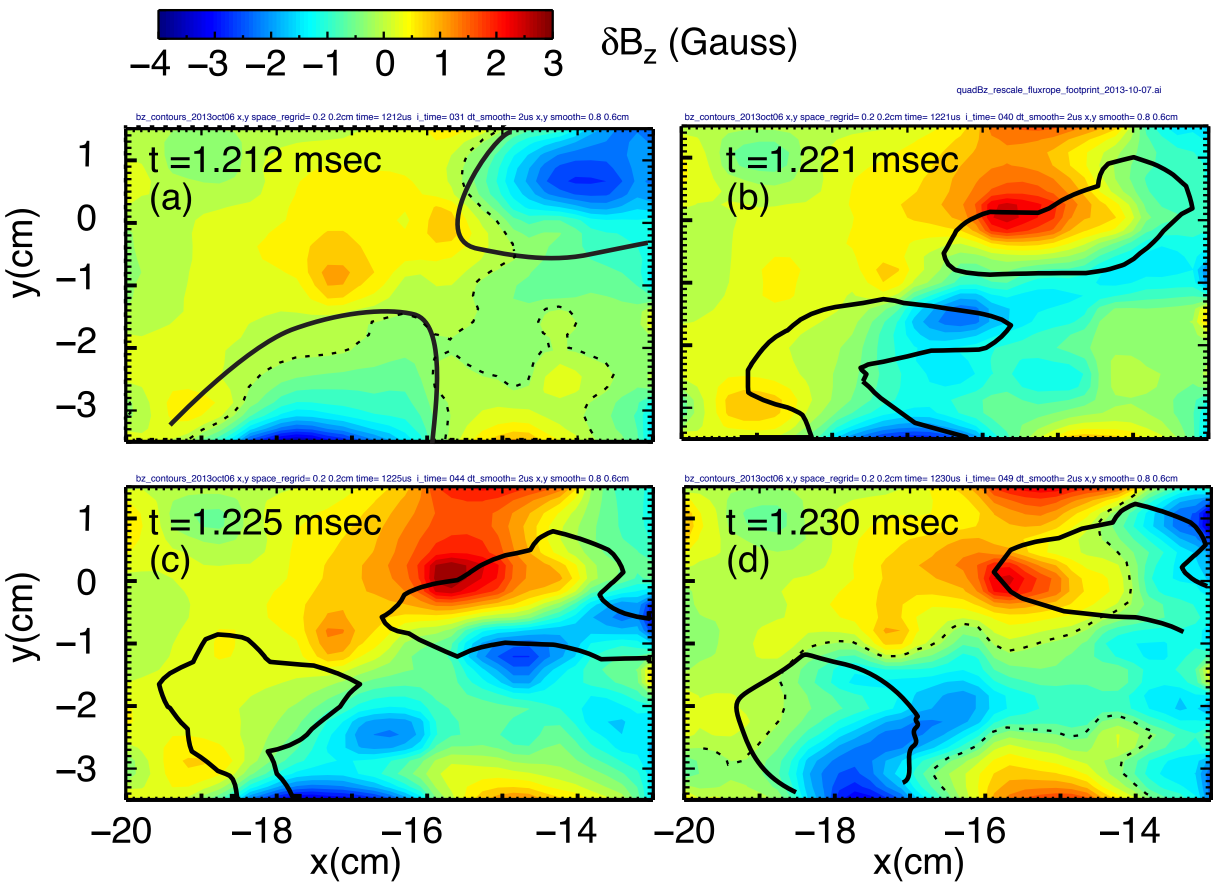
- $J \times B - \nabla P_e = 0 =$
- $J_q \times B_z - J_z \times B_q - \nabla P_e$

Smooth differentiable profiles

Quadrupole dB_z time history



Out of plane quadrupole δB_z field



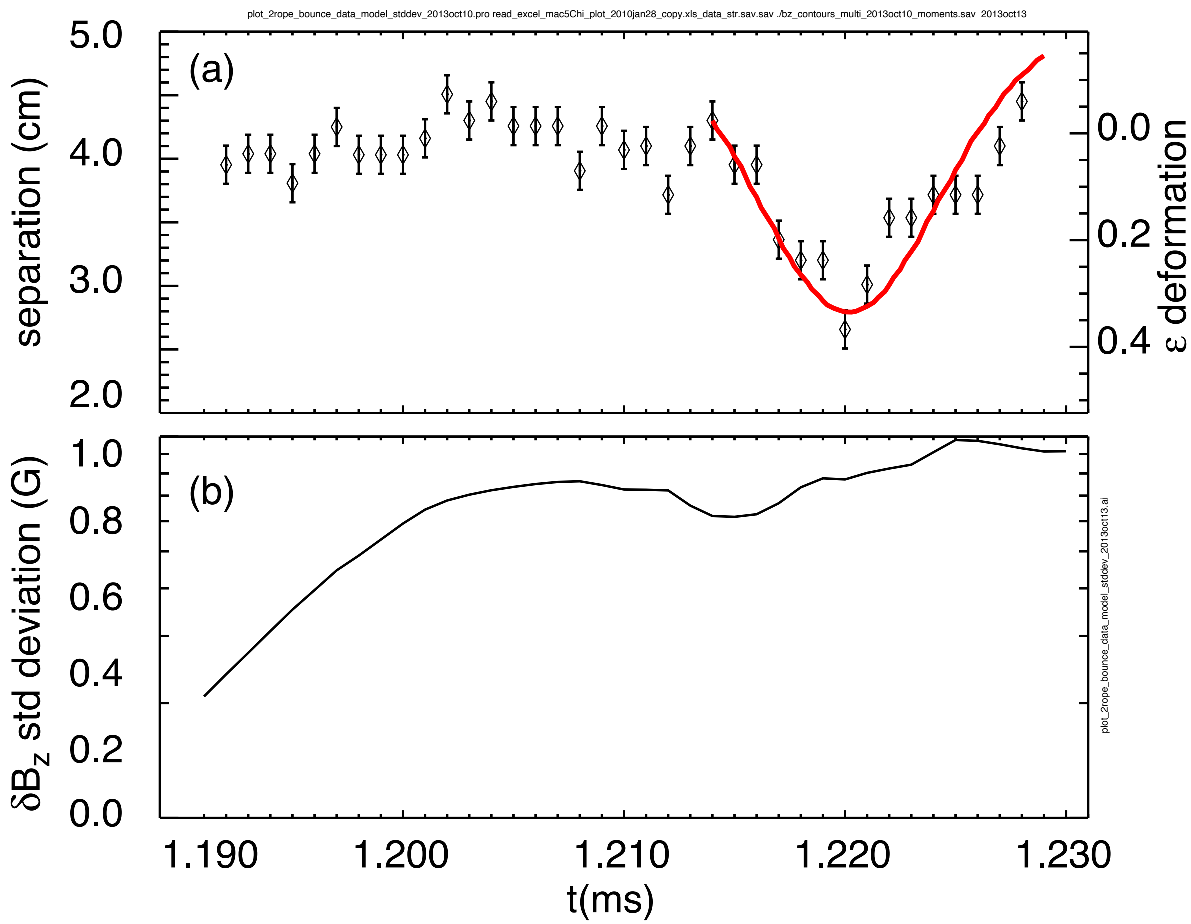
RSX data:

$-\partial B/\partial t$
$= \nabla \times E$
$= -\nabla \times v_e \times B$

For electron fluid v_e

Out-of-plane quadrupole magnetic field, z=50cm. Solid black contours for Jz, dashed for Bz=0 change of sign. electron inertial length $c/w_{pe} \approx$ 1-2mm.

Flux ropes mutually attract, collide, bounce

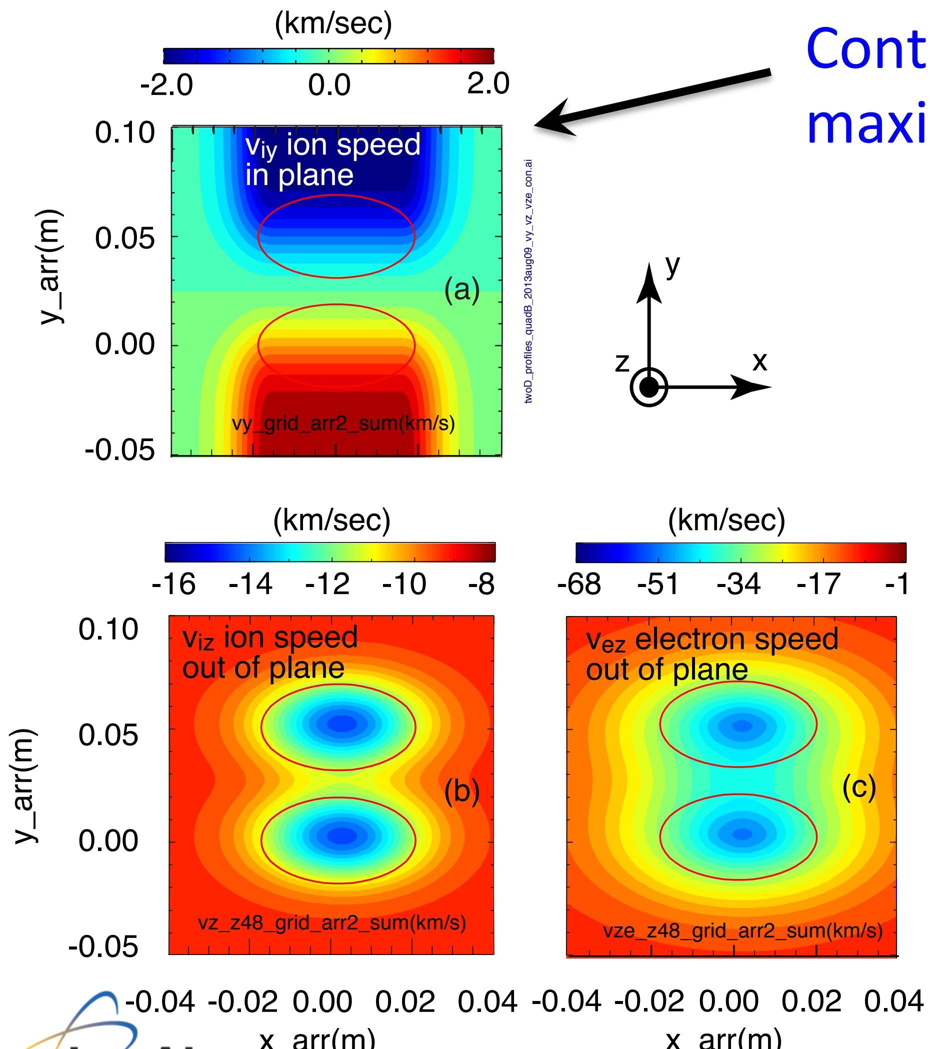


Radial force density balance

- $J \times B - \nabla P_e = 0 =$
- $J_q \times B_z - J_z \times B_q - \nabla P_e$

Smooth differentiable profiles

Two fluid ion and electron flow: $v_e = J - v_i/en$



Contours v_{iy}, x-y cutplane, z=48cm, maximum compression

Two flux ropes approach, collide, and compress each other

Red circles = flux ropes

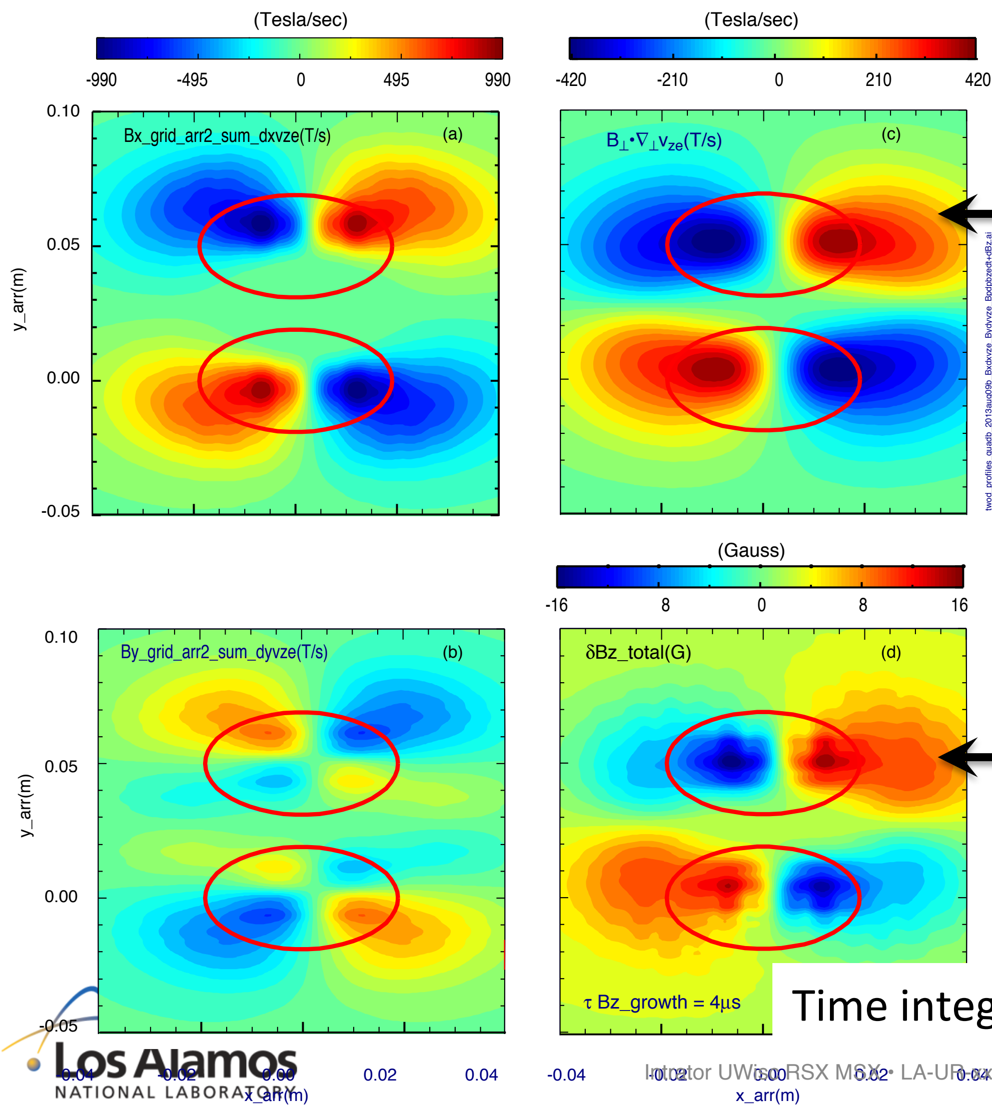
Max compression shown

Approach speed ion flow v_{iy}

- $v_{iy} \approx 0$ at stagnation
- $v_{iy} \approx \pm 2$km/sec flux rope core
- $v_{iz} \approx -15$km/sec flux rope core
- $v_{ez} \approx -50$km/sec flux rope core

$\nabla x v_e x B \rightarrow B_\perp \bullet \nabla_\perp v_{ez}$ contours in x-y plane

perpendicular shear in axial flow



∇ x v_e x B => $B_x \partial_x v_{ze}$ contours, x-y cutplane

electron flow = v_{ze}

Red circles = flux rope footprints

growth rate $\partial_t dB_z$

$-\ \partial B_z/\partial t = B_\perp \bullet \nabla_\perp v_{ez}$

Generation of dBz =

$B_\perp \bullet \nabla_\perp v_{ez} \bullet dt \approx 6G$ in 4µs

Time integrate

Induction of magnetic field? Electron MHD

- *$E + v_e \times B = 0$ … flux is frozen into electron fluid*
- $\nabla \times E = -\partial B/\partial t = -\nabla \times v_e \times B$
- focus on B_z & sheared flow: z component
- $\partial B_z/\partial t = -[\nabla_\perp \cdot v_{e\perp} + v_{e\perp} \cdot \nabla_\perp]B_z + \mathbf{B_\perp \cdot \nabla_\perp v_{ez}}$
- electron dynamics =>
  - **$B_\perp$ & sheared $\nabla_\perp v_{ez}$**
- Measure electron flows v_e?
  - *$J_z = (v_{iz} - v_{ez})en$: measure v_{iz} & J_z in the lab*

Characterize flux rope shear using screw pinch model

- Radial force density balance
  - $J \times B - \nabla P_e = 0 = J_q \times B_z - J_z \times B_q - \nabla P_e$
- Amperes law
  - $J = \nabla \times B/m_0 \Leftrightarrow m_0 J = -(\partial B_z/\partial r)e_q + (1/r)\partial/\partial r(rB_q)e_z$
  - Experimentally measure all terms & match with screw pinch equilibrium, integral energy form
- $v_{e\perp} << v_{ez} \approx c_S$

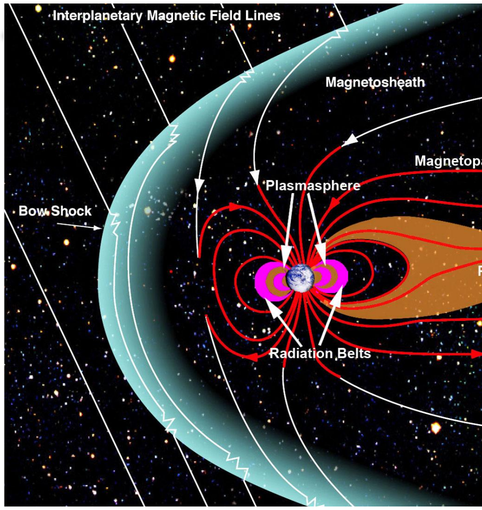
$$\left(P_e + \frac{B_\theta^2}{2\mu_0} + \frac{B_z^2}{2\mu_0} \right)\Bigg|_0^r + \int_0^r \frac{B_\theta^2}{\mu_0 r} dr = 0$$

EMHD accounts for coherent dynamo dB generation

- Generation and destruction of dB is more general than reconnection and dynamo
- Ideal MHD $E+u\,x\,B=0$ is not sufficient
  - Current density $J = ne(v_i - v_e)$
  - $E + v_e \times B = 0$ ⇔ ideal EMHD, B frozen to electrons

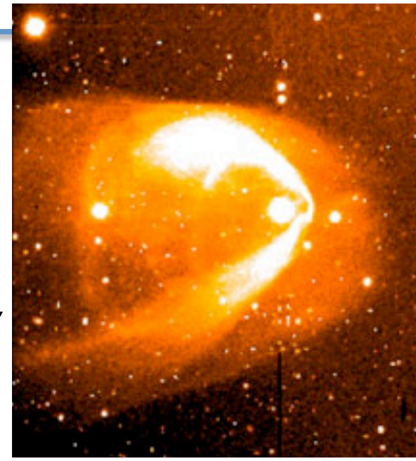
Magnetized Shock Experiment

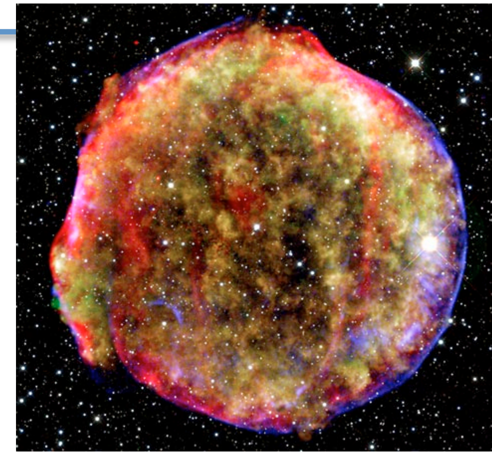
Collisionless shocks: ubiquitous & poorly understood.



Planetary bow shocks

Heliosphere/ Interstellar medium





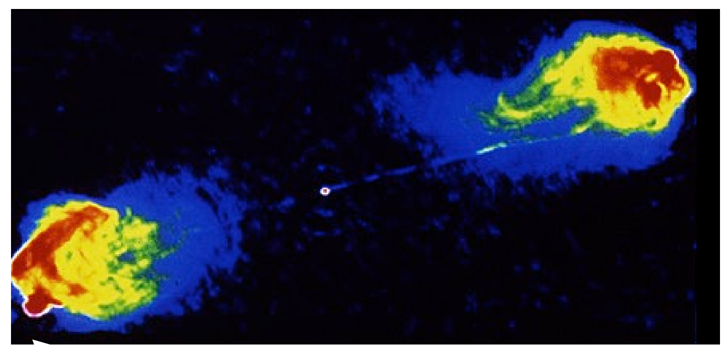
Supernova remnants

Shock thickness << collision mean free path.

Transition mediated by collective effects rather than particle collisions.

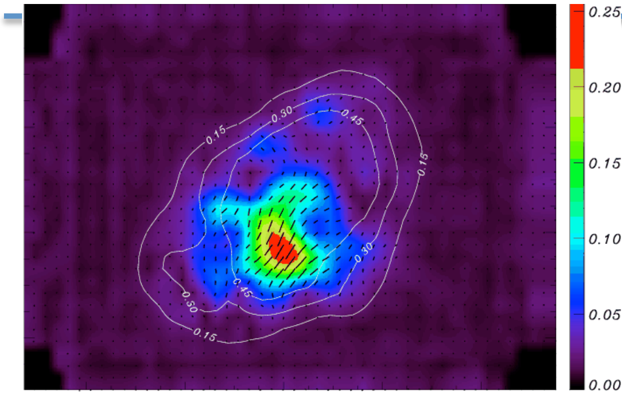
Magnetic field plays an important role.

Large flow speeds and length scales lead to high Mach (sonic, Alfvén), Reynolds (fluid, magnetic).



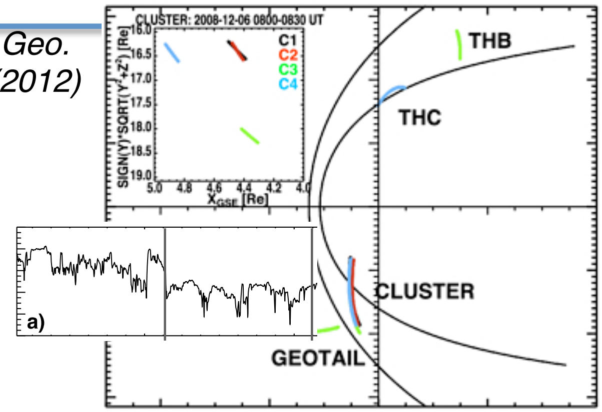
AGN, relativistic jets

Historically only 3 methods of investigation: need experiments!



Aumont, et. al., Astron. & Astro., ***514****, A70 (2010)*

Gutynska, et. al., J. Geo. Res., ***117****, A04214 (2012)*

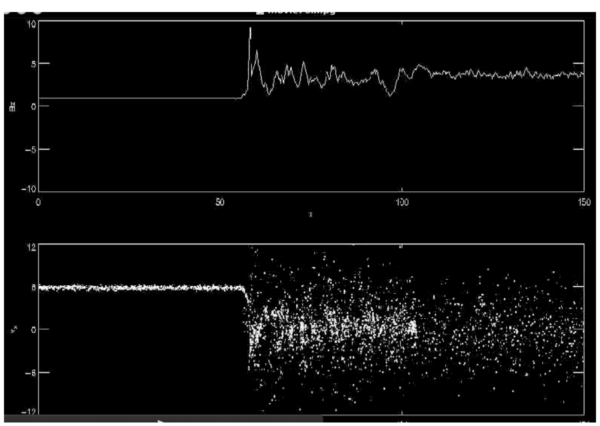


Astronomical observations

Advantages: largest range of parameters.
Limitations: light only, one viewing angle, low resolution, snapshot in time.

Spacecraft measurements

Advantages: high spatial and temporal resolution.
Limitations: limited to spacecraft trajectories, incomplete data.



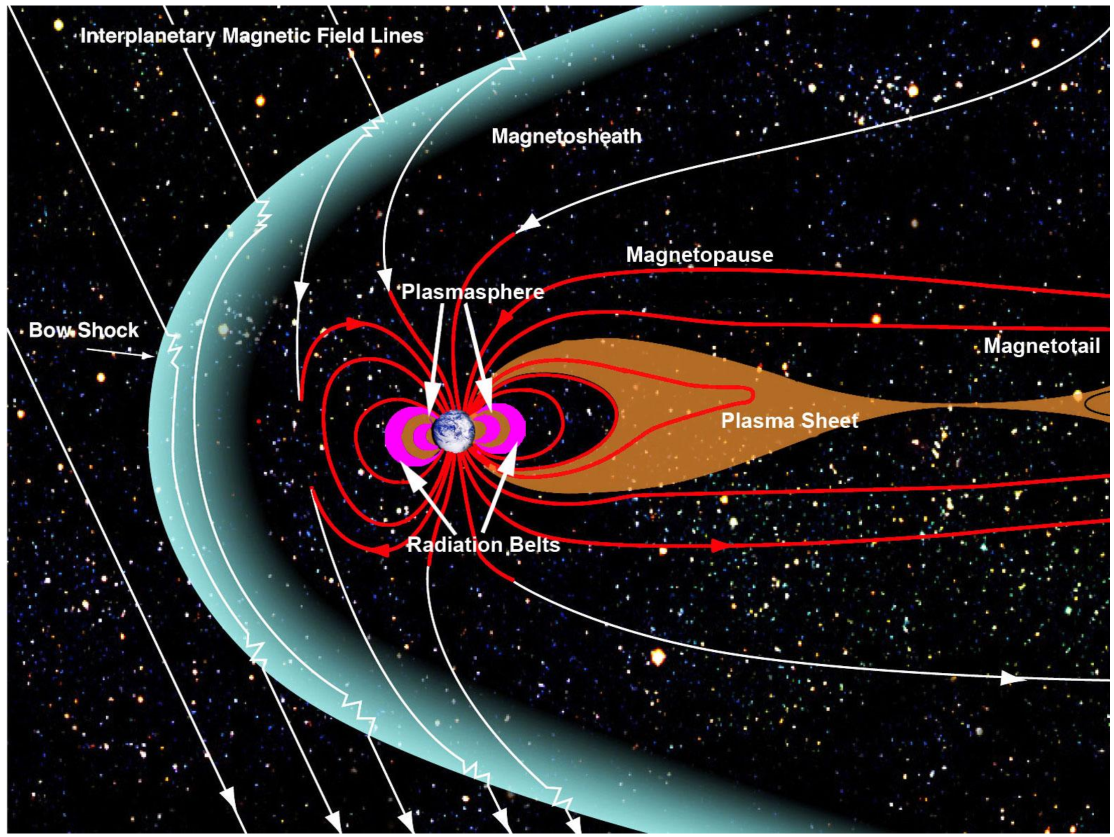
MSX hybrid simulation

Simulation

Advantages: adjustable parameters, “perfect” diagnostics.
Limitations: cannot capture all physics.

Why a laboratory magnetized collisionless shock?

- Example: Earth bowshock varies from perpendicular to oblique
- $M_A \approx$ 5-10
- Generally accepted paradigm (Diffusive Shock Acceleration) has never been tested
- There is no laboratory data



Magnetized Shock Experiment MSX

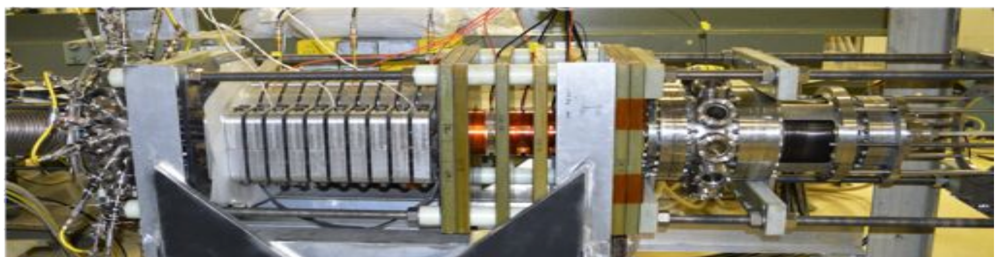
T.P. Intrator
T.E. Weber
R.J. Smith

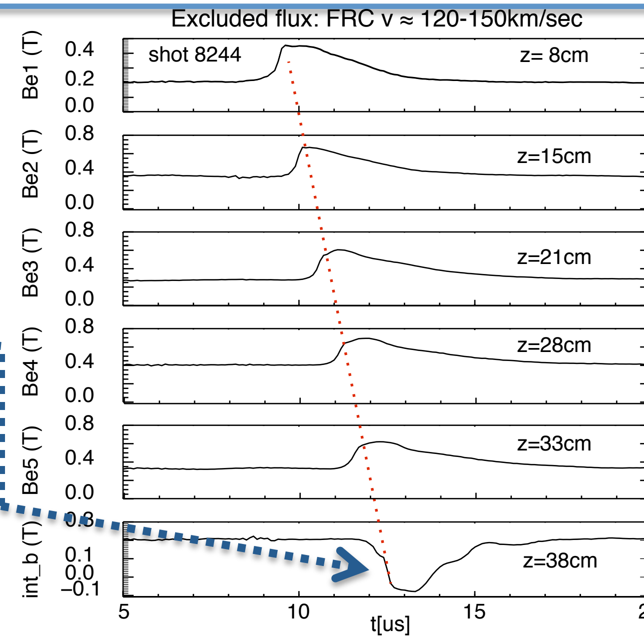
Super Alfvenic FRC $M_A \approx 3$, *threshold for critical shock* onset

Perpendicular, parallel, oblique shocks

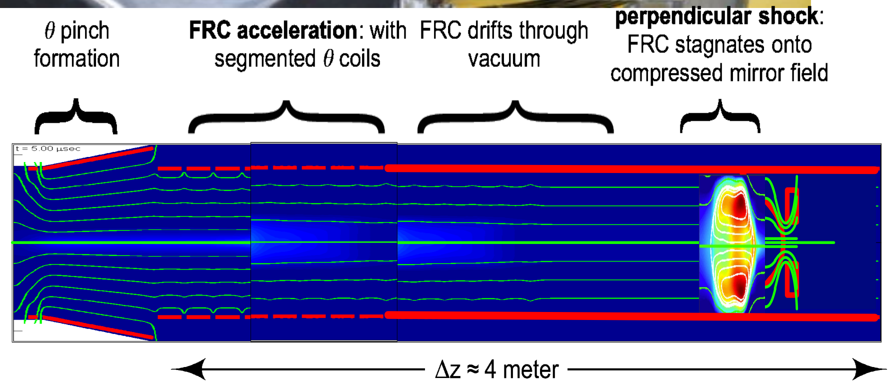
Large size >> ion inertial & gyro size

internal probe measures field reversal





external B probe array data shows FRC speed



Perpendicular shock
propagates backward through FRC

MSX fast, high flux FRC (magnetic signature)

Excluded flux radius = 3.7 cm (x_s=0.75)

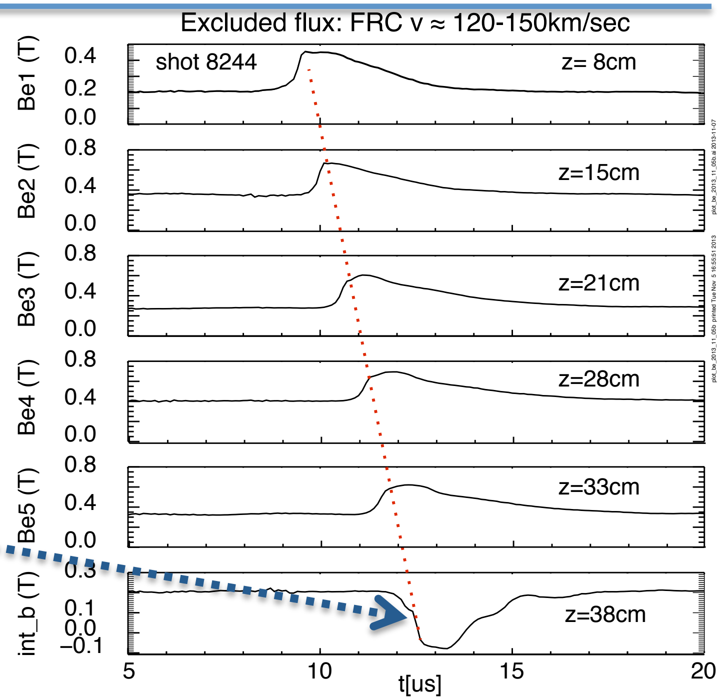
Plasmoid velocity = 120-150 km/s

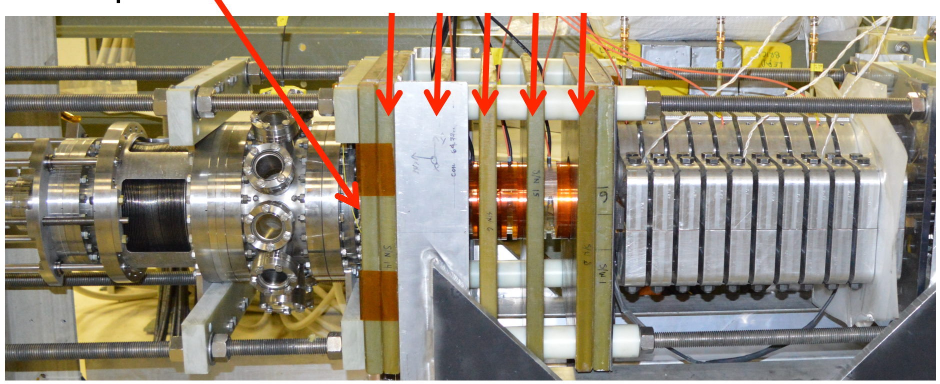
Existing FRC $M_A \approx 3$, *threshold for critical shock* onset

Average beta $\langle\beta\rangle \approx 0.75$

internal probe measures field reversal

Mirror coil is ready for install Nov 2013

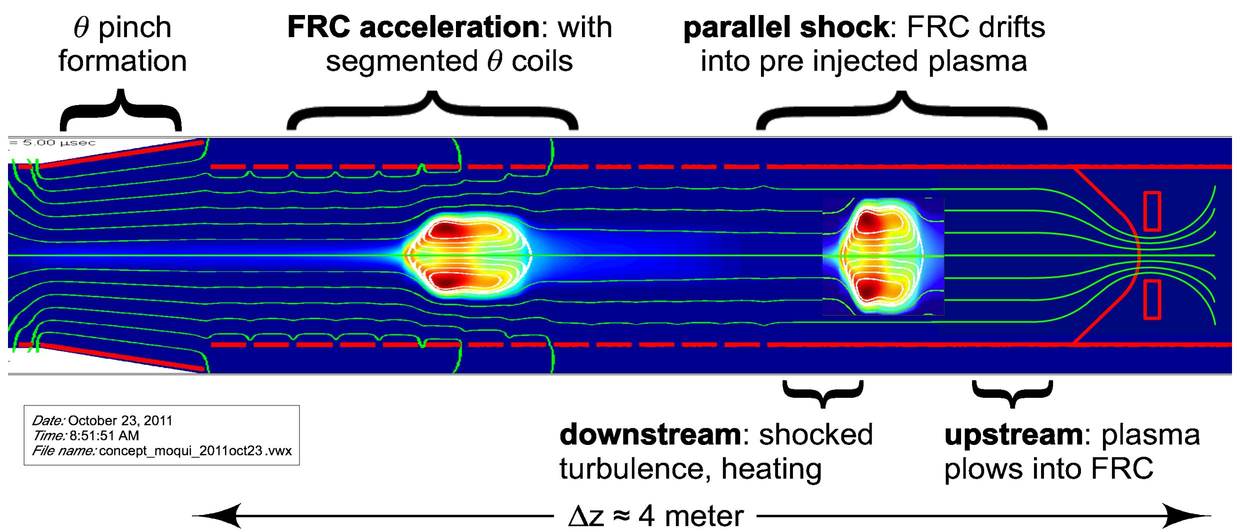




(above) external B probe array data showing a high-β plasmoid traveling downstream, (left) diagram of probe locations on MSX

<u>Come see the posters and talk!</u>
Weber: GP8.00123 Tuesday AM
Smith: GP8.00129 Tuesday AM
Intrator: NO5.00004 Wednesday AM

Magnetized Shock Experiment (MSX)



After formation and ejection, the FRC is accelerated to high velocities using peristaltically pulsed coils, then impacts against a target.

Form Field Reversed Configuration (FRC) plasmoid in conical θ-pinch.

Eject FRC from formation region and accelerate to high velocity.

Stagnate against a target plasma or magnetic field.

Advantages over previous experiments:

potentially very high power

possible long length scales for shock propagation

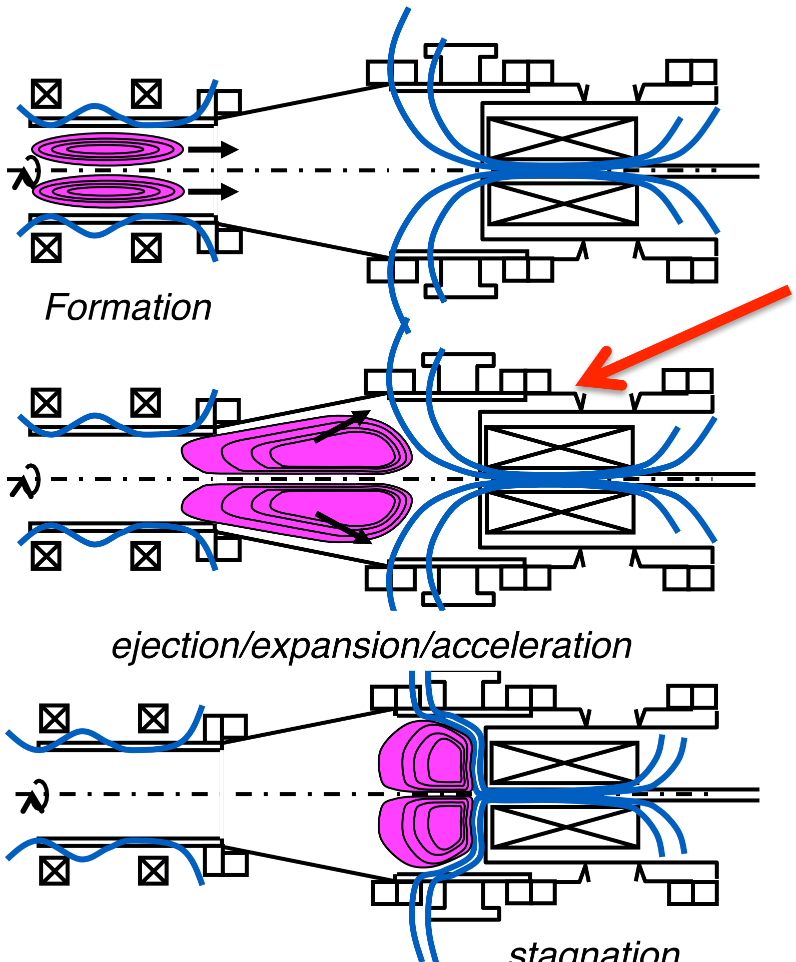
macroscopic targets (cm scale)

plasma is magnetized

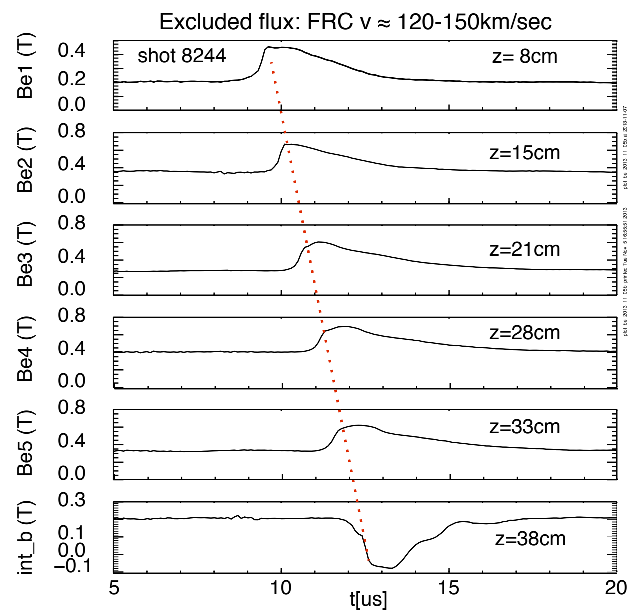
DSA "box" size smaller than experiment

possible driver for magnetized high energy-density physics

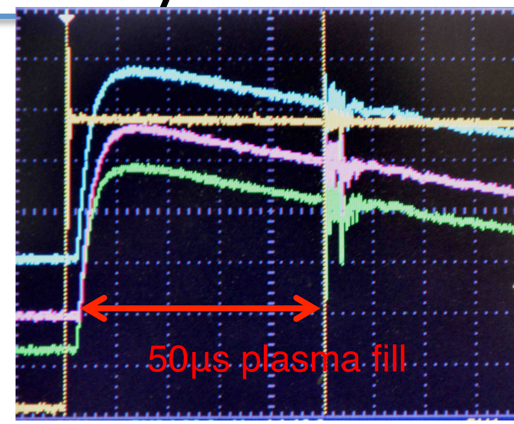
Initial experiments use FRC piston



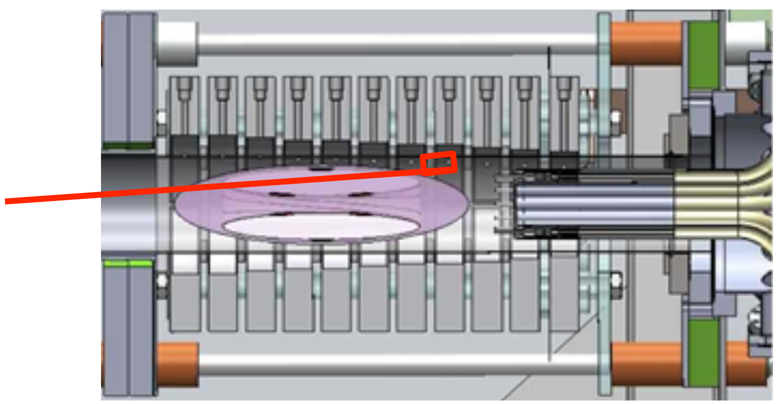
- Existing FRC $M_A \approx 3$
- Threshold for critical shock onset
- accelerator stage is next
- Install mirror coil Nov 2013



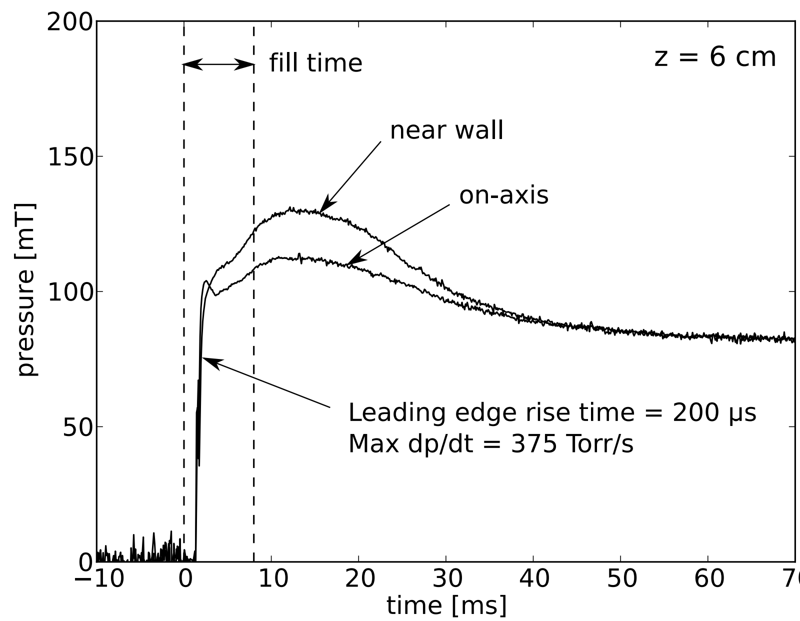
Improved FRC formation using dynamic gas fill and annular plasma gun array.



Inject annular plasma ring prior to ringing-θ pre-ionization to improve ionization.
Puff-fill preserves hard vacuum downstream.
Custom miniature fast ion gauge to determine neutral fill density and distribution
Self-similar fill observed.



3D sampling via tilting feedthrough



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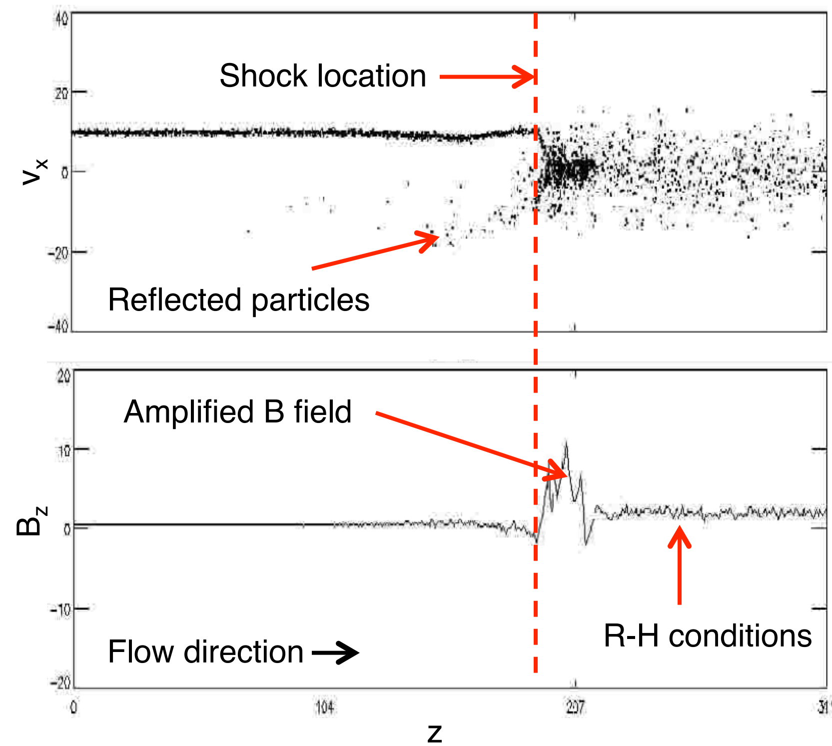
Simulations help investigate non-fluid physics, experimental design and diagnostics interpretation.

MOQUI: 2D resistive MHD code designed to model FRCs

- Experiment design
- Interpretation of experimental data
- Final speed as input for hybrid code



1D hybrid simulation of oblique shock.

1D hybrid code (D. Winske)

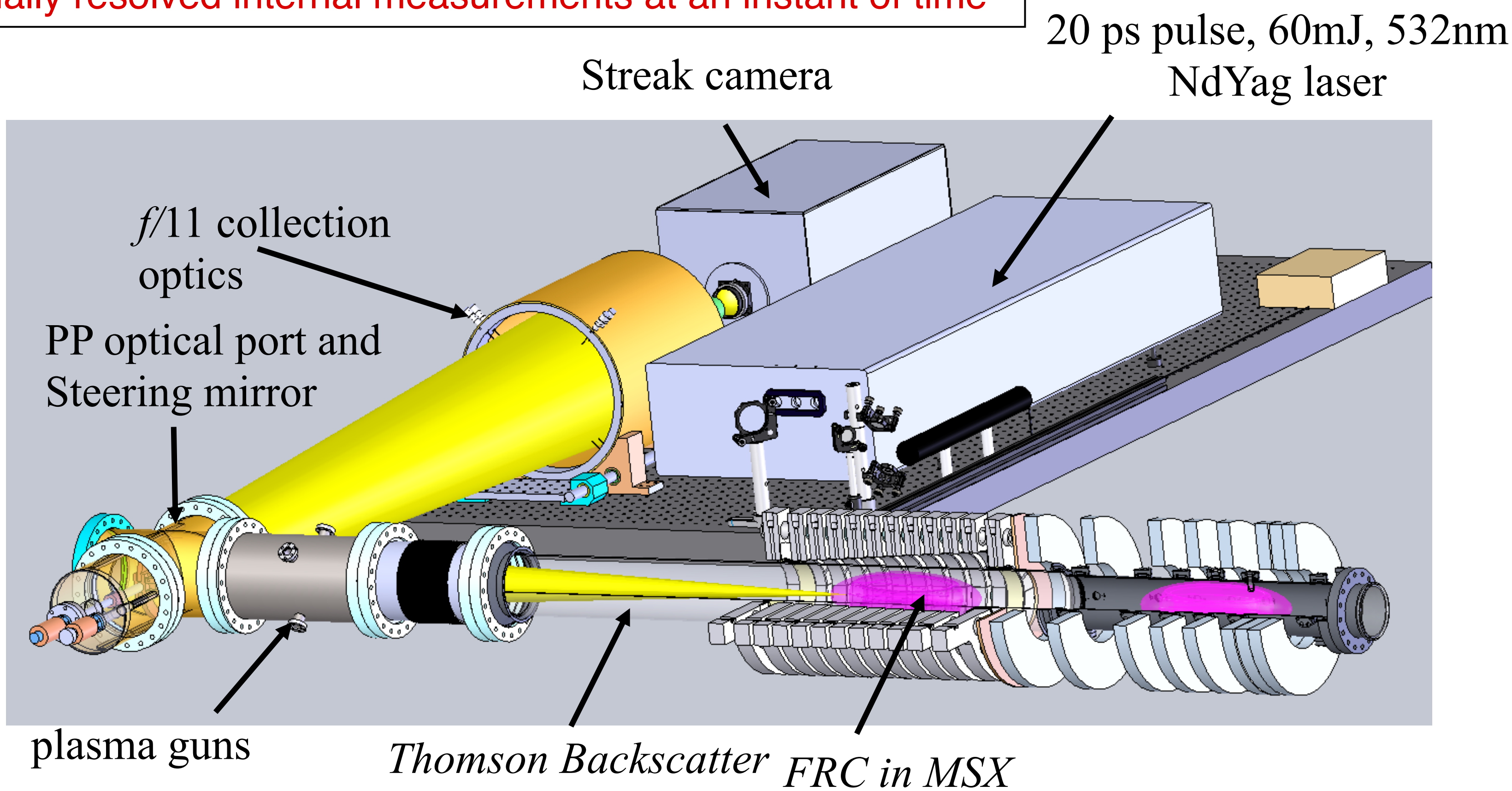
- Identify interesting parameter regimes and micro-physics
- Experiment design
- Interpret experimental data

Future: multidimensional hybrid simulations

- Investigate difficult to interpret 2-3D experimental dynamics.

Pulsed Polarimeter Instrument on MSX

Measures electron temperature, density, magnetic field
Spatially resolved internal measurements at an instant of time

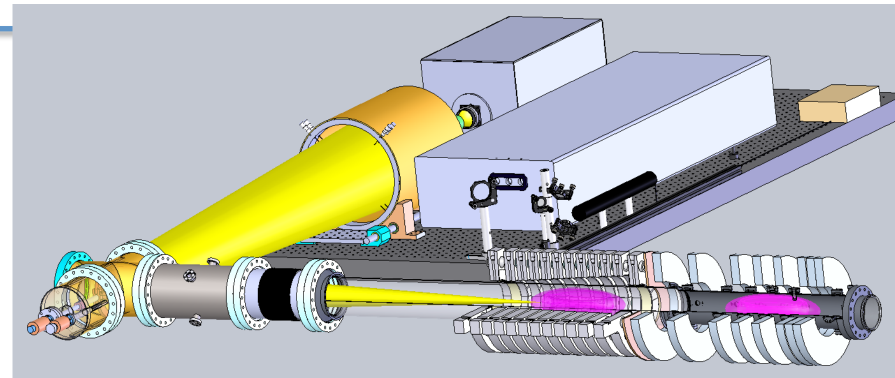


Faraday-Thomson LIDAR to measure T_e, n_e, and B ll k

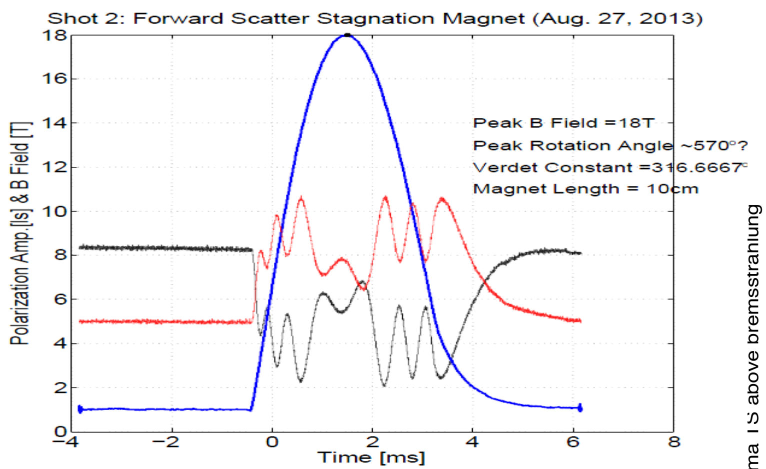
Spatially resolved via time of flight and beam pointing.

Time resolved via short sampling period.

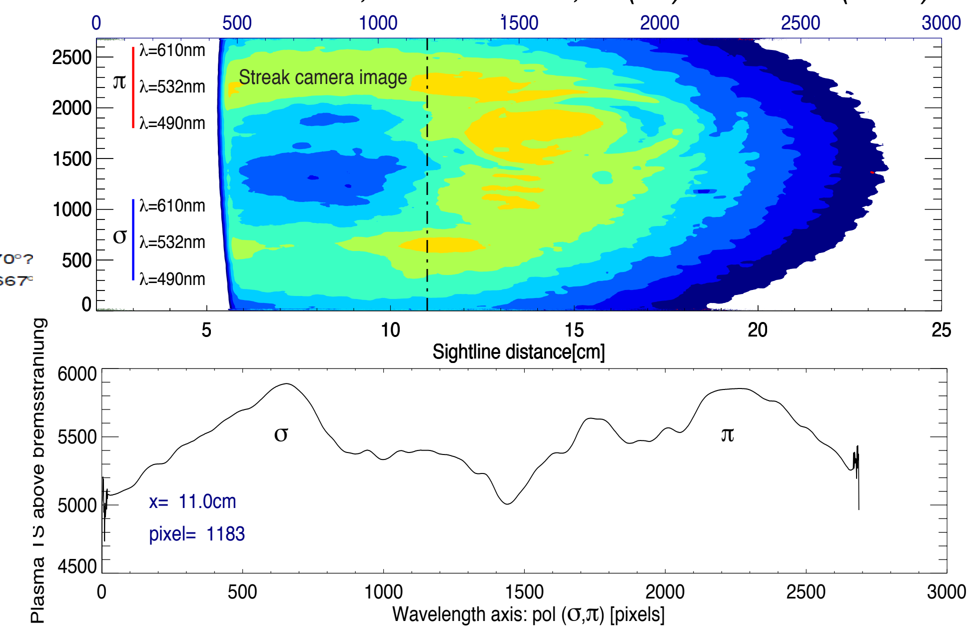
Also developing in-fiber magnetic sensing (see poster GP8.00119, Smith, et. al.)



R.J. Smith, Rev. Sci. Insr., 70(10) 10E703-8 (2008)



In-fiber Faraday rotation



First plasma data Dec. 2012

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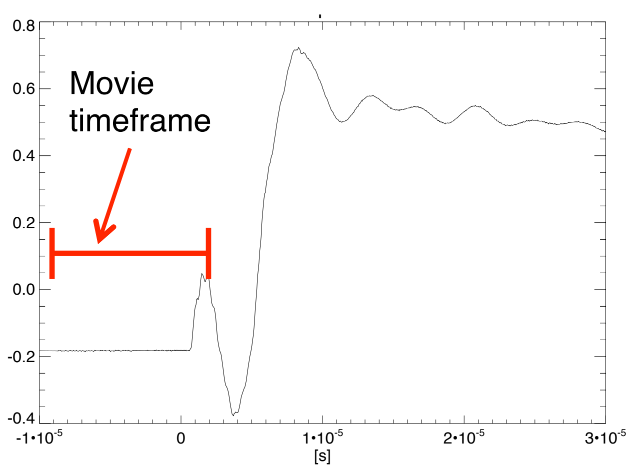
Conical ringing θ-pinch pre-ionization

Ionize neutral gas in θ-coil prior to field-reversal.

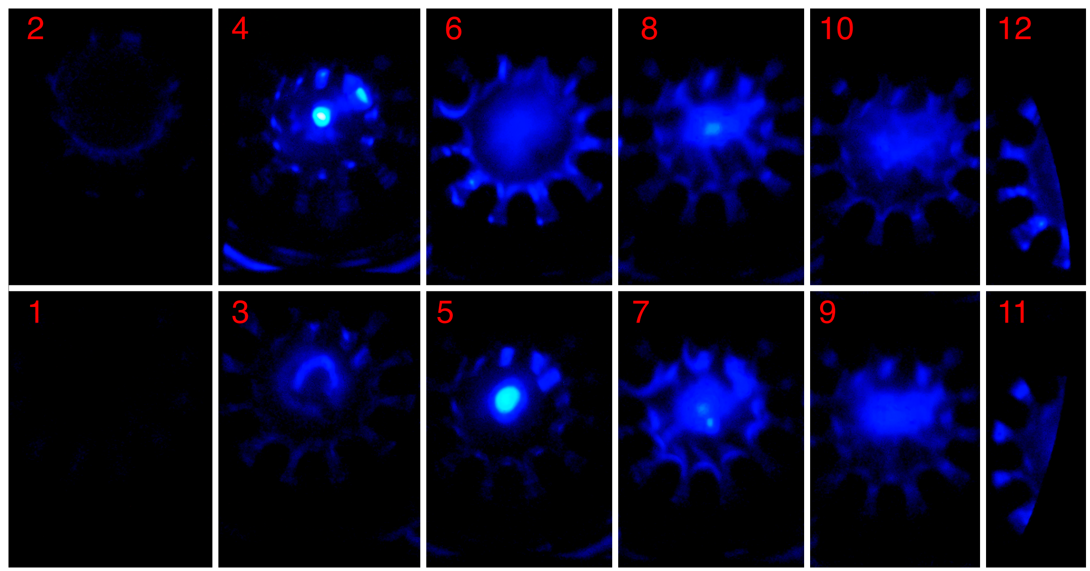
Azimuthal E-field accelerates free electrons, lower axial field = large electron energy gain due to larger gyroradius.

Need zero-crossing to ionize, problematic in conical geometry (plasma is ejected)

Ionization possible without zero-crossing when plasma guns are used.



Axial field in θ-coil



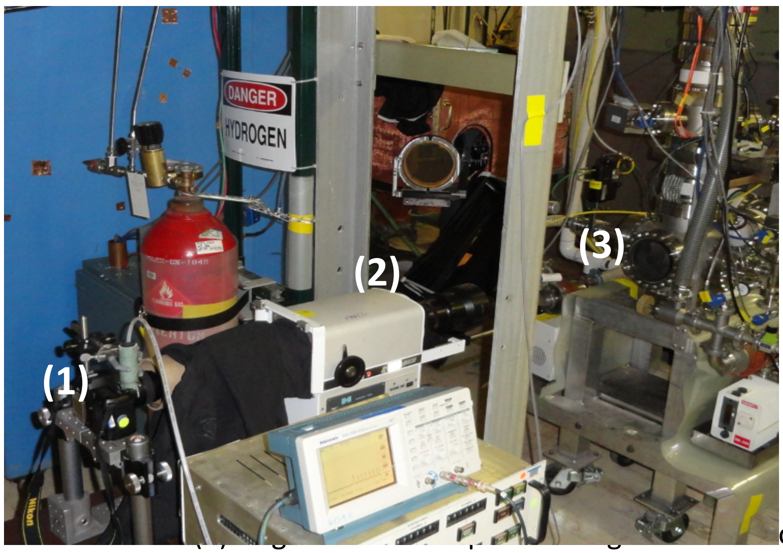
Imacon framing camera move, also see student poster GP8.00125 Boguski, et. al.

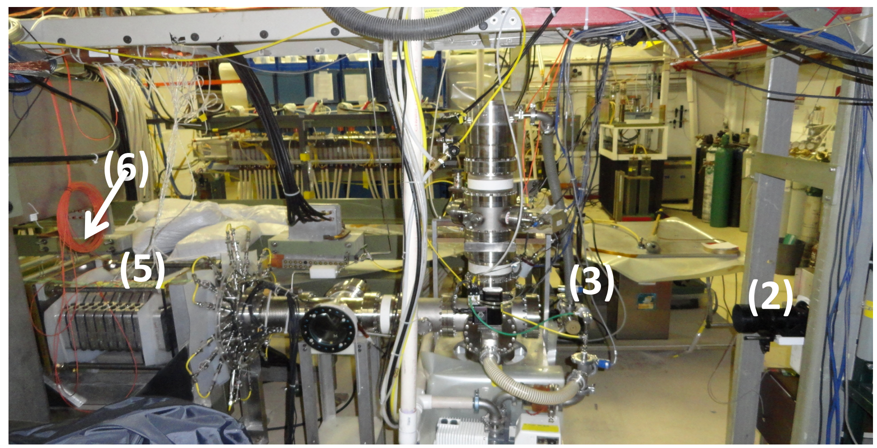
A framing camera can provide details of different phases of the experiment, such as:

- Plasma gun firing dynamics
- Field reversal and FRC formation dynamics
- FRC shape and instability growth

The framing camera in use is a Hadland Photonics Imacon 790

A Nikon D70 captures images from the Imacon phosophor screen using a pneumatic trigger





on phosphor screen

(2): Imacon 790 framing camera

(3): Viewing window into experiment

(4): Plasma Guns

(5): FRC formation region

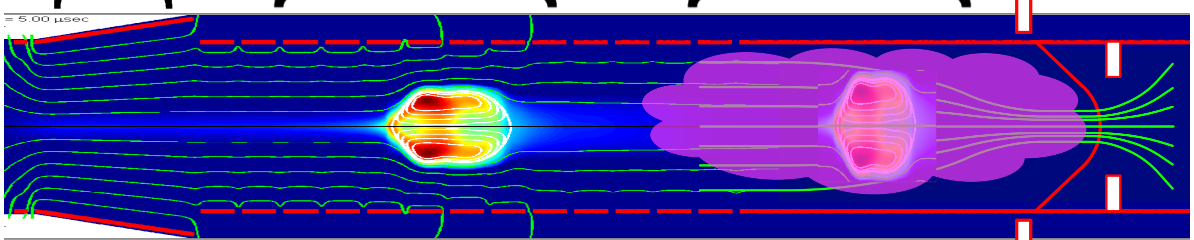
(6): Translation region

Experimental configuration allows arbitrary propagation angle $k \parallel B$ to $k \perp B$.

θ pinch formation

FRC acceleration: with segmented θ coils

oblique shock: FRC drifts into pre injected plasma



concept_moqui_2011oct23.vwx 2011oct23 concept_moqui_2011oct23_oblique_shock.pdf

Oblique shocks

gently increasing axial field

piston decoupled from target plasma

shock frame →

downstream: shocked turbulence, heating

upstream: plasma plows into FRC

MSX conceptual layout

θ pinch formation

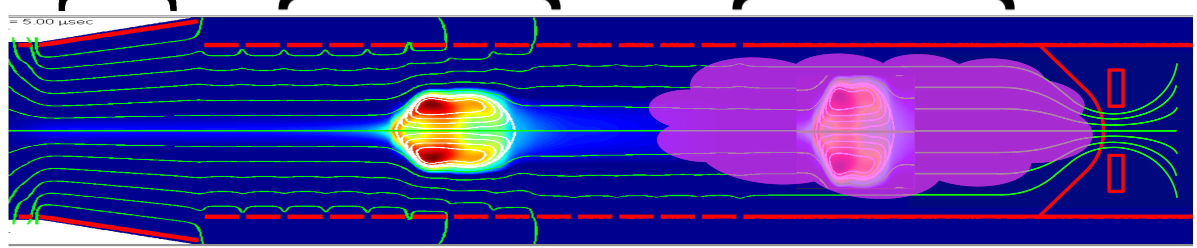
FRC acceleration: with segmented θ coils

parallel shock: FRC drifts into pre injected plasma

Parallel shock

constant axial field

piston decoupled from target plasma

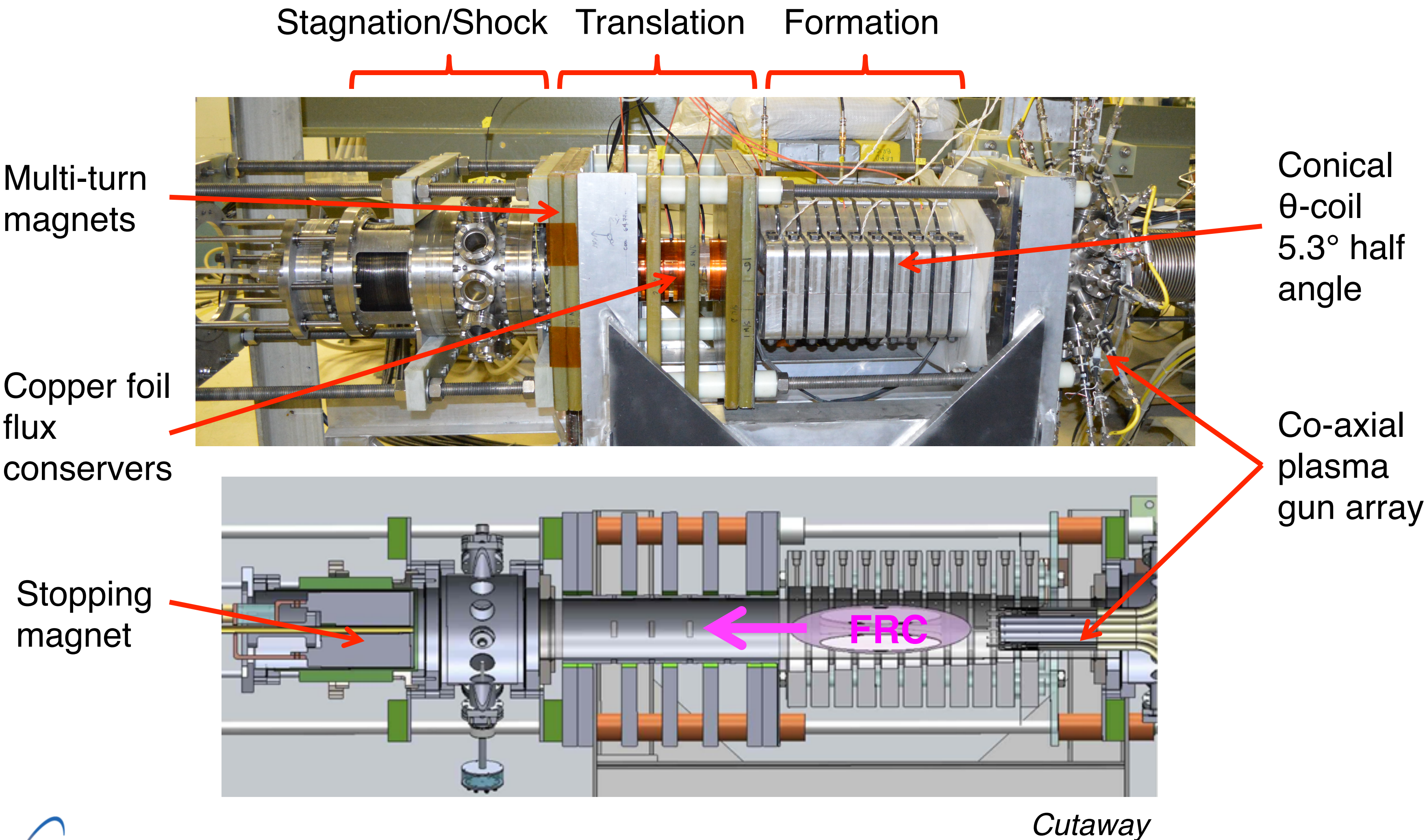


Date: October 23, 2011
Time: 8:51:51 AM
File name: concept_moqui_2011oct23.vwx

downstream: shocked turbulence, heating

upstream: plasma plows into FRC

MSX experimental layout

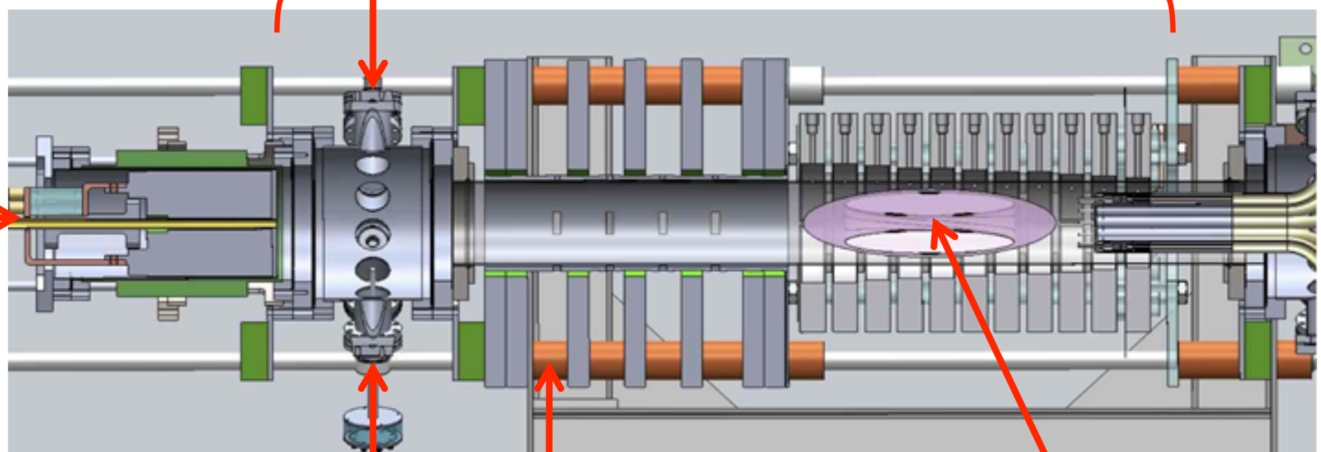


Diagnostics

Internal magnetic probes (near wall)
Retro-reflectors for axial interferometry*

External magnetic probes
Visible light (fiber) array
Axial backscatter fiber (B)*

Pulsed Faraday-Thomson LIDAR (end-on)*
Framing camera
Axial interferometer*



Energy analyzer*

Pulsed Faraday-Thomson LIDAR (side-on)*
Framing/streak imaging
Time-resolved spectroscopy*

Multi-chord interferometer
Fiber interferometer*

Fast ion gauge (no plasma)
Internal magnetic probe
Mach probe

** indicates future diagnostic*

Conclusions

- RSX
  - One flux rope kink metastable
  - Two flux ropes bounce, shear flow dynamo
- MSX
  - Unique magnetized collisionless shock

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 #