Three-dimensional magnetic field line reconnection involving flux ropes and Alfvén waves

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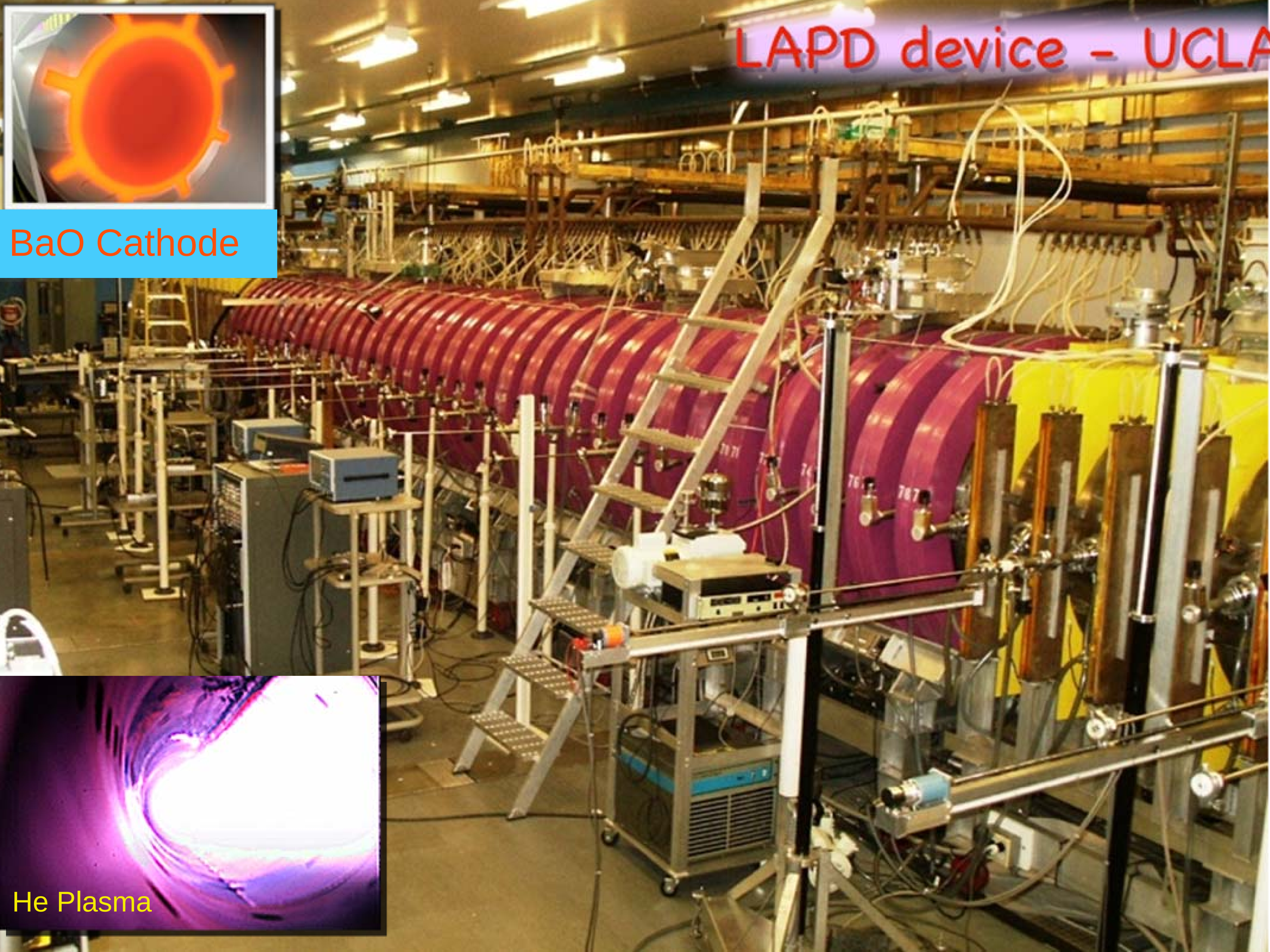
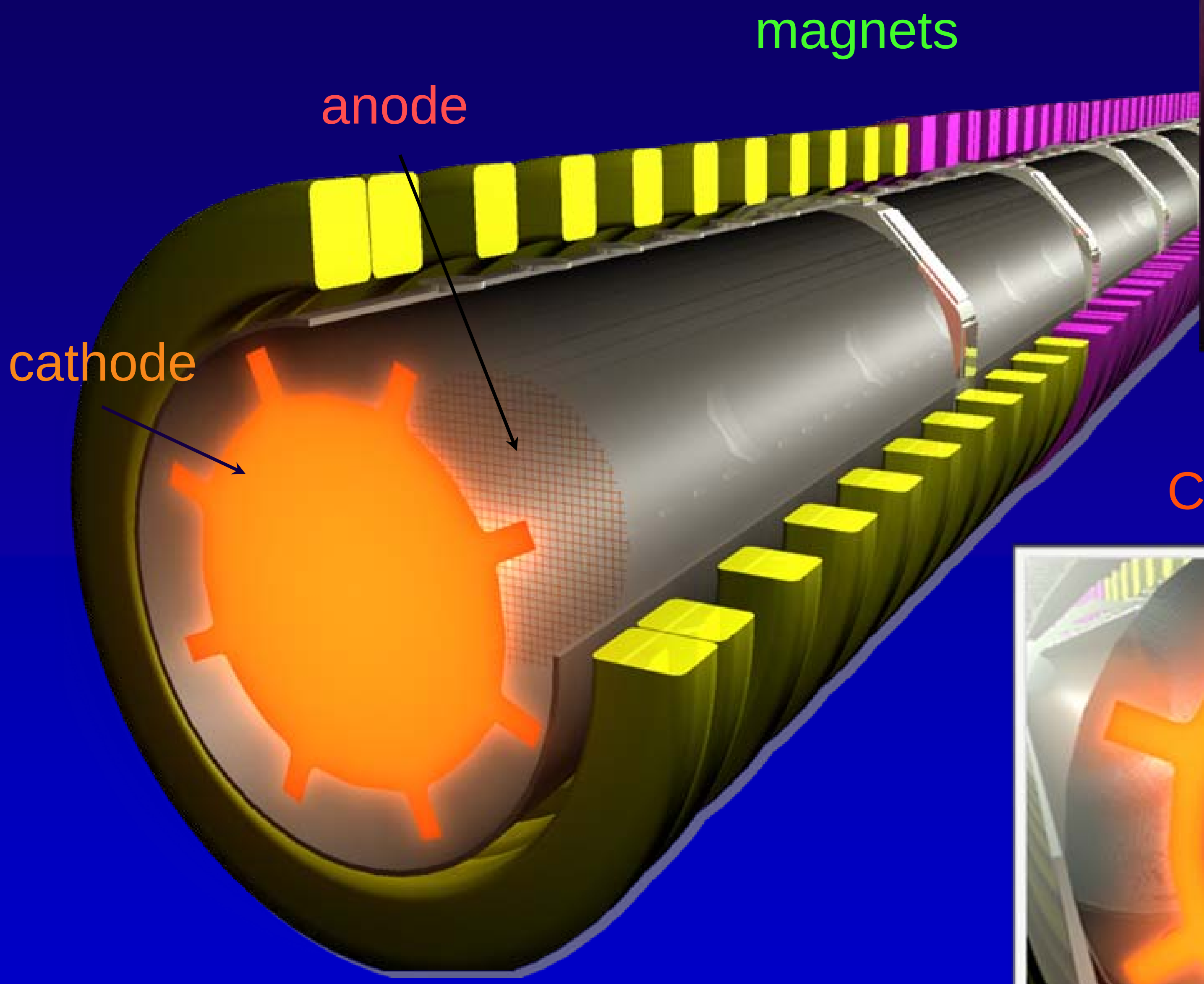
Recurrent questions in Space and Astrophysics

- Magnetic field generation (magnetic helicity)
- Relaxation of complex field geometries into simpler ones
- Magnetic Field Line Reconnection (2D, 3D?)
- role of guide field in reconnection
- Generation and interaction of magnetic flux ropes
- Role of waves (whistlers and Alfvén)
- Bursty verses steady phenomena (plasma instabilities)

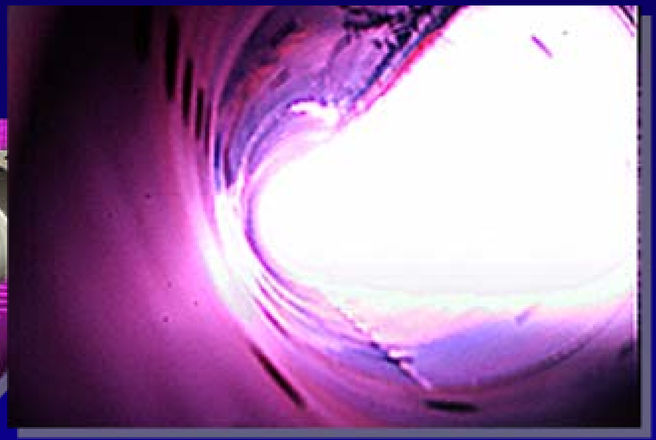
Can we learn something from laboratory experiments?


LAPD device – UCLA
BaO Cathode
He Plasma

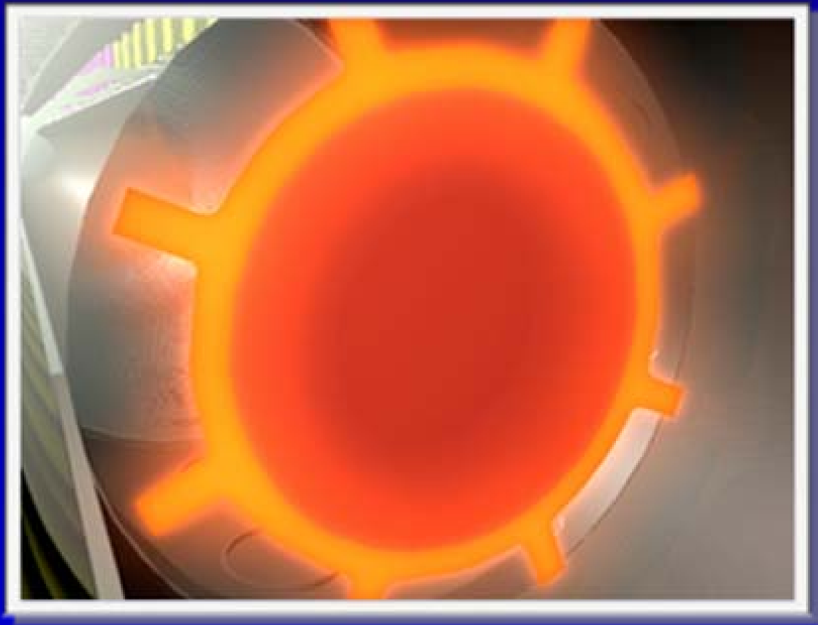
Plasma Production



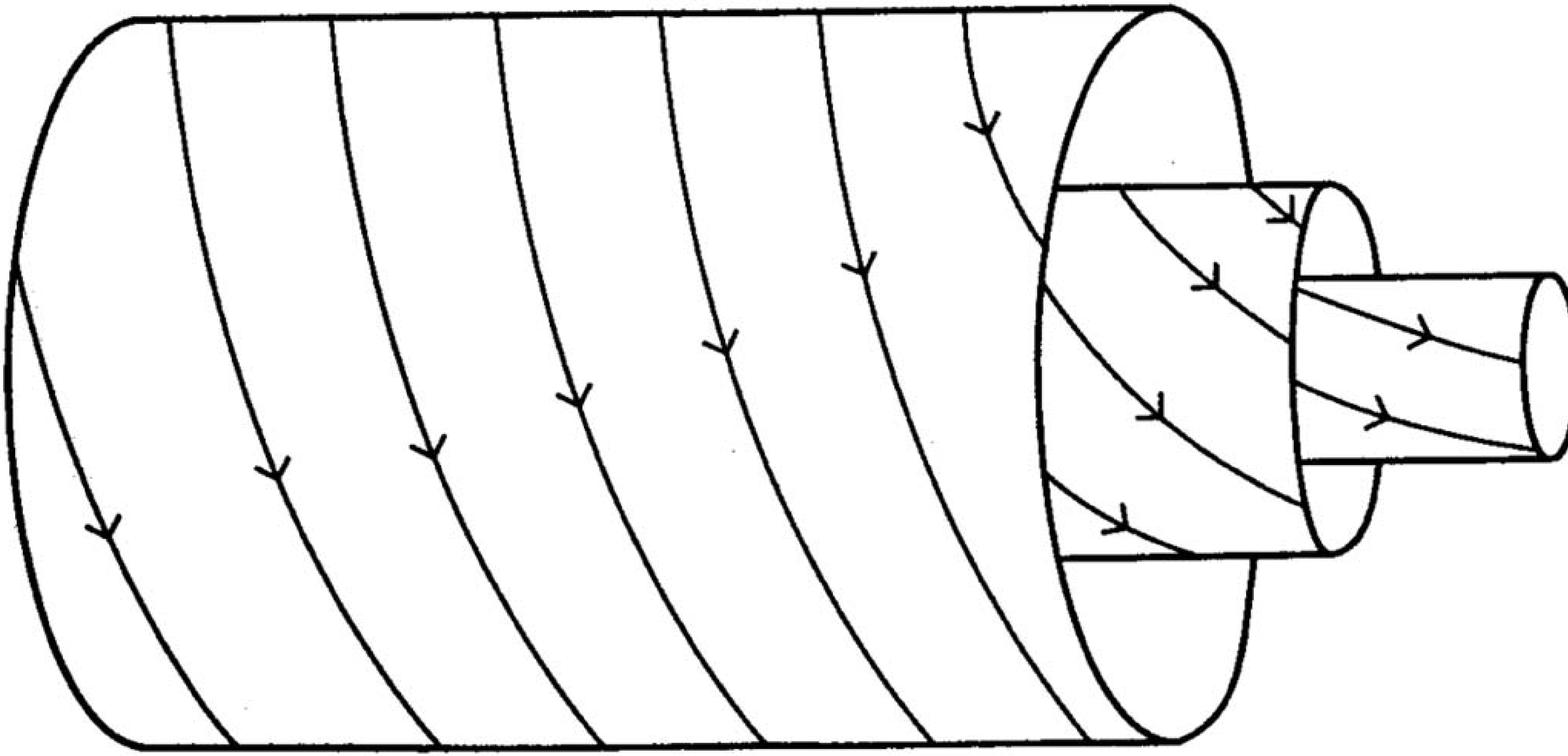
He Plasma



Cathode - Anode

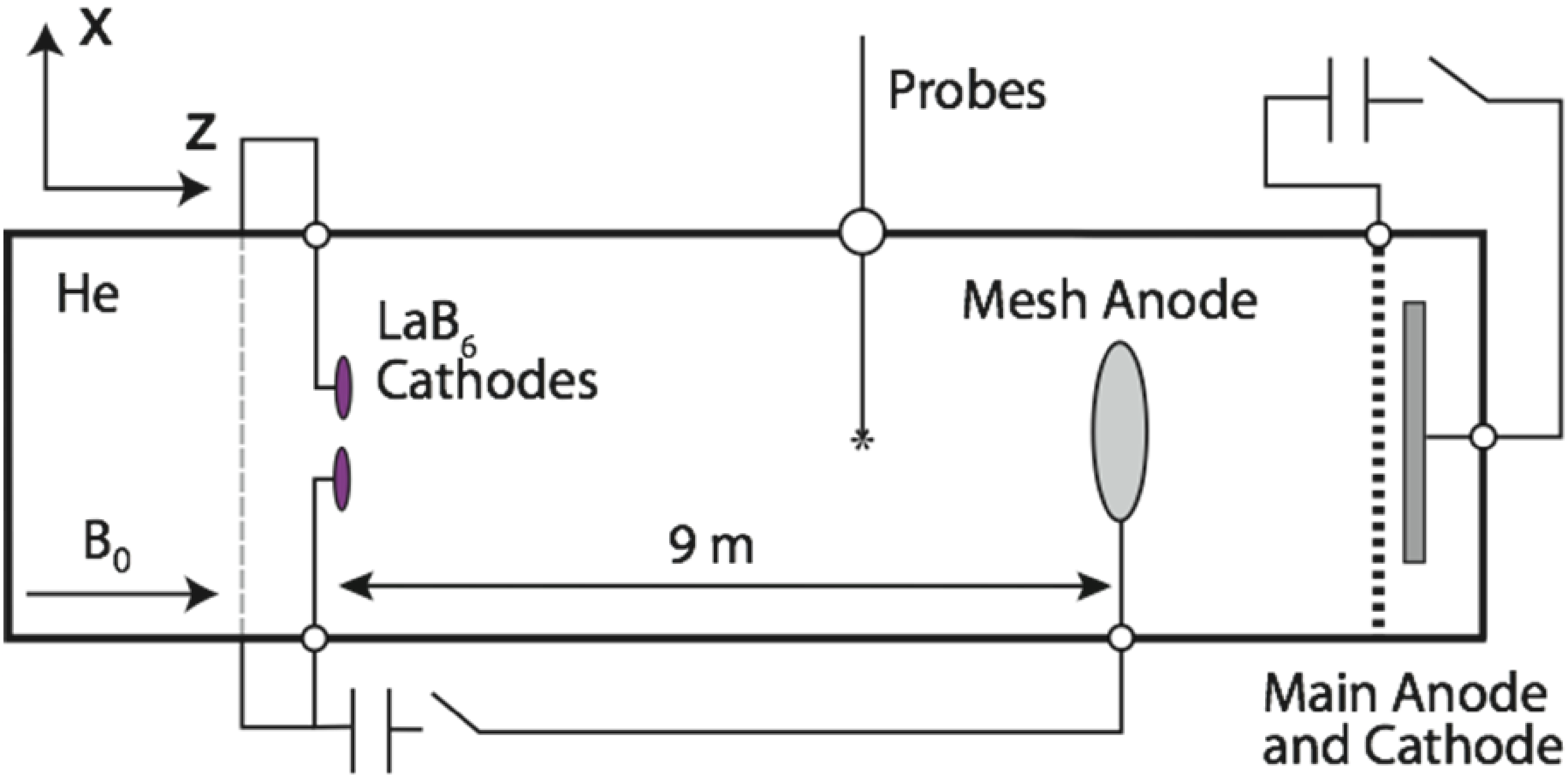


Magnetic Flux Ropes



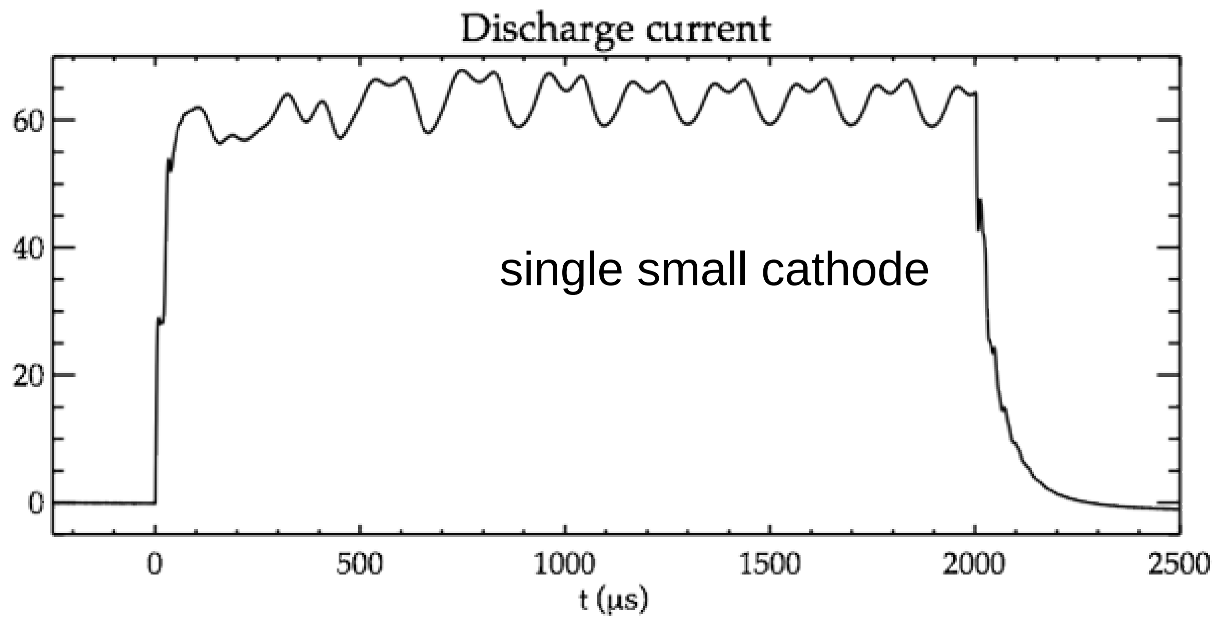
Making Flux Ropes

$\delta x = \delta y = 3mm$, $\delta z = 64$ cm, $\delta t = 40$ ns



$B_{0z} = 270$ G

data acquired: 12 planes (20,000 spatial locations)



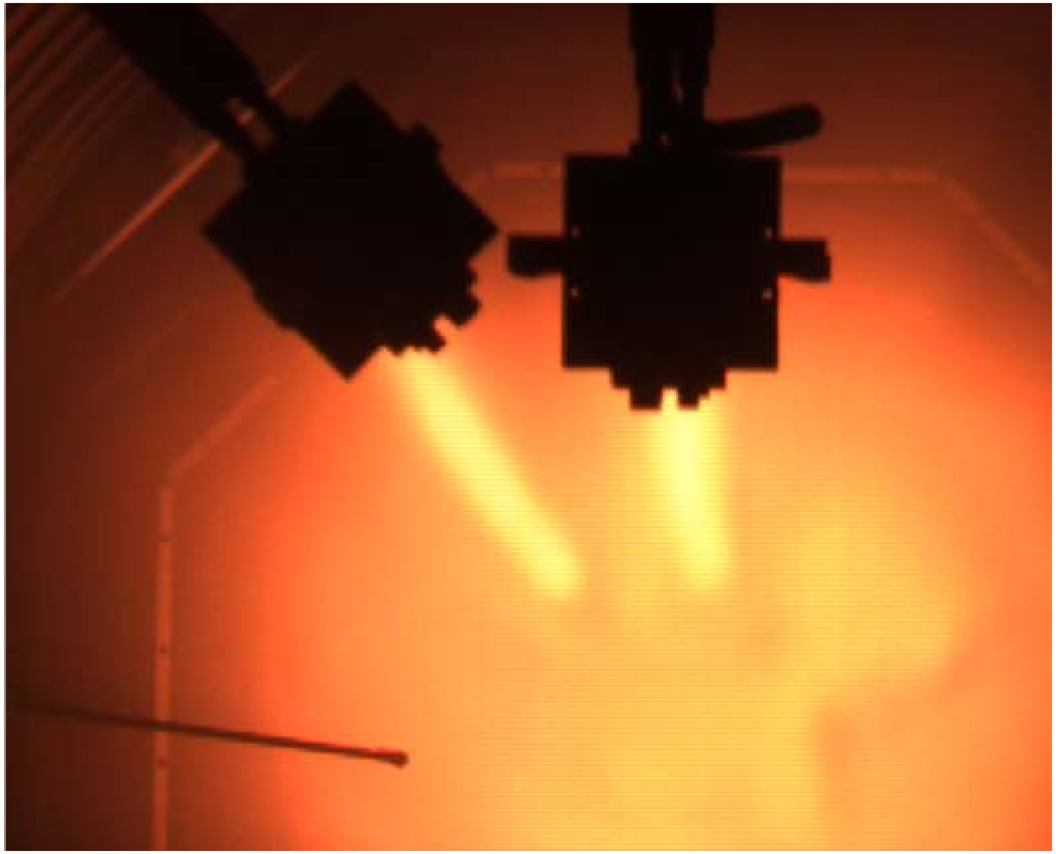
Discharge
V_D = 100V

background plasma

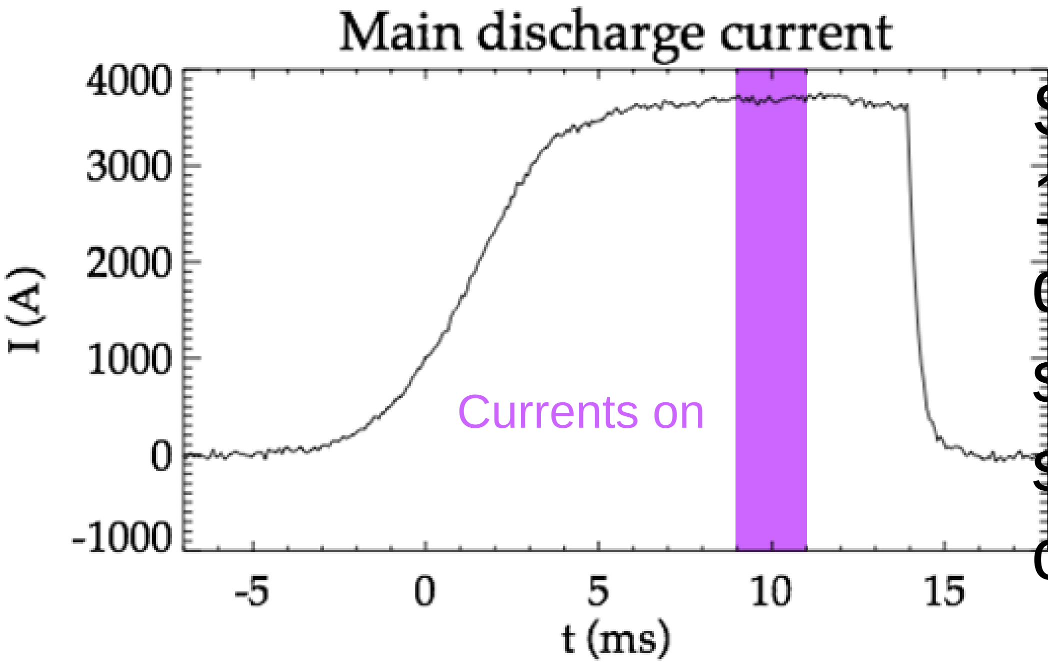
$$\gamma = \frac{c}{\omega_{pe}} = 3mm \qquad \mathrm{S} = \frac{\mu_0 V_A L}{\eta} \cong 3\times 10^3 - 6\times 10^4$$

$$\gamma_I = \frac{c}{\omega_{pi}} = 28cm \qquad \mathrm{R_{ci}} = 7.5mm$$

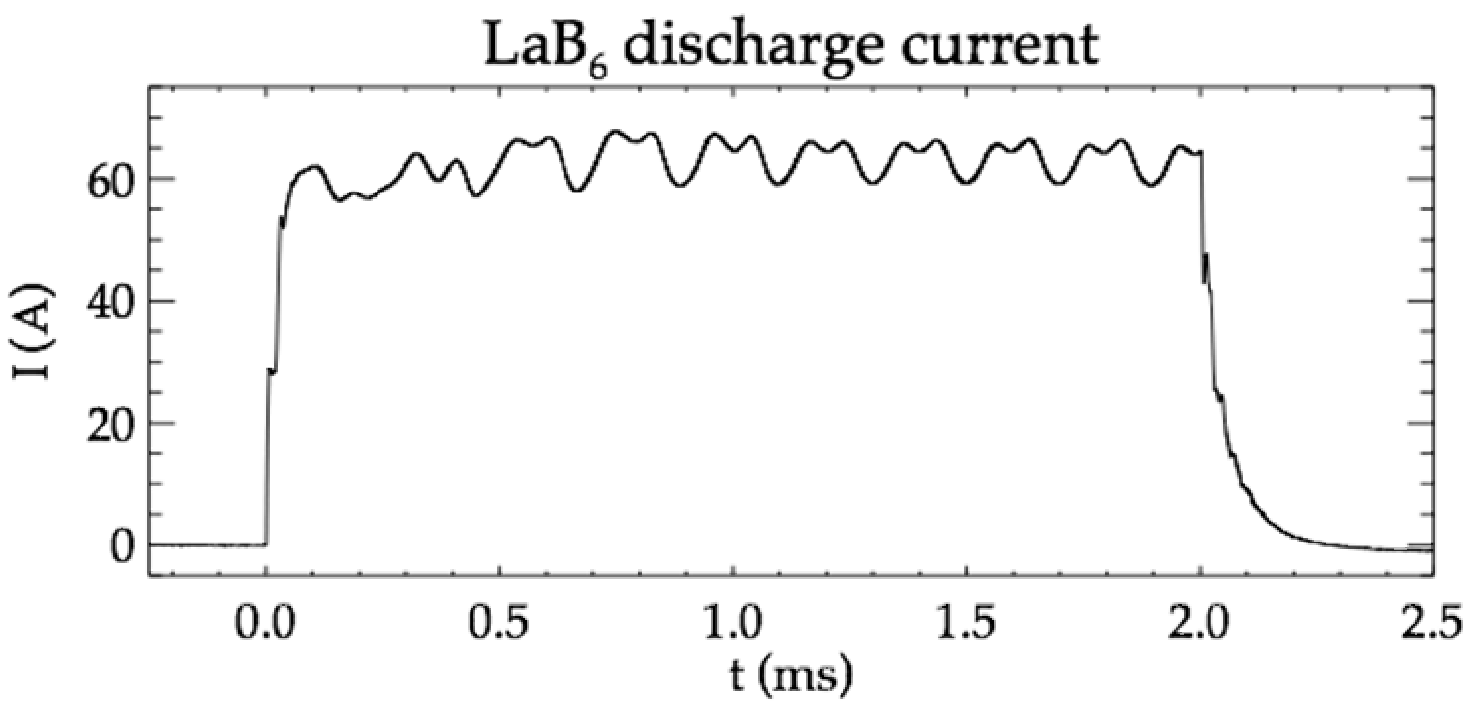
$$Q = \frac{2\pi a B_z}{L B_\theta} \cong 0.7 \quad \mathrm{B_z} = 270G \quad \mathrm{B}_\theta\ ;\ 6G$$



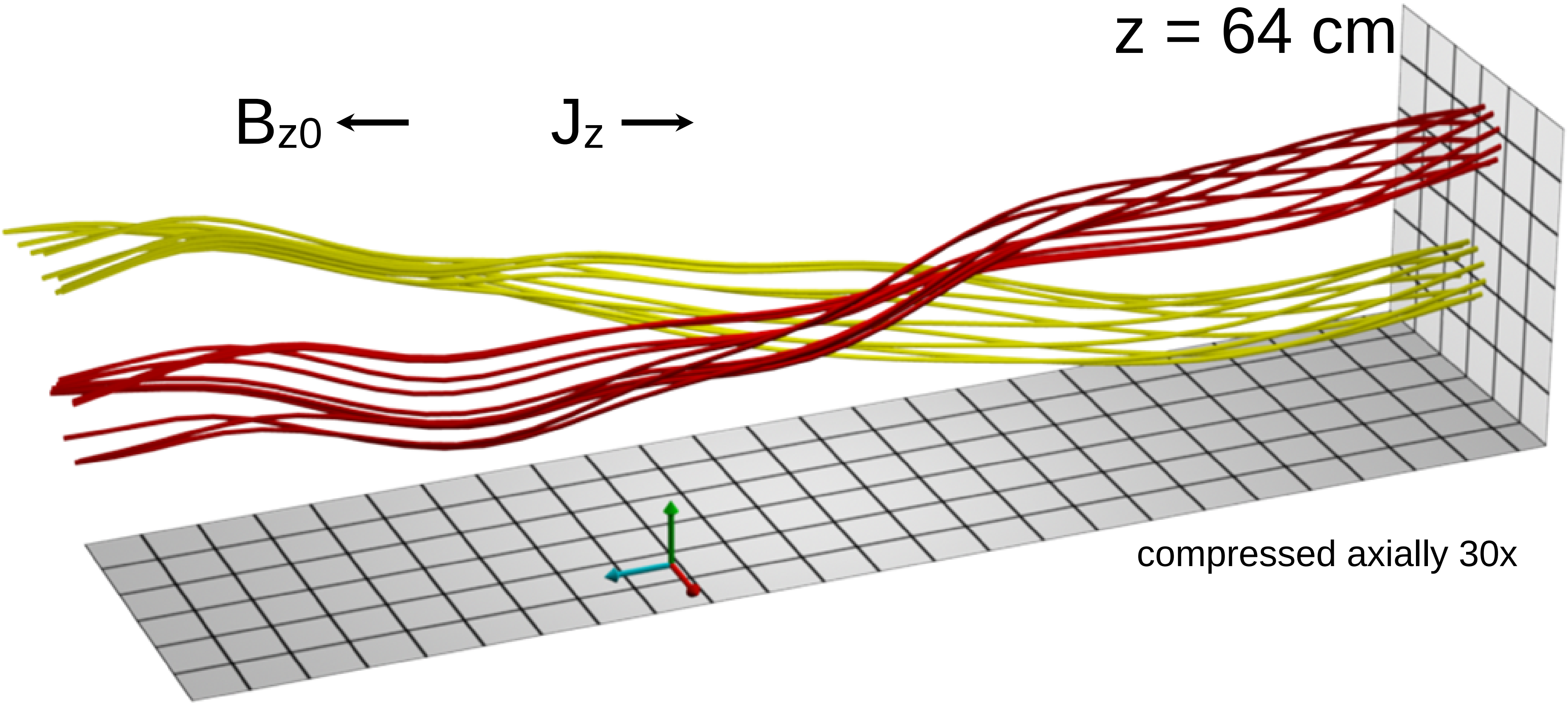
Discharge currents



Small cathodes are biased to 100V for 2 ms during the main discharge. After 300 μs (~3τ_A), spontaneous oscillations are seen in the LaB_6 discharge current.

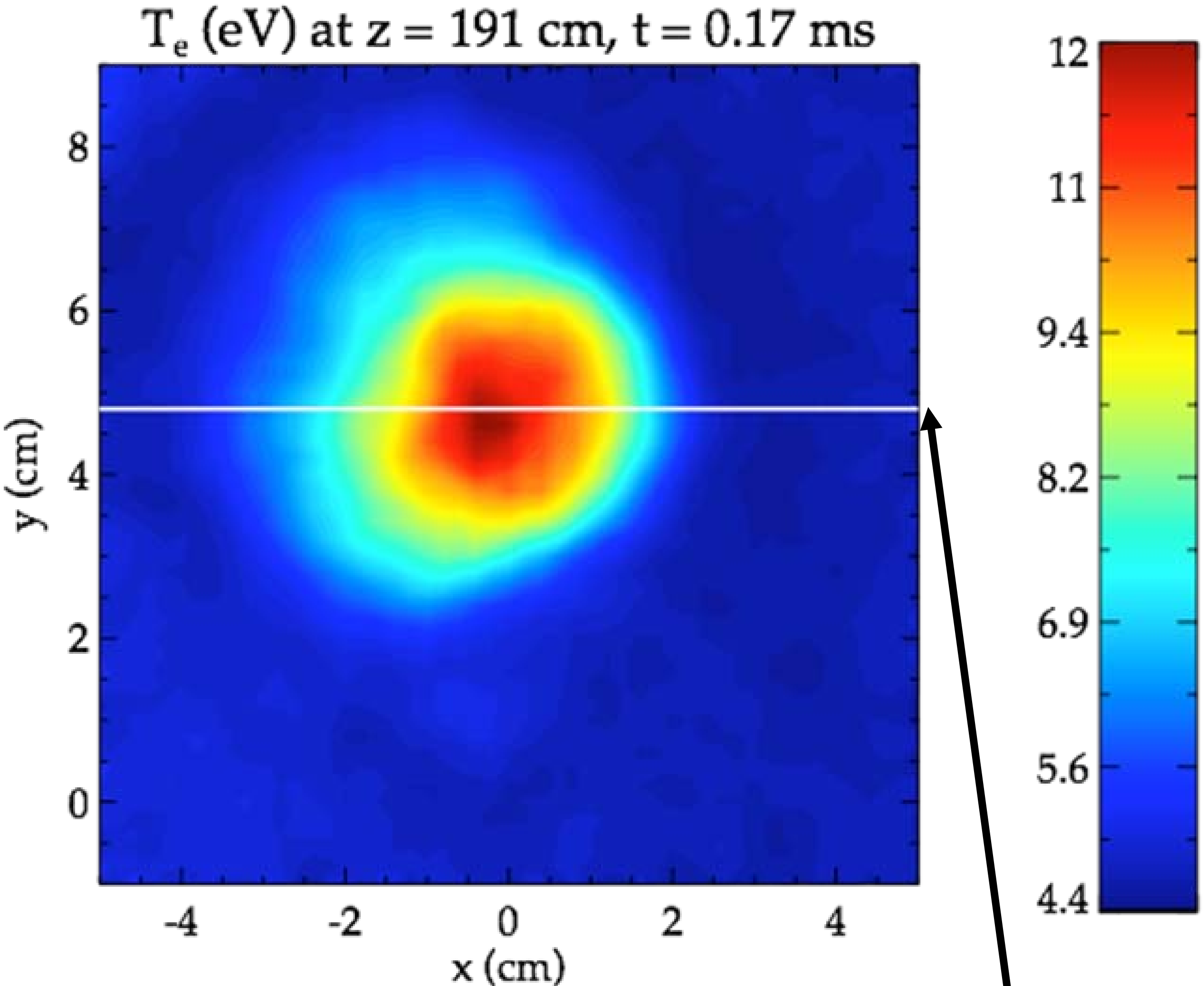


Magnetic field has flux rope structure

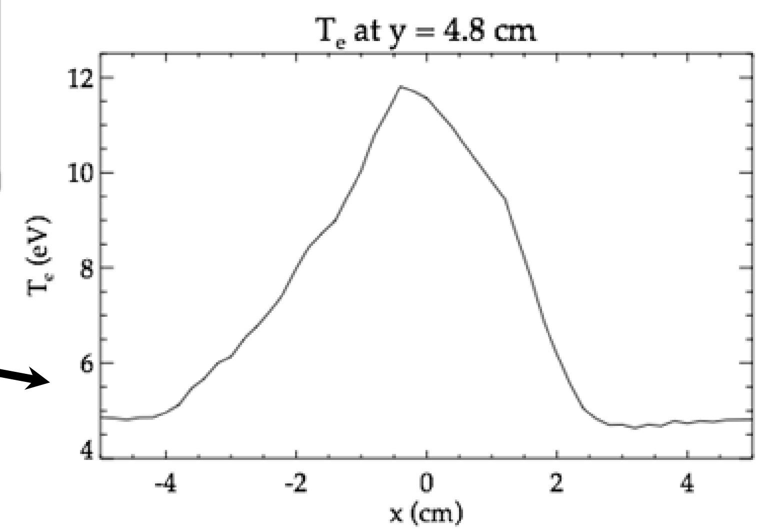


- Flux tube cross section is elliptical at the far end.
- Twist ~ π-3π/2, writhe ~ π.

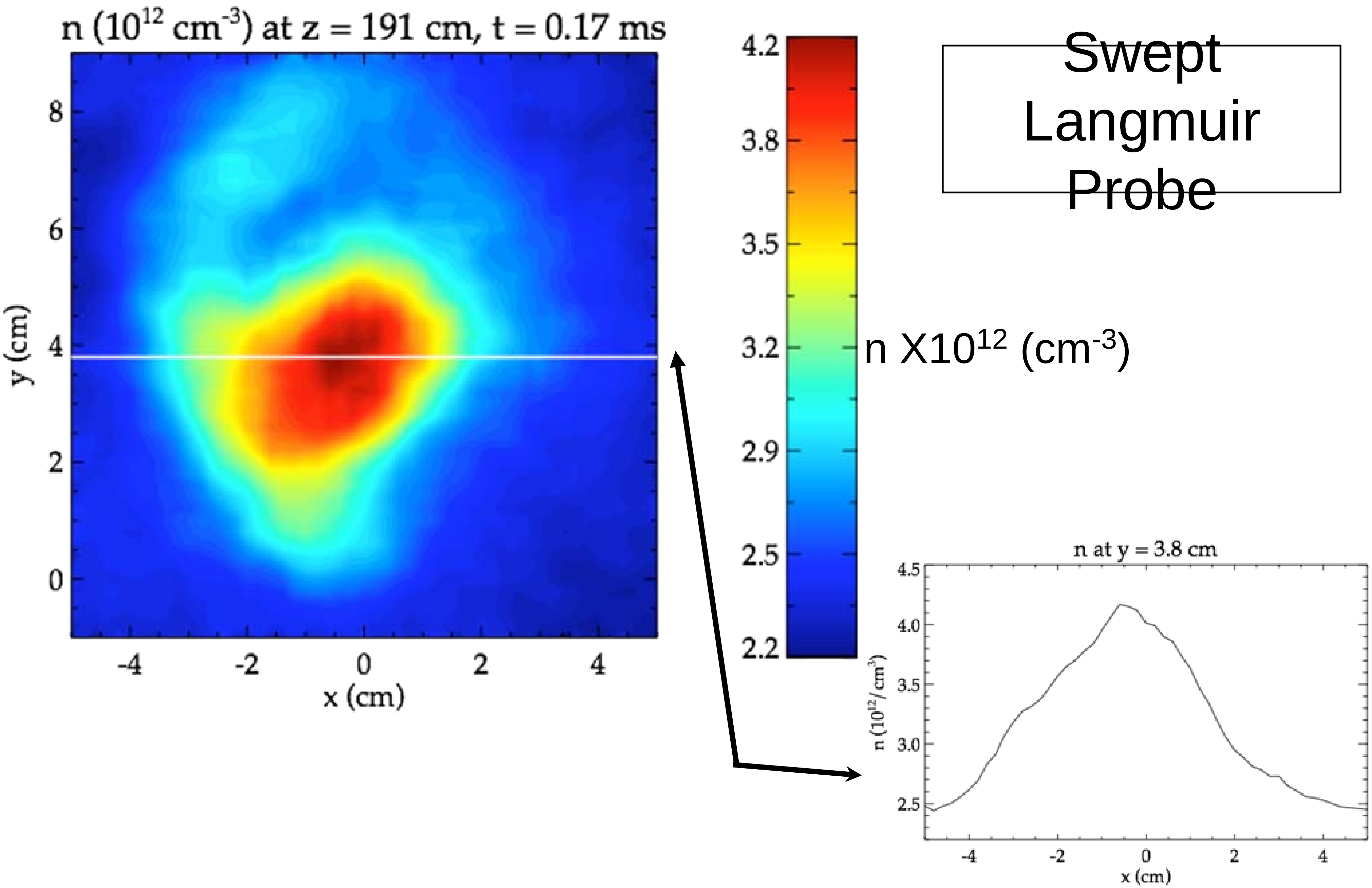
Electron temperature profile of a single channel



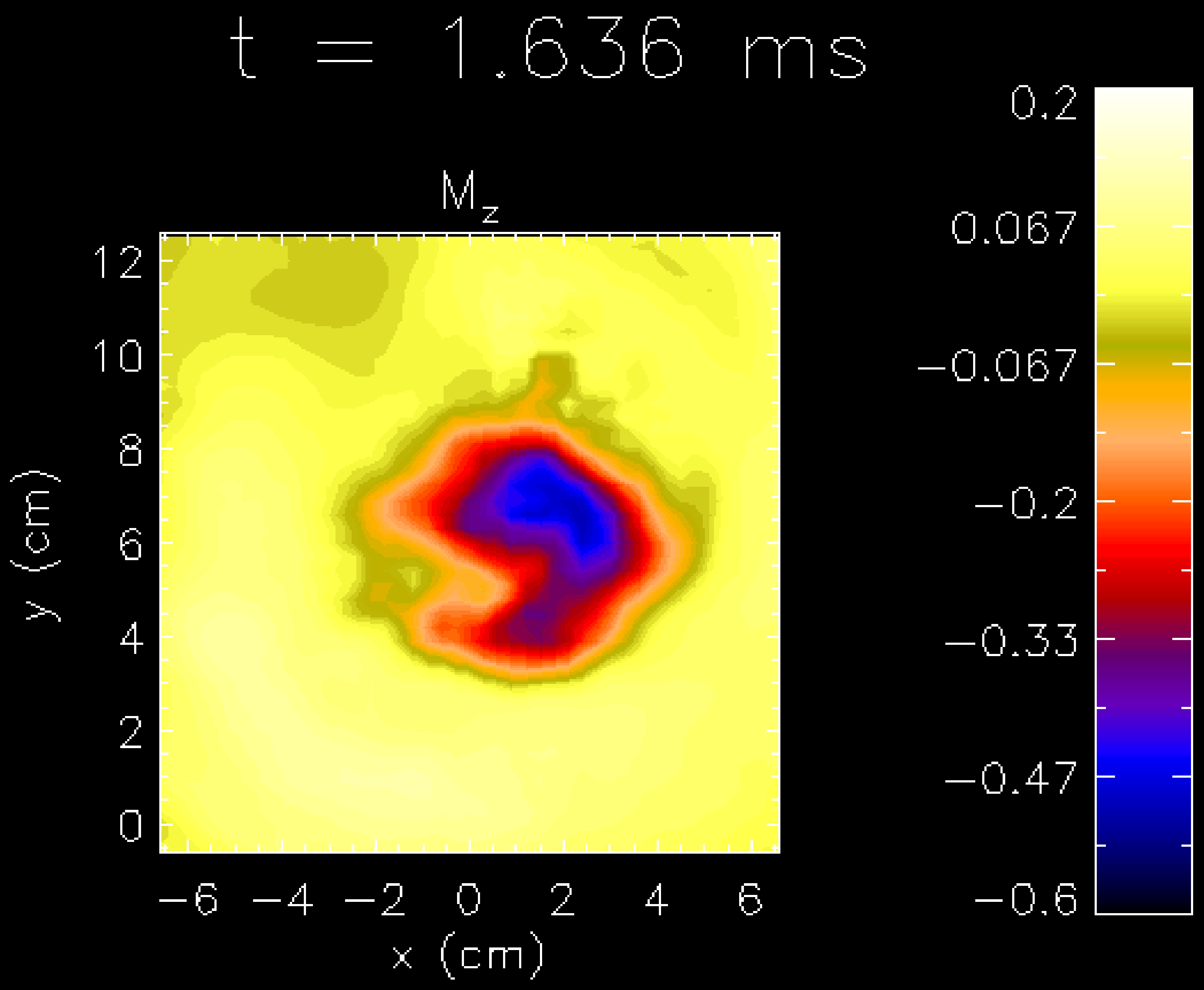
Swept Langmuir Probe



Density profile of a single current channel

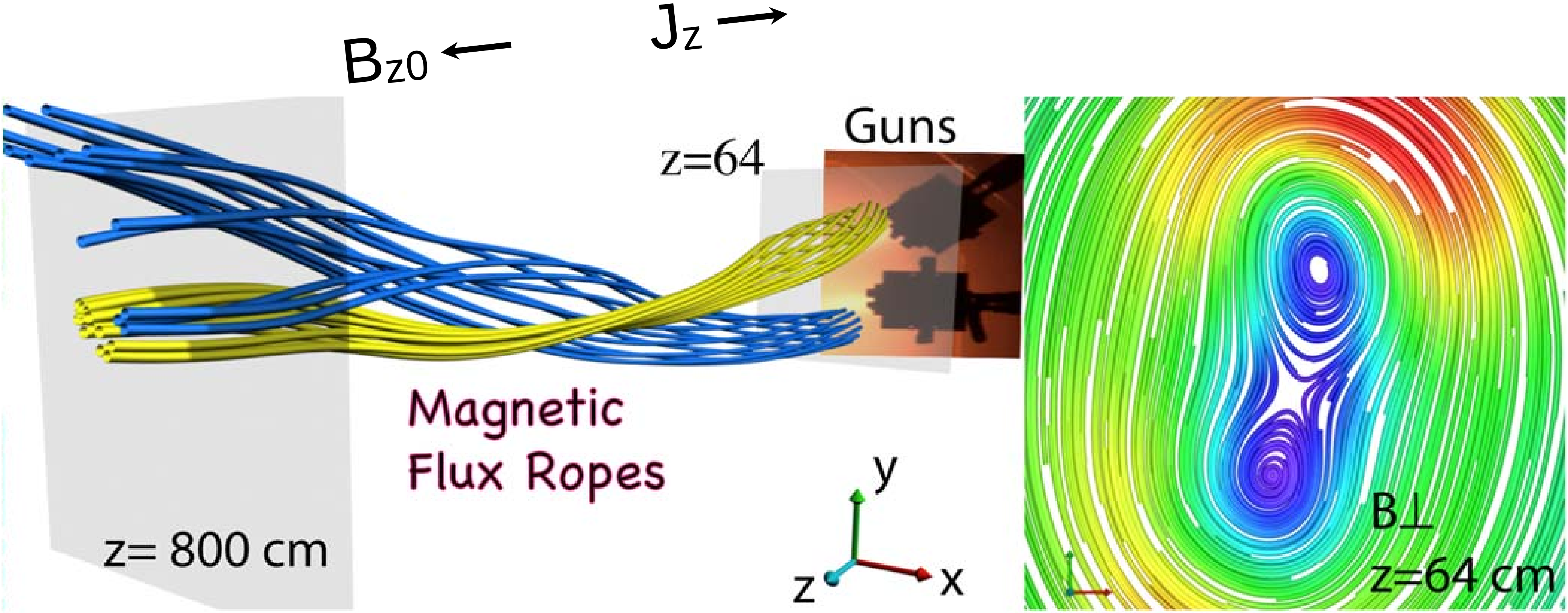


Plasma Flow



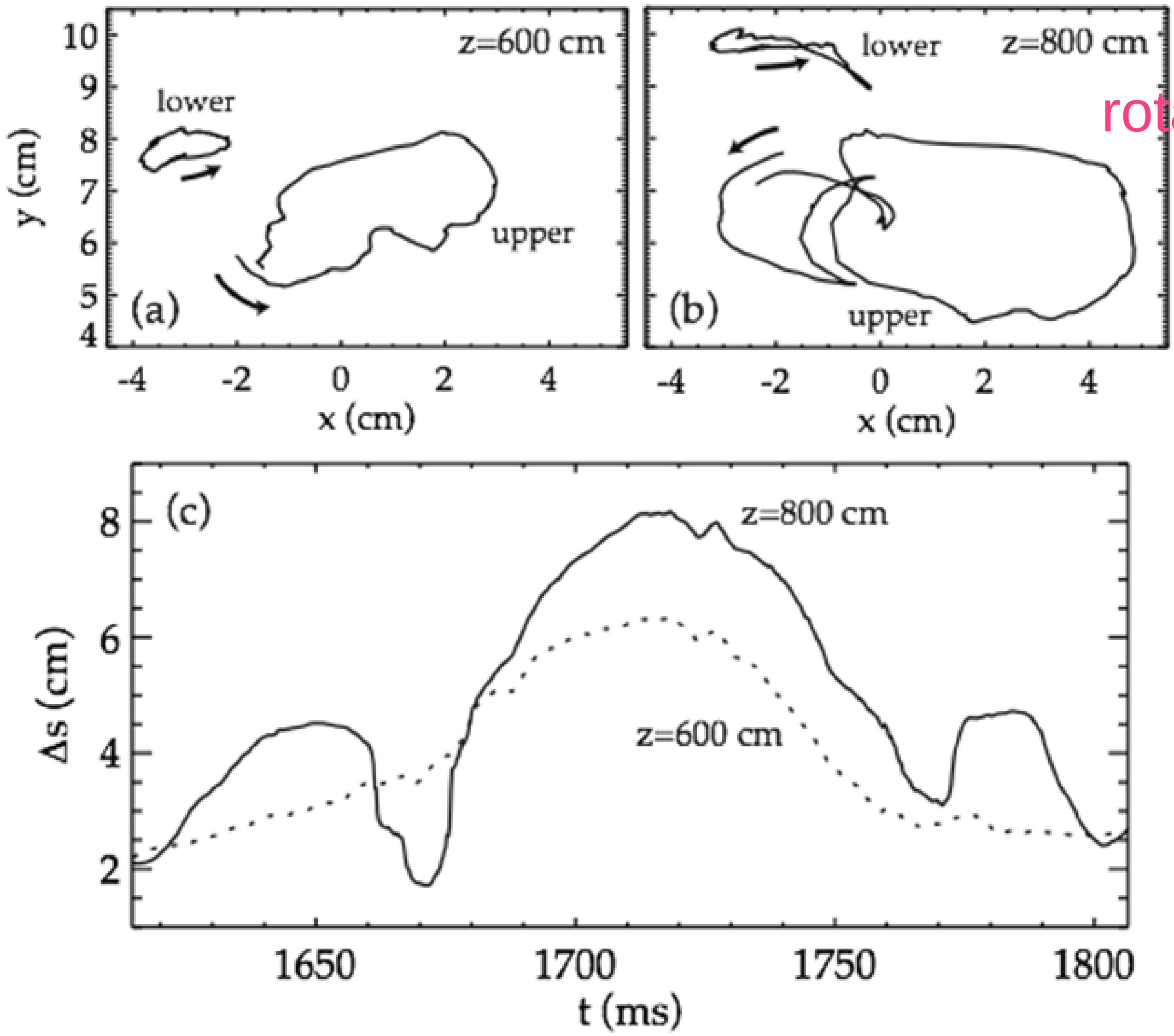
t = 1.636 ms
M_z
y (cm)
x (cm)
12
10
8
6
4
2
0
−6
−4
−2
0
2
4
6
0.2
0.067
−0.067
−0.2
−0.33
−0.47
−0.6

magnetic field is measured at 20,000 locations



- Flux tube cross section is elliptical at the far end.
- Twist ~ π-3π/2, writhe ~ π.

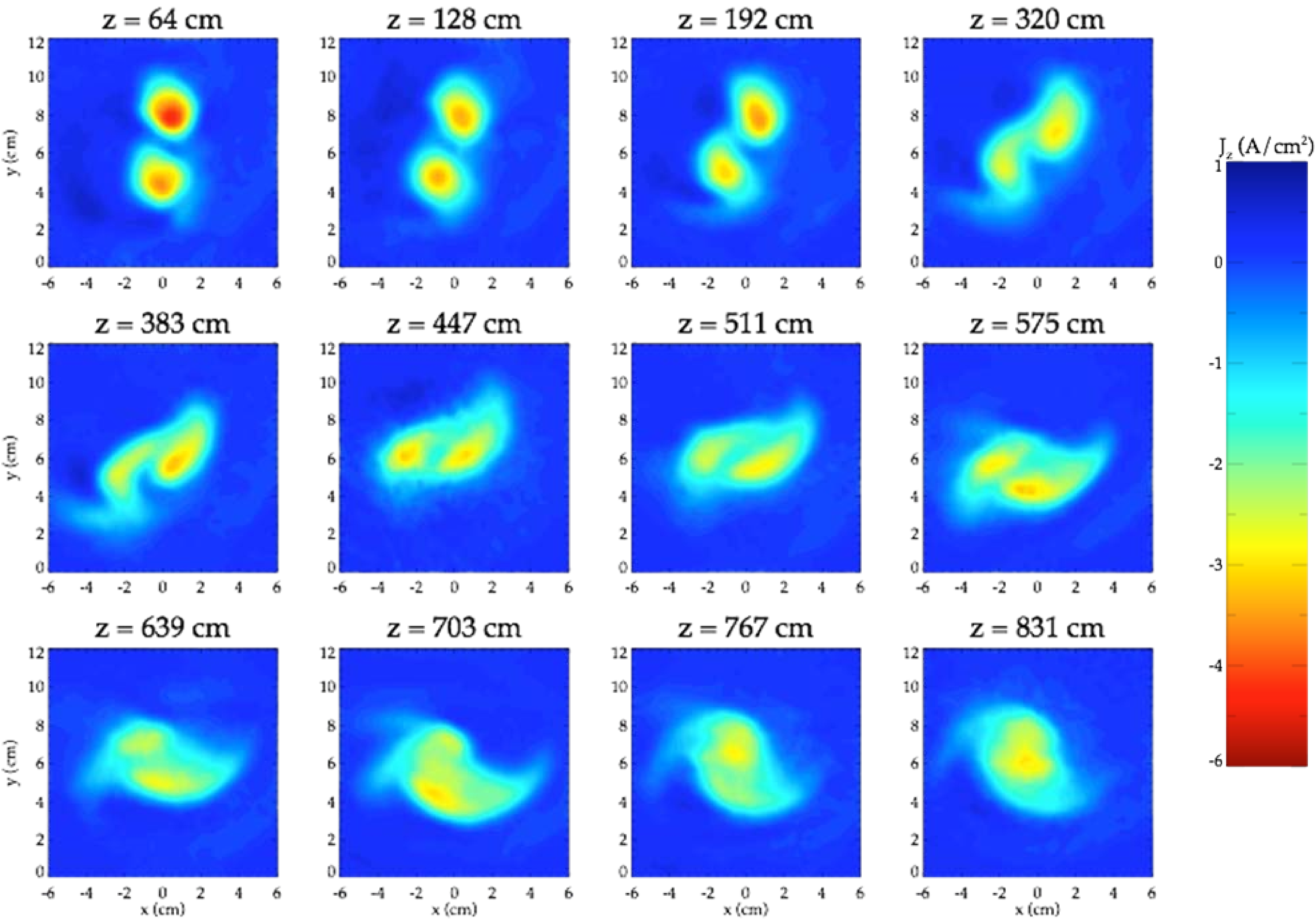
Hodogram of central field line in flux tubes



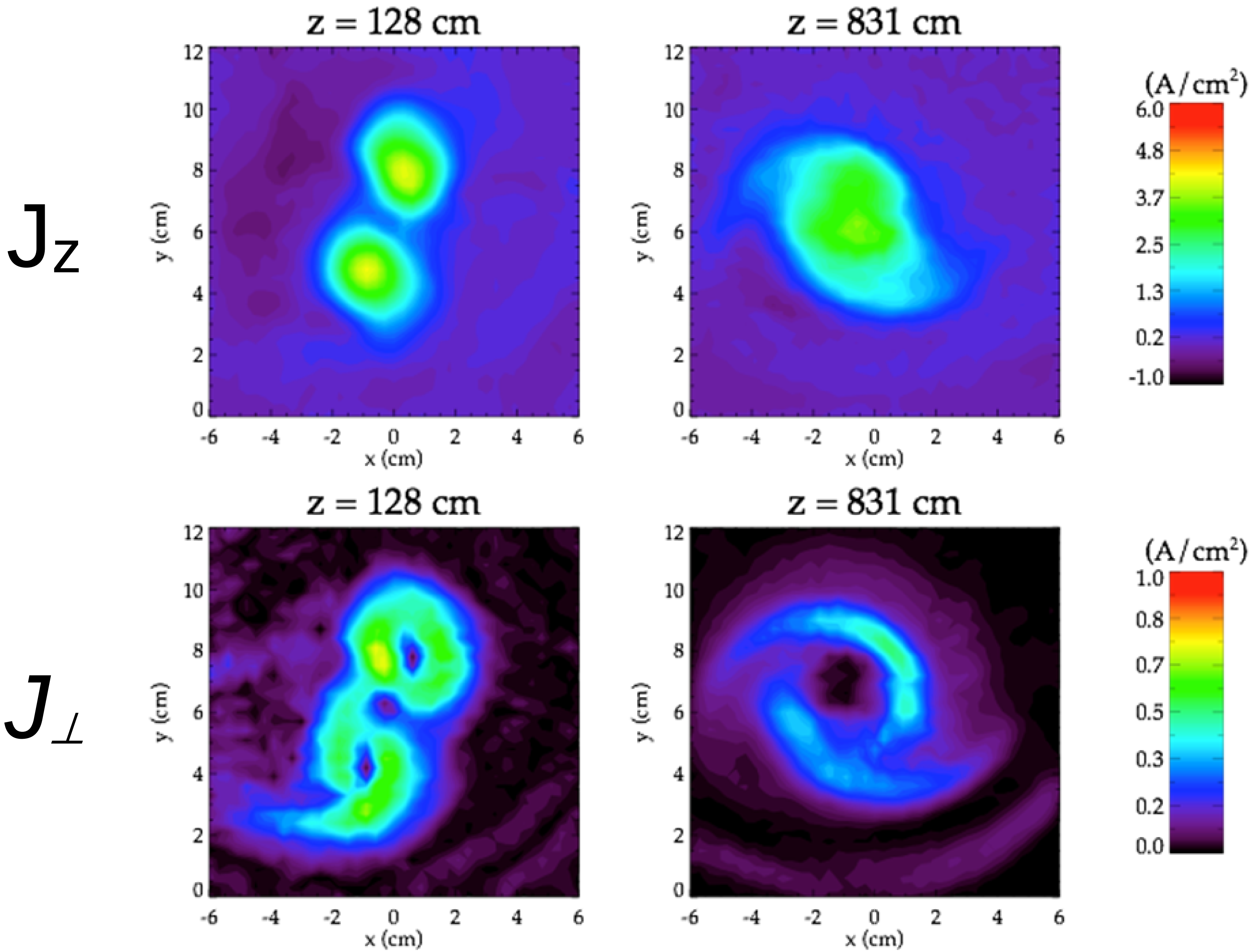
rotation due to parallel flow?

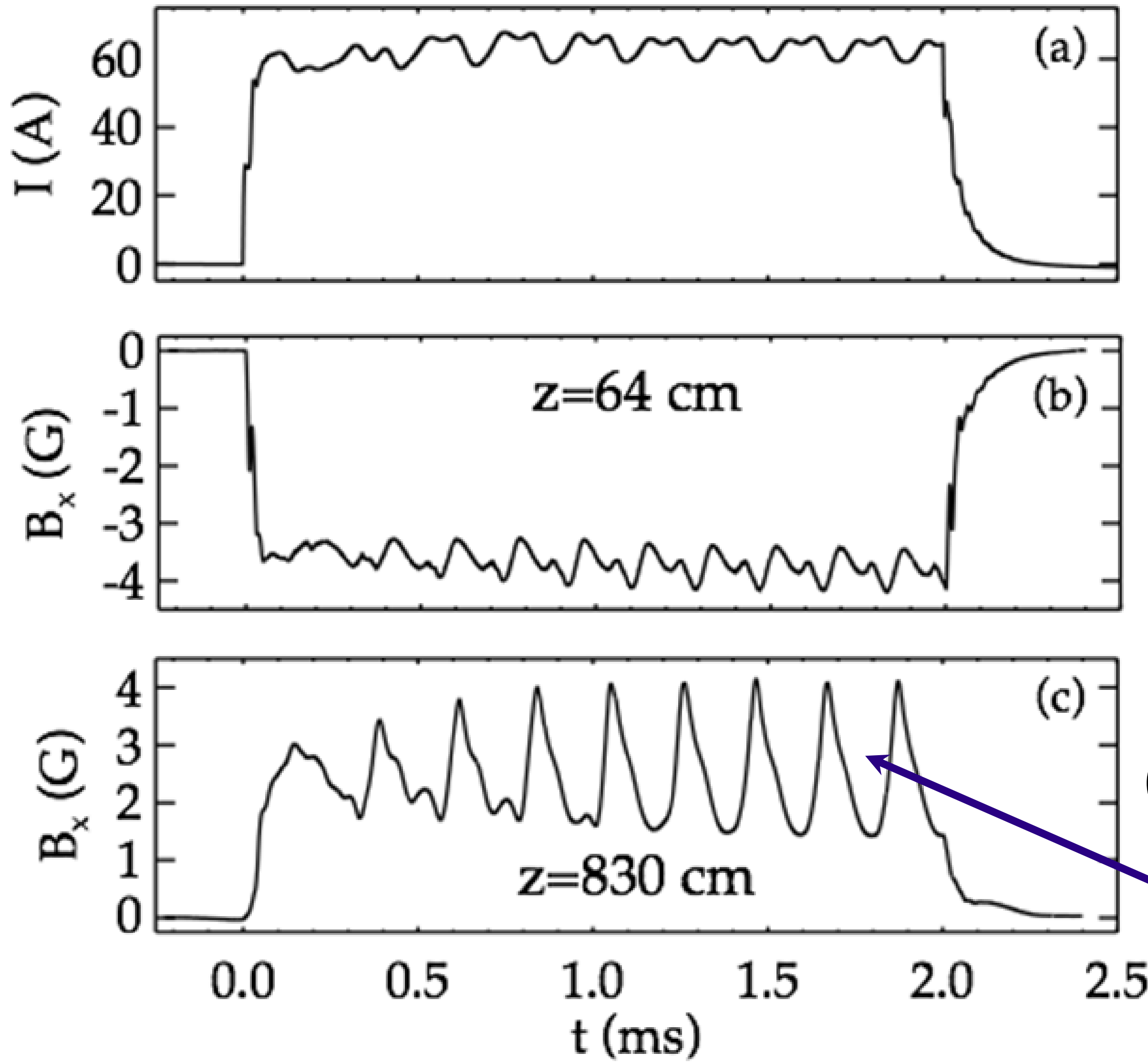
Distance between field lines (upper/lower) at two axial positions

J_z slices at t=190 ❍s (early in time)



Parallel and Perpendicular Current





(a) emission current
from LaB6 cathode

(b) Bx(t) , (0.0,2.7, z=64)

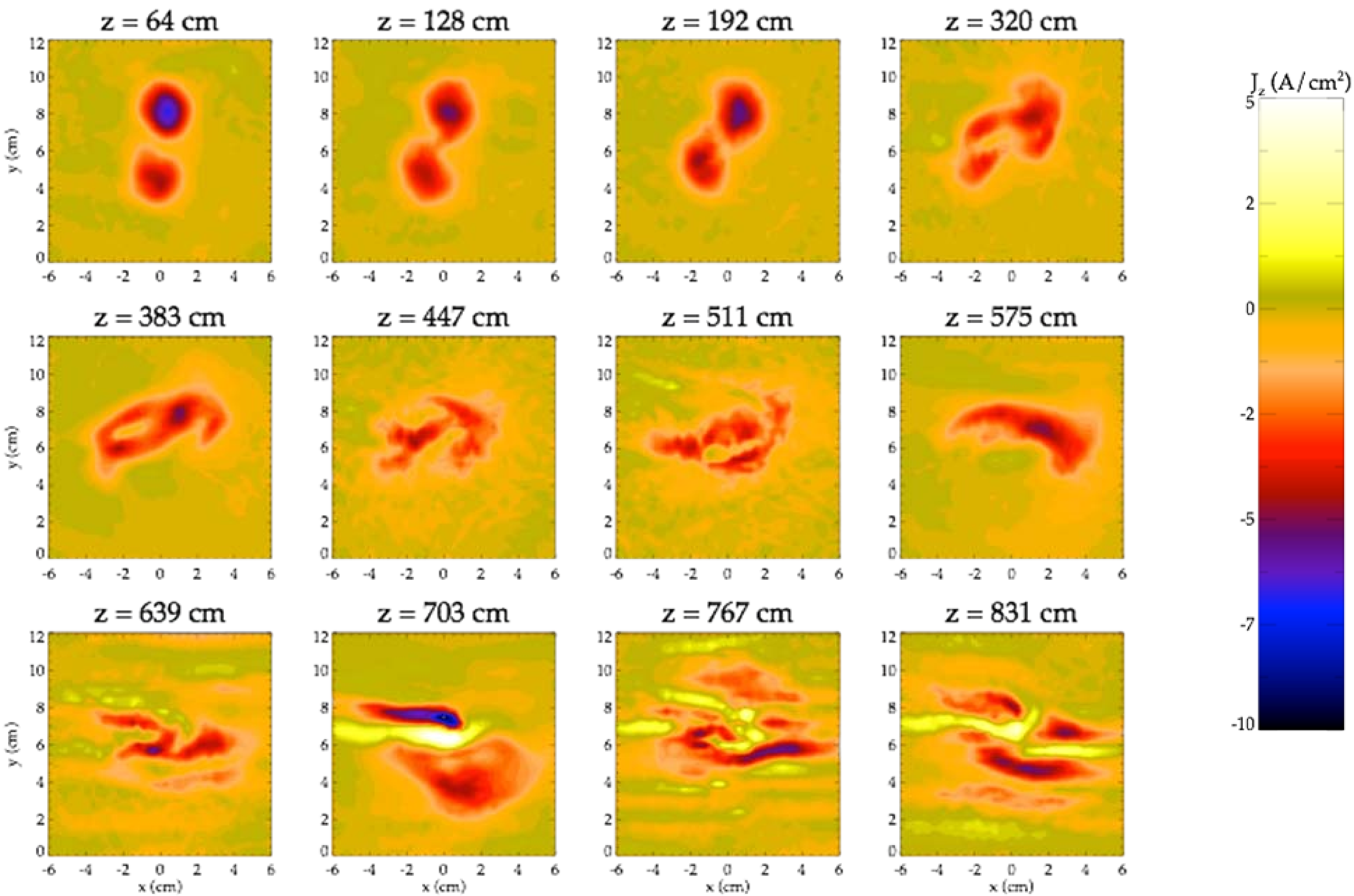
(c) Bx(t) , (-1.5,9.9, z=830)

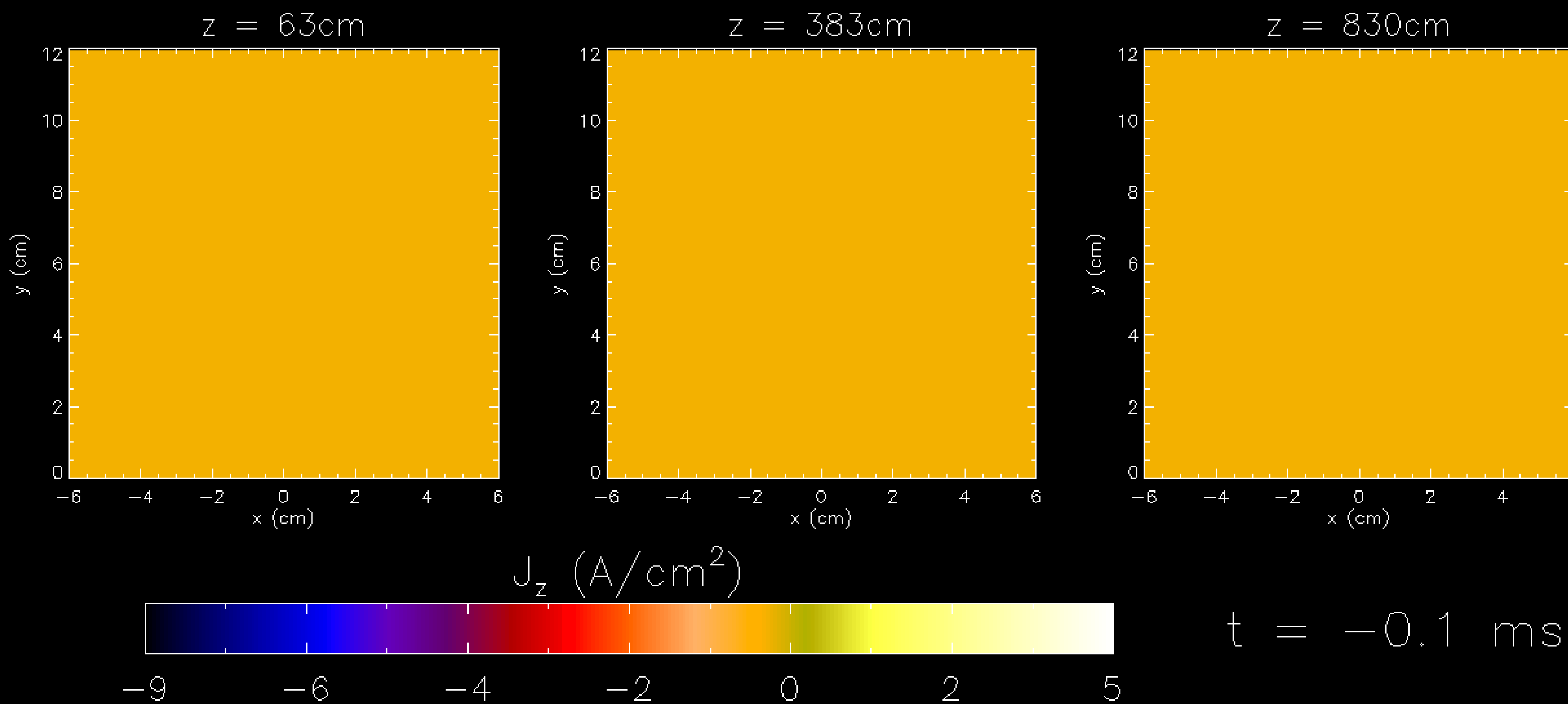
Period t = 190 ❍s

(b) , (c) lie on same approximate flux
surface on the lower flux rope

Jz profiles during oscillations in discharge current

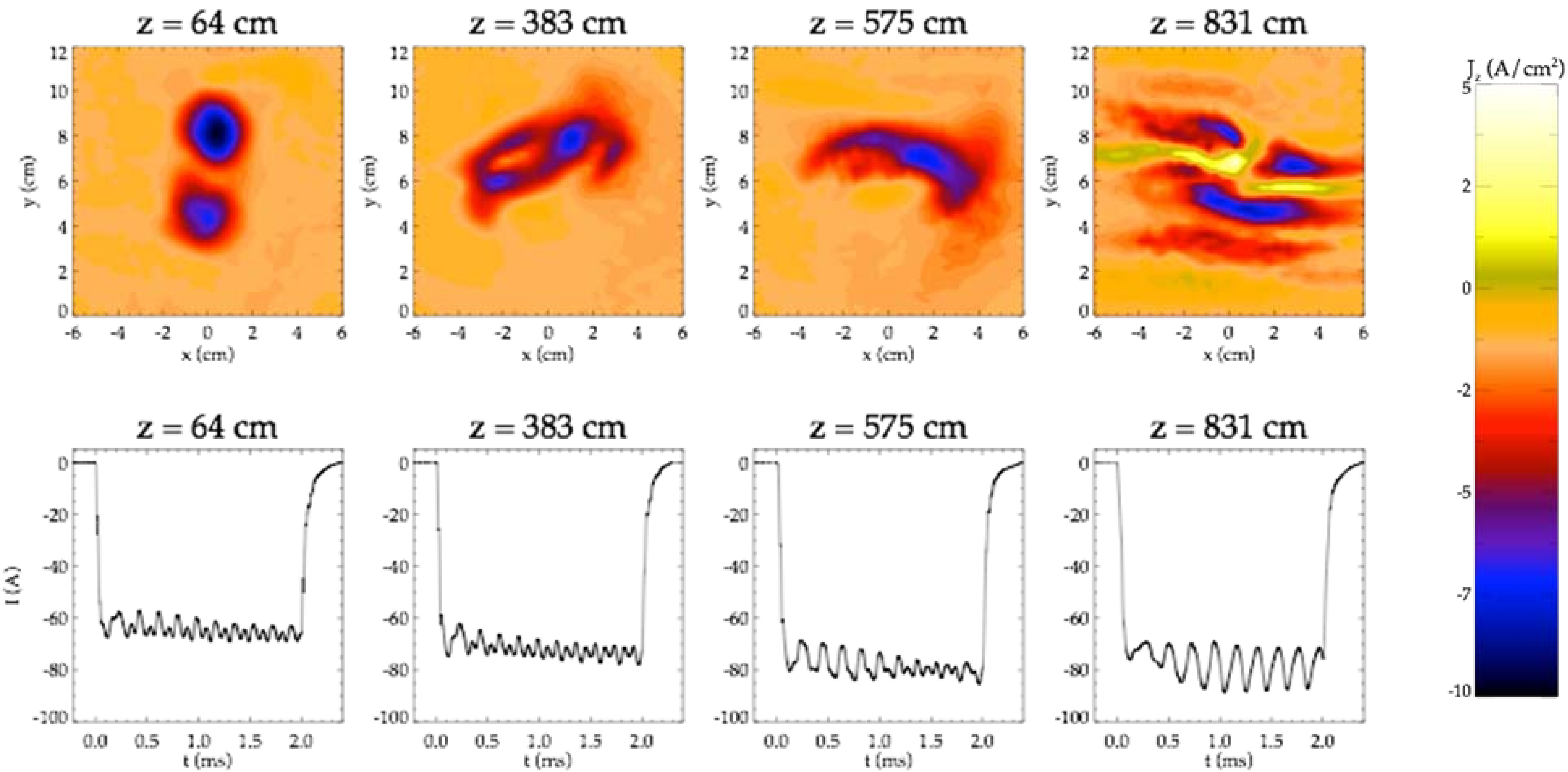
t=1.7ms



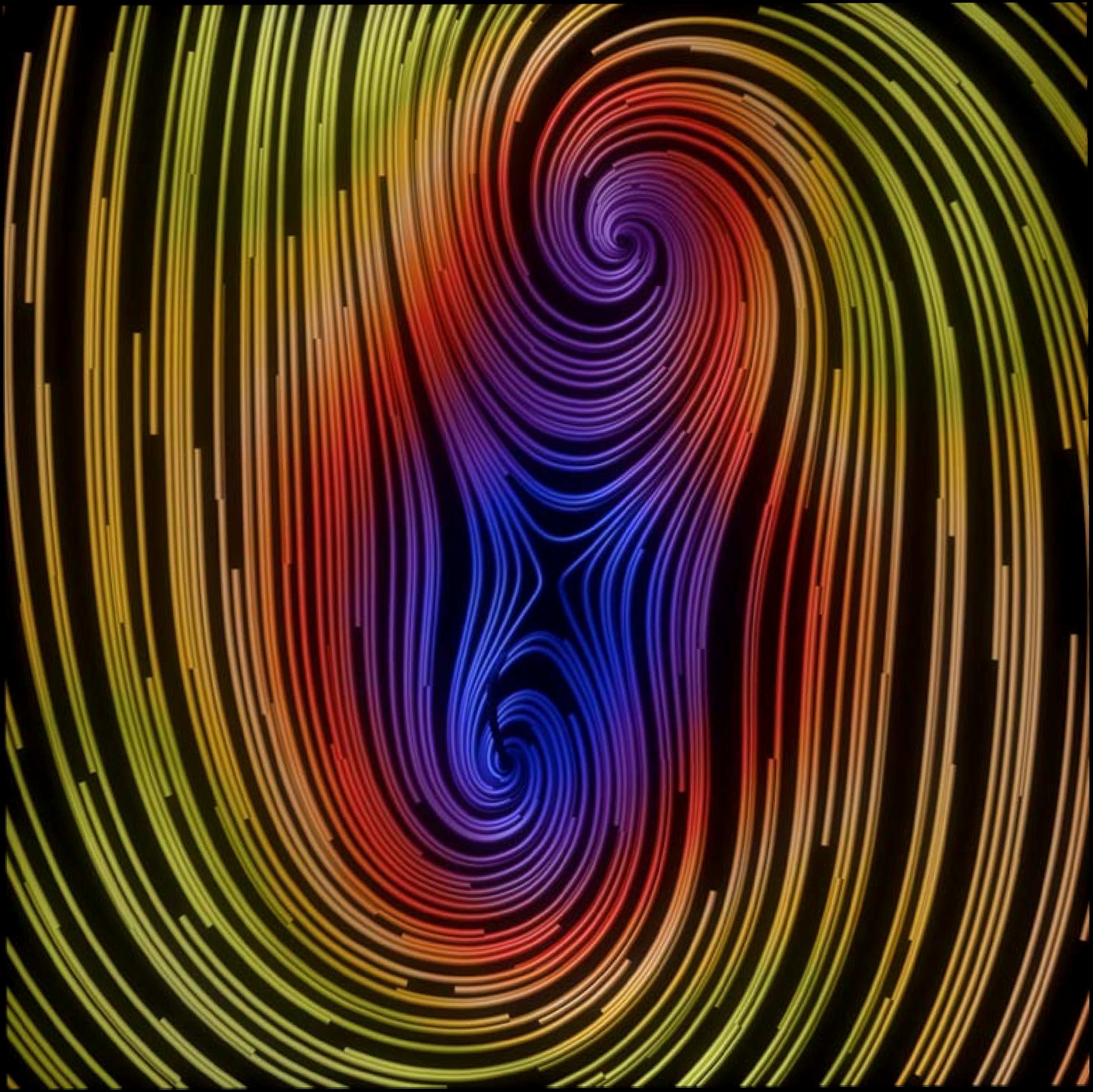


current density

Integrated current density

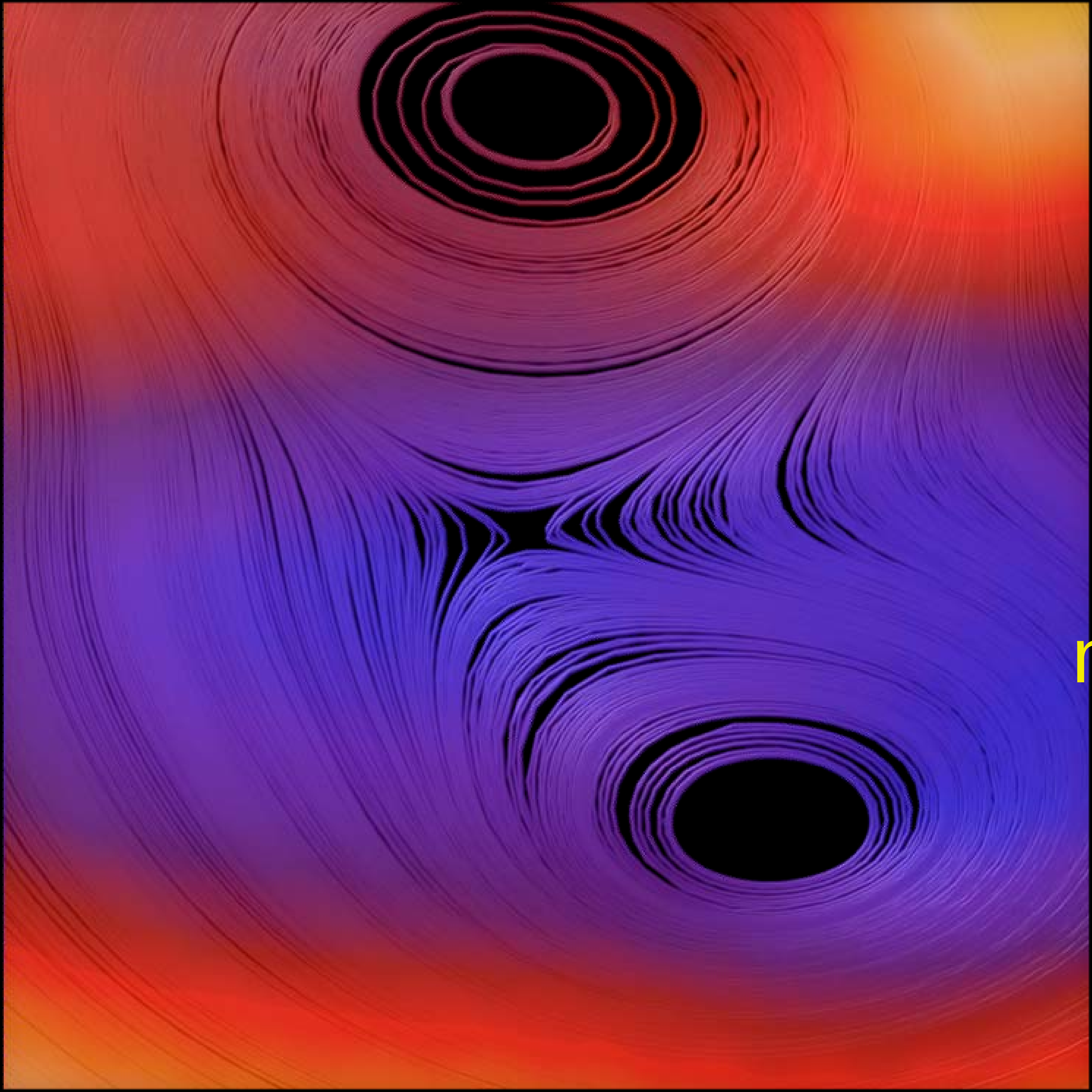


Bottom traces show $\int J_z\, dz$ at various z positions.



Bx-By

♦ = 5 ms
$\underline{\Omega}$z = 64 cm

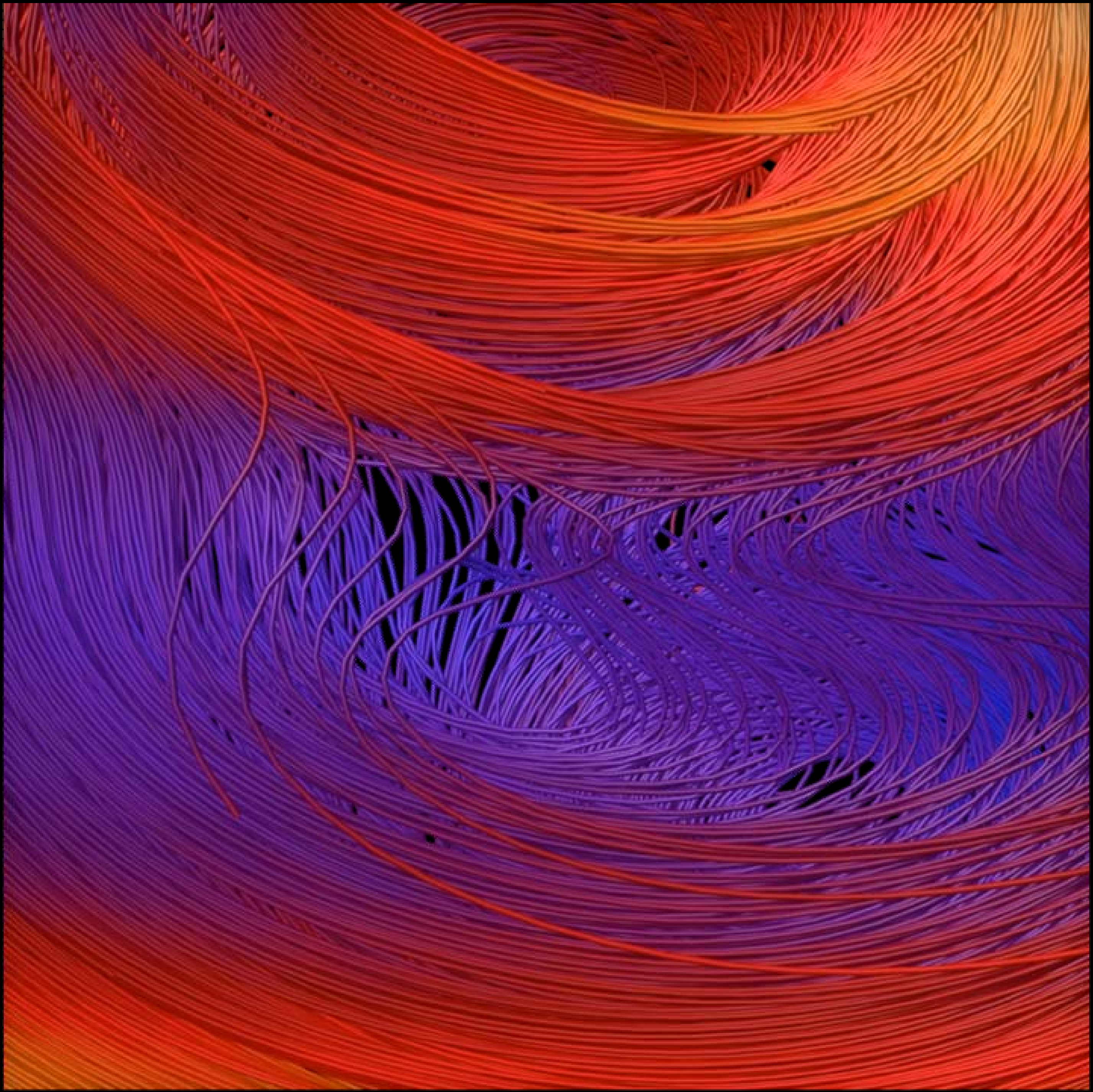


$B_\perp$

z=6.6 m

t=88.8 us

no guide field



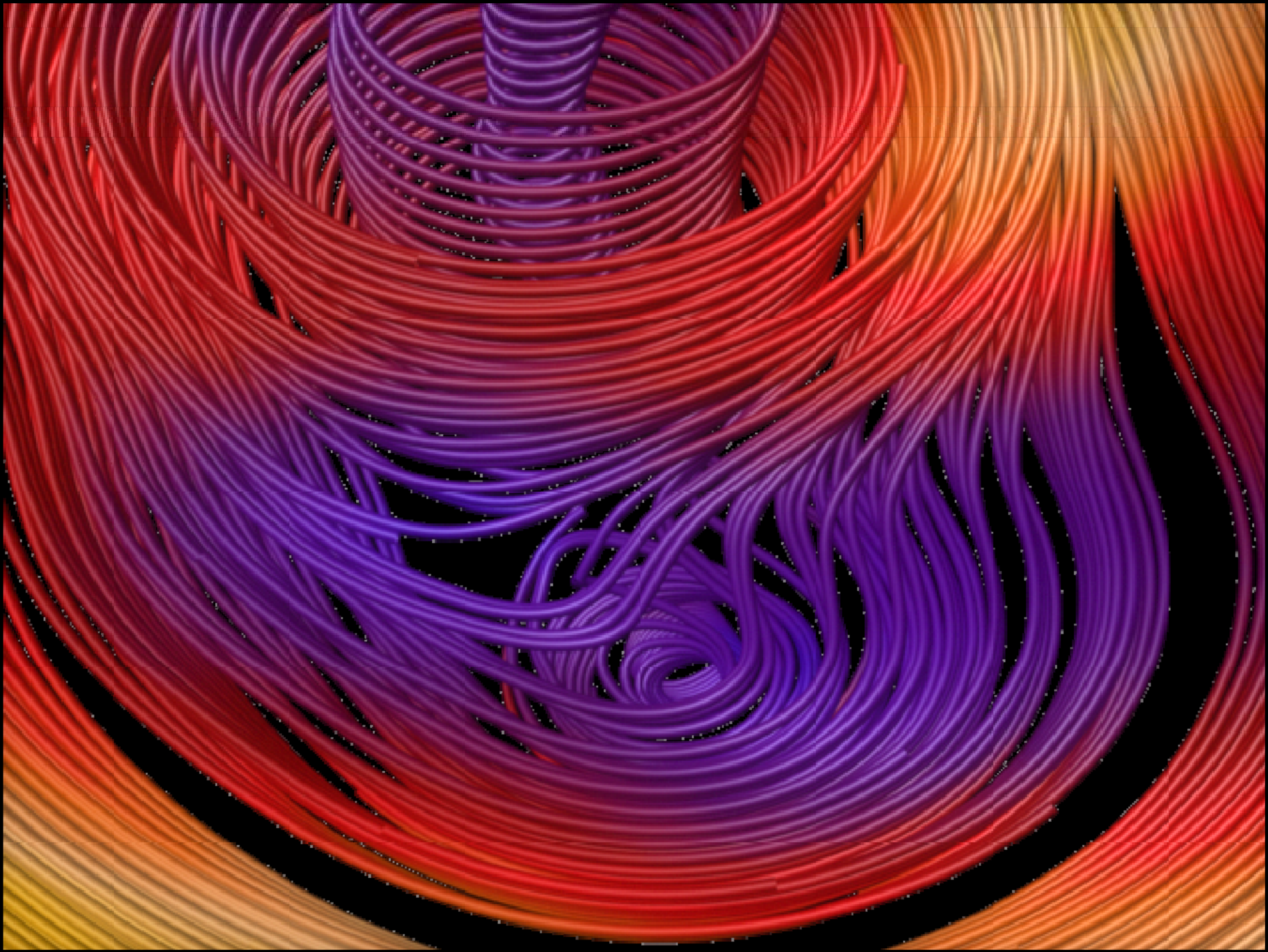
B

z=6.6 m

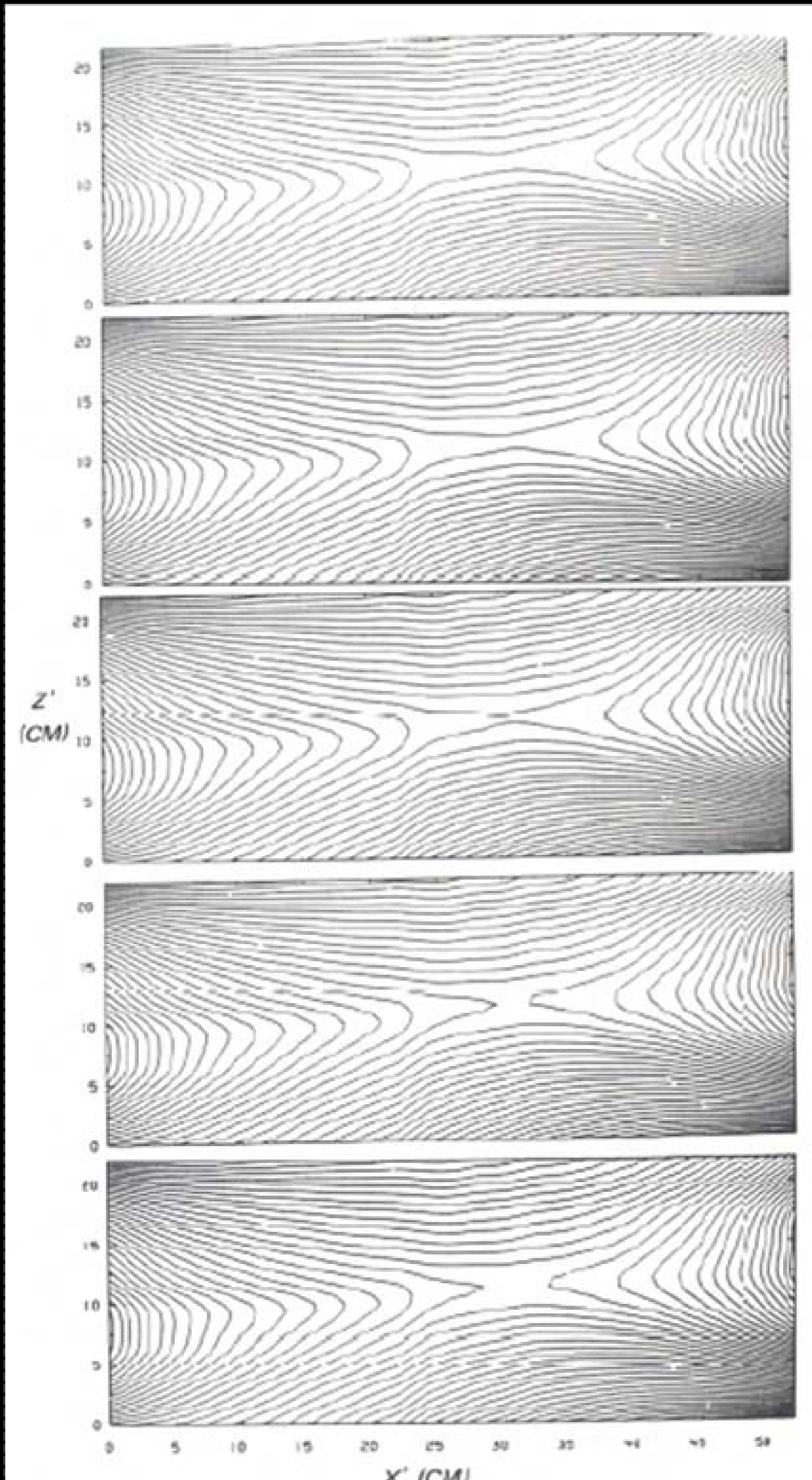
t=88.8 us

no guide field,

B_{zropes}



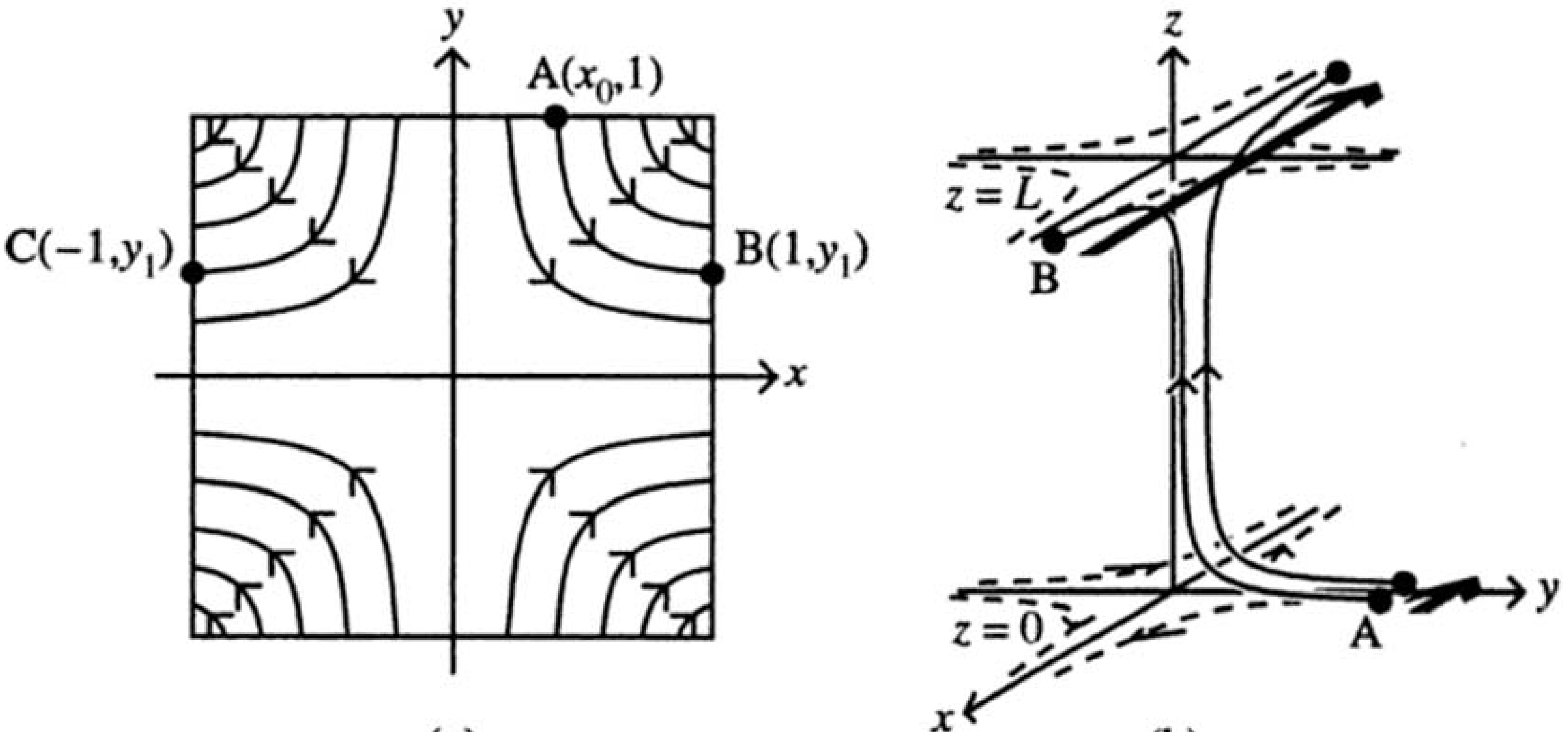
sound generated by R. Fanelli from Alfven wave - waveform



2D reconnection

Gekelman, Stenzel, Wild, Phys. Scripta, T2/2 (1982)

Simple sheared X-point model



(a) (b)

Small footpoint motions at point A would create a drastic shift at point B. In some cases point B can shift discontinuously [Priest and Forbes, 2000,Demoulin, 2006]

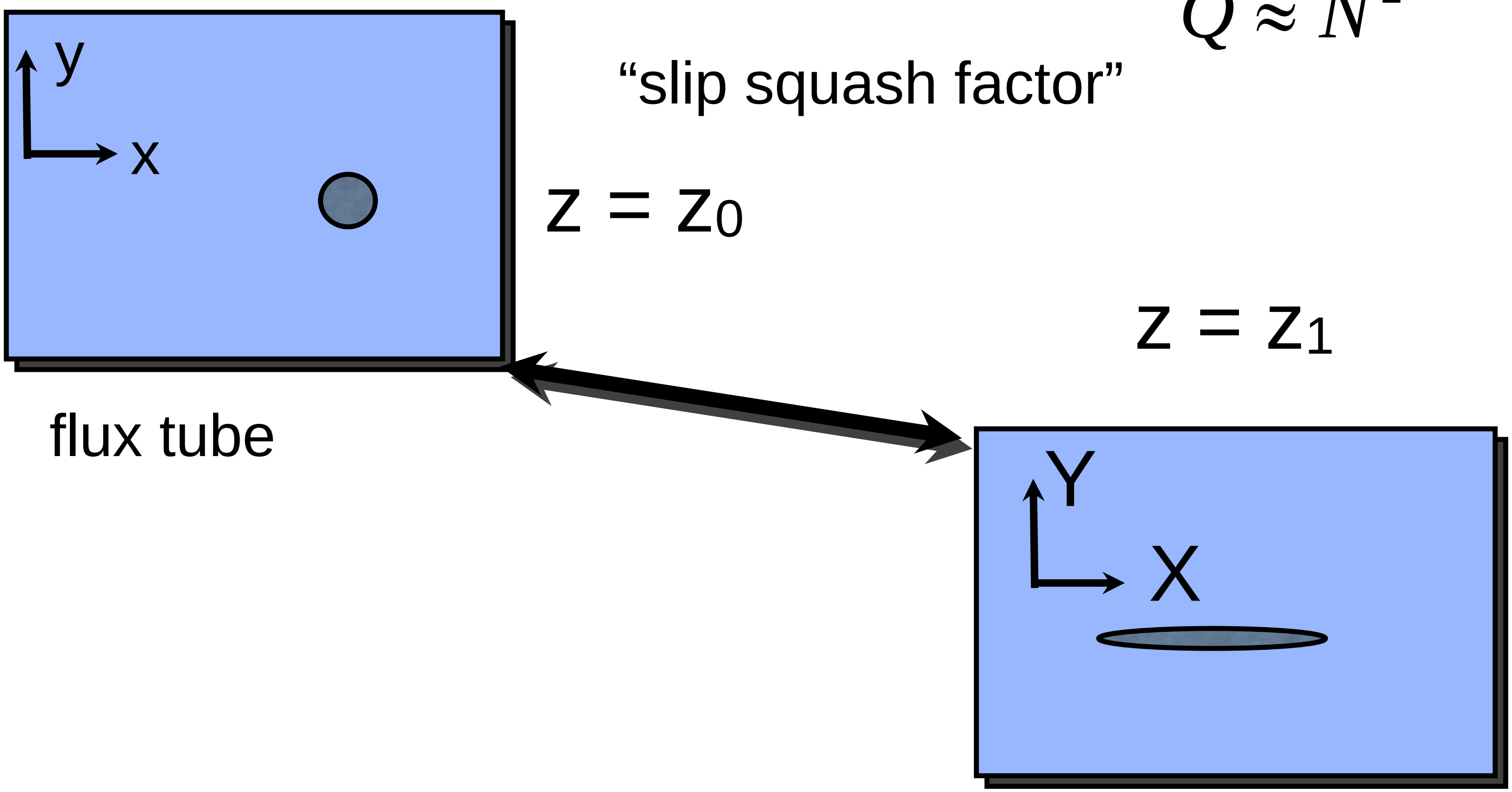
Definition of a quasi-separatrix layer

$$Q = \frac{N^2}{\left| \frac{B_z(z_0)}{B_z(z_1)} \right|} \qquad N = \sqrt{\left(\frac{\partial X}{\partial x}\right)^2 + \left(\frac{\partial X}{\partial y}\right)^2 + \left(\frac{\partial Y}{\partial x}\right)^2 + \left(\frac{\partial Y}{\partial y}\right)^2}$$

in our experiment

$$Q \approx N^2$$

“slip squash factor”

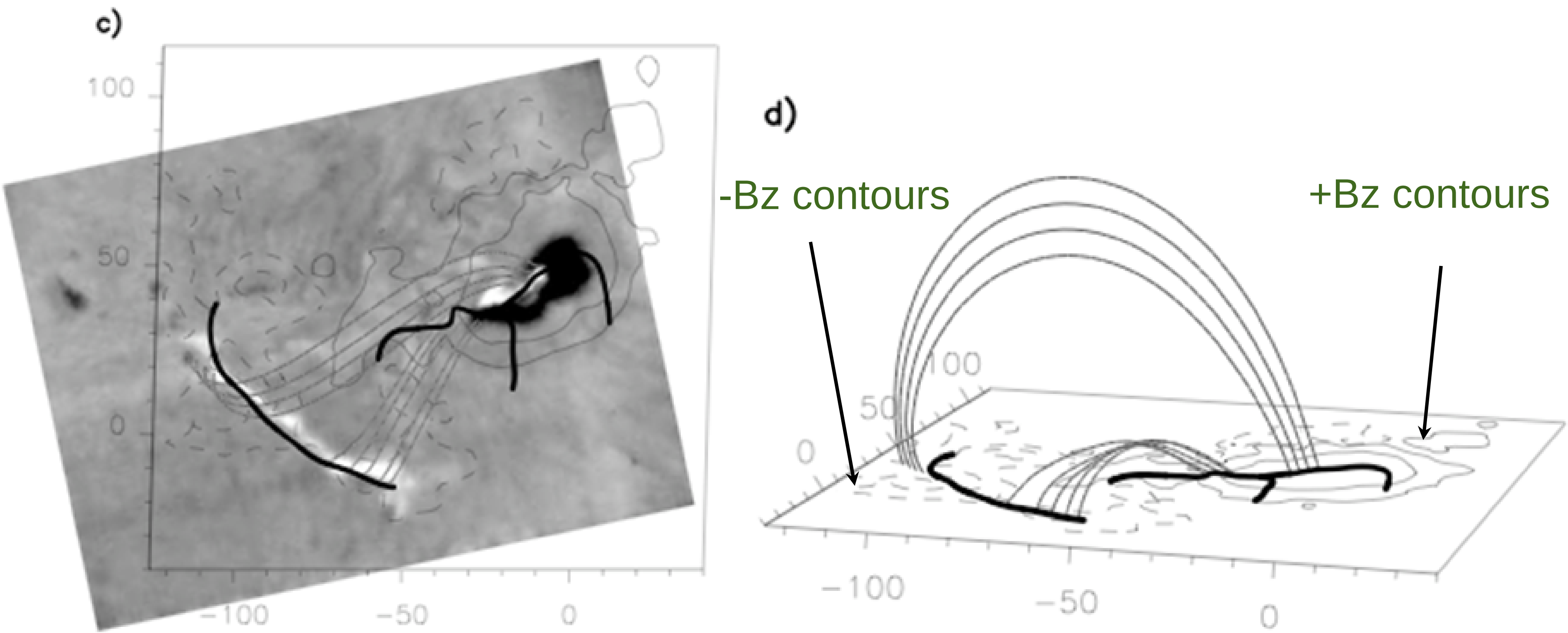


flux tube

Priest and Démoulin,JGR 1995,
Titov,As. J. (2007)

flux tube squashed: aspect ratio = Q

QSLs in solar flare observations



computed field lines

QSLs at boundaries (thick lines) coincident with H_α brightening in solar flares. [Bagalá et al. A&A 2000]

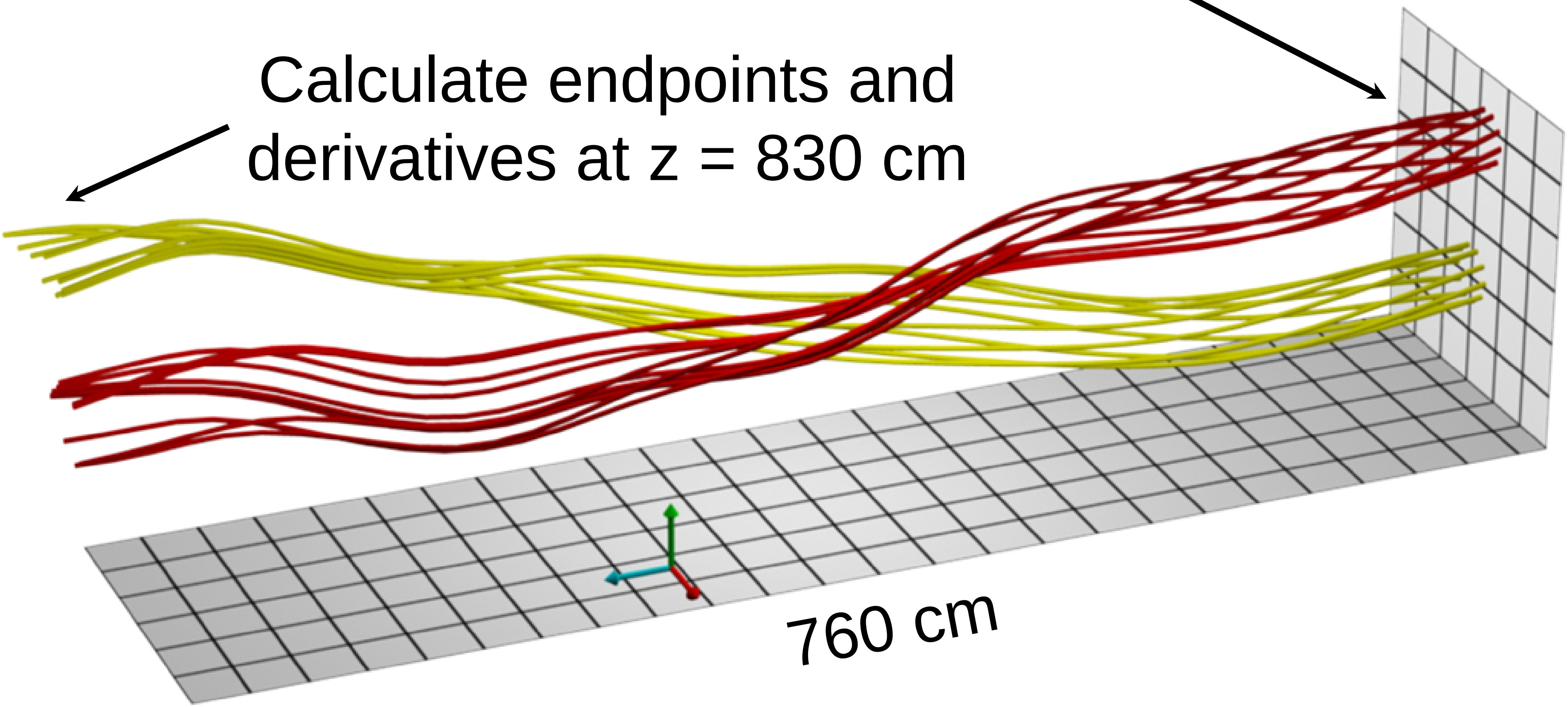
QSL calculation

QSL region if N>>1

in this experiment N=2000

Seed field lines
at z = 64 cm

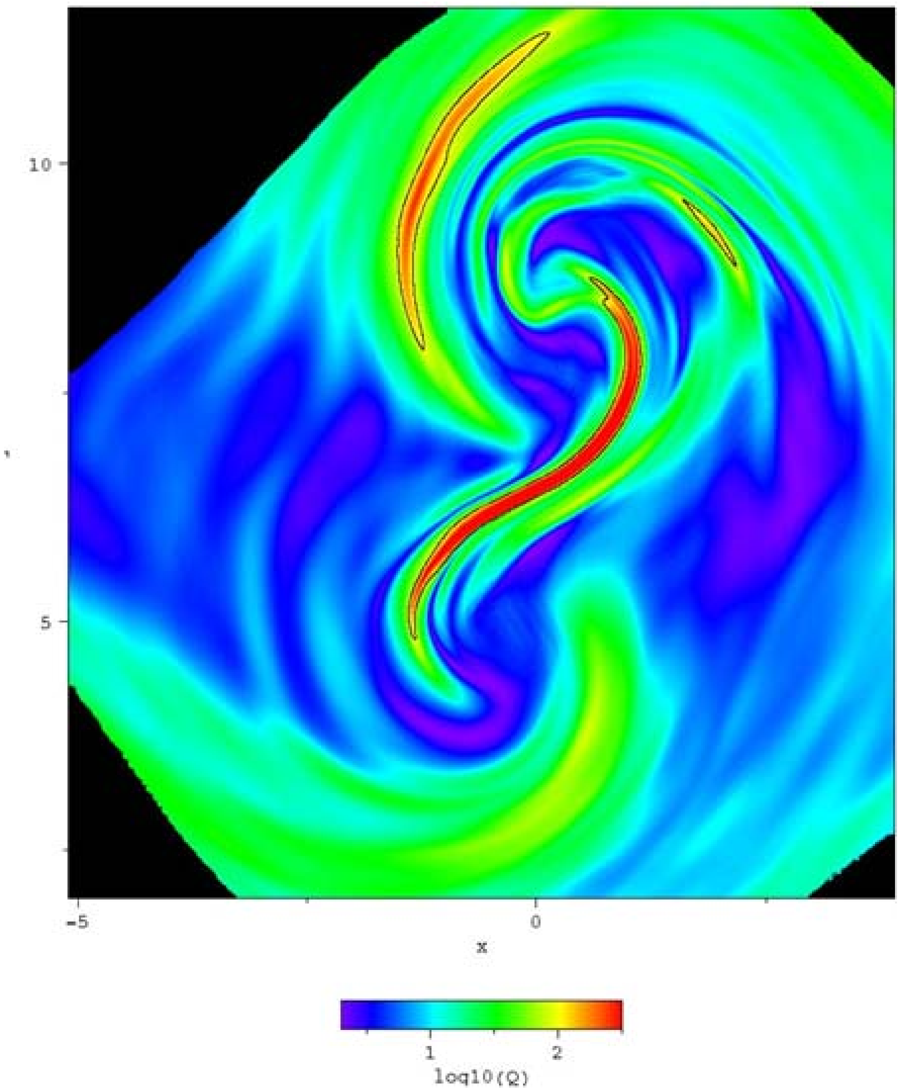
Calculate endpoints and
derivatives at z = 830 cm



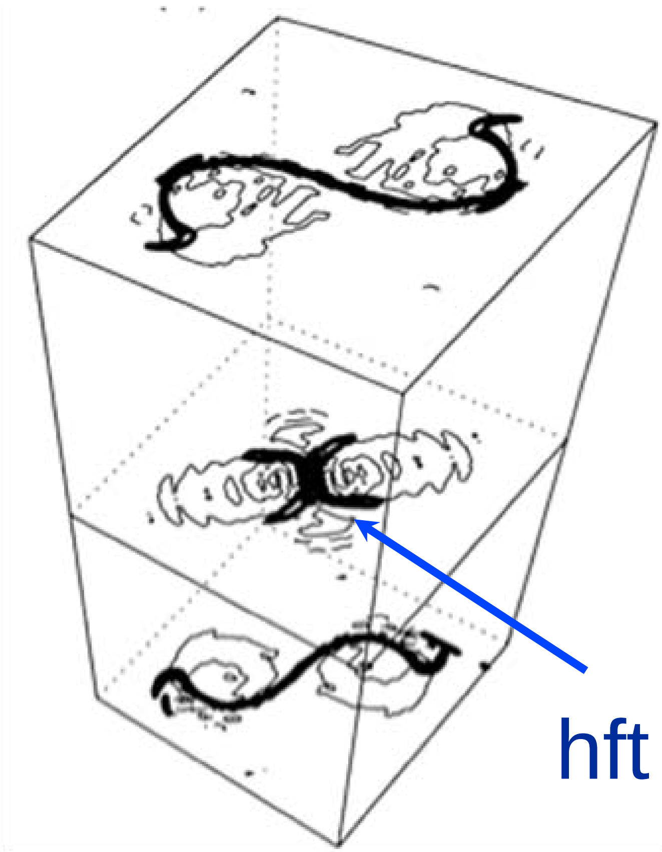
In the following slides, Q is shown during
the merging phases

QSL forms between flux ropes

Experiment

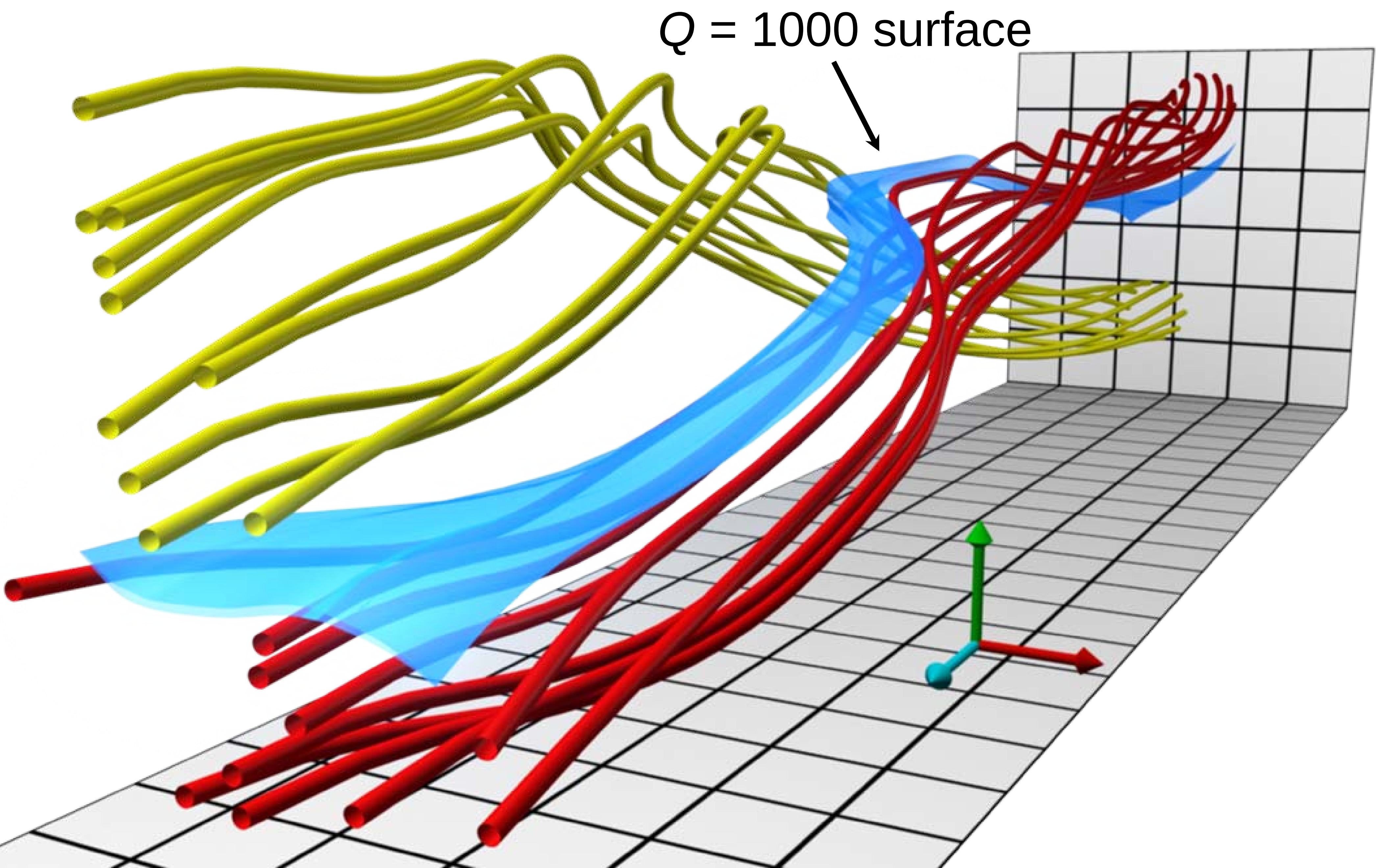


Q calculated between z = 64 cm and z = 830 cm planes at t = 1.7 ms. J_z =-5.5,-3 A/cm^2 contours overplotted.



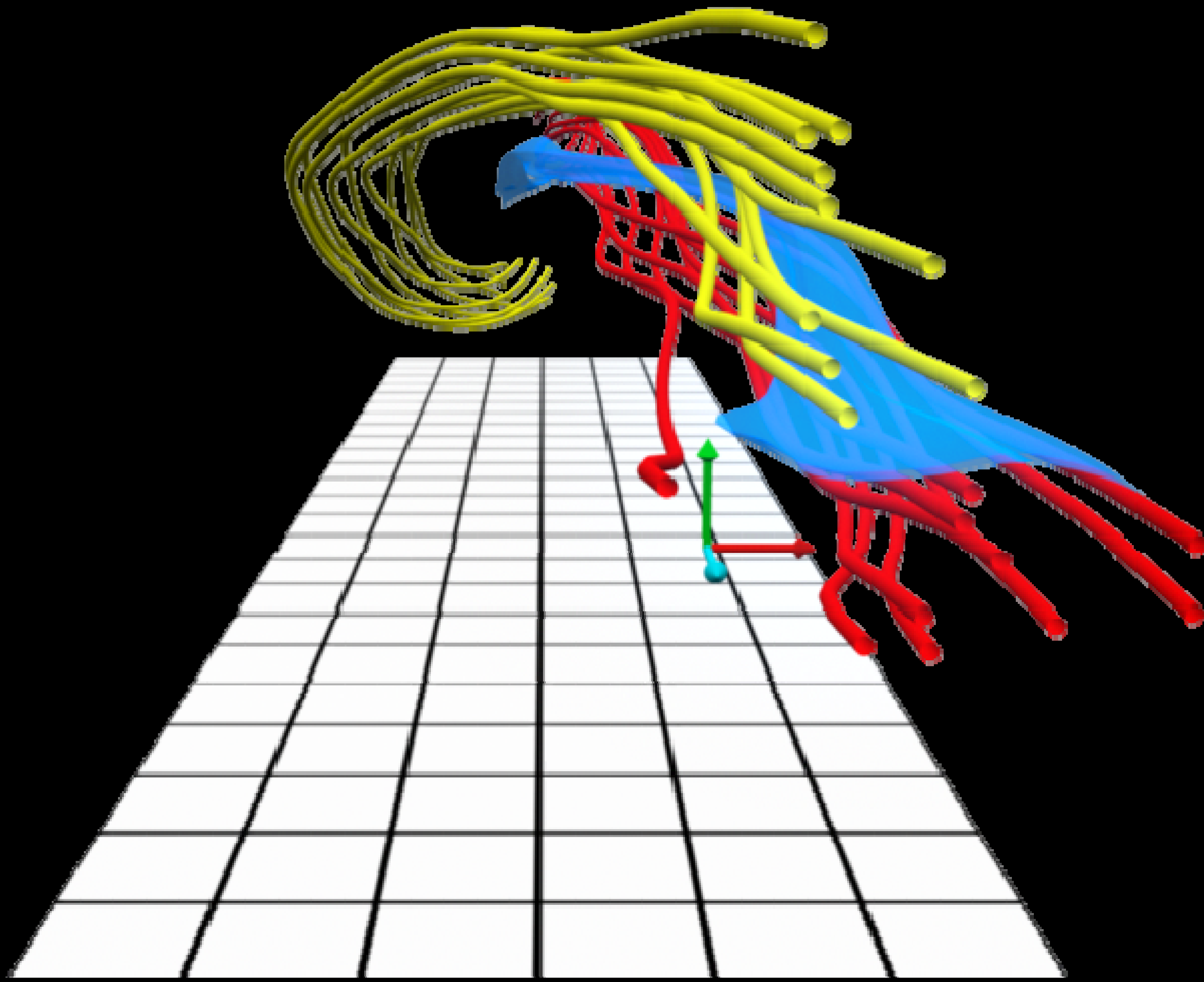
Numerical simulations of merging twisted flux tubes [Milano, et al. ApJ 1999]

QSL forms between flux ropes

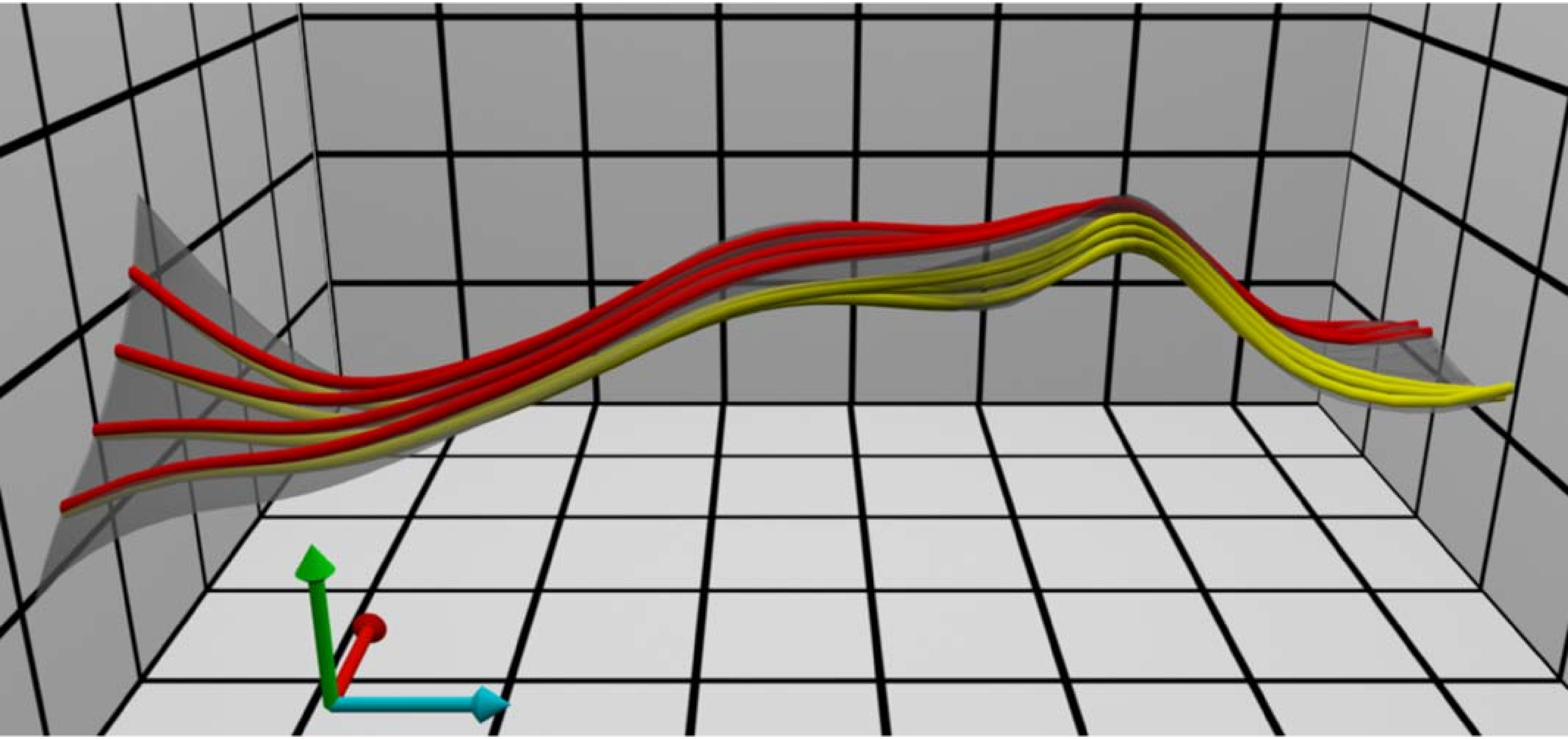


QSL forms between flux ropes

Q = 1000 surface



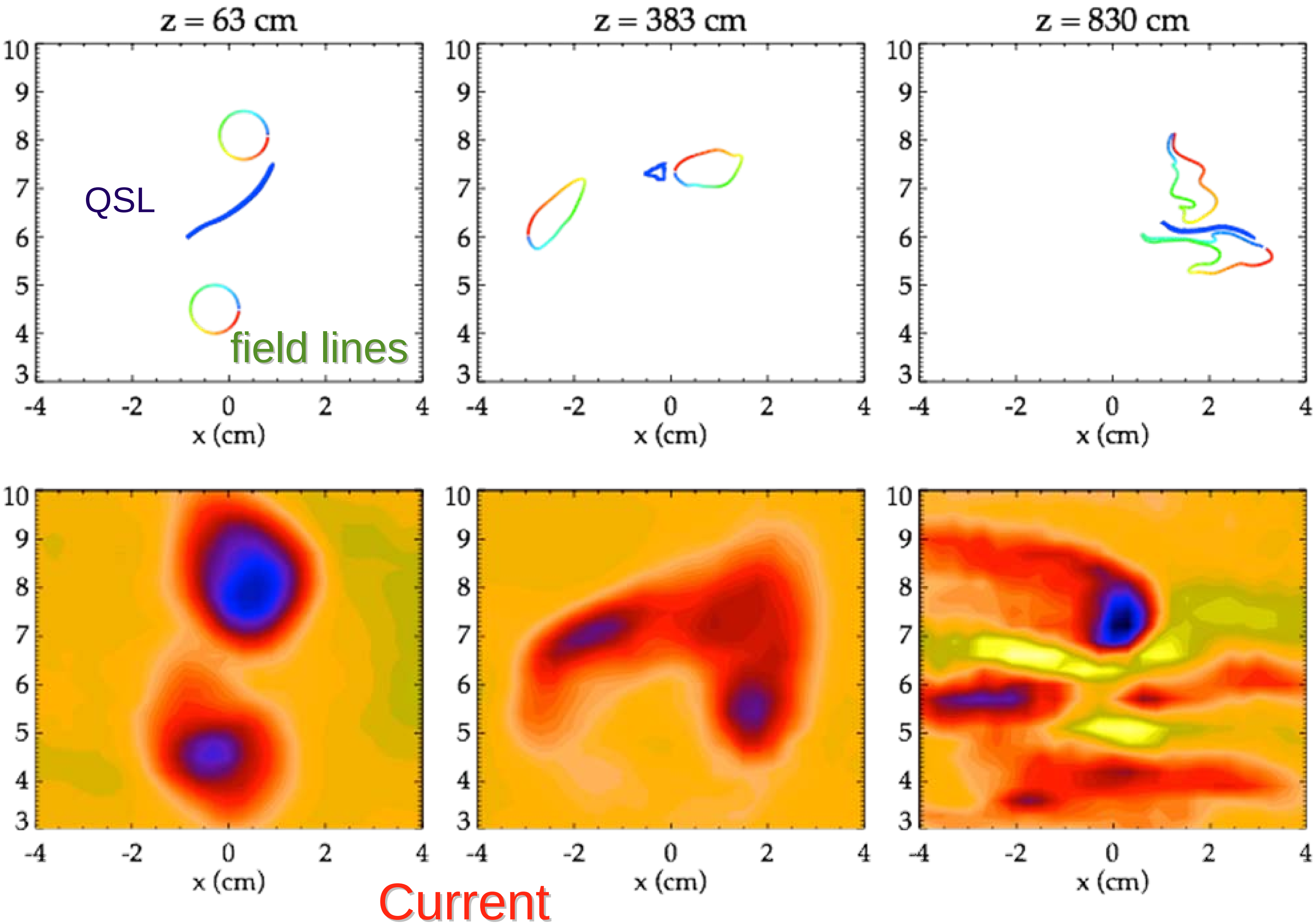
QSL has hyperbolic flux tube geometry

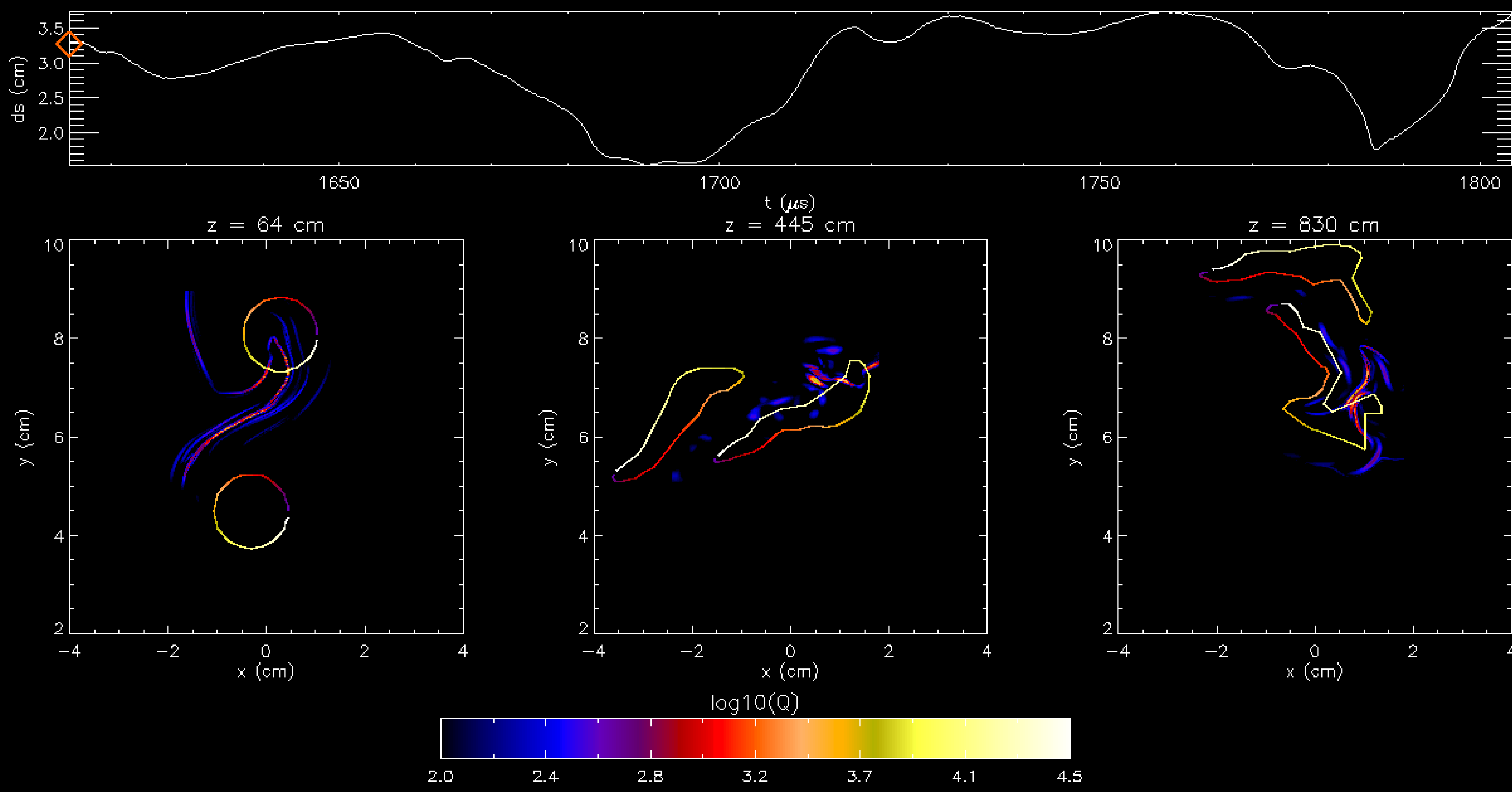


compressed 100x axially

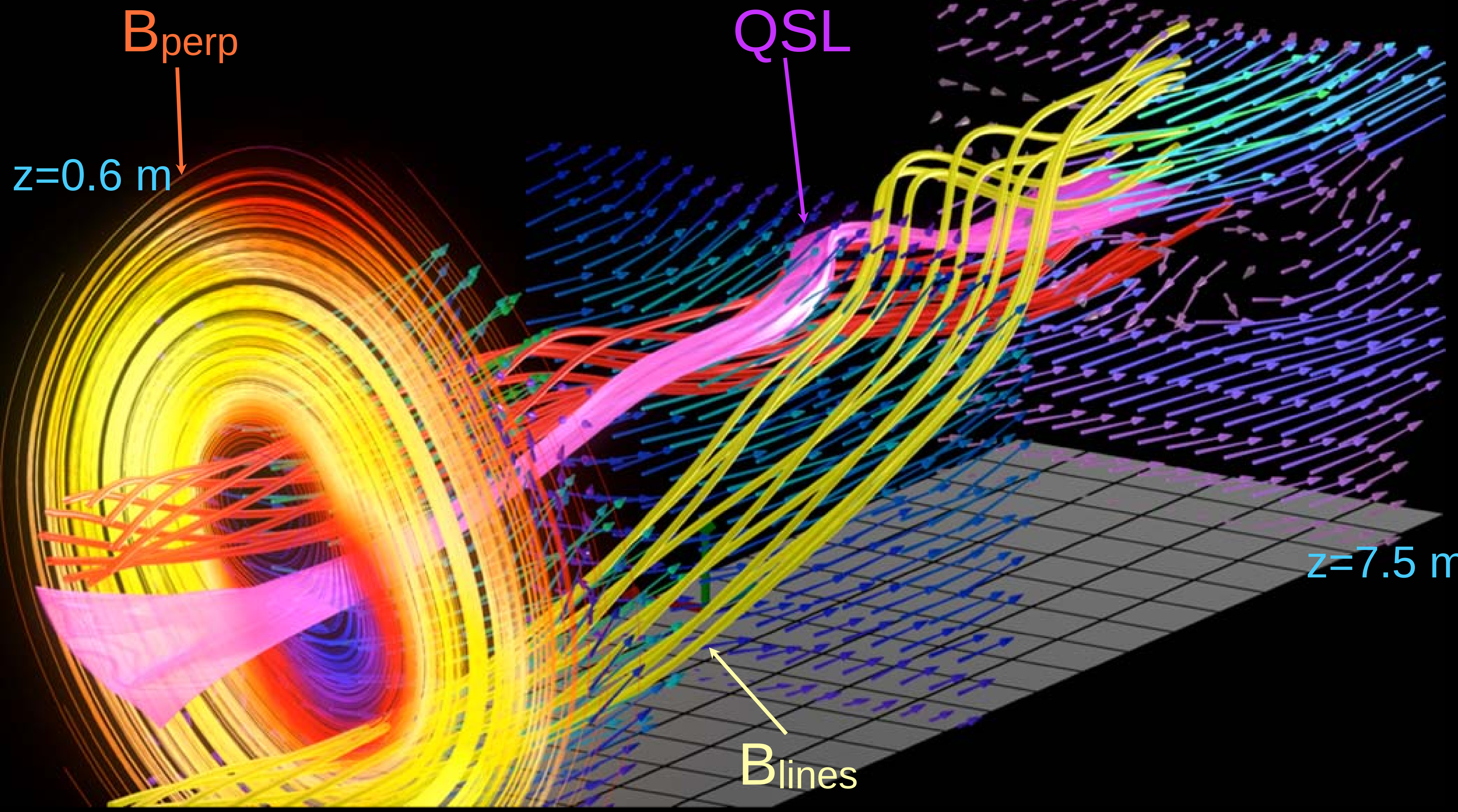
- Initial field line separation is ~0.05 cm, but diverges to ~3 cm.

Axial slices show HFT (hyperbolic flux tube) structure

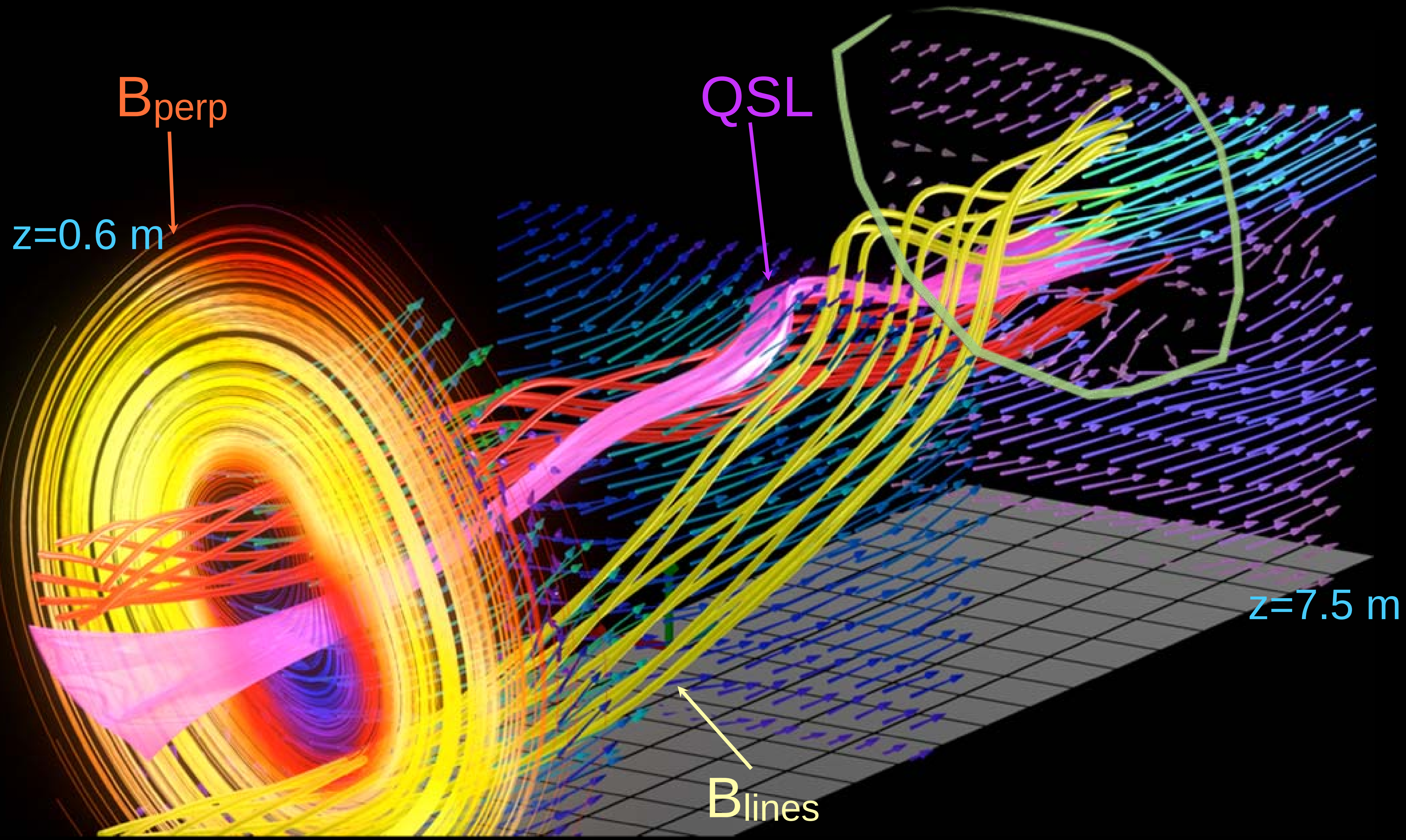




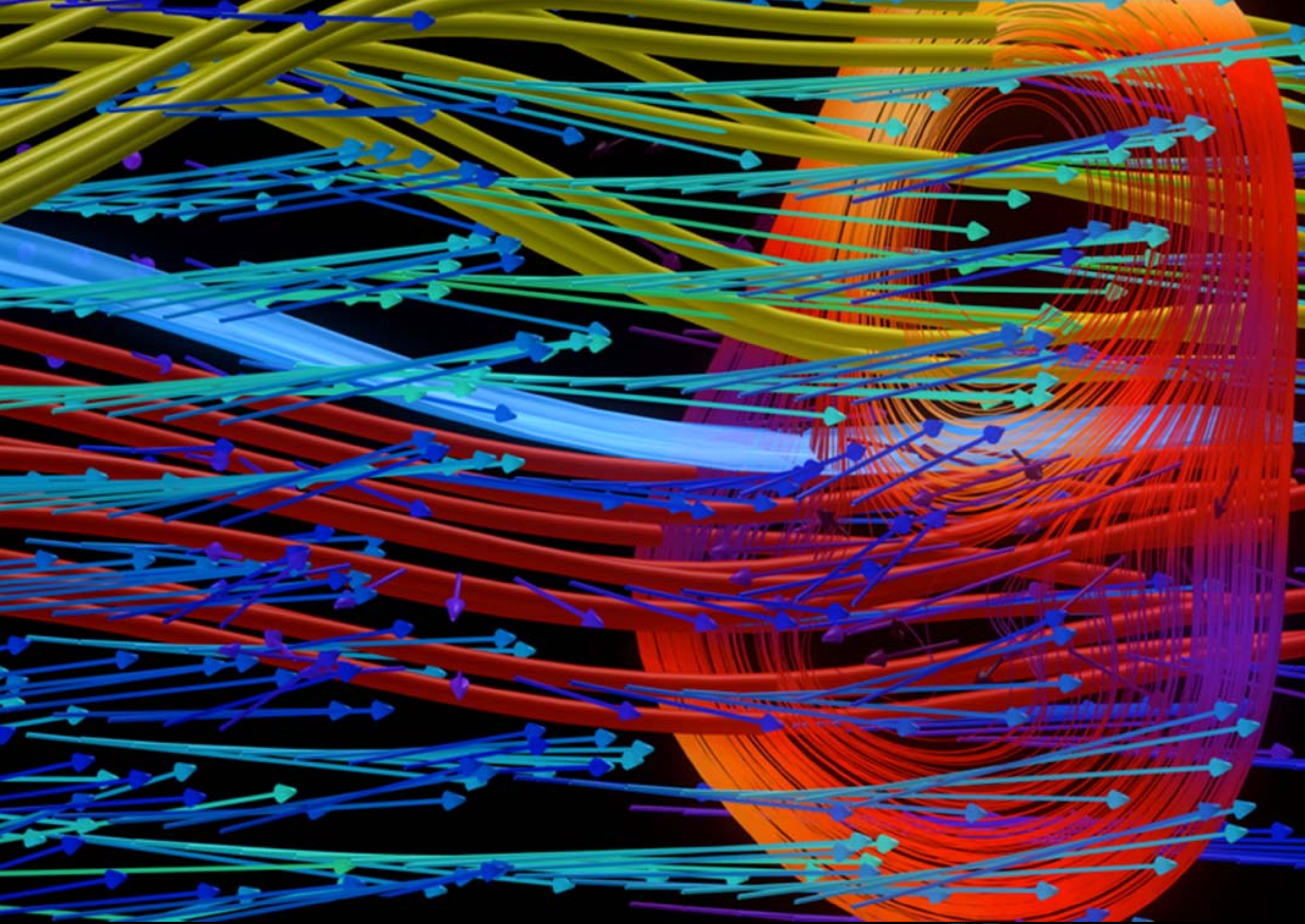
ds (cm)
3.5
3.0
2.5
2.0
1650
1700
1750
1800
t (μs)
z = 64 cm
z = 445 cm
z = 830 cm
10
8
6
4
2
y (cm)
-4
-2
0
2
4
x (cm)
log10(Q)
2.0
2.4
2.8
3.2
3.7
4.1
4.5



Ωt= 1.69 ms



Ωt= 1.69 ms



z=7.5 m

QSL's Quasi-Seperatrix Layers

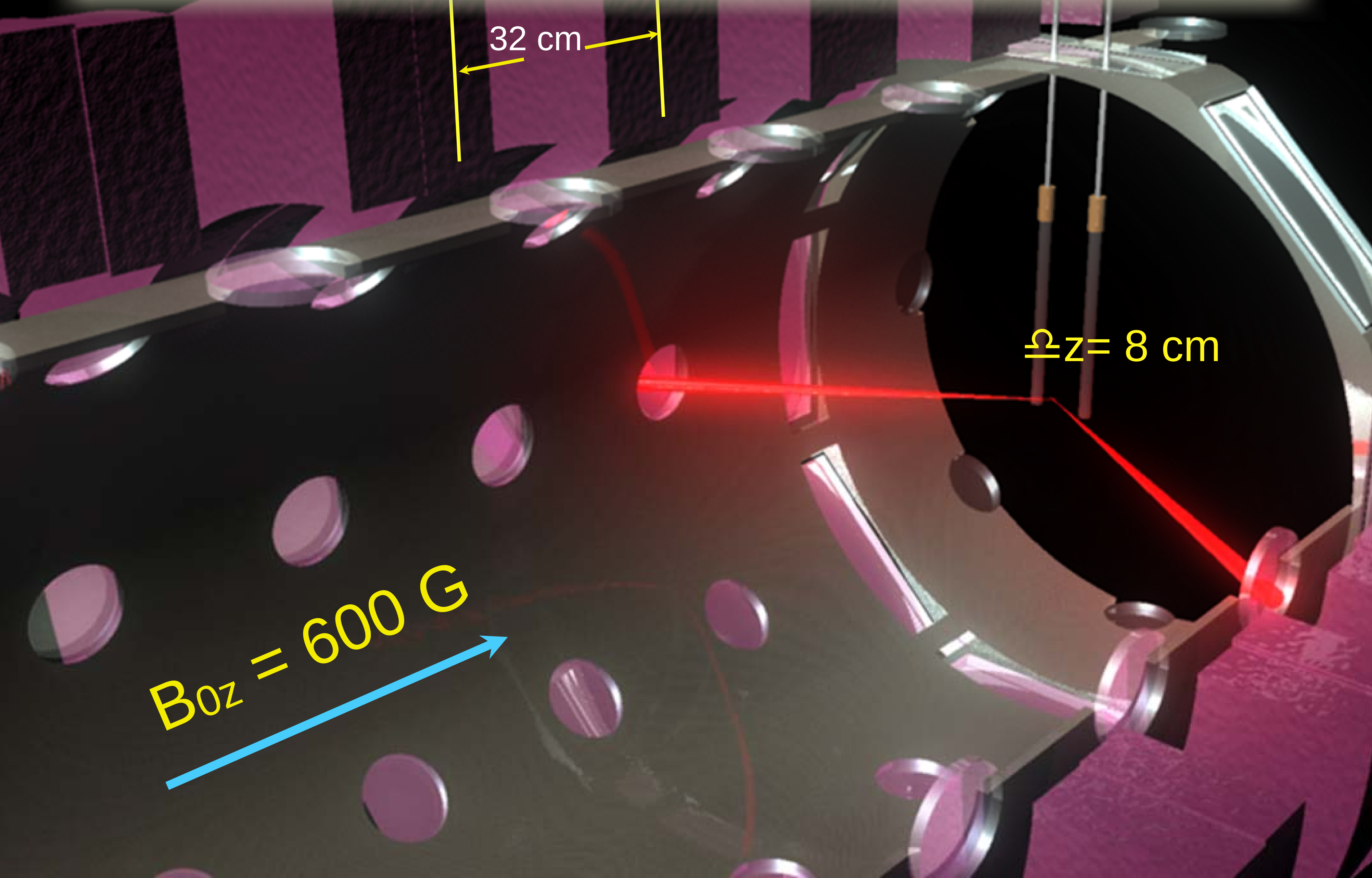
a) Can now be used to identify regions in which field lines become stochastic

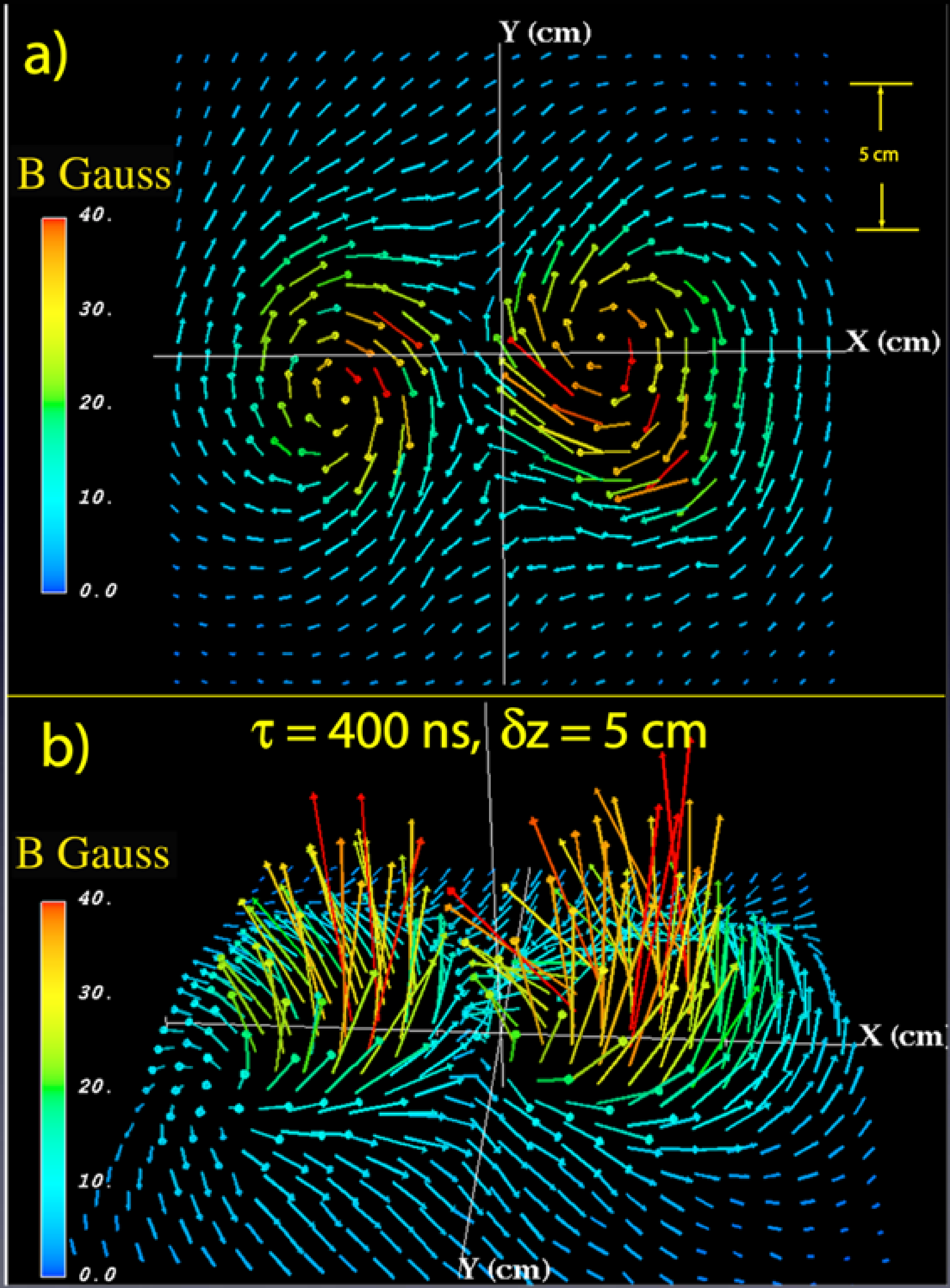
b) A methodology is under development to relate QSL's to current layers and reconnection regions

c) Reconnection can occur when no null points exist. In 3D this is usually the case

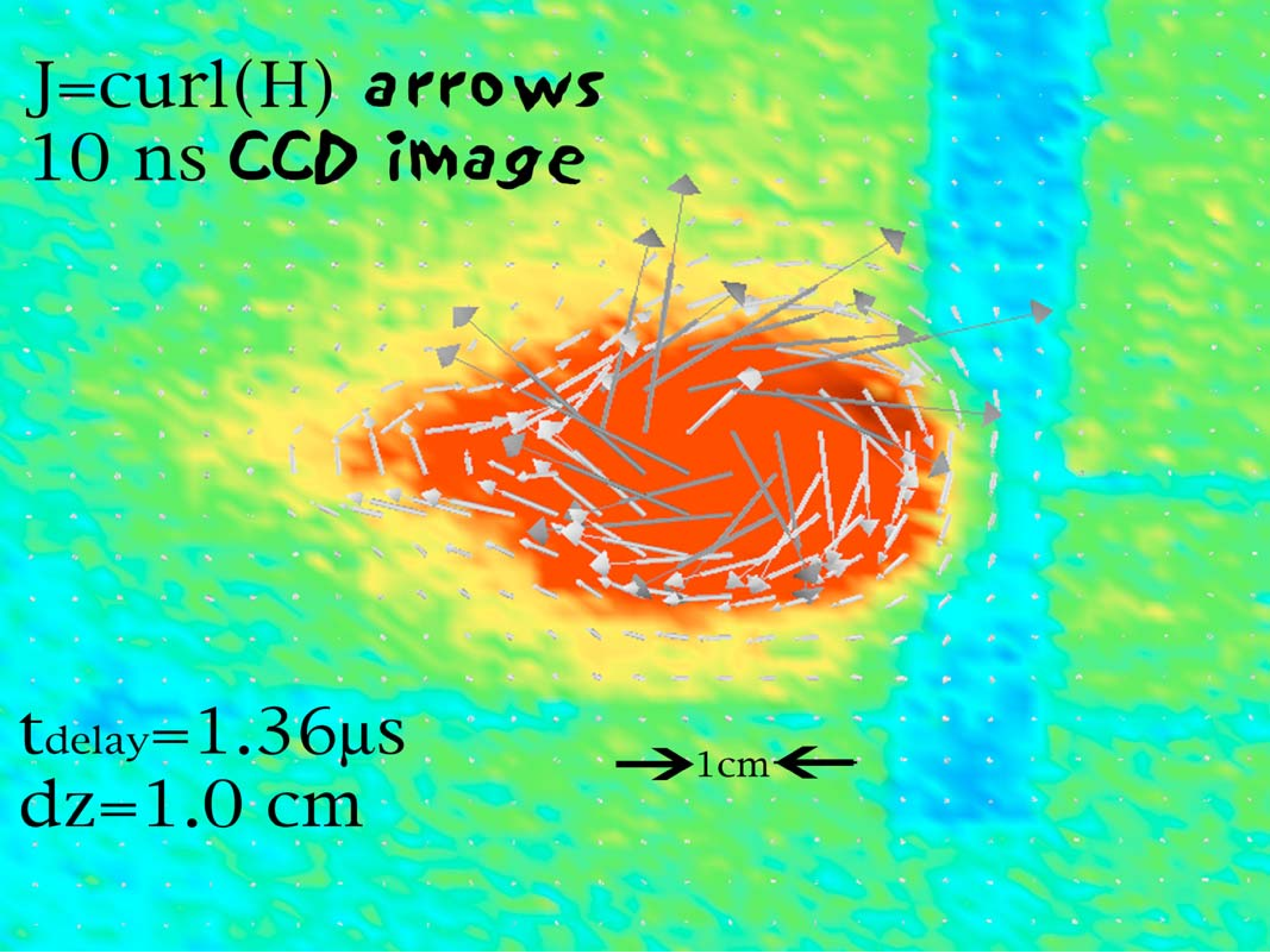
d) QSL's may soon be used to clarify the problem of the role of a guide field in reconnection

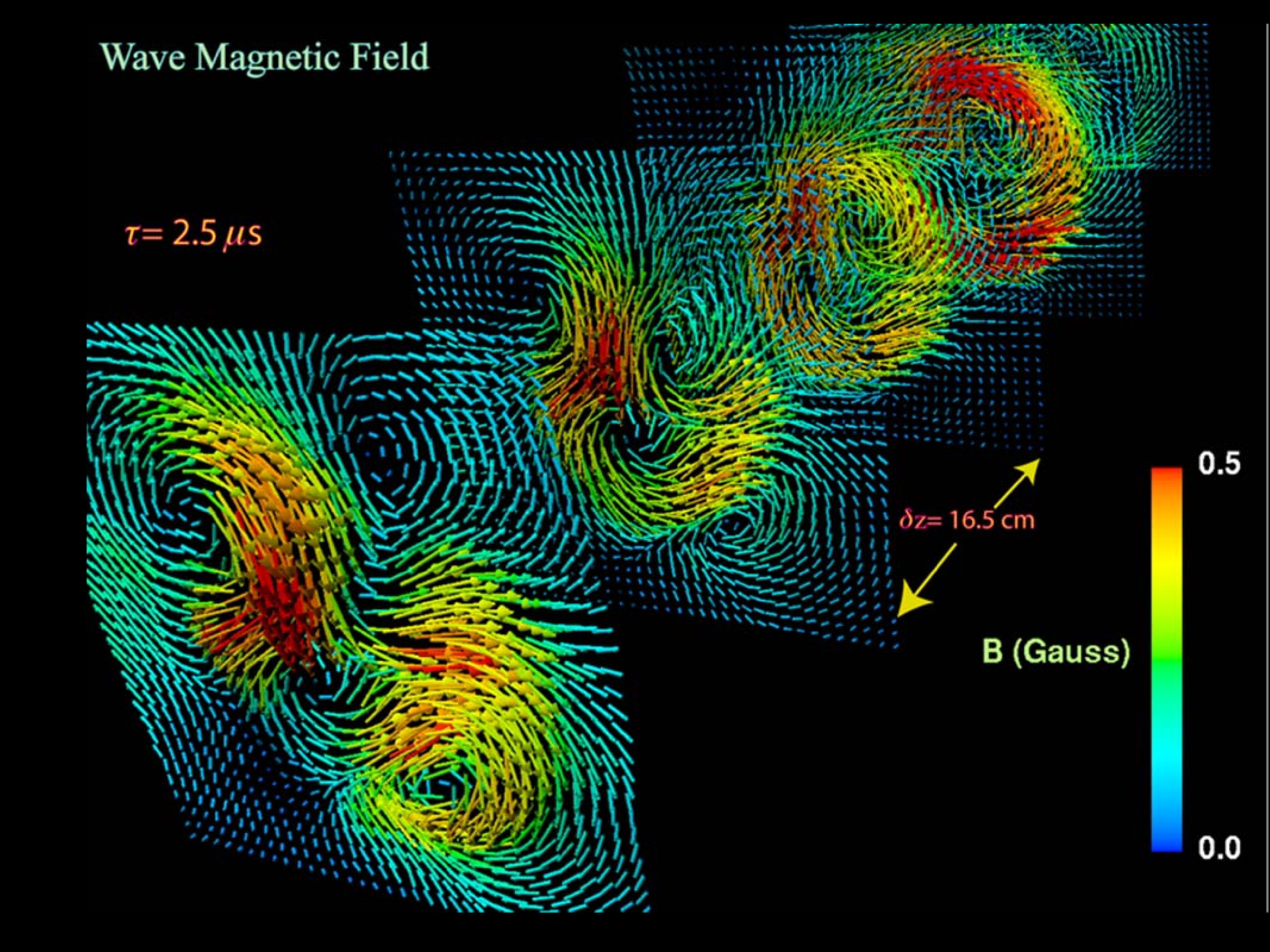
Laser produced plasma in a magnetoplasma



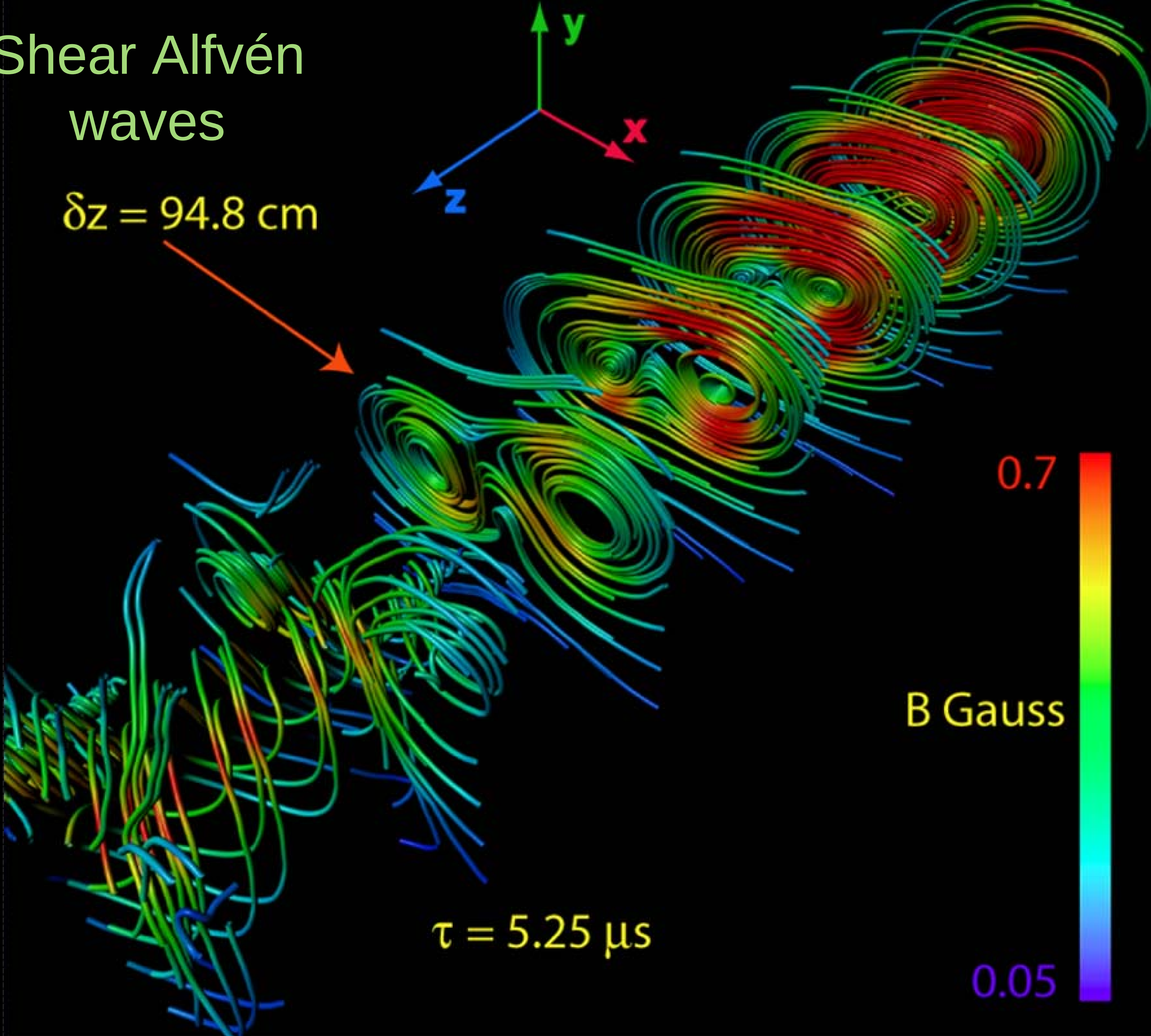


Three dimensional neutral sheet

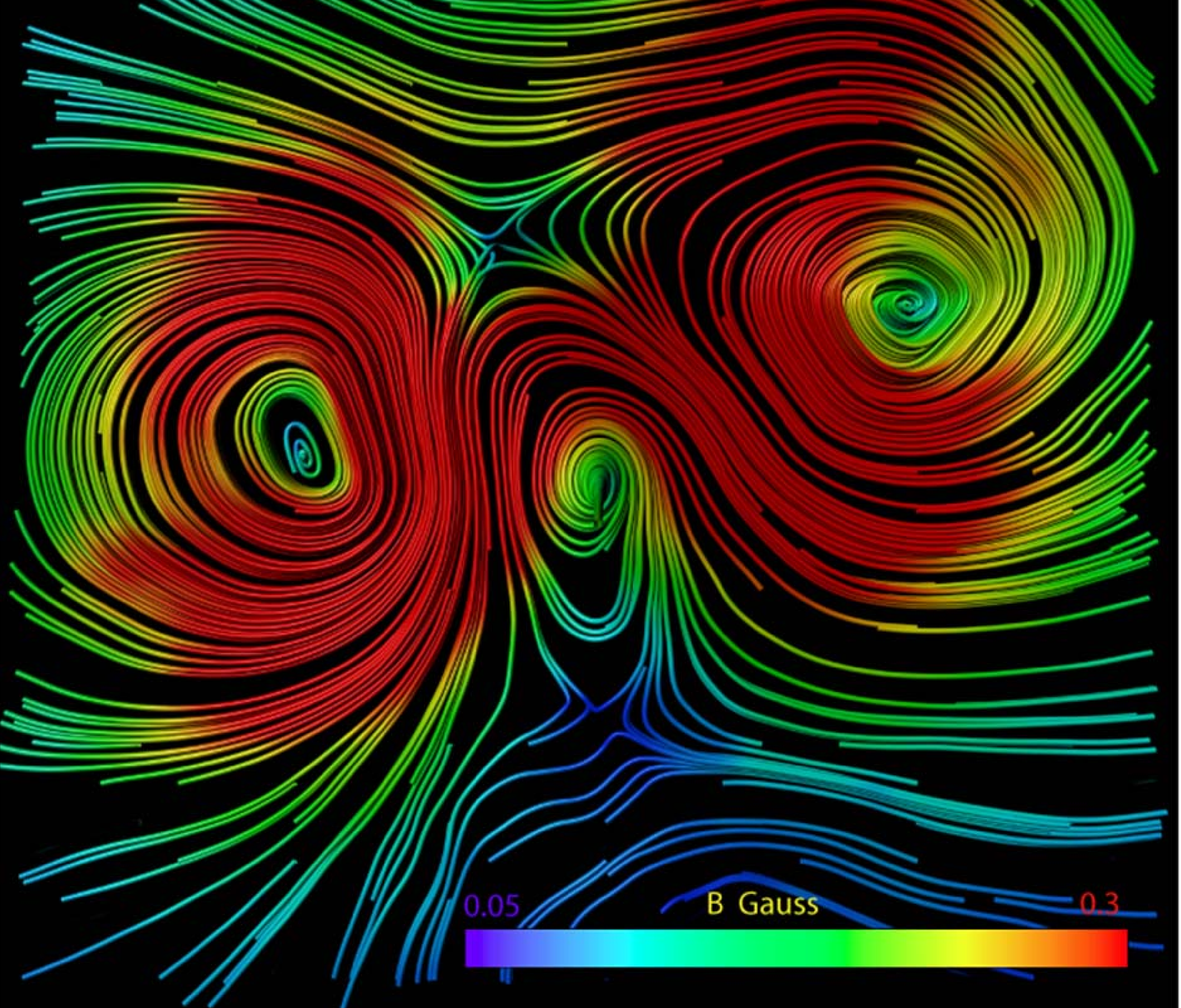

J=curl(H) arrows
10 ns CCD image
tdelay=1.36μs
dz=1.0 cm
1cm


Wave Magnetic Field
τ= 2.5 μs
δz= 16.5 cm
0.5
B (Gauss)
0.0

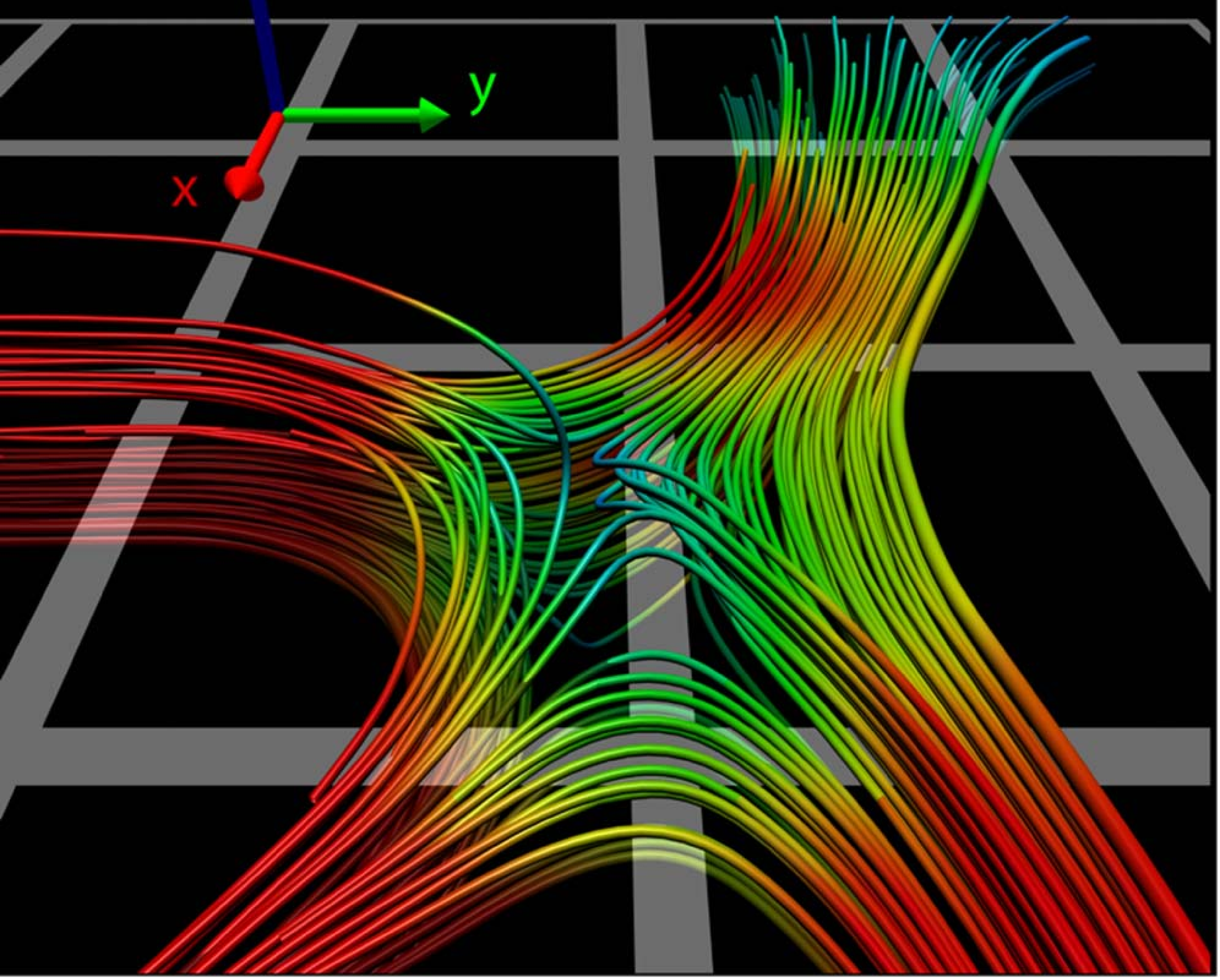
Shear Alfvén waves

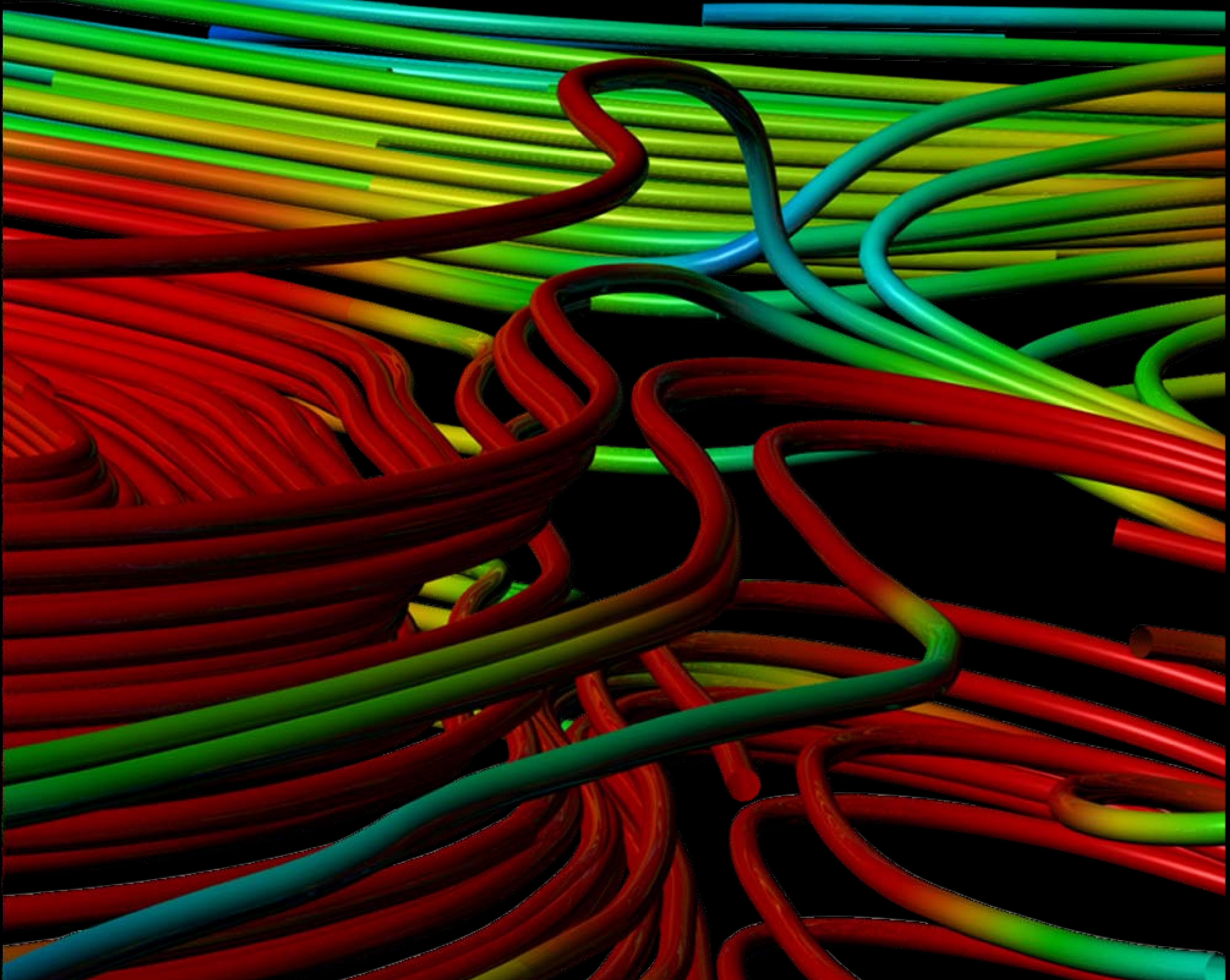


5.25
❍s



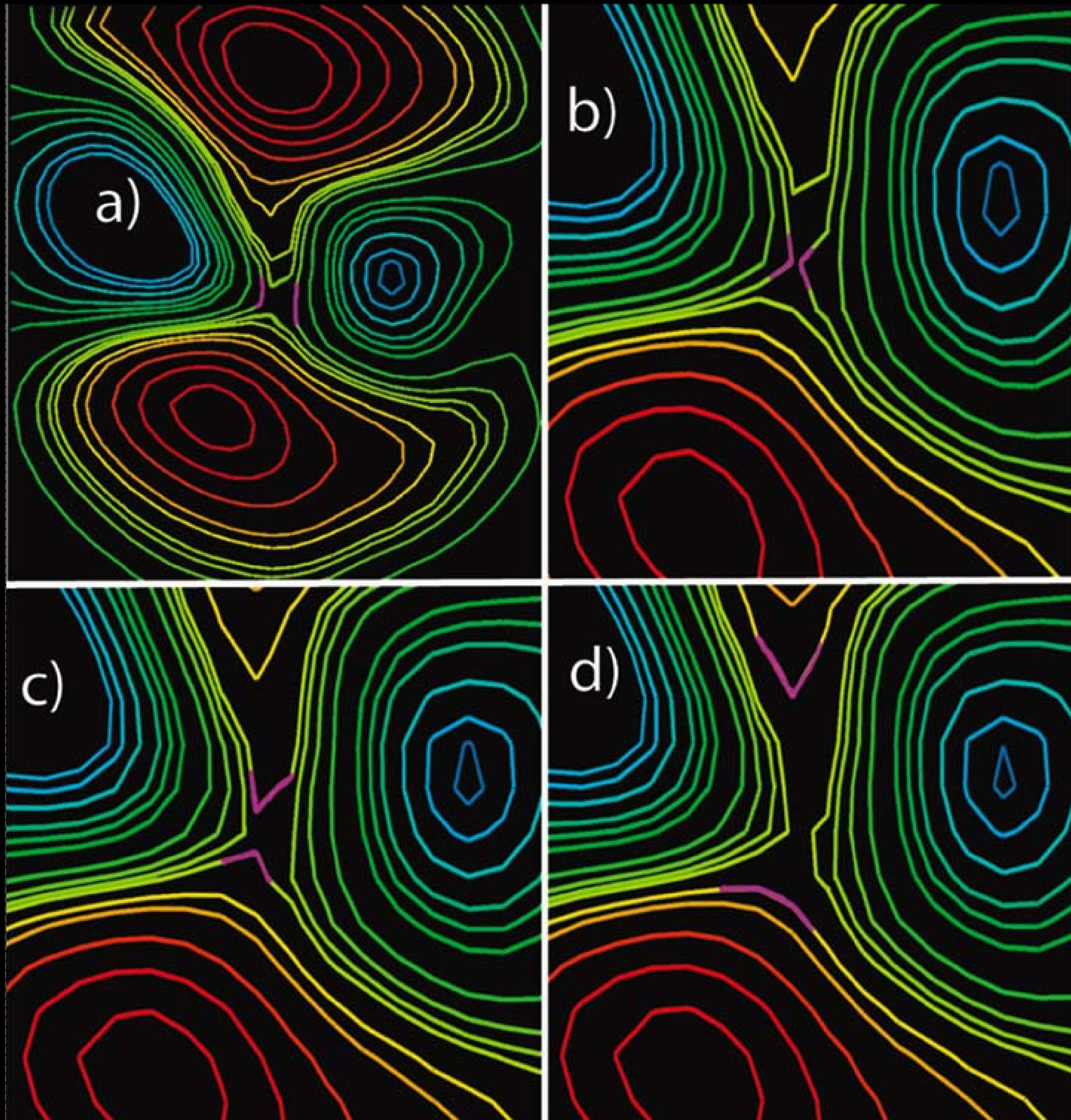
♎z=
95 cm


y
x

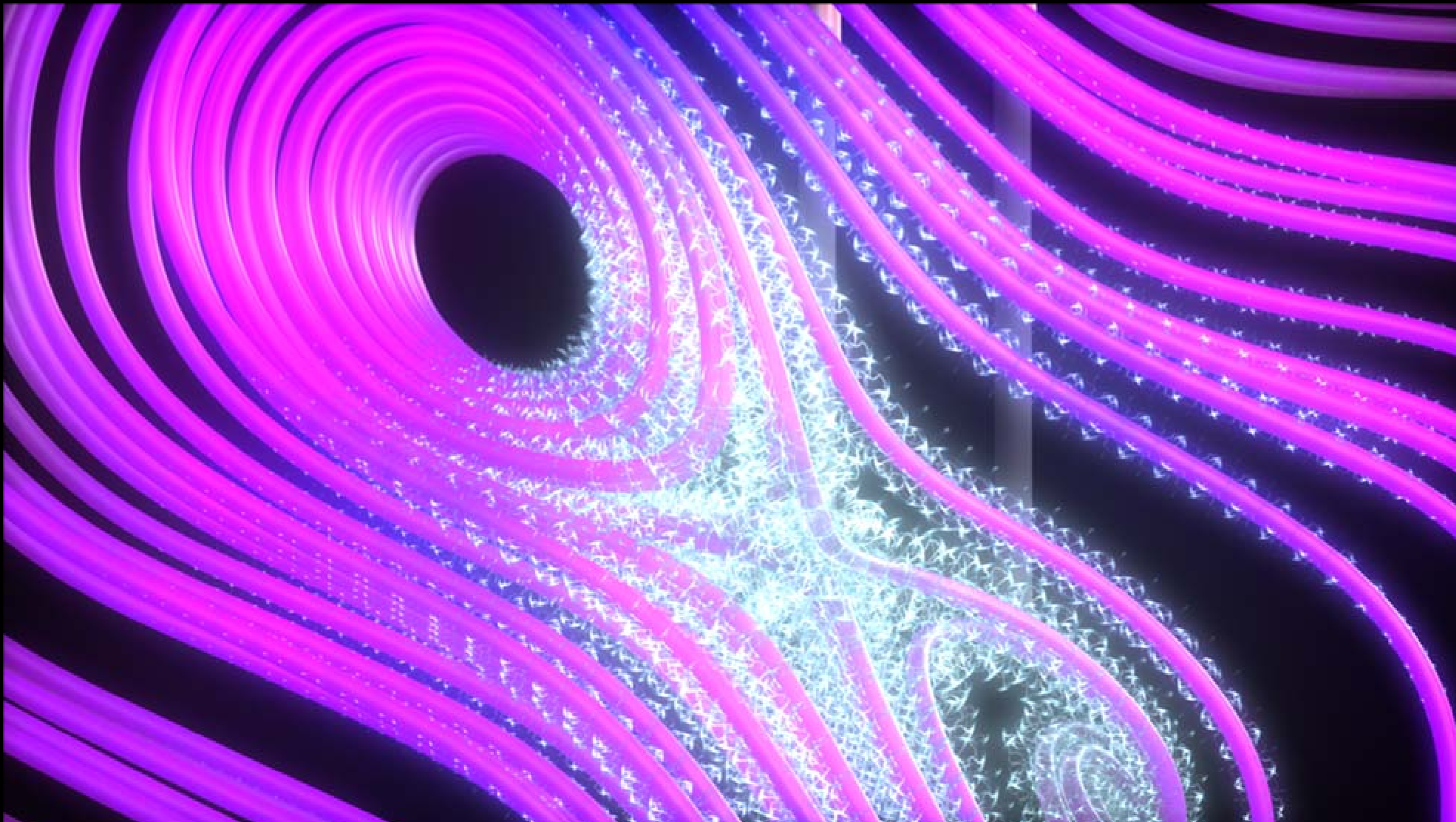


♎z =
158 cm

♦ =
9.8
❍s
♎t =
10 ns



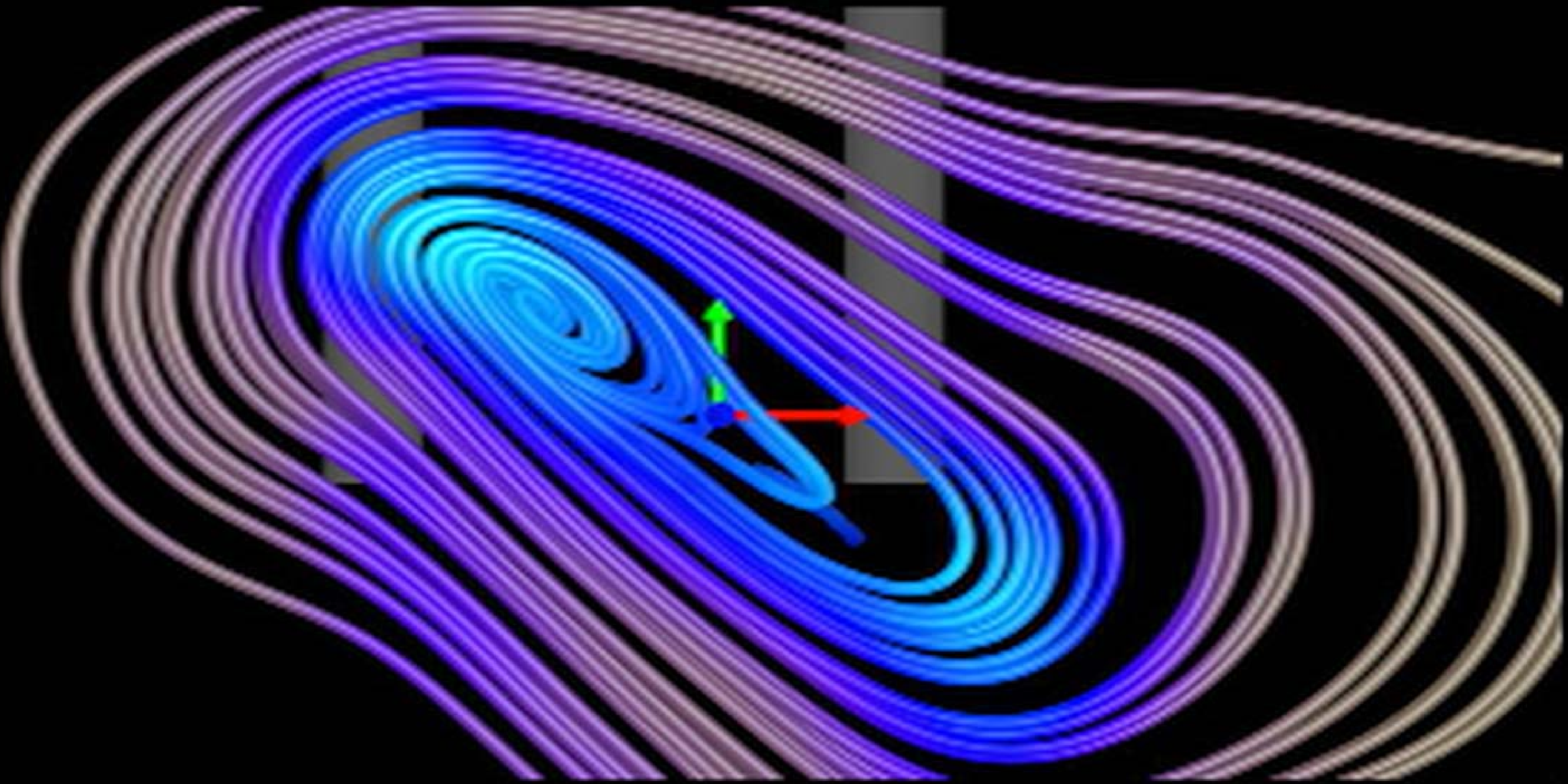
LAPD



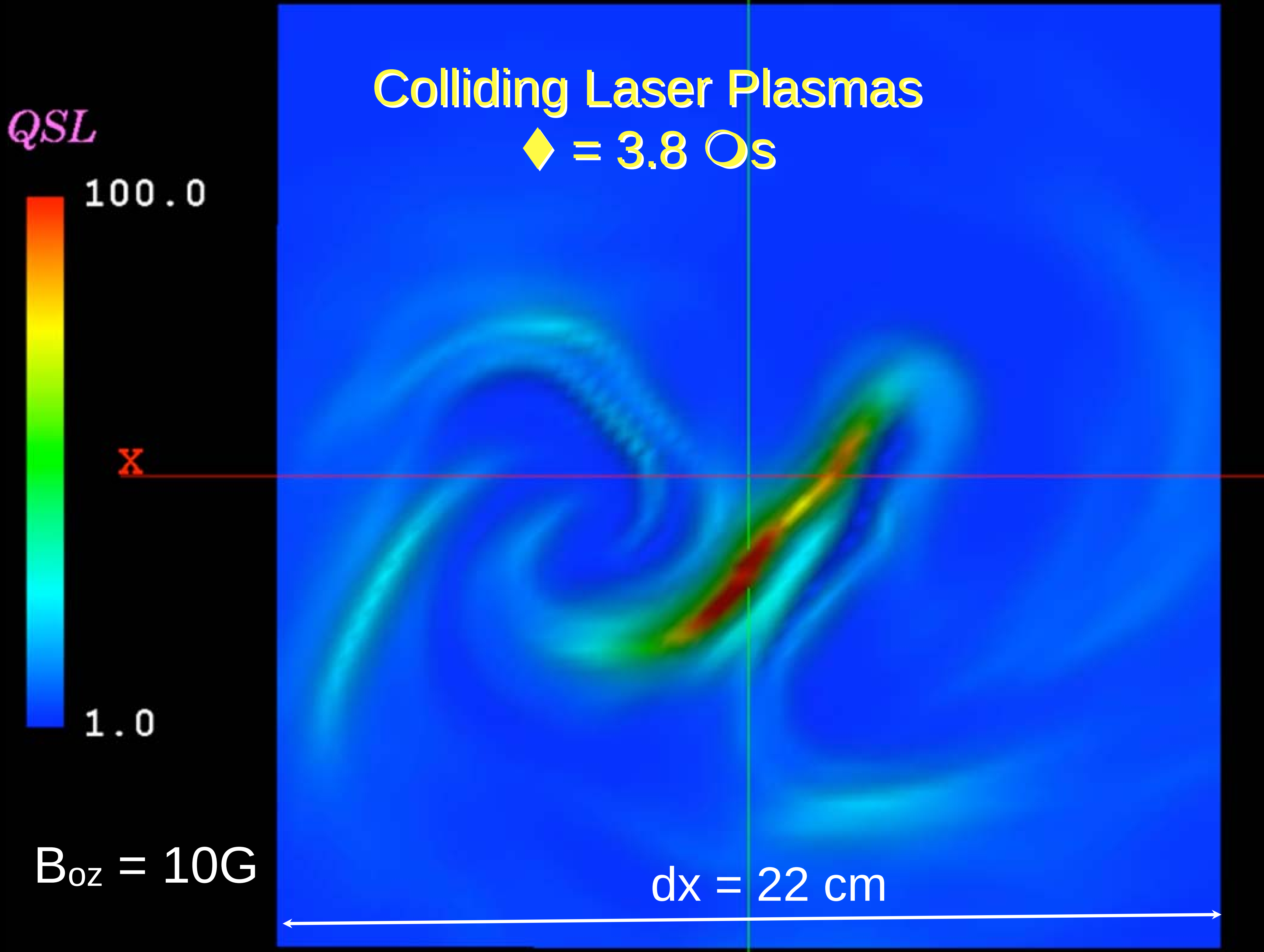
t = 5.12 ❍s

Blines, E field

Colliding laser produced plasmas

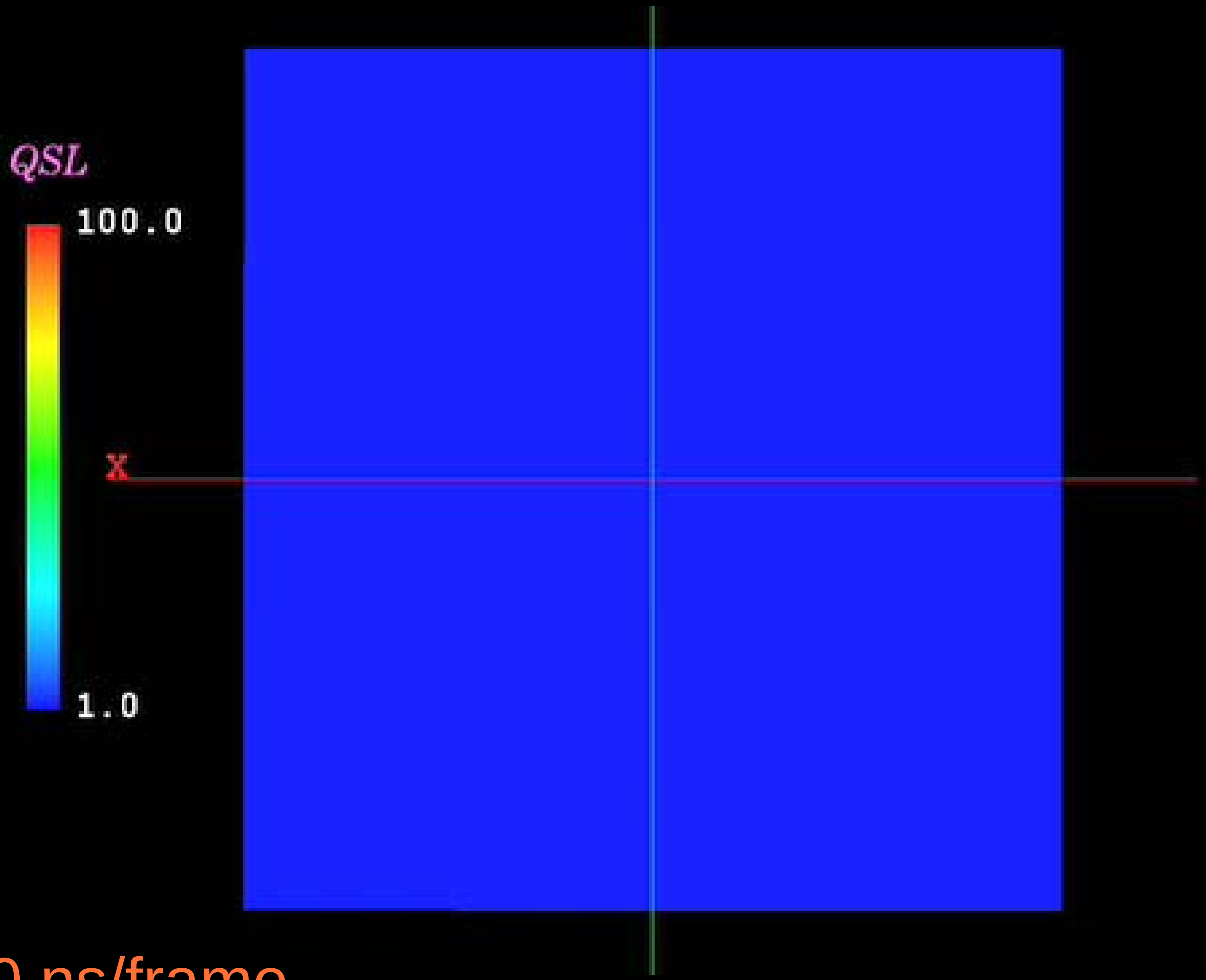


Alfvén wave magnetic field



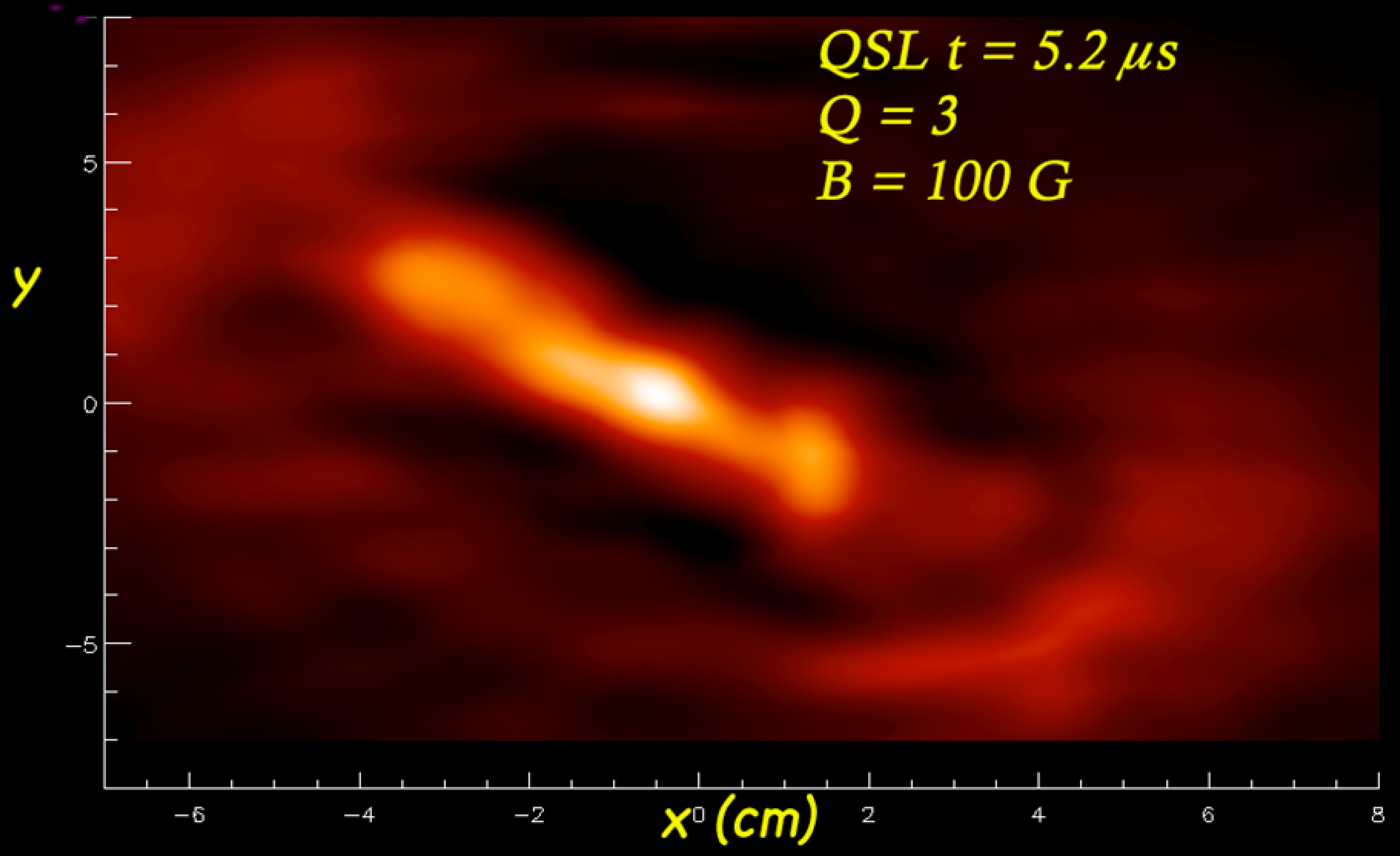
Colliding Laser Plasmas
♦ = 3.8 ❍s
QSL
100.0
x
1.0
B_{oz} = 10G
dx = 22 cm

QSL for Alfvén waves



dt = 20 ns/frame
movie = 1 usec

B_{oz} = 10G



B_{0z} = 100 G

In nature most reconnection is probably three dimensional and the concept of a seperatrix is of limited use

A QSL has been observed when magnetic flux ropes merge and there is reconnection

The flux rope current system becomes, sheetlike, complex and return currents appear.

The QSL is an indicator that reconnection is occurring, we await a relationship between Q and the reconnection rate.