US-Japan Workshop on
Magnetic Reconnection 2012,
Princeton, 23-25 May 2012

A Laboratory Experiment of Magnetic Reconnection: Outflows, Heating and Waves in Chromospheric Jets

[1]N. Nishhizuka, [2]Y. Hayashi, [2]H. Tanabe, [2]A. Kuwahata, [2]Y. Kamino,
[2]M. Inomoto, [2]Y. Ono, [1]T. Shimizu, and TS-4 group

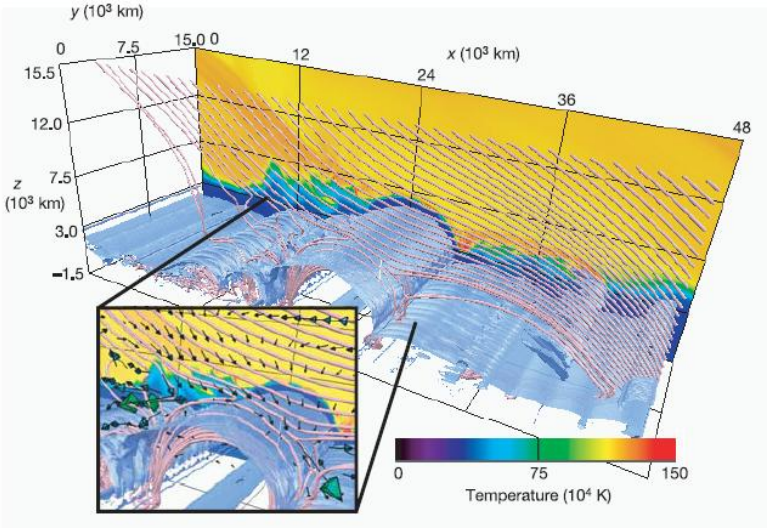
[1]ISAS/JAXA, Hinode project
[2]Tokyo University, TS-4 group

Contents of my talk

- Introduction

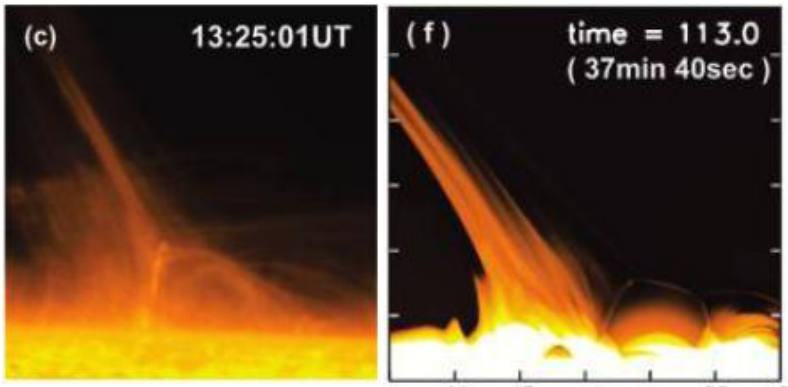
  --Similarity of Solar Jet (above the sunspot light bridge) and spheromak of laboratory plasma.
- Set up of Experiment
- Experimental result
- Summary and Discussion

Flux Emergence and Solar Jets by Reconnection

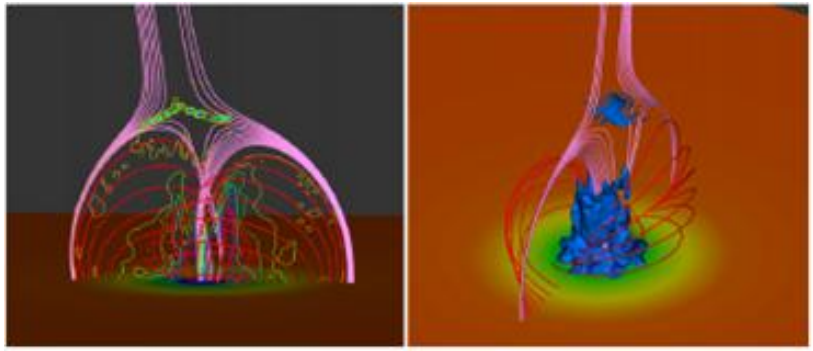


[Isobe et al. 2005 Nature]

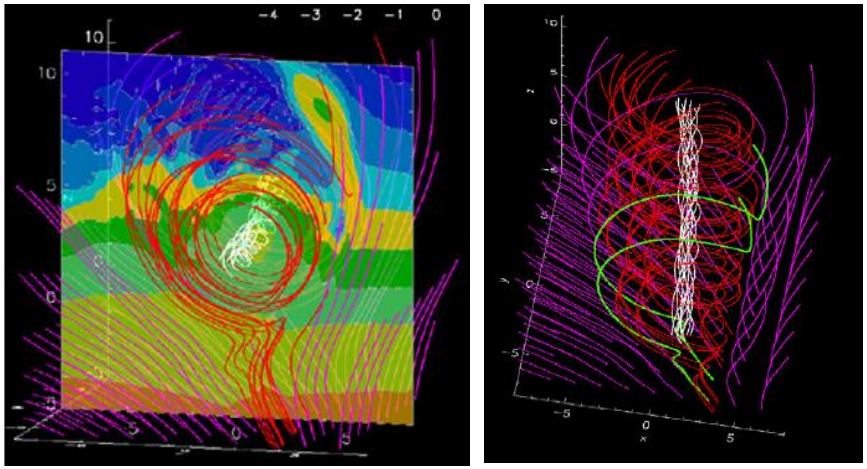
Hinode obs. MHD simulation



[Nishizuka et al. 2008 ApJL]



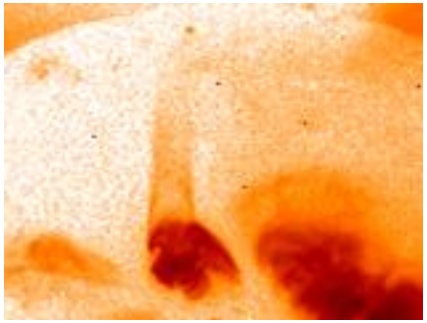
[Pariat, Antiochos & DeVore 2010 ApJ]



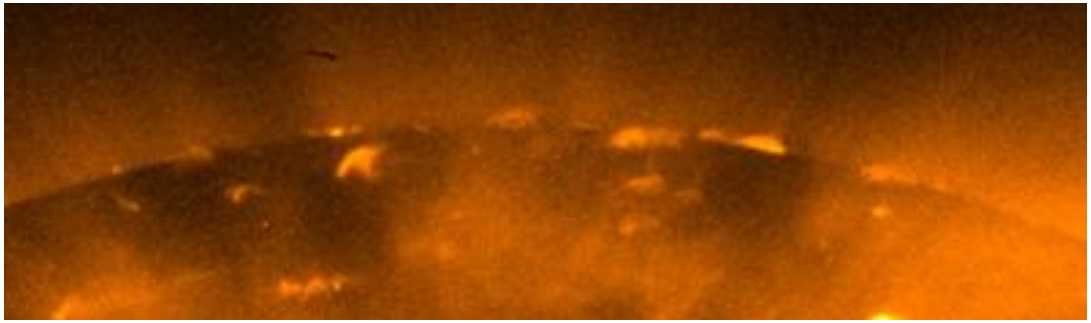
[Magara 2010 ApJ]

Ubiquitous Reconnection and Jets in the Sun

Coronal Jets (X-ray jets)

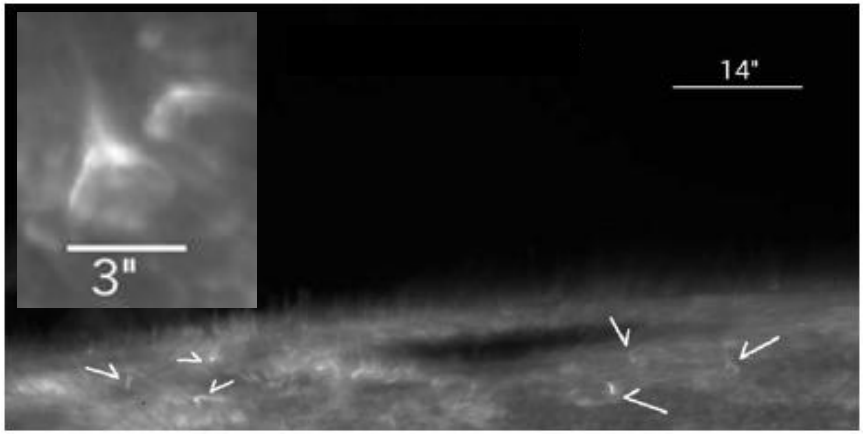


Polar Jets

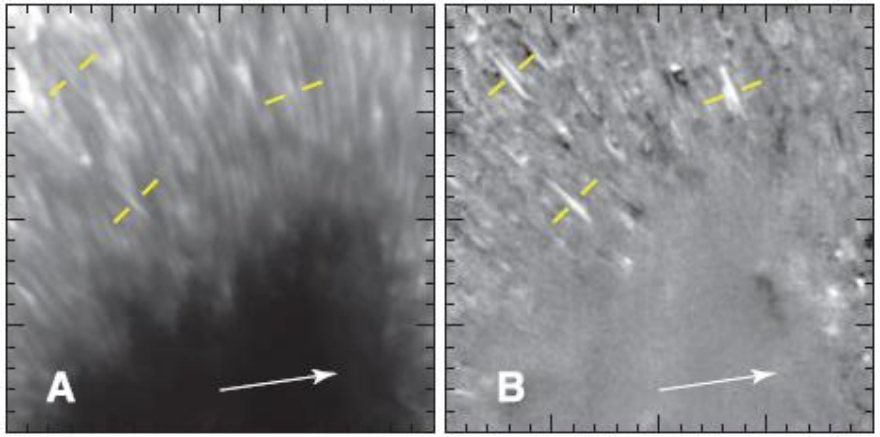


Alfvenic waves have also been discovered in the solar atmosphere associated with jets, with the wave period of ~200 s.

[Cirtain et al. 2007, Nishizuka et al. 2008, Okamoto & DePontieu 2011]



[Shibata et al. 2007 Science, Nishizuka et al. 2011, Singh et al. 2011]

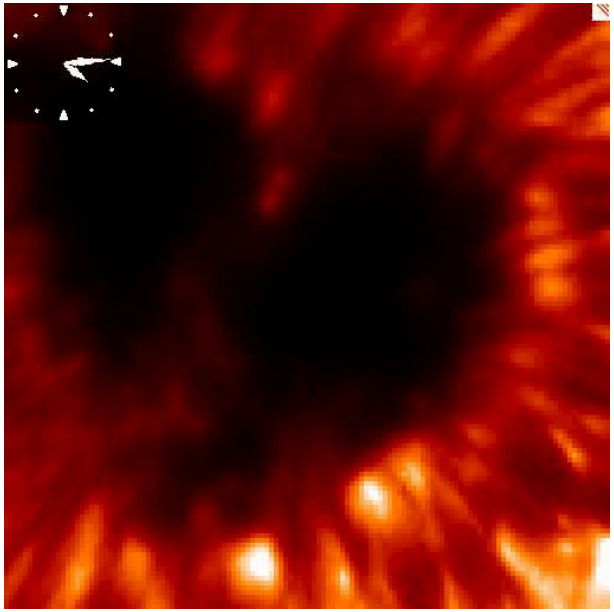


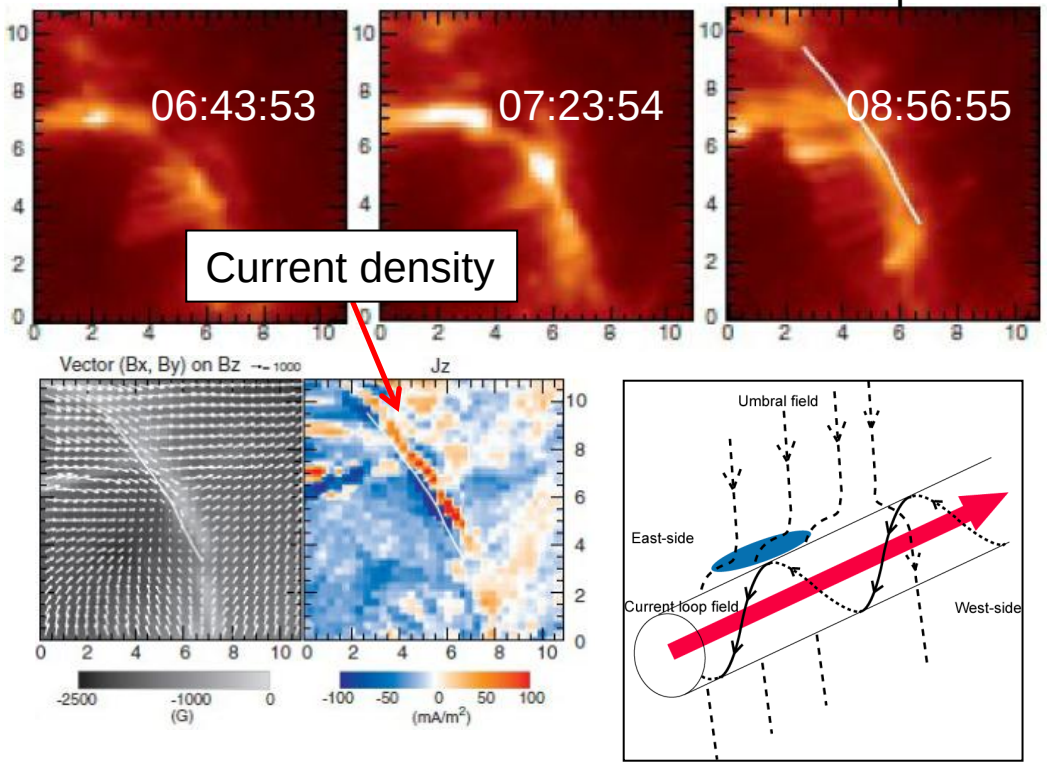
[Katsukawa et al. 2007 Science, Jurcak et al. 2008 A&A, 2011, Ryutova et al .2008]

Measurement of B-field and Jz In the Sunspot Lightbridge

- Recurrent Chromospheric Jets over Light Bridge

NOAA10953
30 April 2007





(Shimizu et al. 2009, ApJ, 696, L66)

Evidence of Magnetic Reconnection : long-lasting ejections for a few days

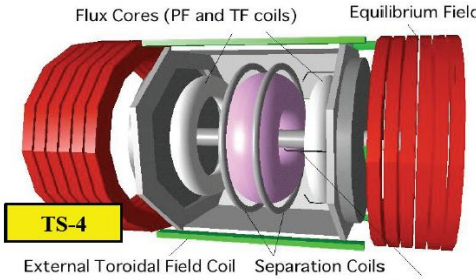
--Bi-directional flows (Up: 26-180km/s, Down: ~0.7 km/s e.g.) C_s~9 km/s, V_A~420 km/s

--The existence of Horizontal Flux tube (strong current 60-175 mA/m2, B~700-1700 G)

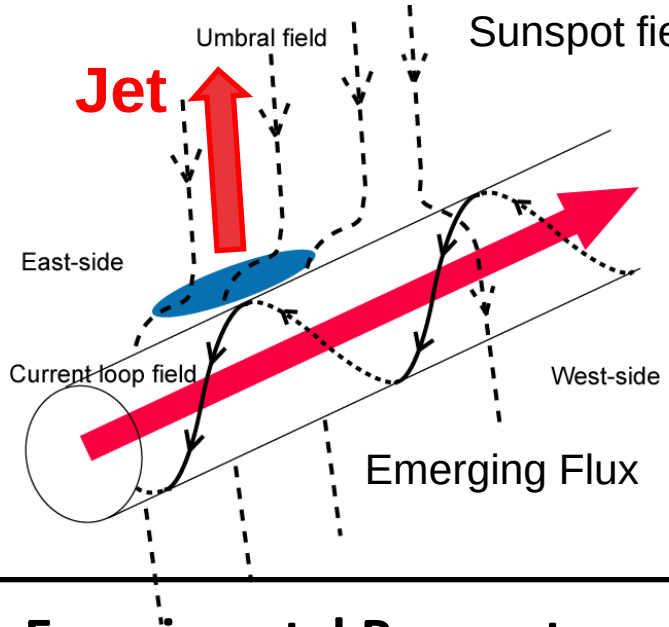
Remaining puzzles of Solar Jets

- What is the **acceleration mechanism** of a jet in microscopic and macroscopic point of view?
- How does the **ion/electron heating** occur?
- **Wave** generation, propagation and dissipation due to reconnection
- What is the reconnection rate in the chromosphere? How is the **resistivity**?
- The component reconnection between an emerging flux and the surrounding magnetic field lines. How does the angle of reconnecting fields affects the dynamics?
- Why are plasma ejections intermittently produced for a long time in the sunspot lightbridge? What is the energy storage mechanism?
- How do the **different kinds of plasma** result in different dynamics of jets?

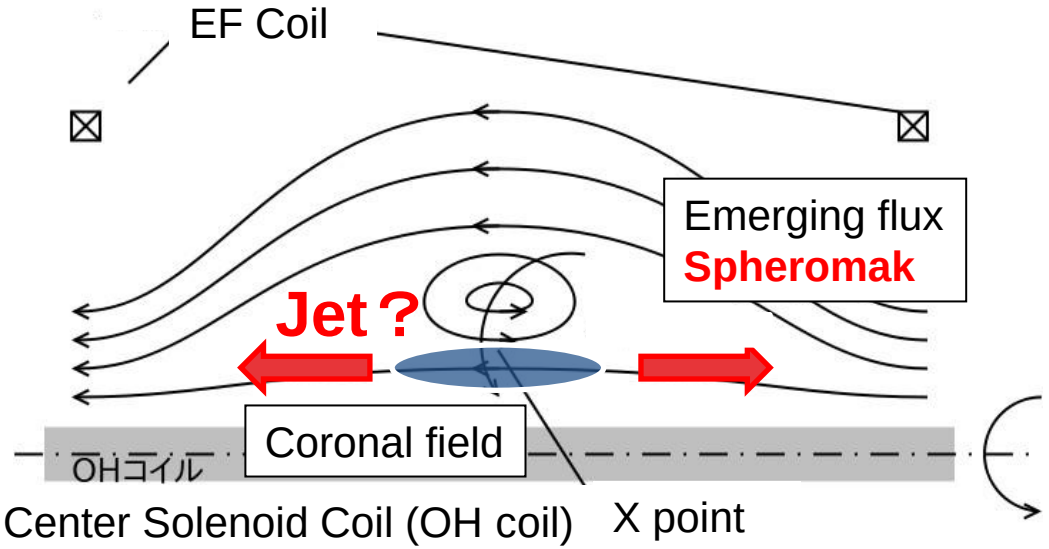
Similarity of LB configuration (Jets) to Laboratory Spheromak Plasma



Solar obs. (Light Bridge)



Laboratory (Spheromak)



Experimental Parameters:

n: 10^{14} [cm^{-3}],

Te:5-10 [eV]=(0.5-1.0)x10^5 [K]

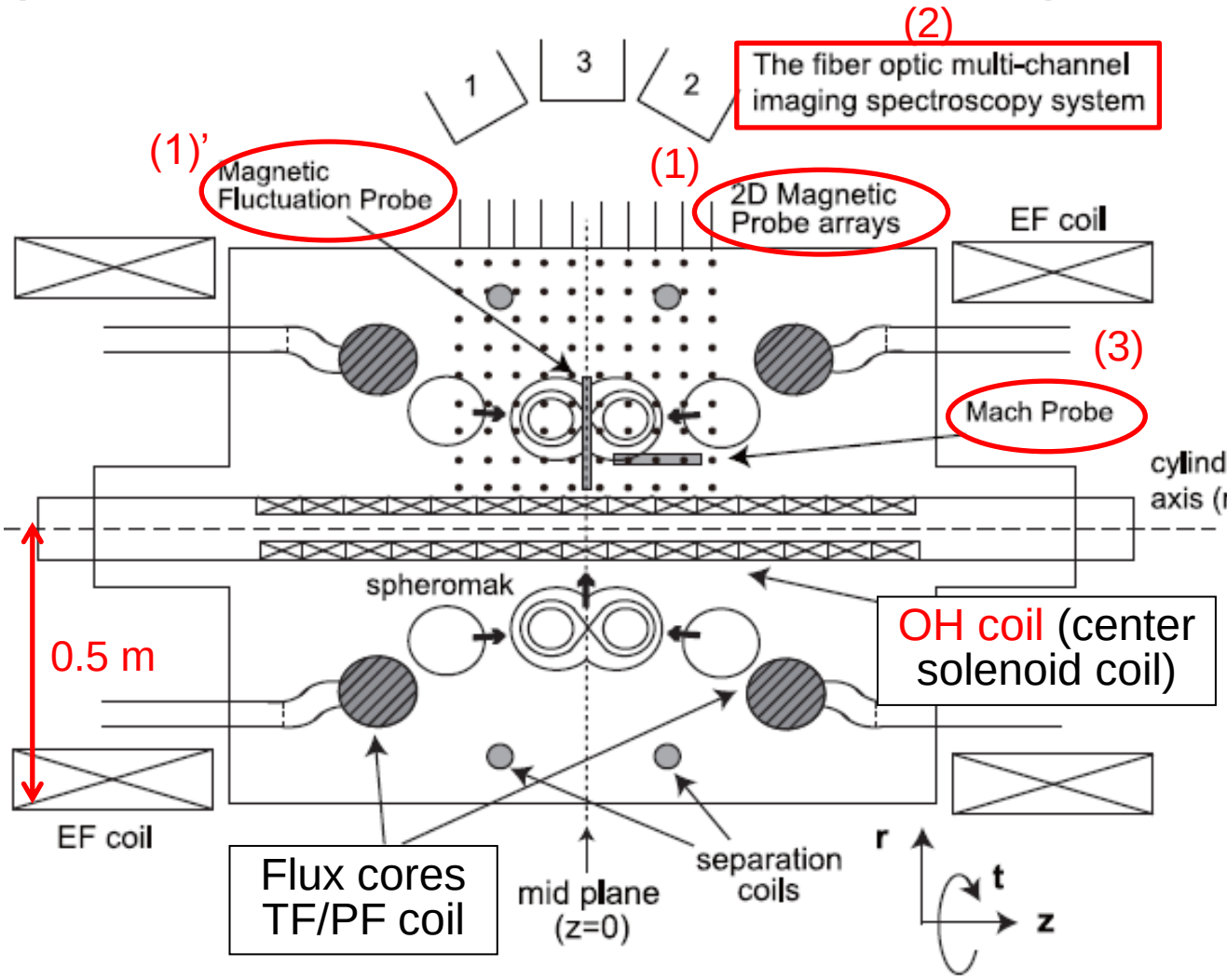
Fully Ionized Ar II (~90%) not H II

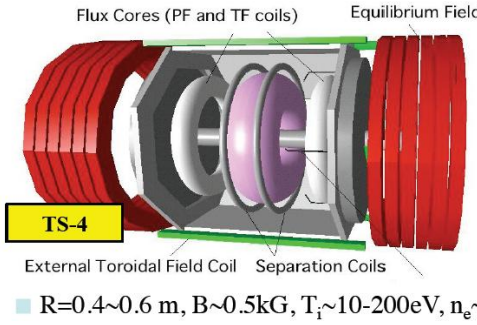
Bt/Bp=230G/340G=0.67

First challenge to measure Jet, Ion heating and Waves during Magnetic Reconnection In this configuration **with lab plasma**.

Experimental setup of TS-4 (Tokyo-Spehromak)

[Ono et al. 1993, Yamada et al. 1997; Kawamori & Ono 2005]





Measurements by

(1) **Magnetic probes**

⇒ **Bz**, **Et**, **Jt**, **η** (=Et/Jt)

(2) **Spectroscopic** mes-urement ⇒ **Ti**, **Vi**

(3) **Mach probes** ⇒ **Vi**

axial-symmetric

$$B_r(r,z) = -\frac{1}{2\pi r}\frac{\partial \Psi}{\partial z}$$

$$J_t(r,z) = \frac{\partial B_r}{\partial z} - \frac{\partial B_z}{\partial r}$$

$$E_t(r,z) = -\frac{1}{2\pi r}\frac{\partial \Psi}{\partial t},$$

magnetic flux

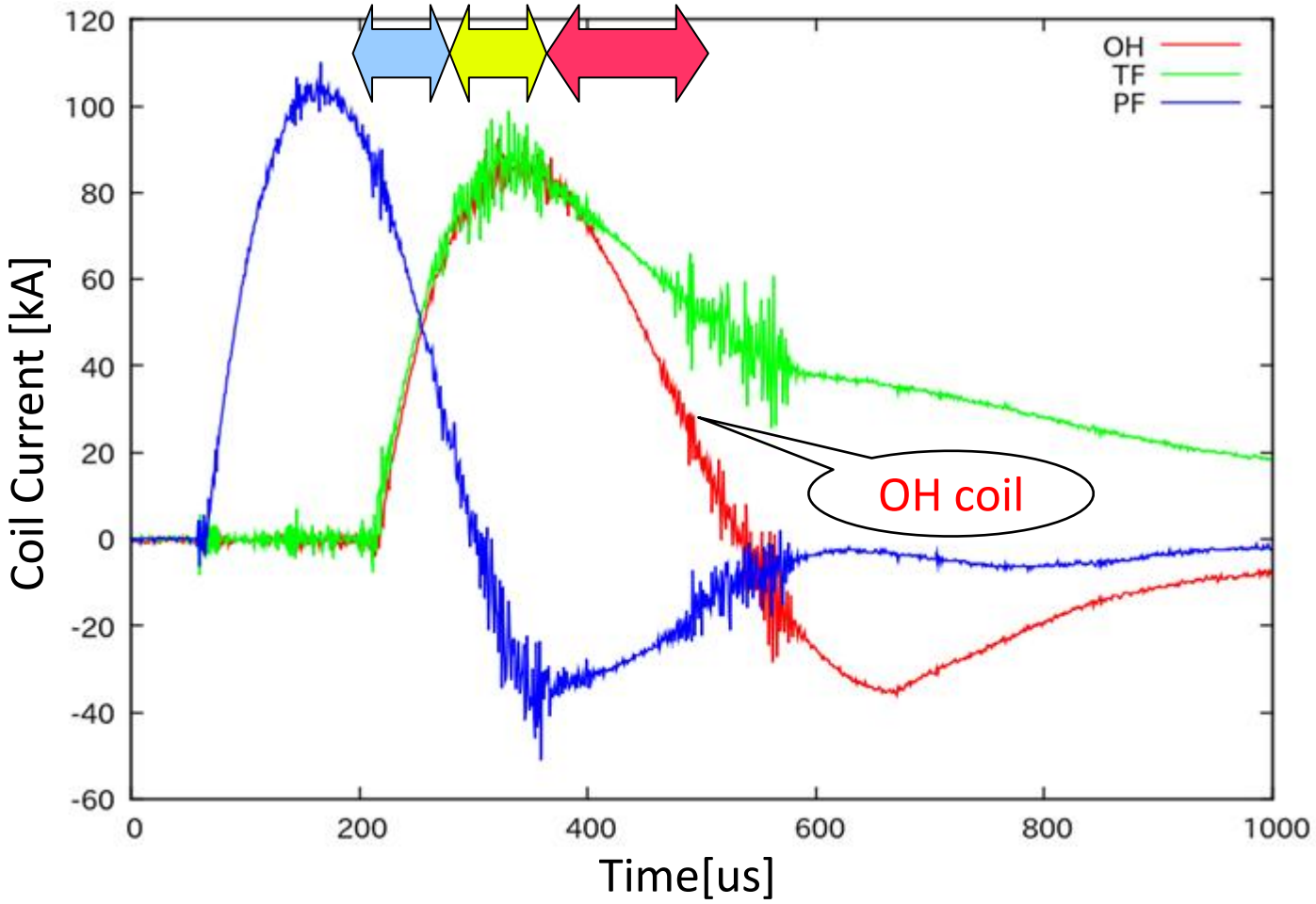
$$\Psi(r,z,t) = \int_{r_{min}}^{r} 2\pi r' B_z dr'$$

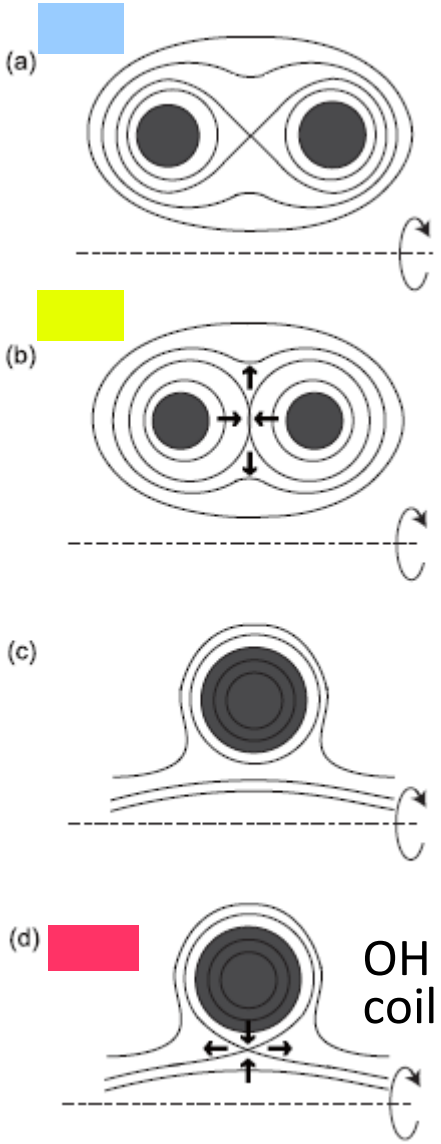
Coil current waveform and reconnection process

2 spheromak formation

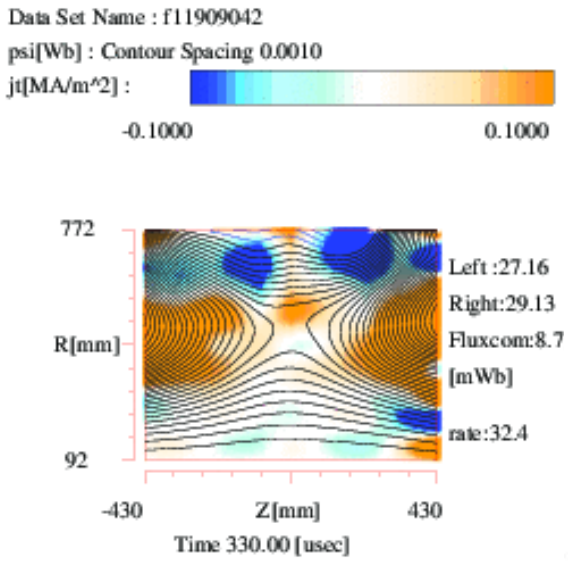
2 spheromak merging

Spheromak-OH field (LB-like) Reconnection



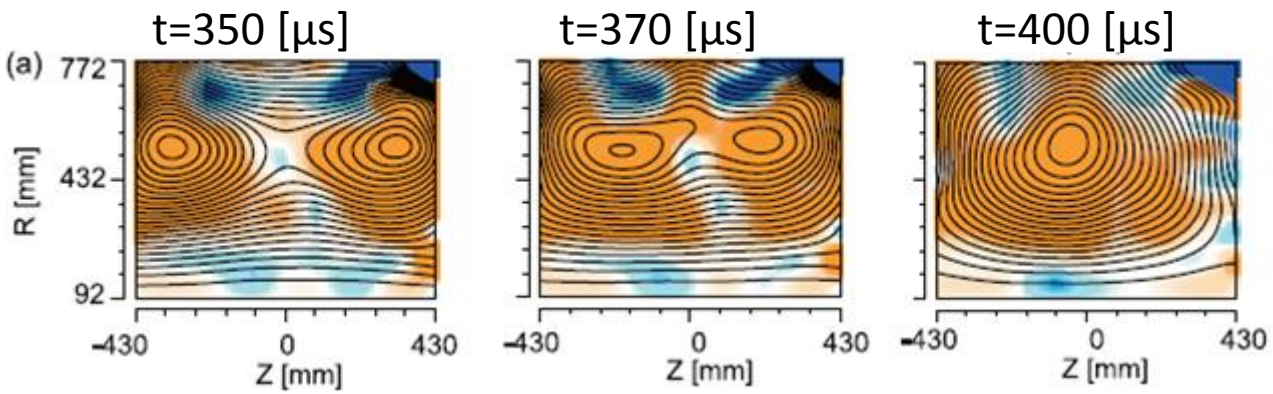


Time variations of B-field & Jt configurations (Bt/Bp= 230G/340G =0.67)

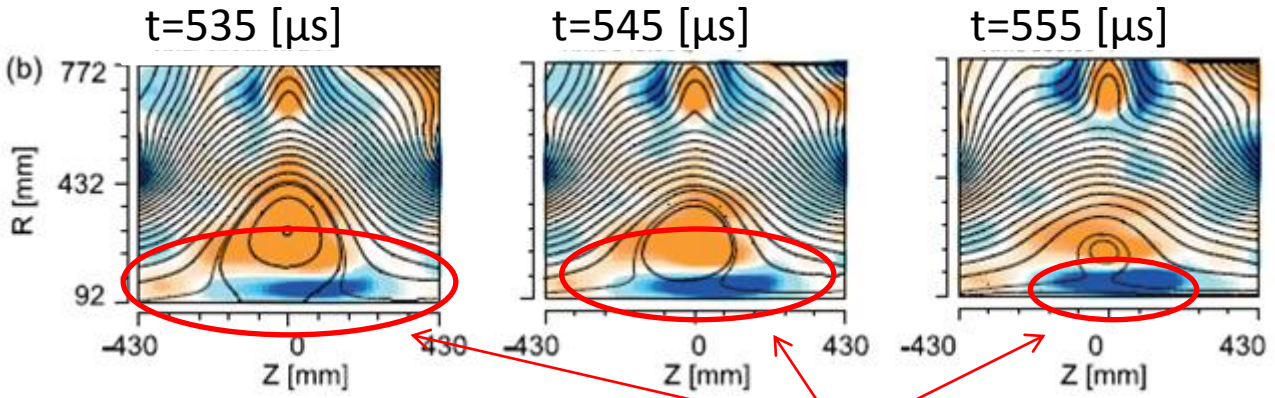


**reconnection is hard to see in the later phase, because of small B-field.

Two Spheromak Merging Reconnection



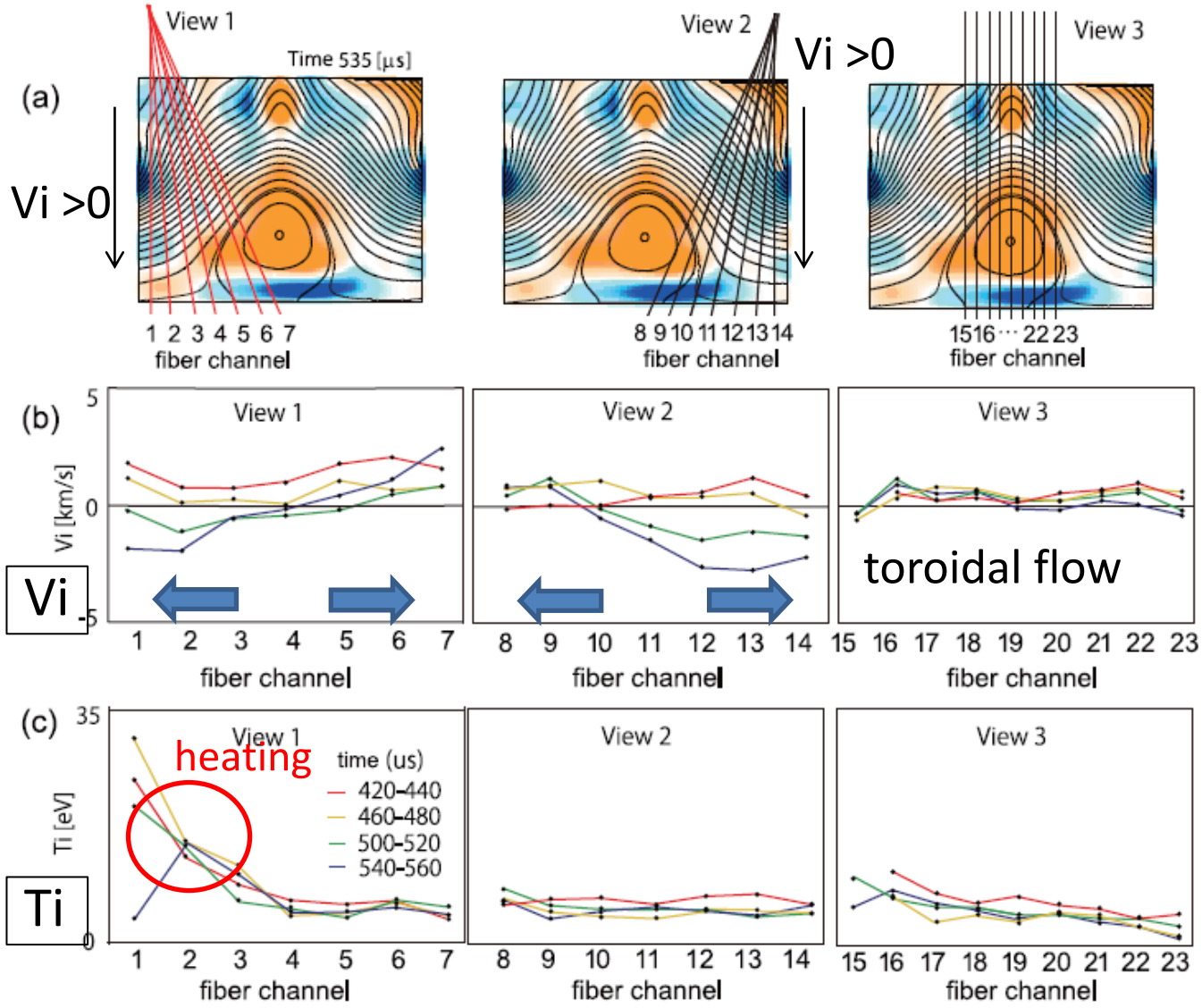
Spheromak-OH field (LB-like) Reconnection



Current density J_t [MA/m^2]

Reconnection occur!!

Spectroscopic obs. by the fiber optic multi-channel imaging spectroscopy system (Ti and Vi measurements: Heating and Outflow)



- Bi-directional Ion flow Vi=3 km/s (Ar)
  Cs=7 km/s,
  V_A=22 km/s

Kinetic energy
$E_{kin} \sim \rho V_i^2 L^3 \sim 3.2 \times 10^5$ erg

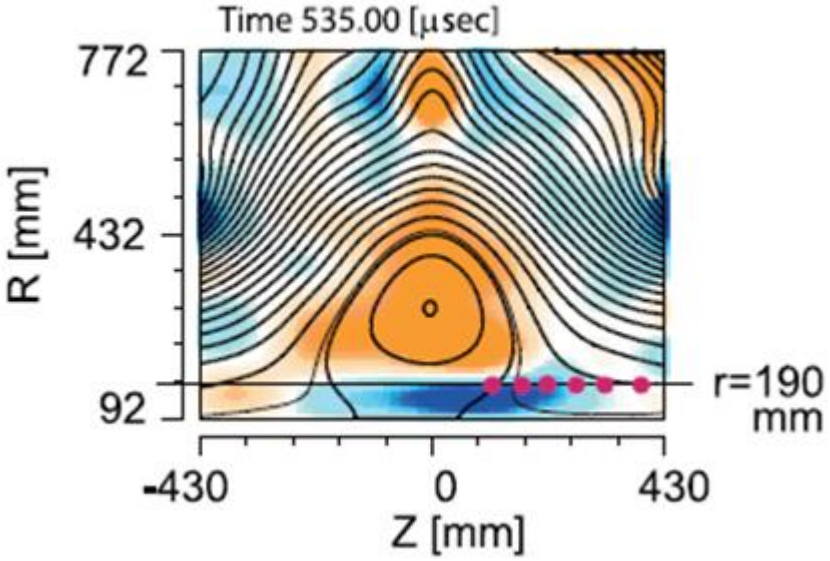
- Ion heating
  T_i=30 eV ←5-10 eV

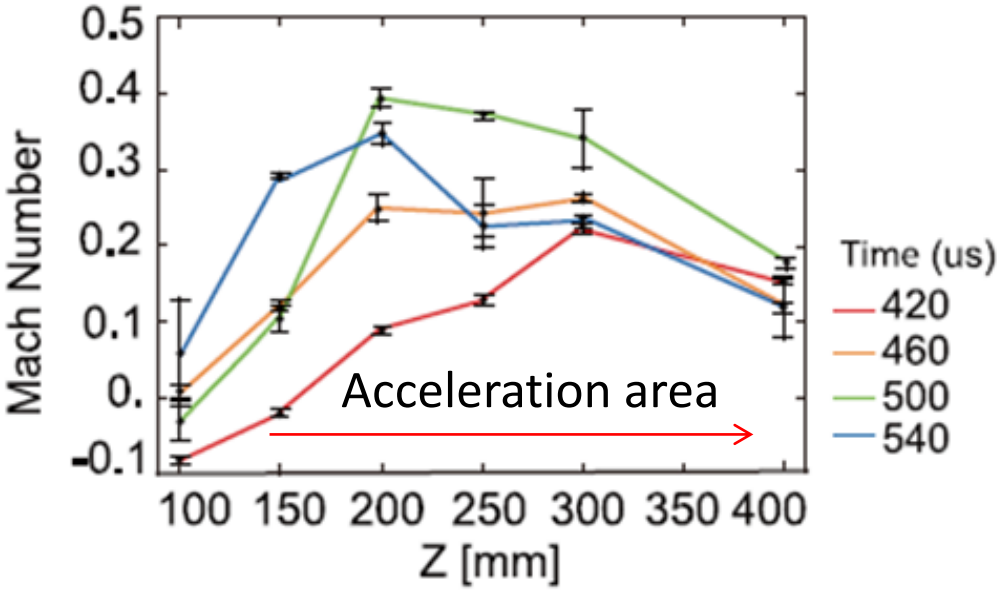
Thermal energy
$E_{th} \sim n_i k_B T L^3 \sim 1.1 \times 10^7$ erg

Mag. energy ~3×10^8 erg

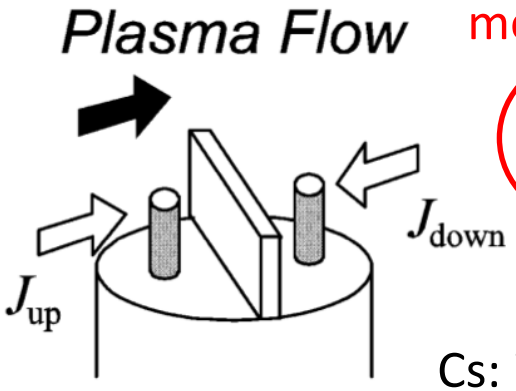
$E_{kin} << E_{th} << E_{mag}$

Acceleration of Reconnection Outflow measured by Mach Probe





Vi=0.4Cs=2.8 km/s



measure Jup, Jdown

$$\frac{J_{up}}{J_{down}} = \exp(KM_i)$$

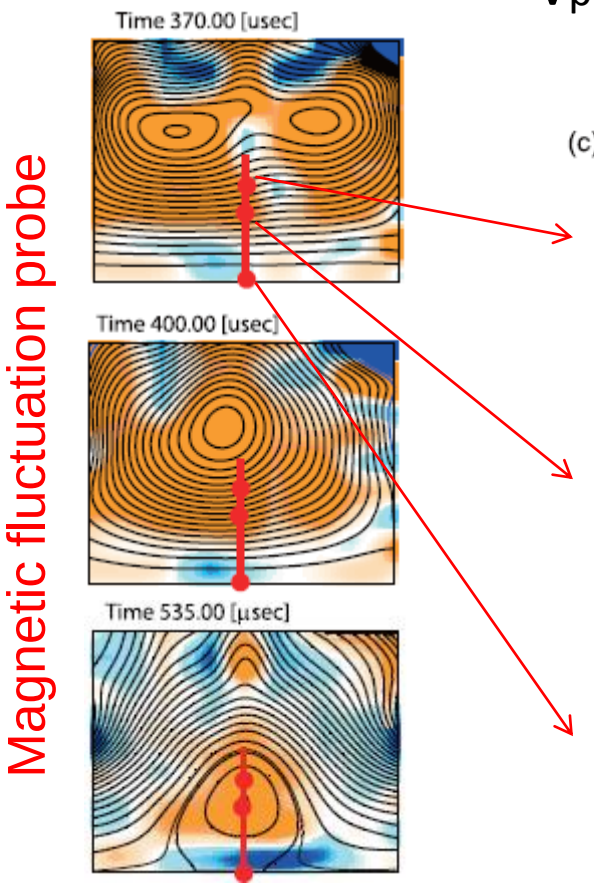
$$M_i = \frac{v_d}{c_s}$$

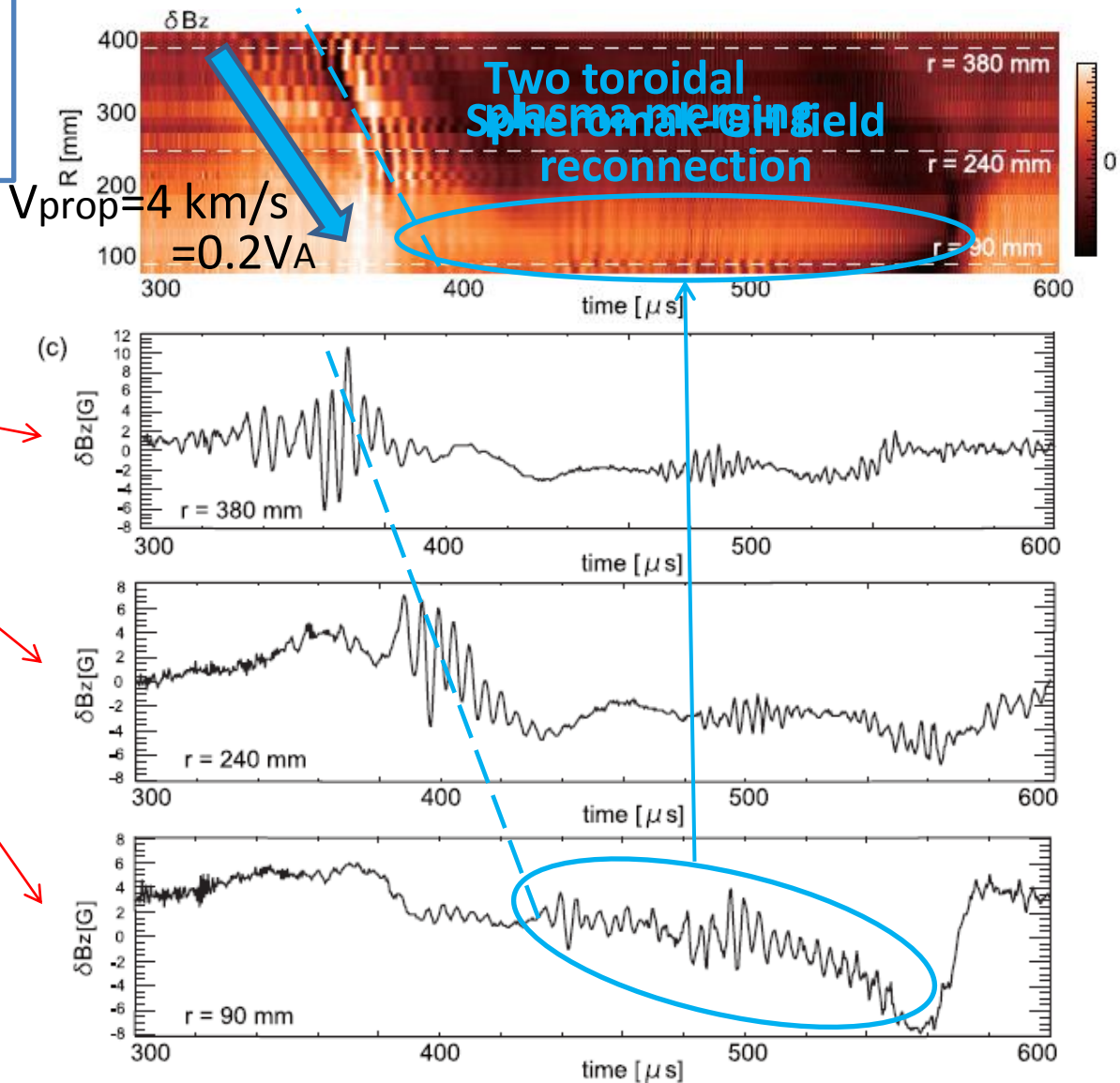
Cs: ion sound speed (7 km/s)

- The outflow is accelerated from the center region (z=0 mm)
- In the later phase, the flow near the center is also accelerated.
- Mi is always less than 1, indicating no shock in the outflow region(?)

Wave generation and propagation during Reconnection

Magnetic fluctuation measurements (digitized by 0.5, 1GS/s 8bit ADCs)
- **Radial δBz probe** (27 locations;
- 10 or 20 mm spacing)

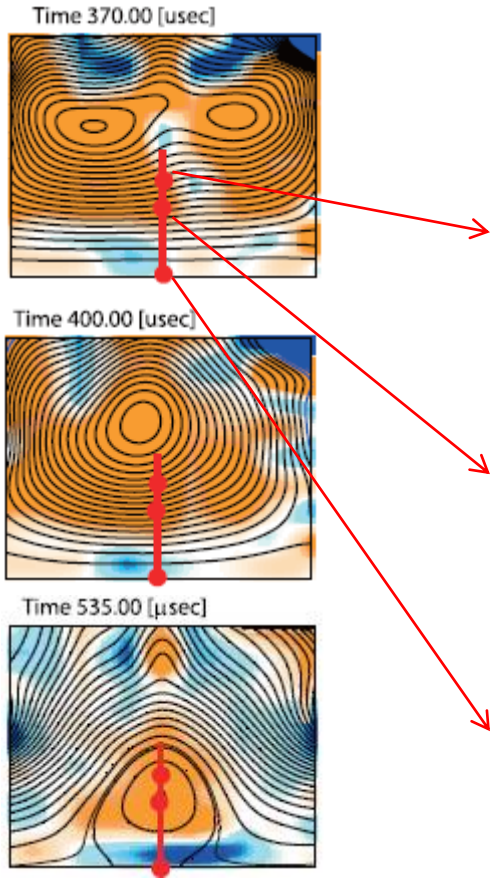


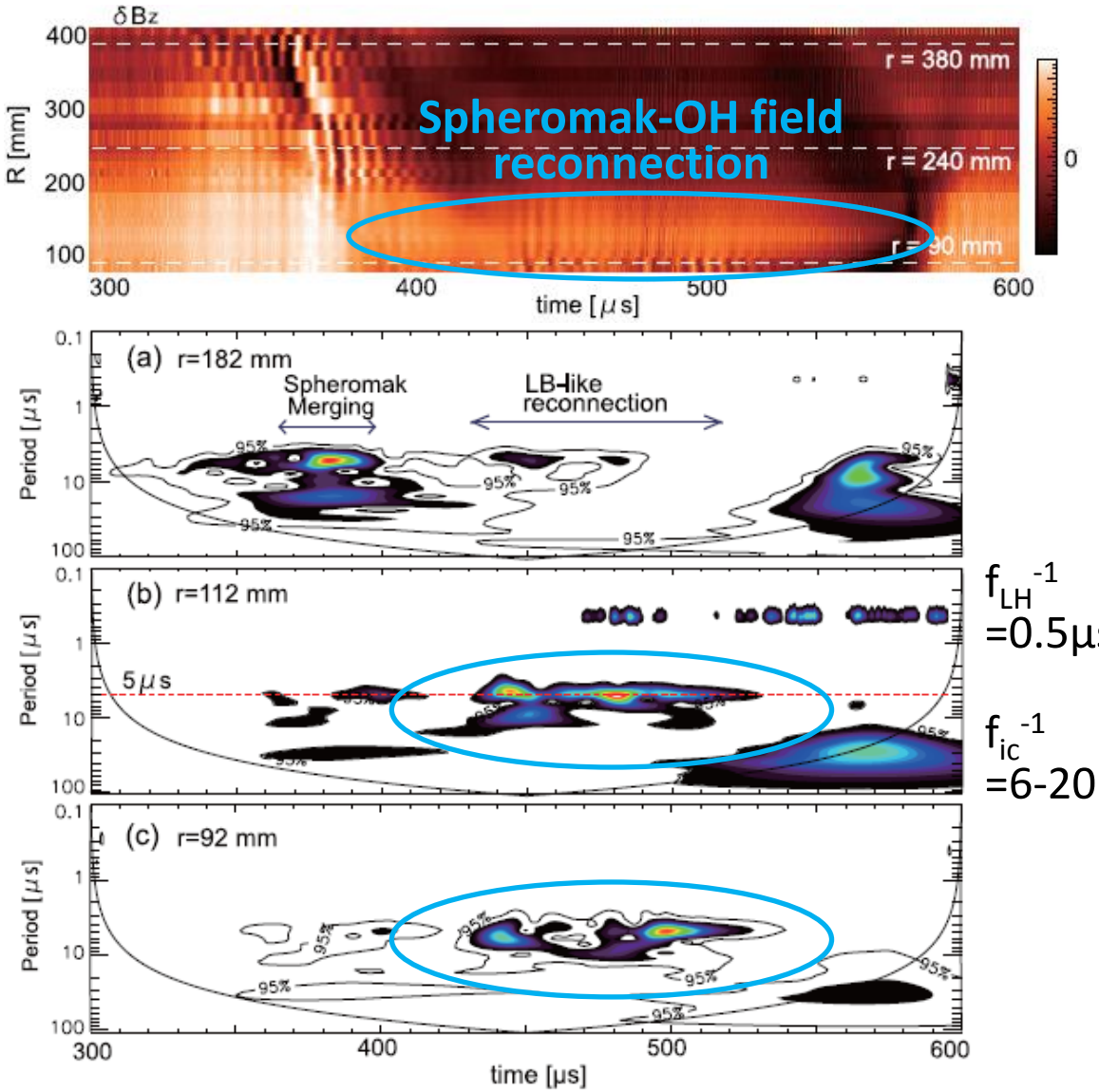


Wave generation and propagation during Reconnection

Magnetic fluctuation measurements (digitized by 0.5, 1GS/s 8bit ADCs)
- **Radial δBz probe** (27 locations;
- 10 or 20 mm spacing)

Magnetic fluctuation probe

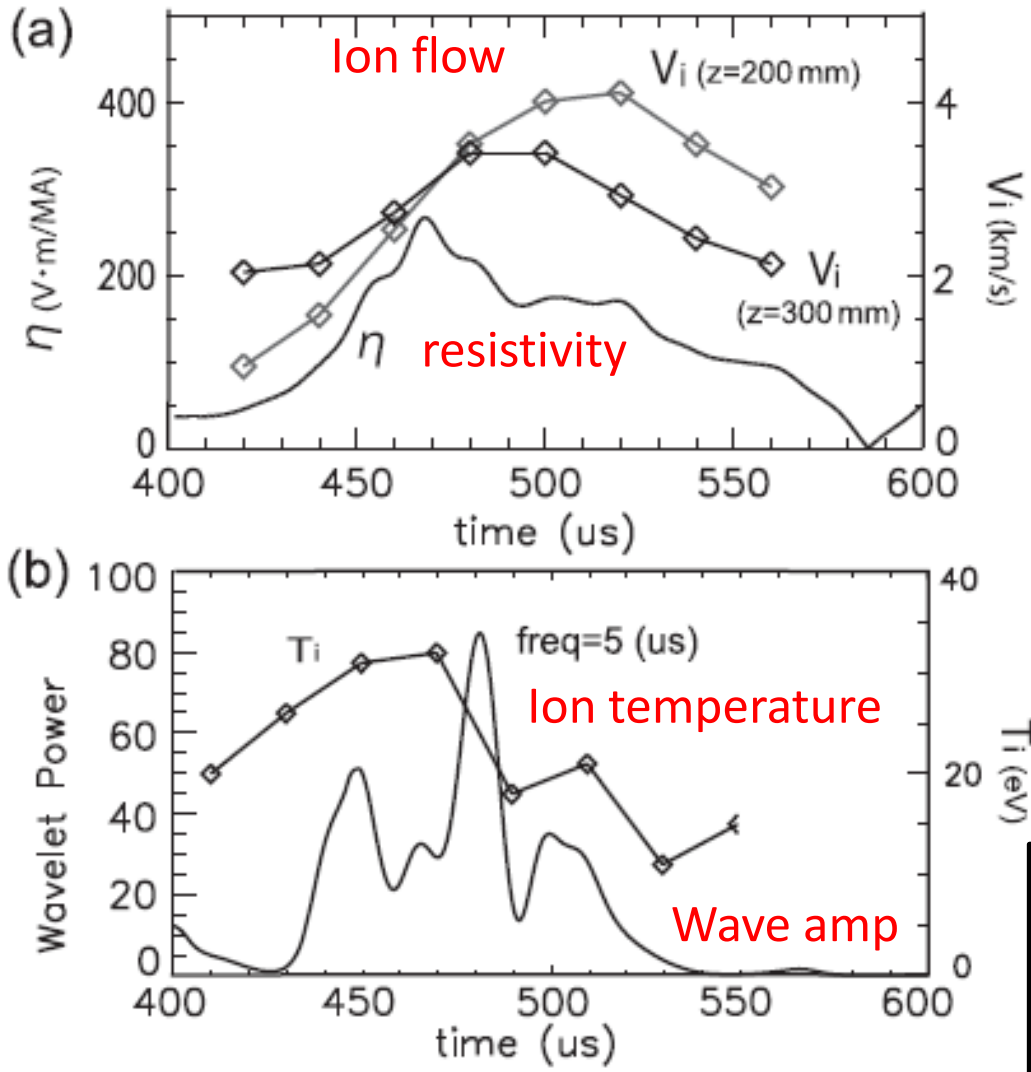




f_{LH}^{-1} =0.5μs

f_{ic}^{-1} =6-20μs

Relationship between Outflow, Mag. Resistivity, ion Temperature and Wave amplitude



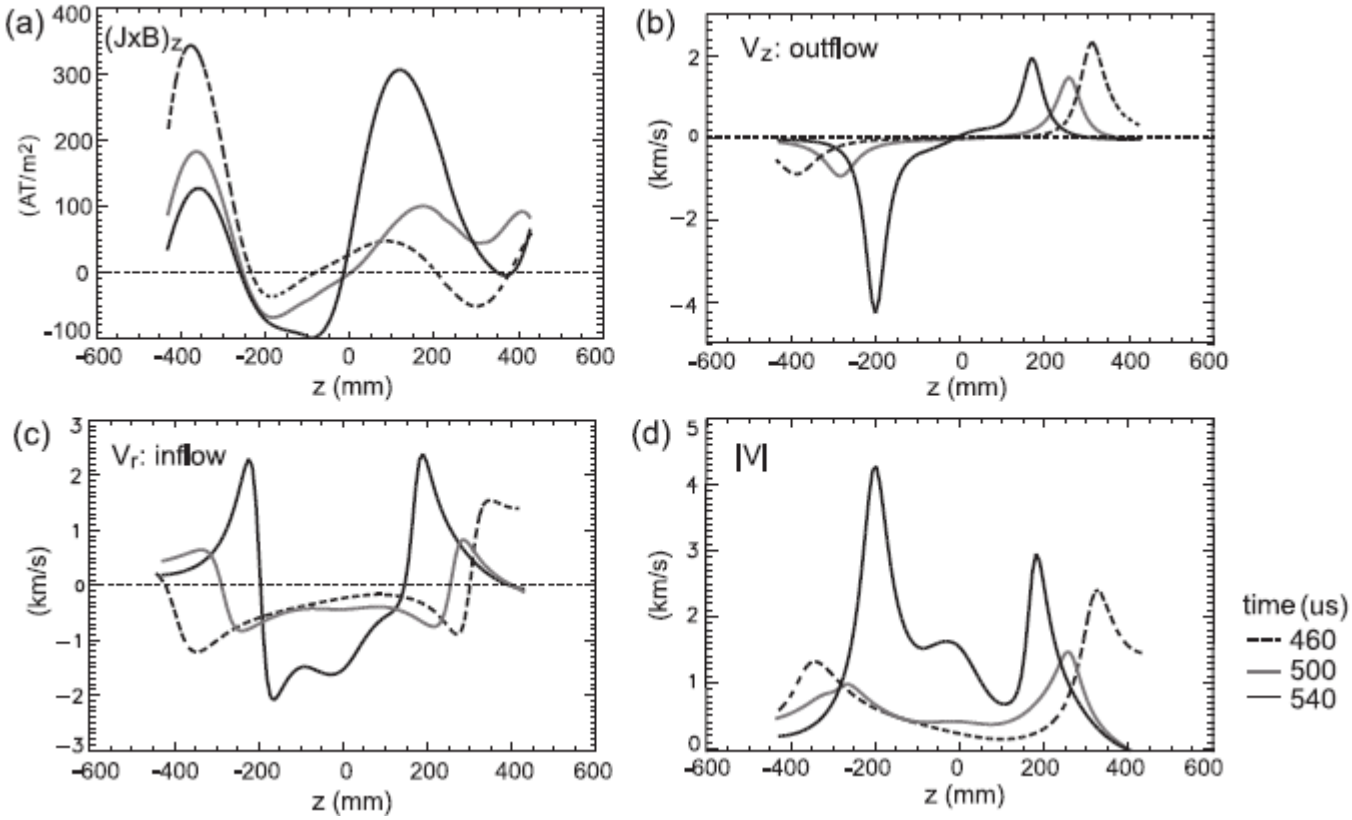
- During LB-like reconnection, **resistivity** is enhanced, when **wave** amplitude inside the current sheet is also large. (Wave generation⇔Resistivity)
- Ion **flow** is accelerated at the peak times of mag. **resistivity**.
- Ion **heating** occurs (outflow area) in association with the enhancement of **resistivity** and **wave** amplitude (current sheet).

- Poynting flux of the wave
  F~ 3.8x10^7 erg/cm^3/s
→ Ewave~ 3x10^7 erg (50 μs)
  1-10% of magnetic energy.

Summary

- We reproduced magnetic configuration of solar jets (the sunspot lightbridge) with laboratory plasma, focusing on the similarity with the spheromak and the flux tube of a jet.
- We succeeded in measuring reconnection outflow 0.4Cs and ion heating up to 30 eV in the outflow region. The acceleration region of ion flow moves toward inside (z=0) in the later phase.
- We also observed magnetic fluctuation or wave with the oscillation period 5-6 μs and 10 μs, which is comparable to the ion cycrotron frequency.
- During the reconnection, resistivity enhancement occurred associated with wave generation, ion heating and ion flow acceleration.
- We qualitatively succeeded in reproducing a jet with laboratory plasma, though some of our results are quantitatively different from the solar observations. That may come from the differences of microscopic and macroscopic, collisional and collisionless, and the difference of plasma (Ar and H).

Estimation of Lorenz force and Inflow/Outflow



Under frozen in condition

$$\mathbf{v}_\perp = \frac{\mathbf{E}\times\mathbf{B}}{|B|^2} = (\frac{E_t B_z}{|B|^2}, 0, -\frac{E_t B_r}{|B|^2}),$$

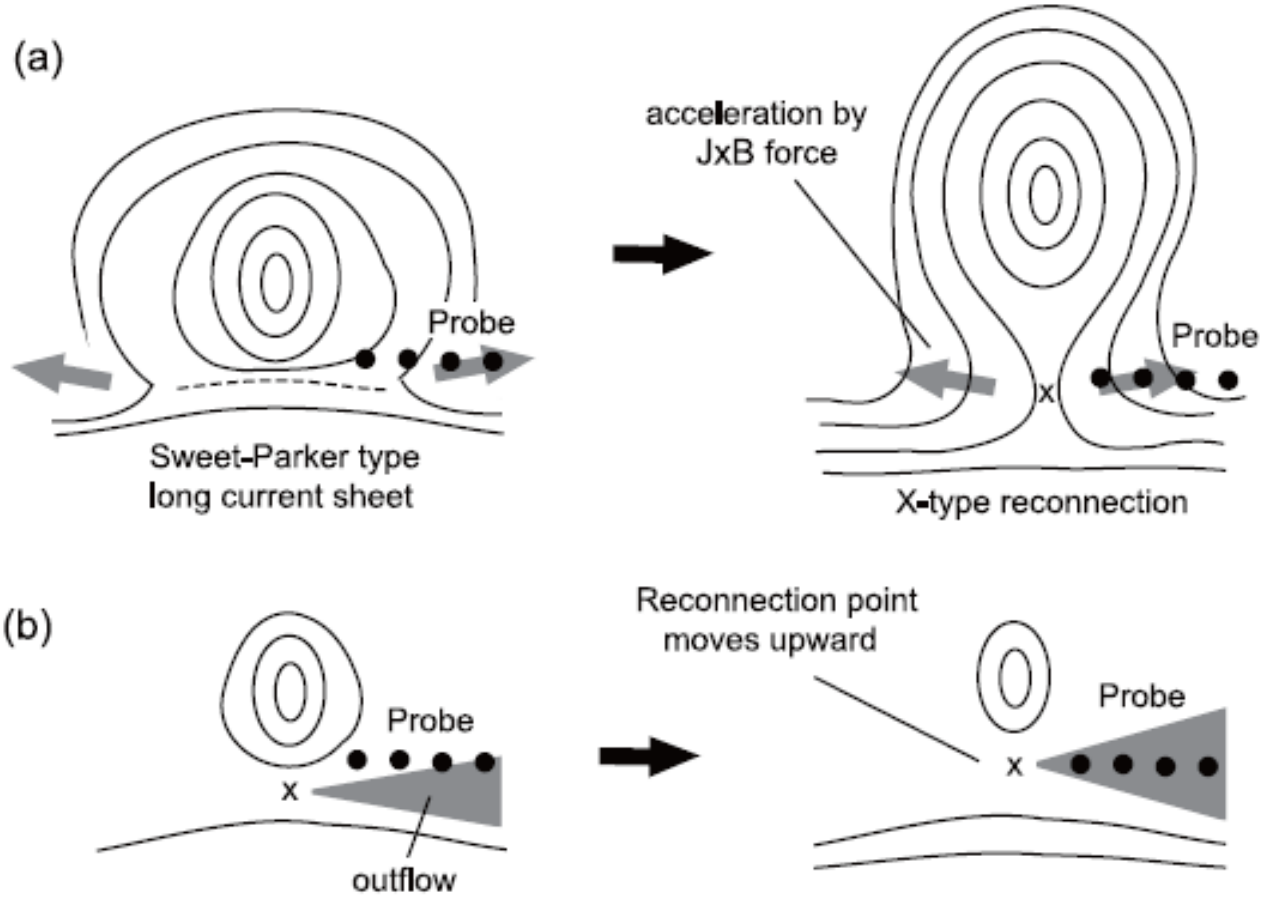
Reconnection rate

V **Inflow** / V outflow

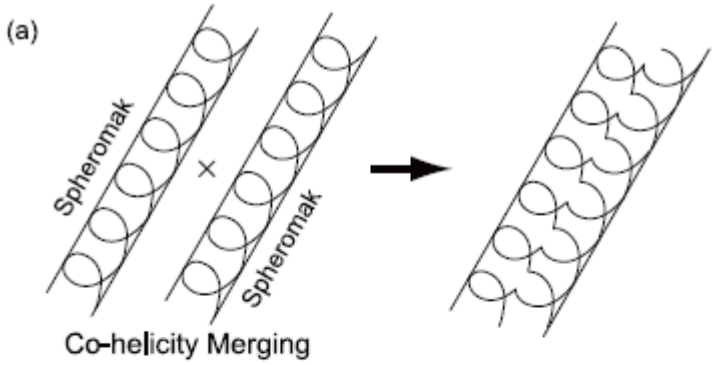
= (0.5-1 km/s)/(2-4 km/s)

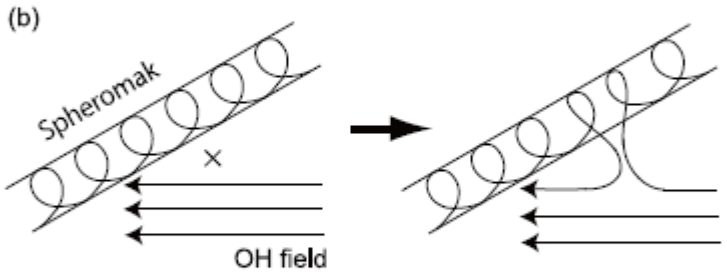
=0.12-0.5 >> **SP** reconnection

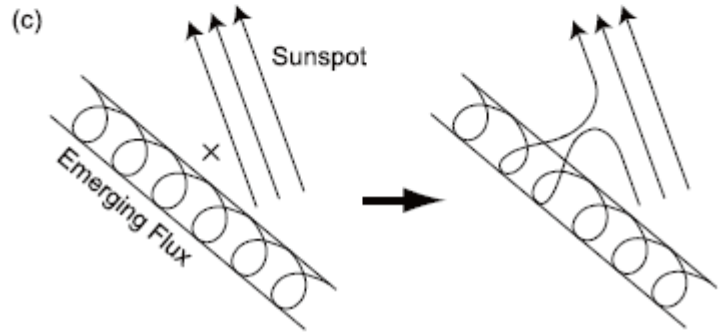
Interpretation of Outflow Acceleration near the center measured by Mach prove

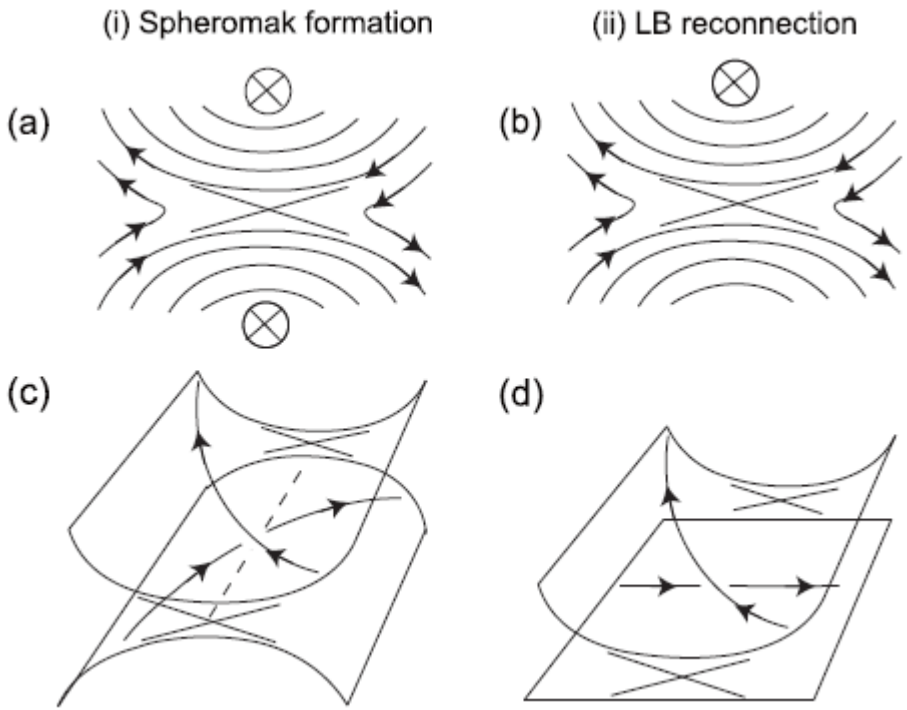


Discussion


(a)
Spheromak
Spheromak
Co-helicity Merging

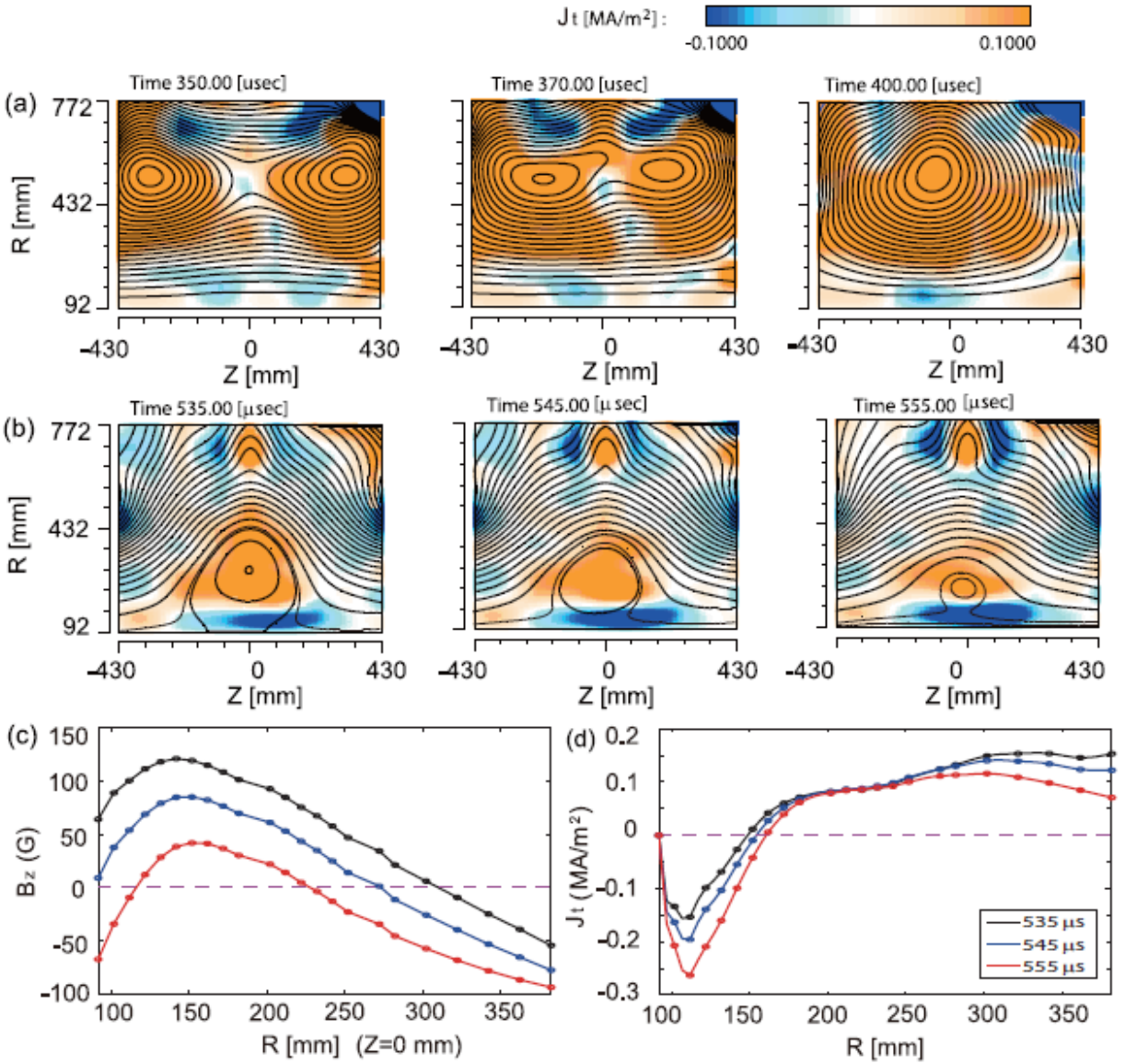

(b)
Spheromak
OH field


(c)
Sunspot
Emerging Flux


(i) Spheromak formation
(ii) LB reconnection
(a)
(b)
(c)
(d)

Measurement of Magnetic field:

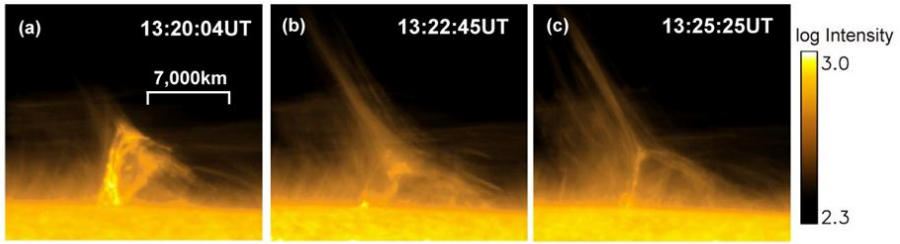
(Bt/Bp= 230G/340G =0.67)



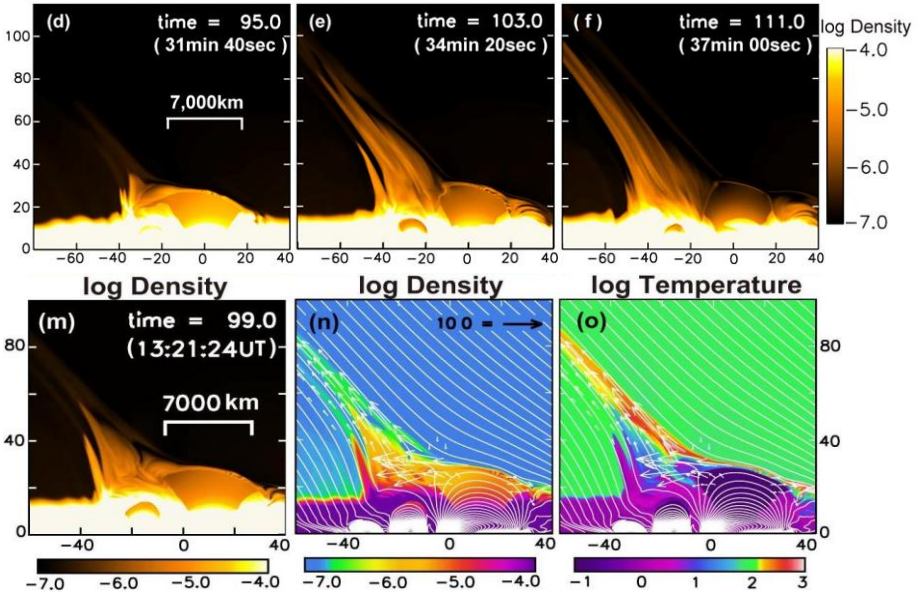
Flux Emergence and Solar Jets by Reconnection

Cf) Yokoyama and Shibata 1995

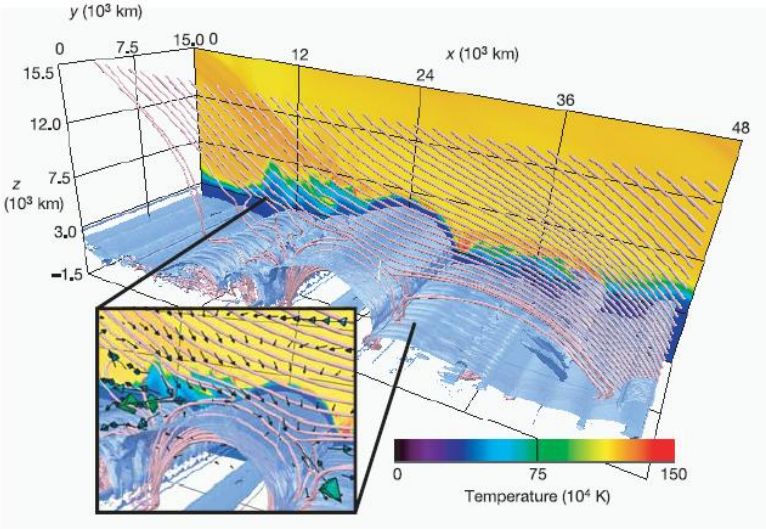
Observation ---- Hinode/SOT



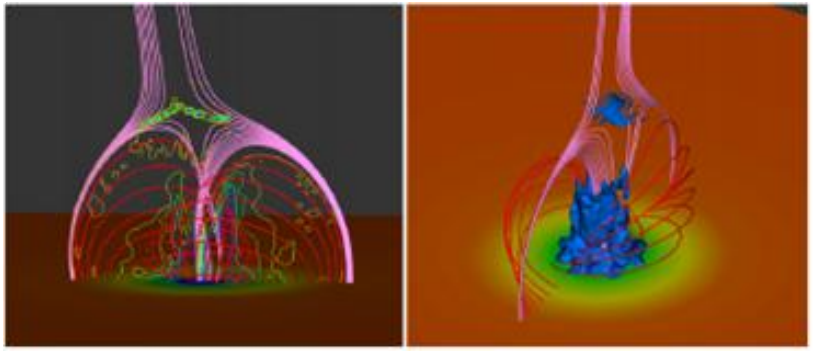
MHD Simulation



[Nishizuka et al. 2008 ApJL]



[Isobe et al. 2005 Nature]



[Pariat, Antiochos & DeVore 2010 ApJ]