Laboratory studies of magnetic reconnection: How can they be applied to CT research?

Masaaki Yamada*
August 23, 2016

US-Japan CT Workshop

In collaboration with Jongsoo Yoo

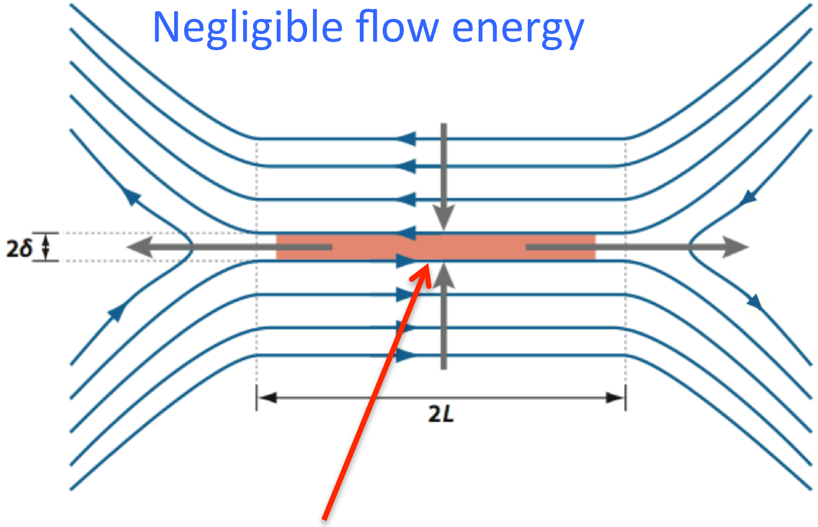
PPPL
PRINCETON
PLASMA PHYSICS
LABORATORY

Motivation and Contents

- Magnetic reconnection is known for efficient conversion of magnetic to particle energy.
- Identification of mechanisms for the energy conversion has not been made while it has been a central problem.
- **Is there a fundamental principle for energy partitioning in a proto-typical reconnection layer?**
- How can the results be applied to CT Research?

Nature Comms, **5**, 4774 (2014)
Phys. Plasmas, **23**, 055402 (2016)

Energy Conversion in the Sweet-Parker Model



Incoming Poynting flux ; S = E x B
Negligible flow energy

Alfvénic outflow
Hot plasma
Negligible Poynting flux

$S = (E \times B)_{out} \sim 0$

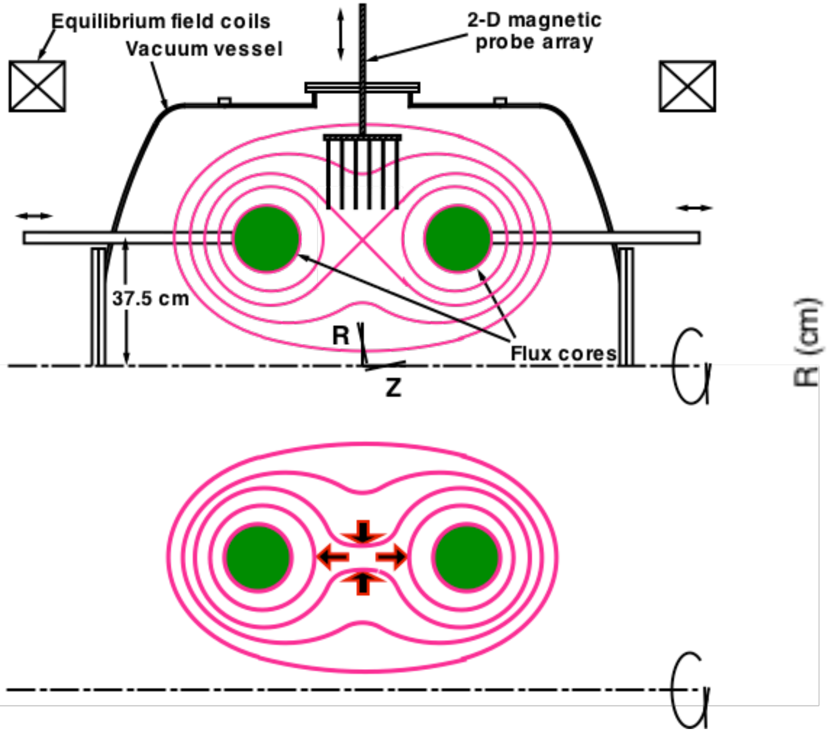
Ohmic heating ηj^2

2-D, resistive MHD model

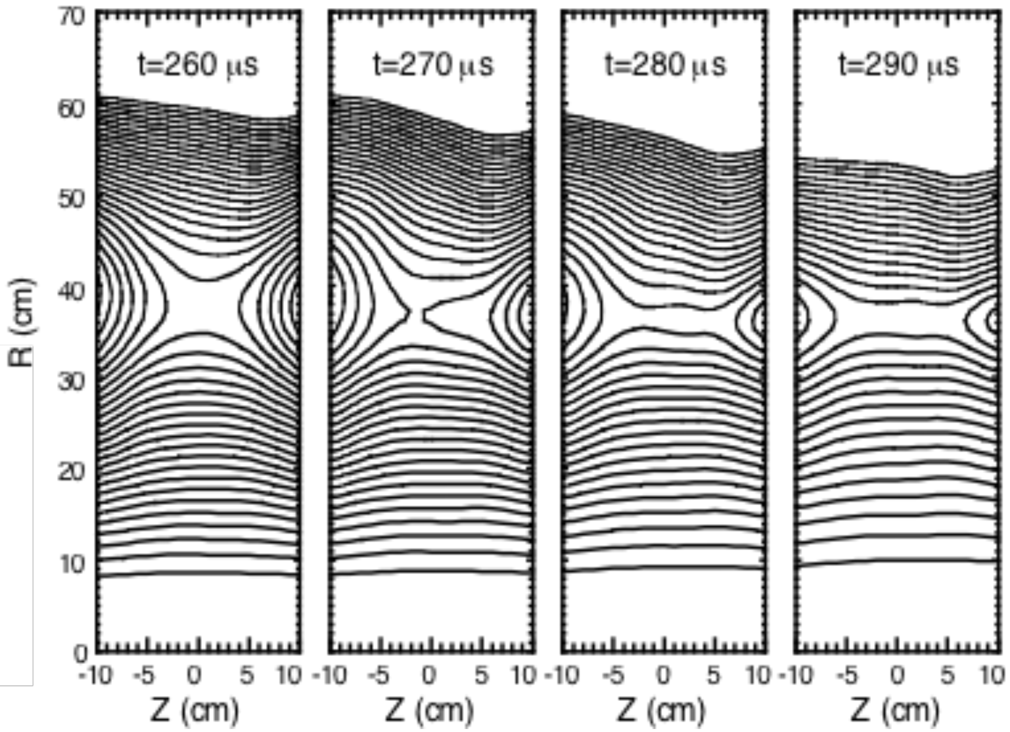
- Plasma heating occurs slowly on Ohmic dissipation inside the diffusion region.

$$\frac{B_{in}{}^2}{\mu_0} \rightarrow Wp + \frac{\rho}{2} V_s^2$$

Experimental Setup and Formation of Current Sheet on MRX



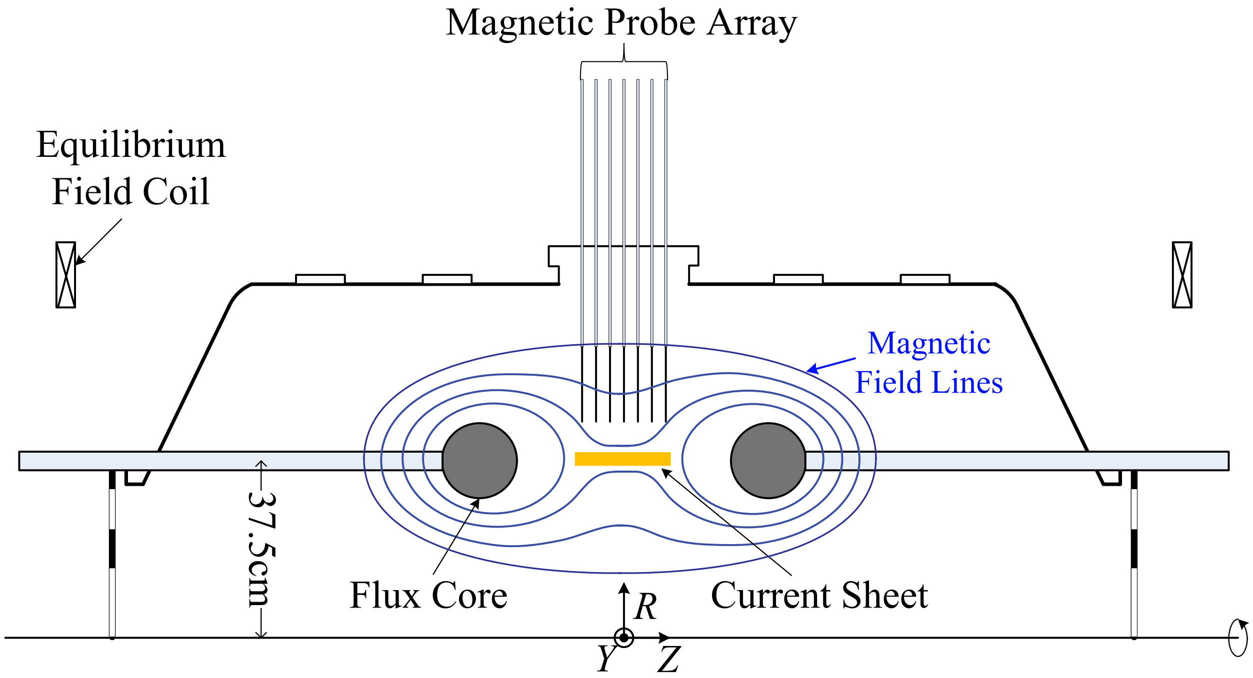
Experimentally measured flux evolution

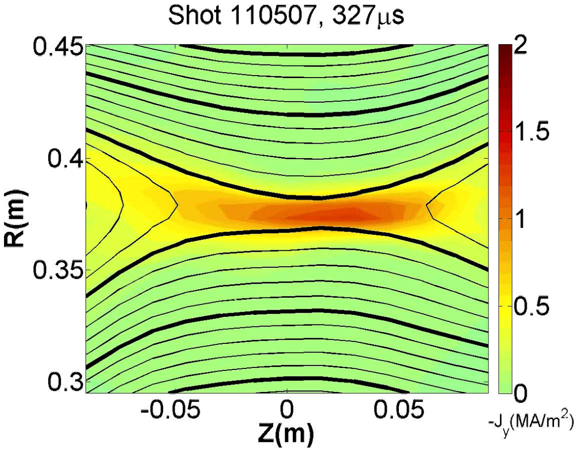


n_e= 1-10 x10^{13} cm^{-3},
T_e~5-15 eV,
B~100-500 G,

How is magnetic energy converted to plasma?

Experimental set-up [Yoo et al, 2013]





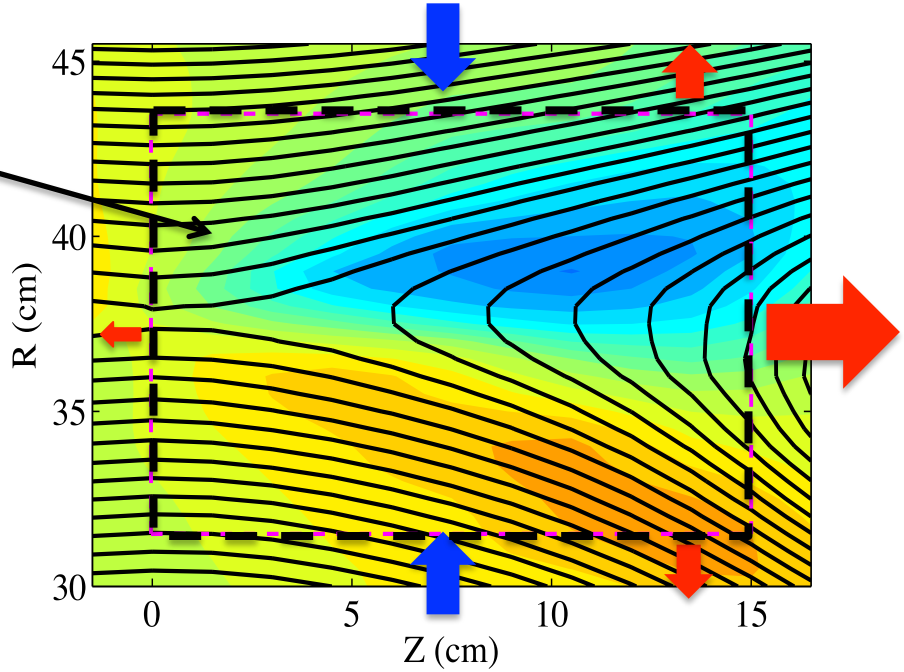
- Helium discharge
- IDSP to measure T_i
- $\lambda_{mfp,e} \geq c/\omega_{pi} > \delta_{CS}$ (~2cm)

Two fluid regime

Measurement of energy inventory in MRX

Incoming Fluxes

Changes in energy enclosed in the volume



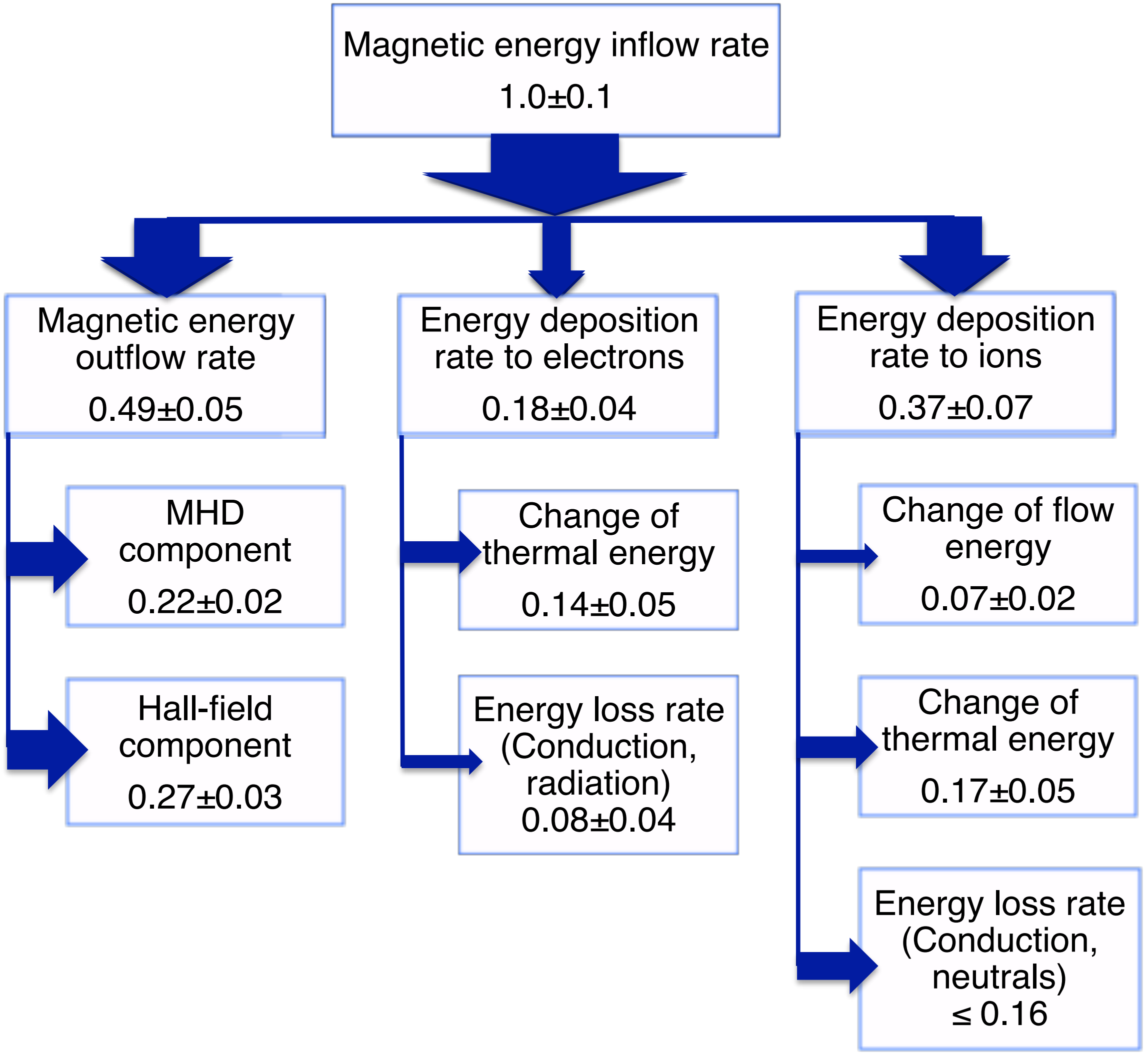
Outgoing Fluxes

- Energy transport equation :

$$\frac{\partial}{\partial t}\left[\frac{B^2}{2\mu_0}+\sum_{s=e,i}\left(\frac{3}{2}n_sT_s+\frac{\rho}{2}V_s^2\right)\right]+\nabla\cdot\left[\vec{S}+\sum_{s=e,i}\left(\frac{5}{2}n_sT_s\vec{V}_s+\frac{\rho}{2}V_s^2\vec{V}_s\right)+q_s\right]=0$$

Birn and Hesse, 2005

Inventory of Energy



Magnetic energy inflow rate
1.0±0.1

Magnetic energy outflow rate
0.49±0.05

MHD component
0.22±0.02

Hall-field component
0.27±0.03

Energy deposition rate to electrons
0.18±0.04

Change of thermal energy
0.14±0.05

Energy loss rate (Conduction, radiation)
0.08±0.04

Energy deposition rate to ions
0.37±0.07

Change of flow energy
0.07±0.02

Change of thermal energy
0.17±0.05

Energy loss rate (Conduction, neutrals)
≤ 0.16

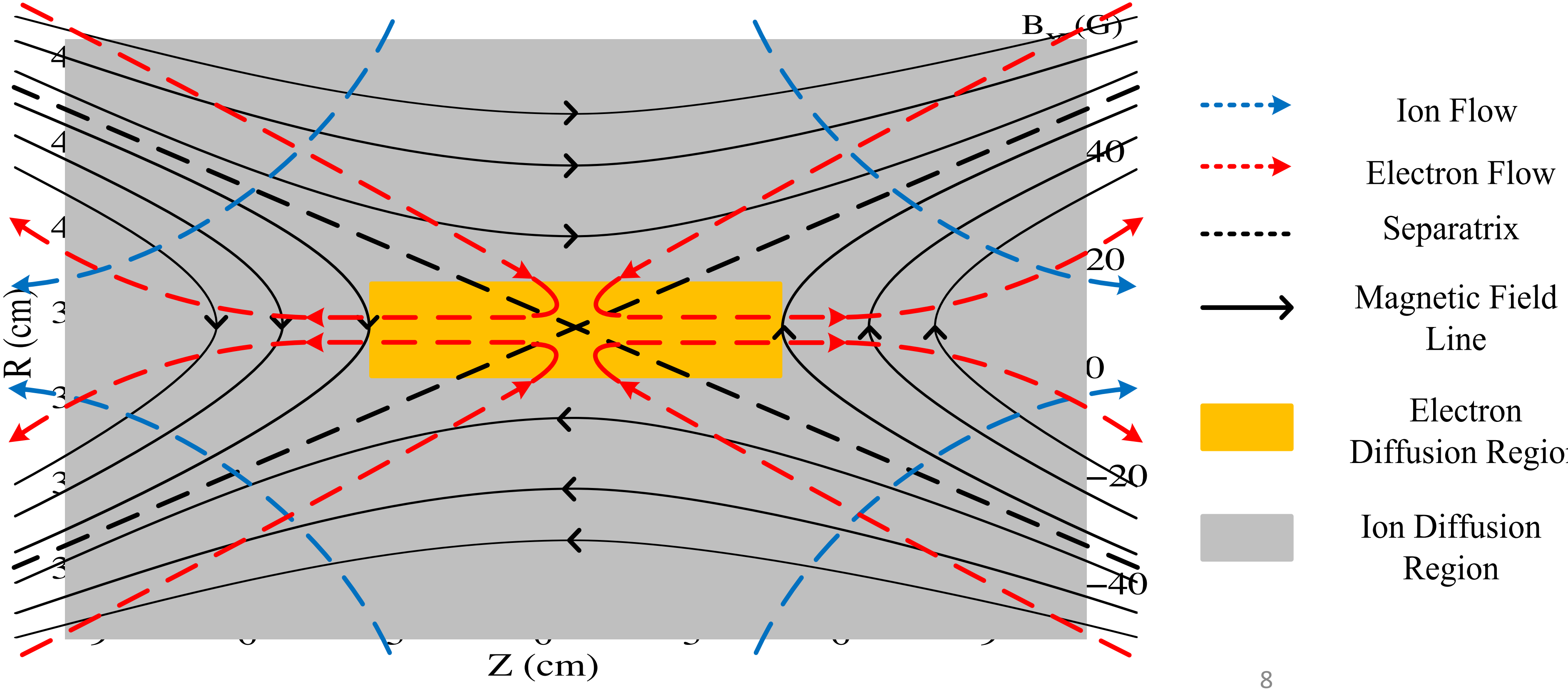
Yamada et al, Nature Communications (2014)

Particle dynamics of the two-fluid reconnection layer

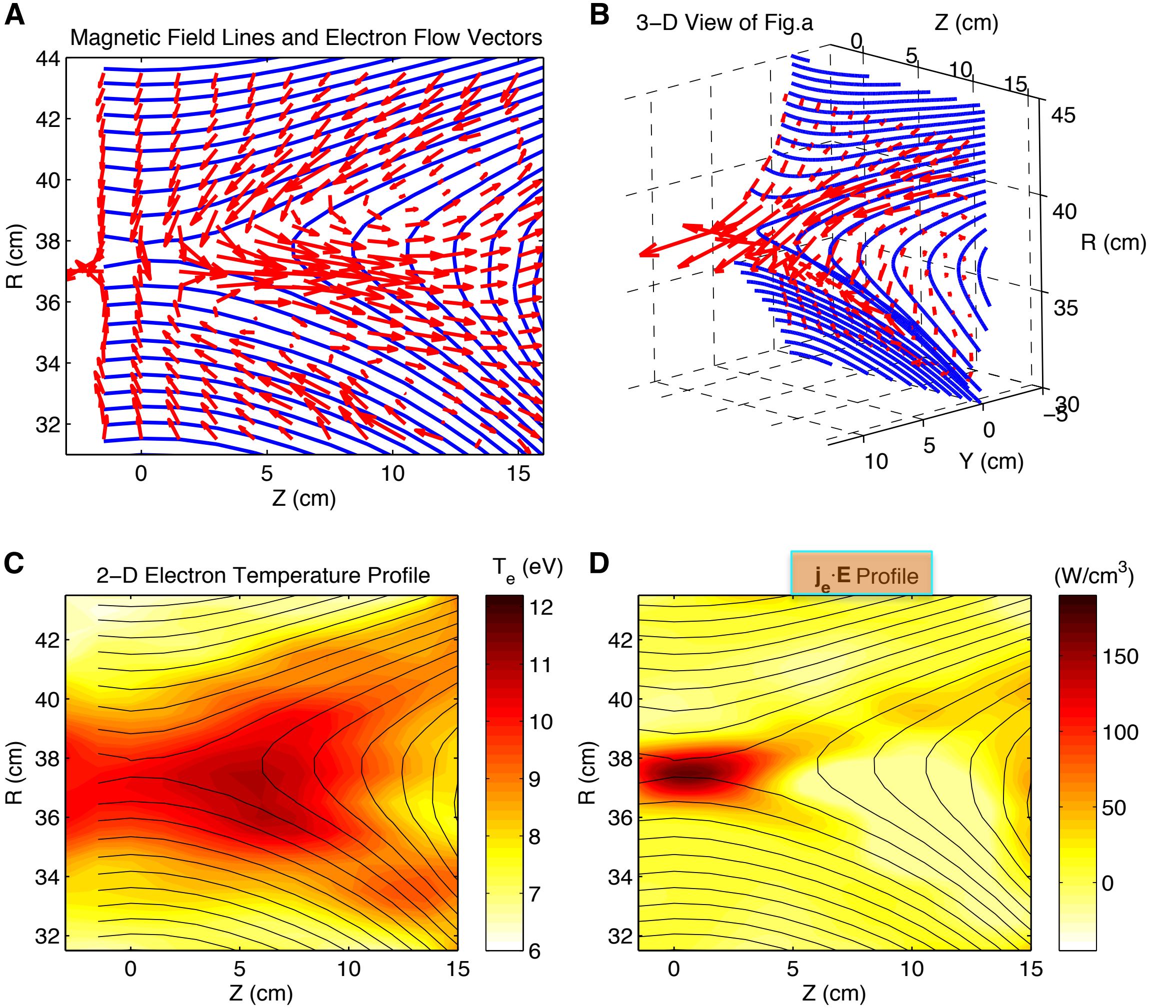
Generalized Ohm's law: Normalized with $x/\Delta \to x,\ V/V_A \to V,\ B/B_0 \to B$

$$E_{rec} + V_{in} \times B_{rec} = 0 + \underbrace{\frac{\delta_i}{\Delta}\frac{j_{in} \times B_{rec}}{n}}_{\text{Hall term}} - \underbrace{\frac{\delta_e^2}{\Delta^2}\frac{1}{n}\frac{dj_{rec}}{dt}}_{\text{Electron inertia term}} + \underbrace{\frac{\delta_i}{\Delta}\frac{(\nabla \cdot P_e)_{off}}{n}}_{\text{Electron pressure term}}$$

$$V_e \times B_{rec} \approx E_{rec} \approx \frac{d\Psi}{dt}$$



Electron dynamics and electron heating in MRX



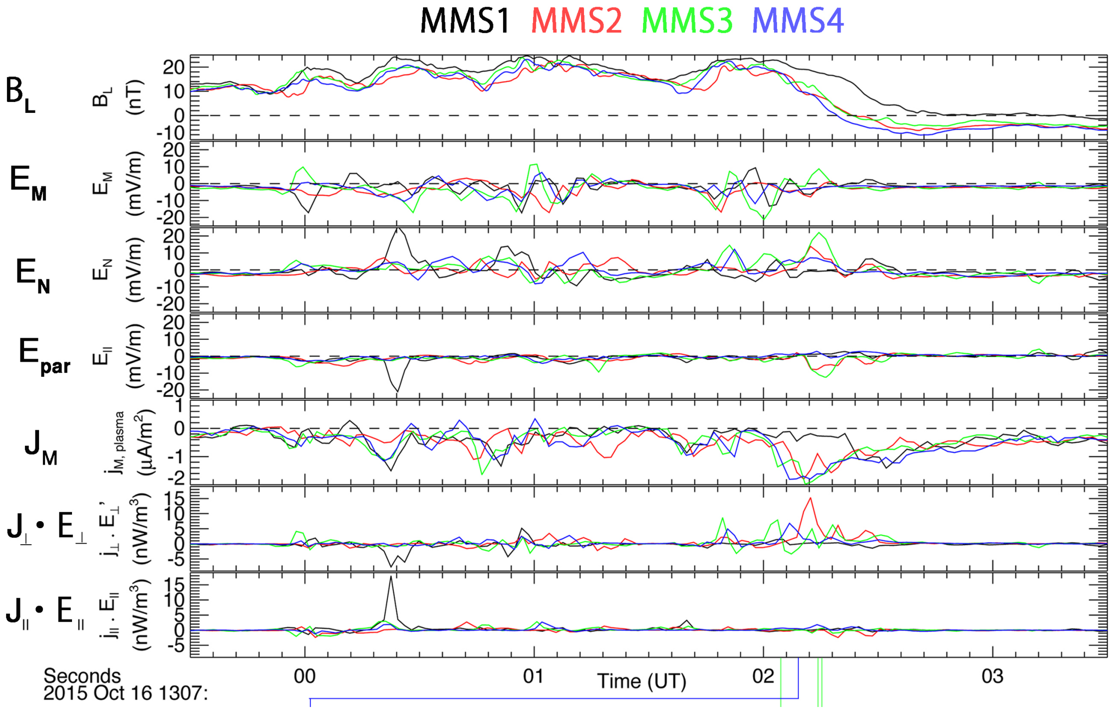
$\mathbf{j}$ = Curl $\mathbf{B}$, $\mathbf{V}_e = \mathbf{j}_e / n_e$

Electron gain energy by E_y

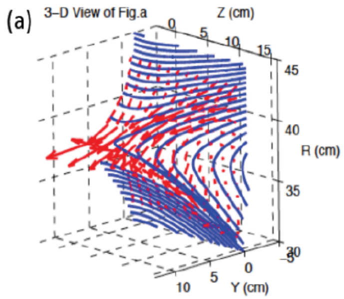
- Energy deposition occurs very near the X-point.
- The electron heating seen in wider region through heat conduction

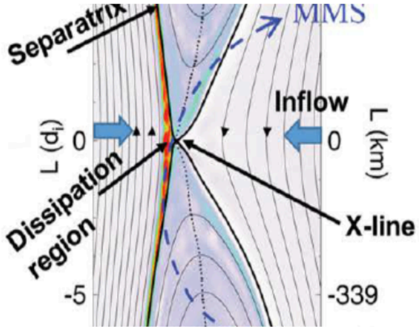
$$j_\perp E_\perp >> j_{//} E_{//}$$

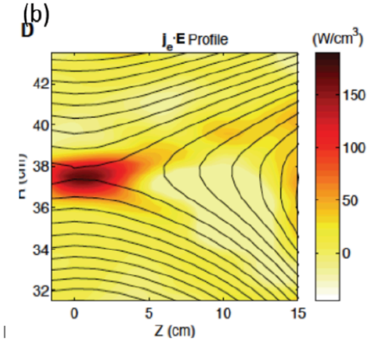
The physics of the high energy deposition rate is not yet resolsved.

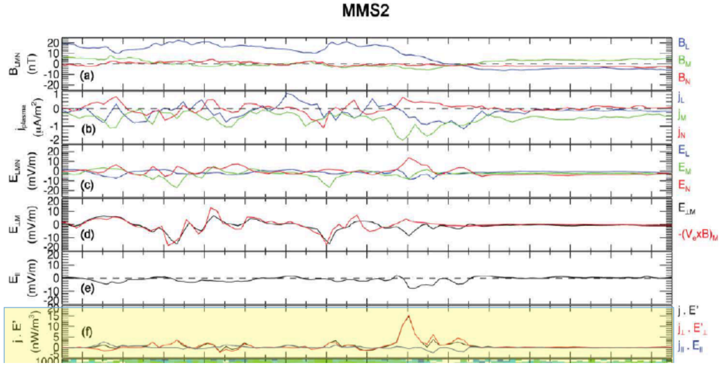


4 seconds of data

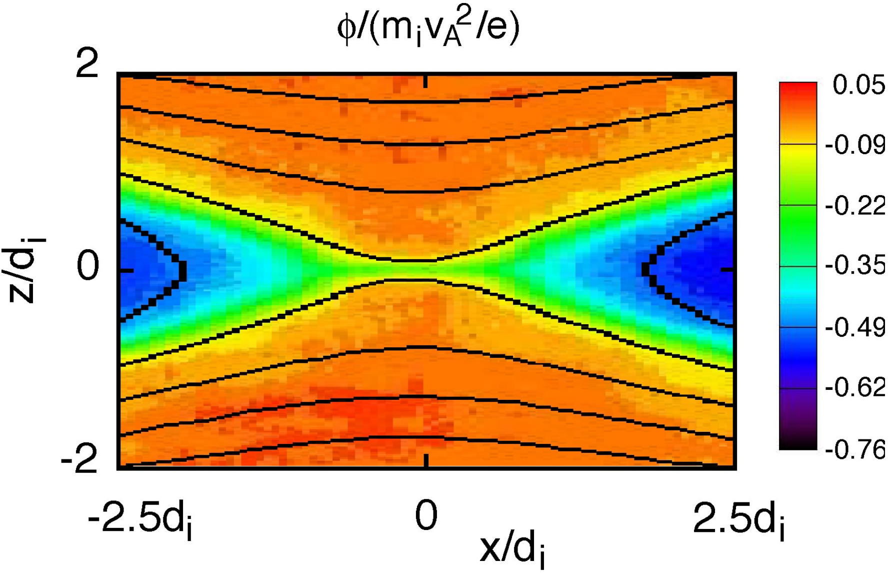




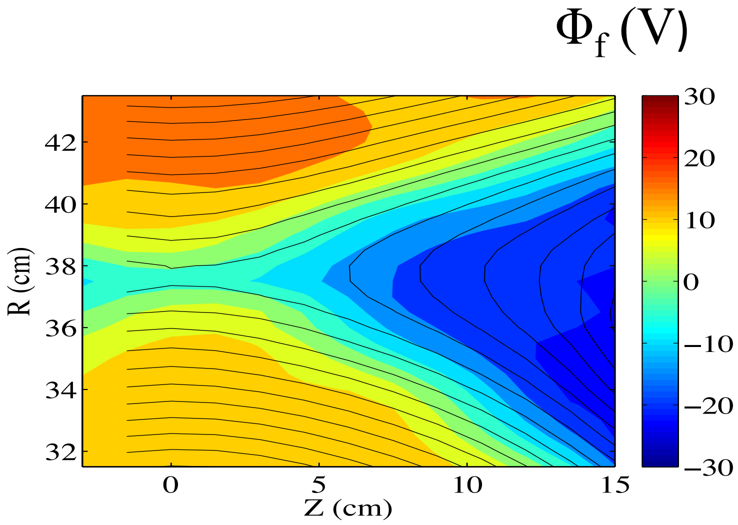


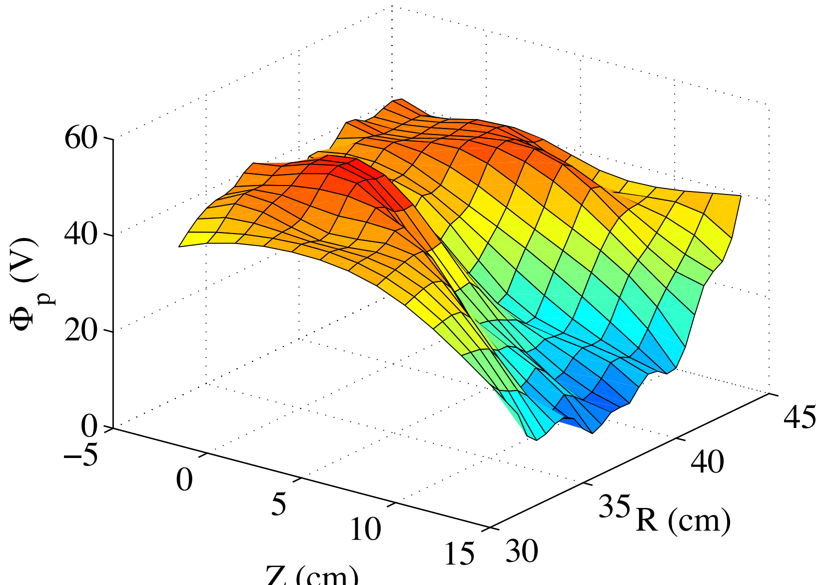


A large in-plane electric Hall field verified in the MRX reconnection layer due to two-fluid effects.



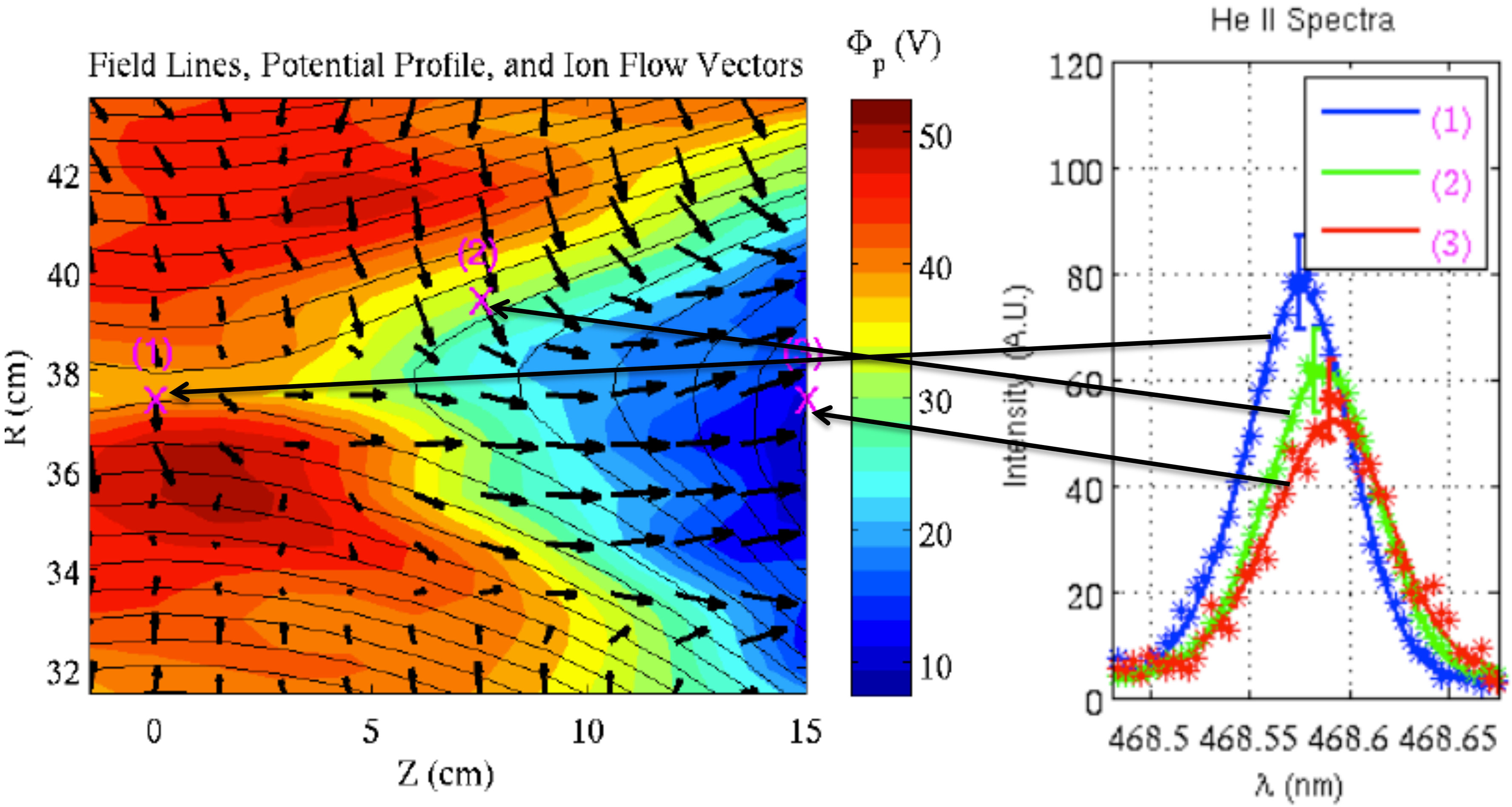
L-J. Chen *et al*, 2008





Wygant et al, 2005
Hoshino et al, 1998
Drake et al, 2009

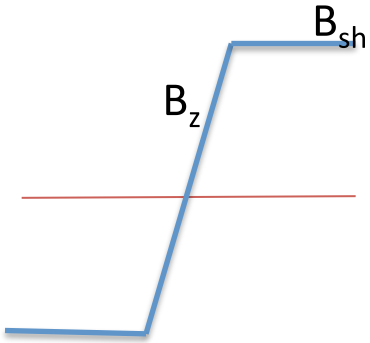
Ion acceleration and heating in the reconnection layer



Ion heating is attributed to re-magnetization of accelerated ions

Size of potential drop can be analytically estimated

Yamada et al,
PoP (2016)



$$E_R \approx V_{ey} B_Z - \frac{1}{e n_e} \frac{\partial p_e}{\partial R}$$ (1)

Equation of motion for electrons

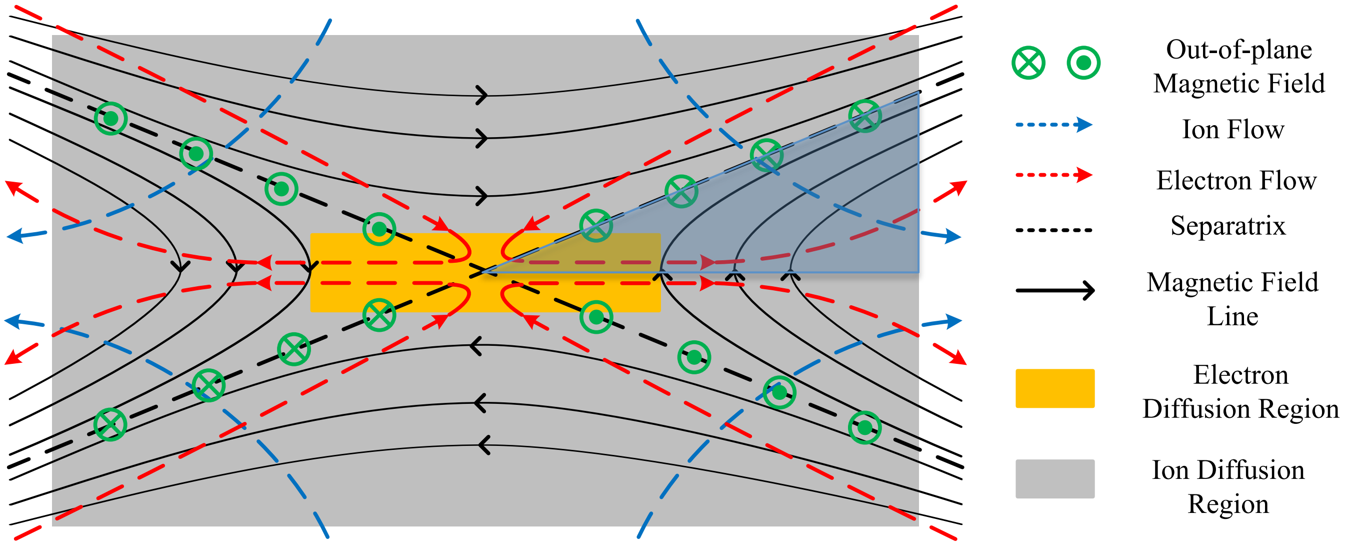
$$\Delta \Phi_p \approx \frac{B_{sh}^2}{2\mu_0 e \langle n_e \rangle} - \Delta T_e$$ (2)

After integrating (1) w.r.t. R

- **Is there a fundamental principle for energy partitioning in a proto-typical reconnection layer?**

Energy Conversion in Two-fluid Reconnection:

Ions gains energy primarily on the separatrices



$$W_{ion} \sim L_i V_{in}\, n_e e <\delta\Phi> \sim L_i V_{in} \frac{B_{sh}^2}{2\mu_0}$$

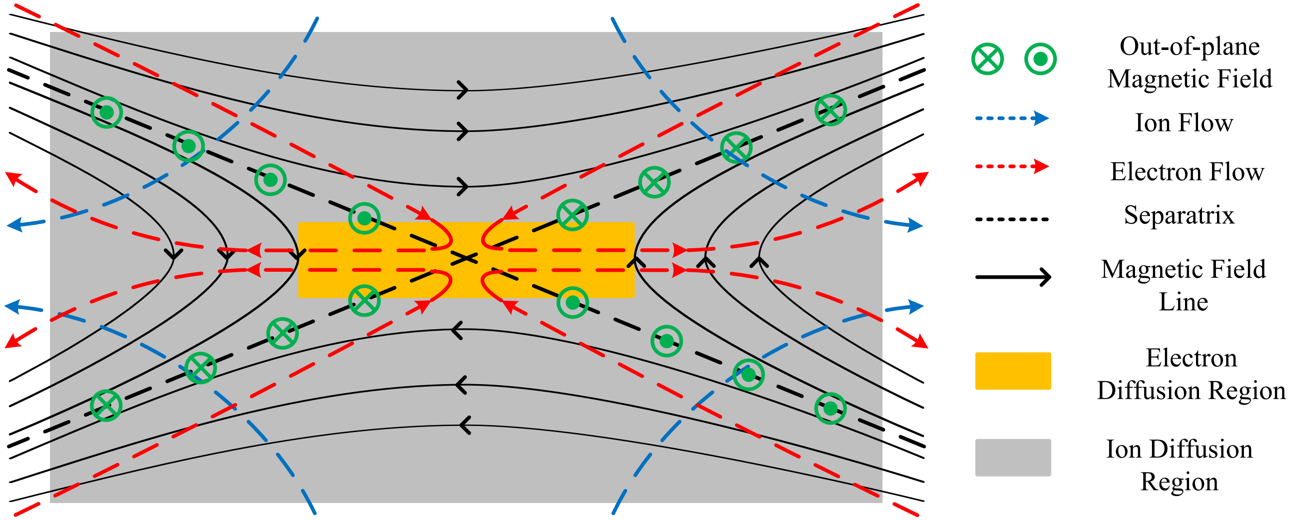
$$W_M \sim L_i V_{in} \frac{B_{sh}^2}{\mu_0}$$

$$W_{ion}/W_M \sim 1/2$$

As large as 50% of incoming magnetic energy is converted to particle energy of ions

Energy Conversion in Two-fluid Reconnection:

Energy deposition to electrons only occurs at the e-diffusion region



We use Sweet-Parker model for electron heating/bulk acceleration

$$W_e \sim L_e V_{in} \frac{B_{sh}^2}{\mu_0}$$

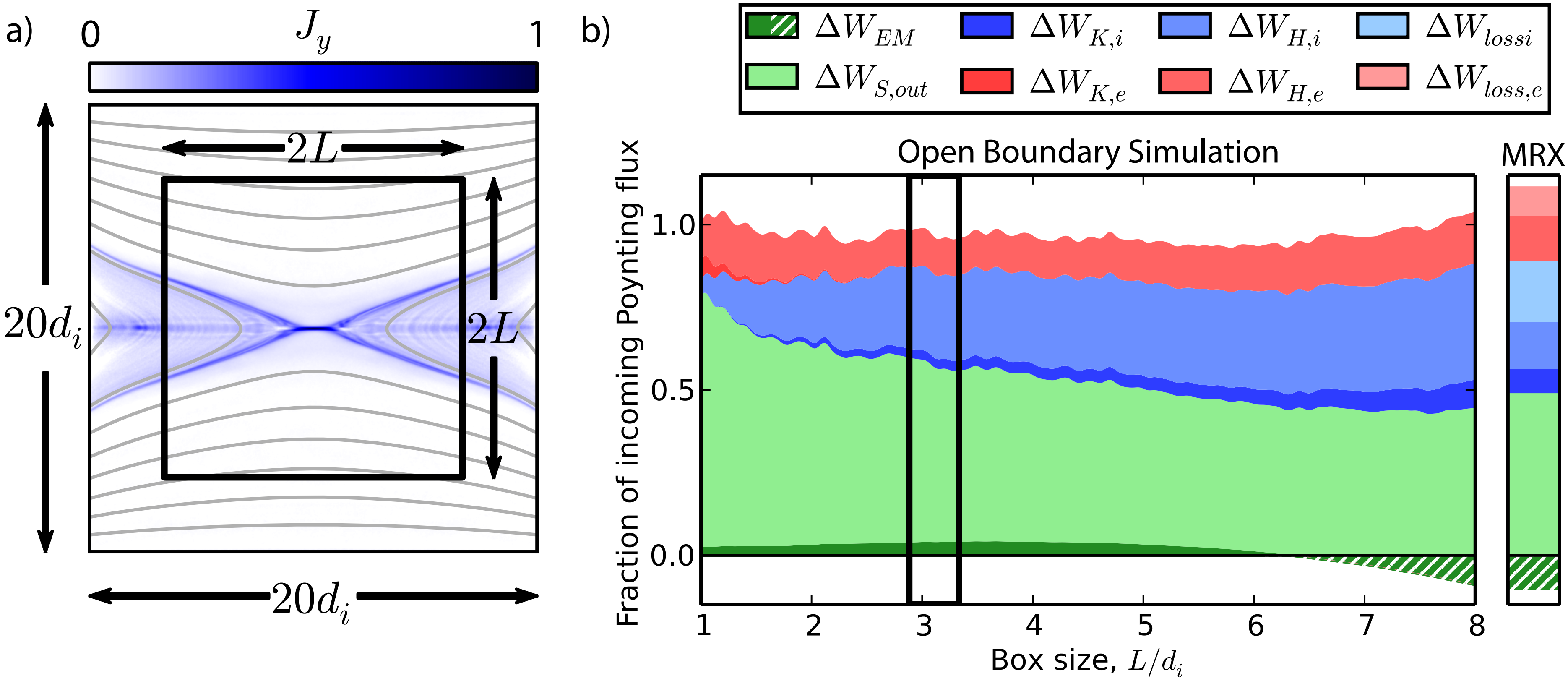
$$=> \frac{W_e}{W_M} \sim \frac{L_e}{L_i} \sim \frac{1}{4}$$

$$W_M \sim L_i V_{in} \frac{B_{sh}^2}{\mu_0}$$

Only a fraction of incoming magnetic energy is converted to particle energy of electrons

2D PIC simulation on energetics;

by J. Jara Almonte and W. Daughton



The energy partitioning does not strongly depend on the size of monitoring boundary

MRX data is compared with simulations and space data

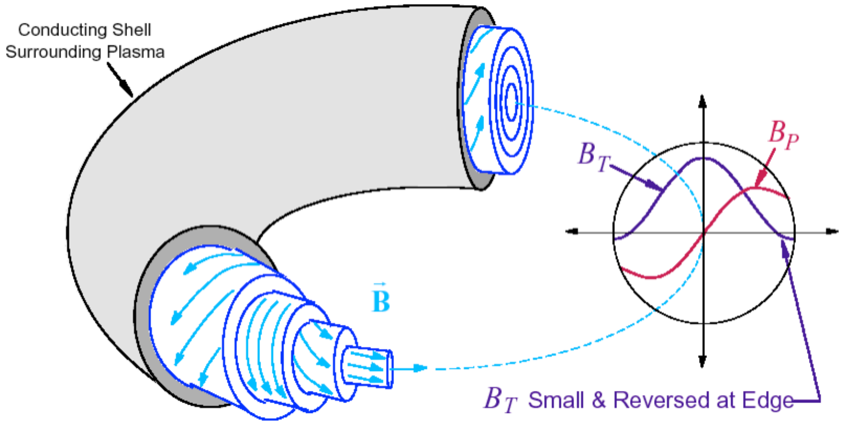
	Magnetic energy Inflow	Magnetic Energy outflow rate	Energy deposition to ions	Energy deposition to electrons
MRX Data	1.0	0. 45	0.35	0.20
Numerical simulation	1.0	0. 42	0.34	0.22
Magnetotail data (Eastwood)	1.0	0.4	0.39	0.18

- Enthalpy flux dominates in the down flow region
- Magnetic energy outflow substantial

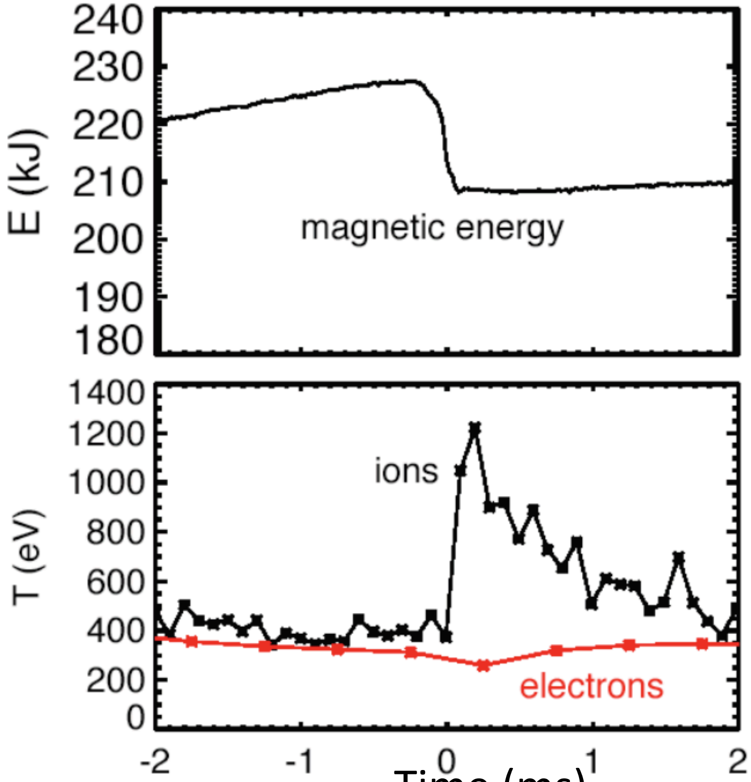
Energy deposition to ions is generally larger than to electrons.
With the electrons' heat transport loss is larger than that of ions',
$\Rightarrow T_i >> T_e$

Very important for reconnection in CT plasmas

Strong ion heating is observed during sawtooth reconnection in RFP

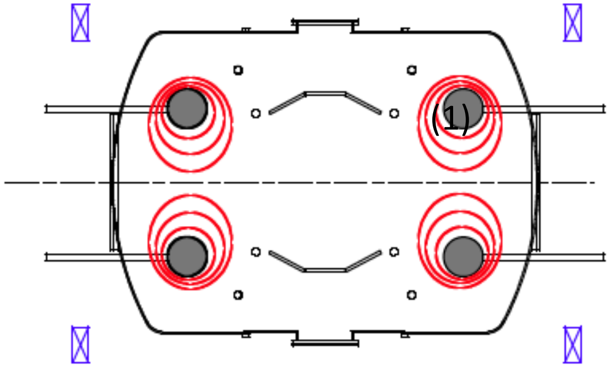


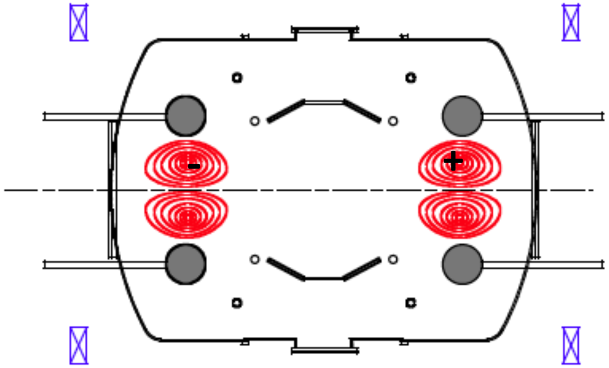
Reconnection Event

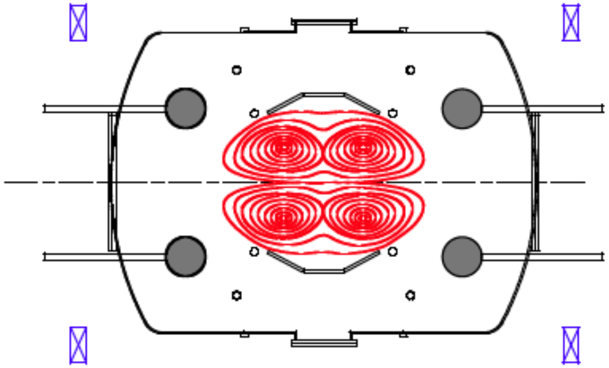


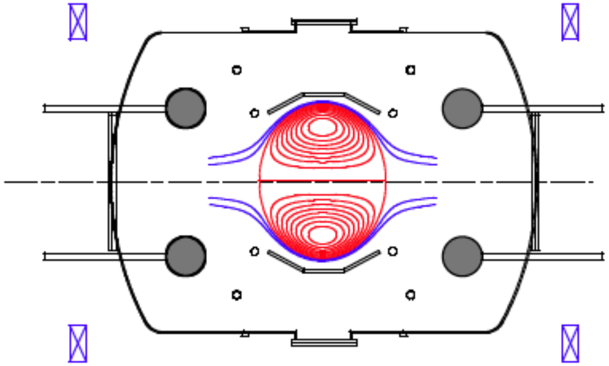
Time (ms)
(relative to reconnection event)

Spheromak Merging Experiments in MRX (Toroidal Energy => Plasma Kinetic Energy)


Plasma Initiation

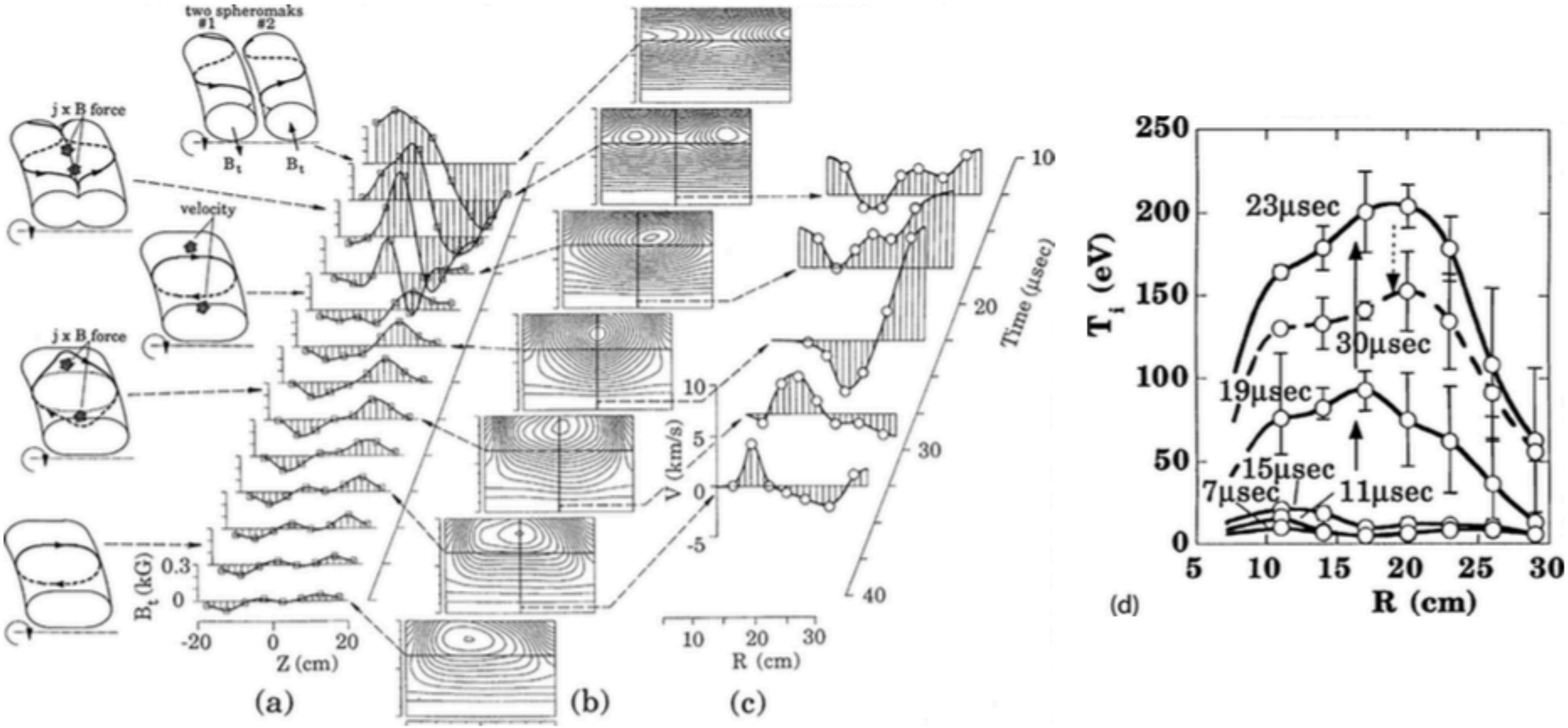

Spheromak Formation


Speromak Merging


Final CT

(1)

Spheromak Merging Experiments in U. Tokyo
(Toroidal Energy => Plasma Kinetic Energy)



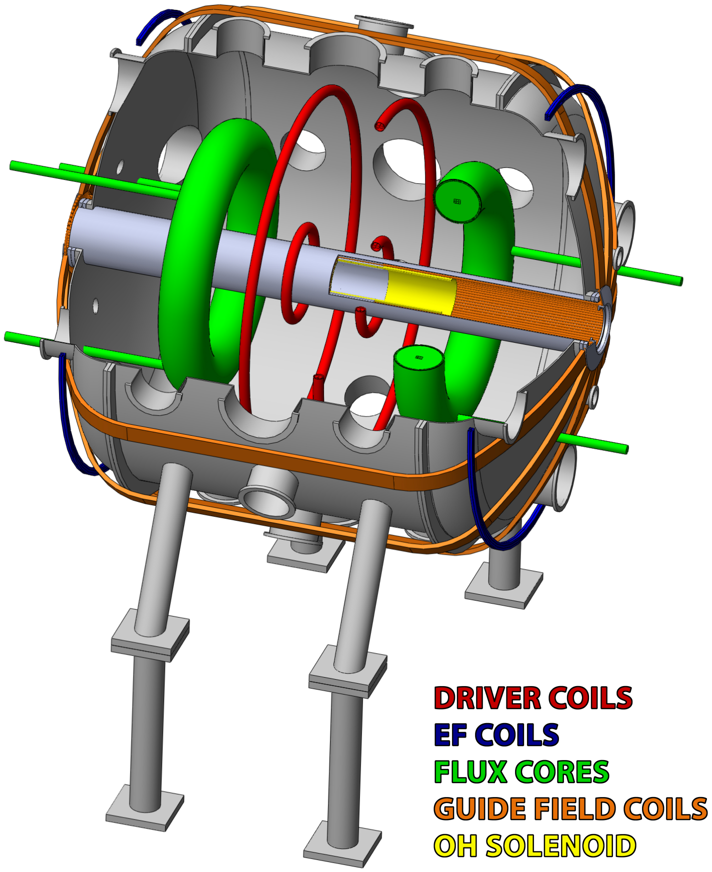
TS-3; Yamada et al PRL (1990)
Ono et al PRL(1996)

Norman’s 70 year Symposium (1995)

FLARE (Facility for Laboratory Reconnection Experiment)

Ji (PI) et al

Parameters	MRX	FLARE
Device diameter	1.5 m	3 m
Device length	2 m	3.6 m
Flux core major diameters	0.75 m	1.5 m
Flux core minor diameter	0.2 m	0.3 m
Stored energy	25 kJ	4 MJ
Ohmic heating/ drive	No	0.3 V-s
Outer driving coil	Yes	Yes
Inner driving coil	No	Yes
S (anti-parallel)	600-1,400	5,000-16,000
$\lambda=(Z/\delta_i)$	35-10	100-30
S (guide field)	2900	100,000
$\lambda=(Z/\rho_S)$	180	1,000



DRIVER COILS
EF COILS
FLUX CORES
GUIDE FIELD COILS
OH SOLENOID

Summary

- Energy partitioning are quantitatively analyzed in the MRX reconnection layer

- This result is consistent with theory for the dynamics of two-fluid reconnection layer with a single X-line geometry
  - Energy deposition to electrons occurs near the X-point through $j_{\perp e}E_{\perp}$
  - Energy deposition to ions occurs near the separatrices through $j_{\perp i}E_{\perp}$

- Based on the MRX data and analytical consideration, we conclude a fundamental principle for energy partitioning in a proto-typical reconnection layer.
  - Substantial component of outgoing magnetic energy (~ 50%) in the Hall reconnection
  - ~ 50 % of incoming magnetic energy can go to plasma particles

- **The results have an important message to CT research**
  During two-fluid magnetic reconnection, a significant amount of E field is generated and magnetic energy is converted to ions kinetic energy.