Fundamentals for energy partitioning in the reconnection layer

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June 24 th, 2016

PPPL, Theory Research Review Seminar,

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Motivation

- Magnetic reconnection is known for efficient conversion from magnetic to particle energy.
- Identification of mechanisms for the energy conversion is the central problem of reconnection research.
- **Is there a fundamental principle for energy partitioning in a 2-fluid proto-typical reconnection layer?**

Summary of the recent MRX results

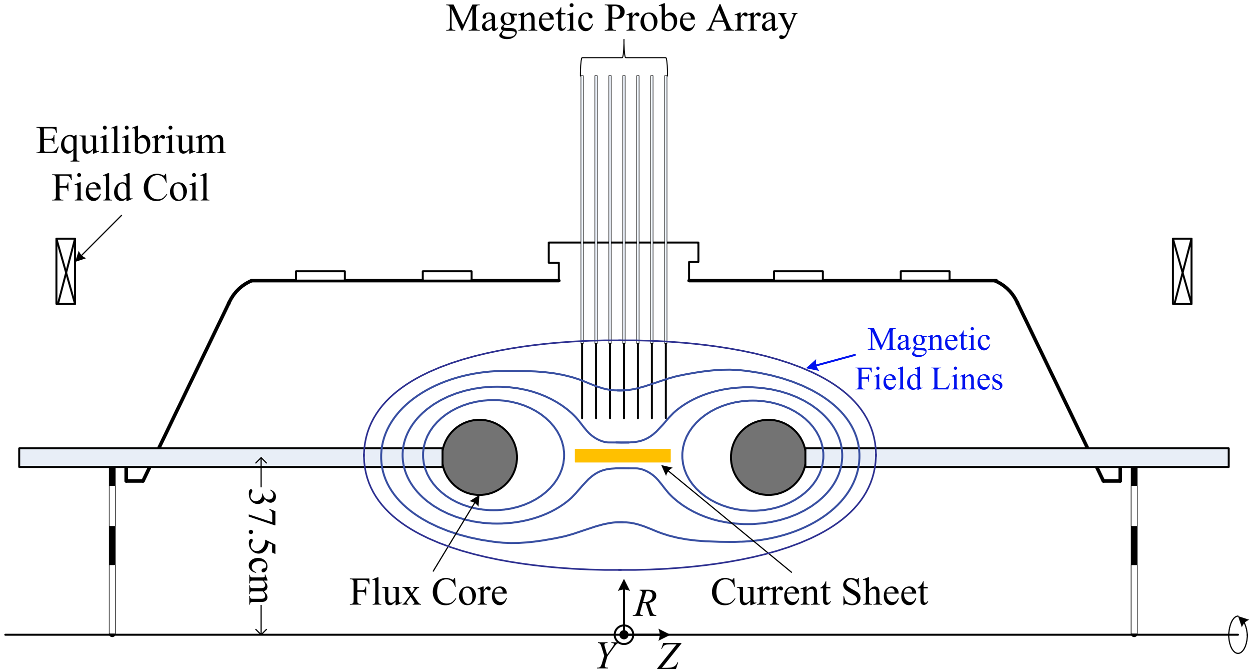
- Energy partitioning are quantitatively analyzed in the MRX reconnection layer [Yamada et al, Phys. Plasmas, **23**, 055402 (2016), Yoo et al, 2013-]
  - Outgoing magnetic energy (~ 50%)
  - ~50 % of incoming magnetic energy goes to plasma particles

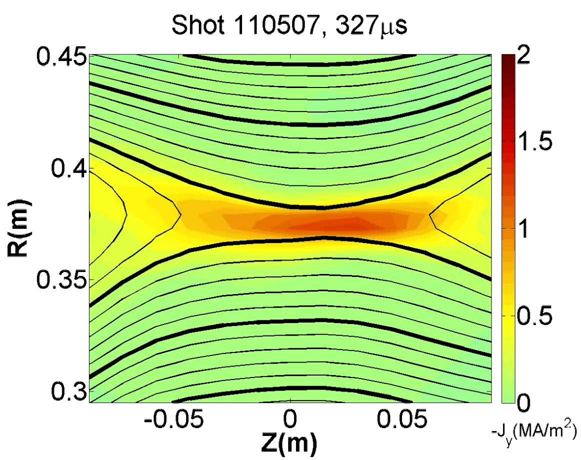
- This result is consistent with theory for the dynamics of two-fluid reconnection layer with a single X-line geometry

How do we extend our study to more general reconnection phenomena or larger systems?

How is magnetic energy converted to plasma?

Experimental set-up [Yoo et al, 2013]

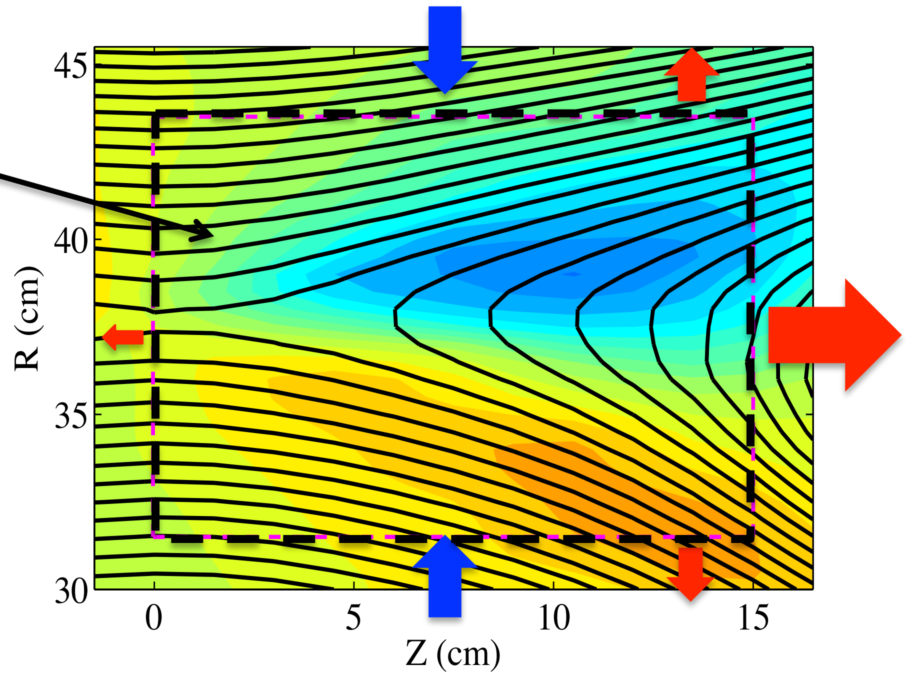




- Helium discharge
- IDSP to measure T_i
- $\lambda_{mfp,e} \geq c/\omega_{pi} > \delta_{CS}$ (~2cm)

Measurement of energy inventory in MRX

Changes in energy enclosed in the volume

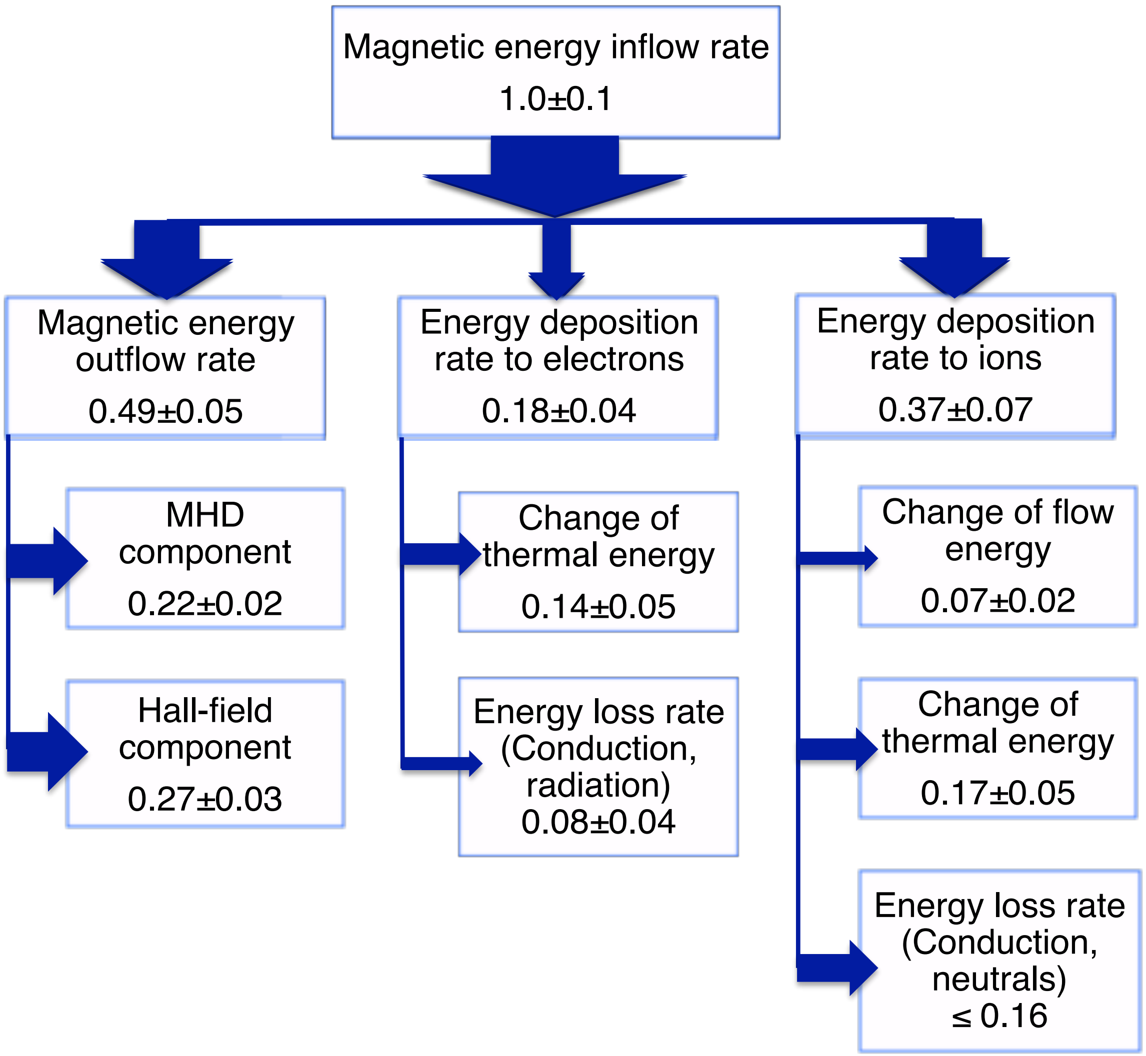


- Energy transport equation :

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

Birn and Hesse, 2005

Inventory of Energy



Yamada et al, Nature Communications (2014)

MRX data is compared with simulations and space data

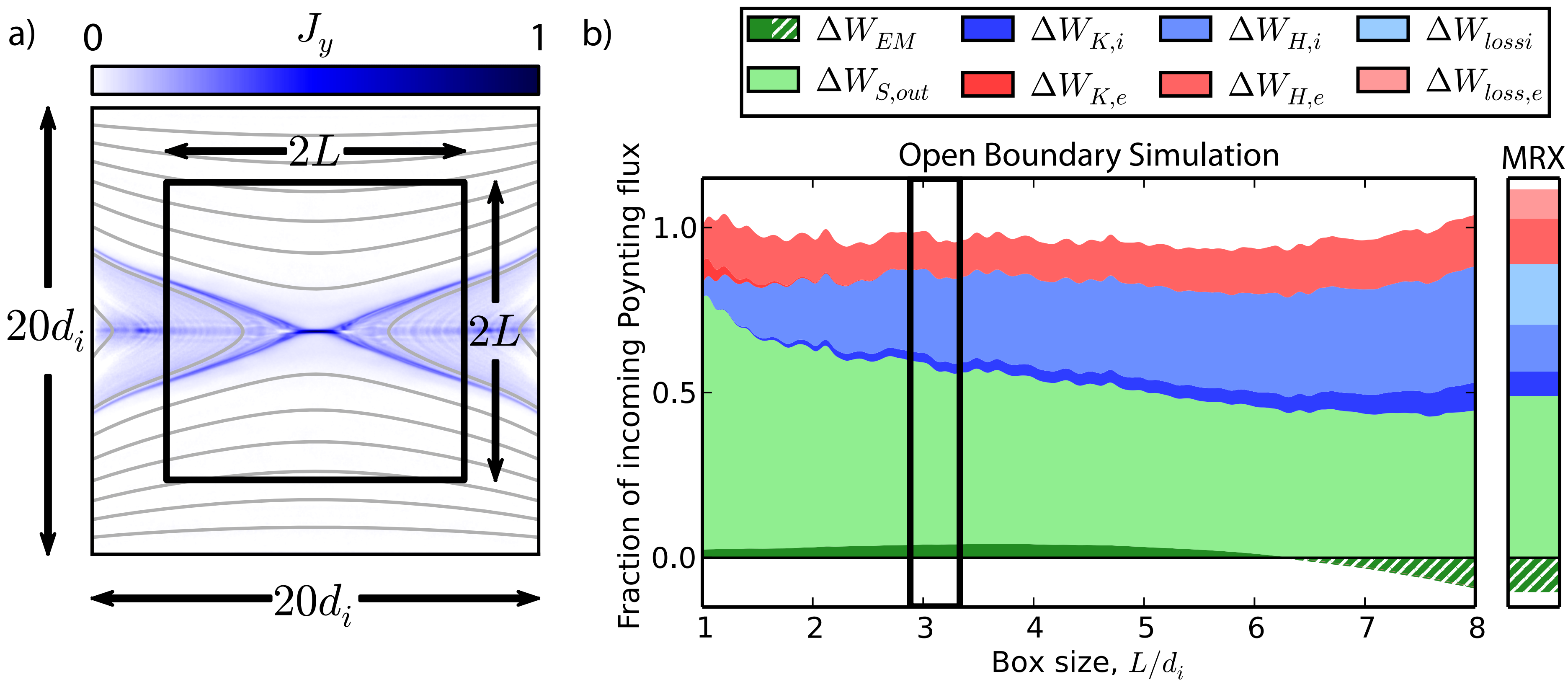
	Magnetic energy Inflow	Magnetic Energy outflow rate	Energy deposition to ions	Energy deposition to electrons
MRX Data	1.0	0. 45	0.35	0.20
Numerical simulation	1.0	0. 42	0.34	0.22
Magnetotail data (Eastwood)	1.0	0.4	0.39	0.18

- 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 ions',
=> $T_i >> T_e$

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

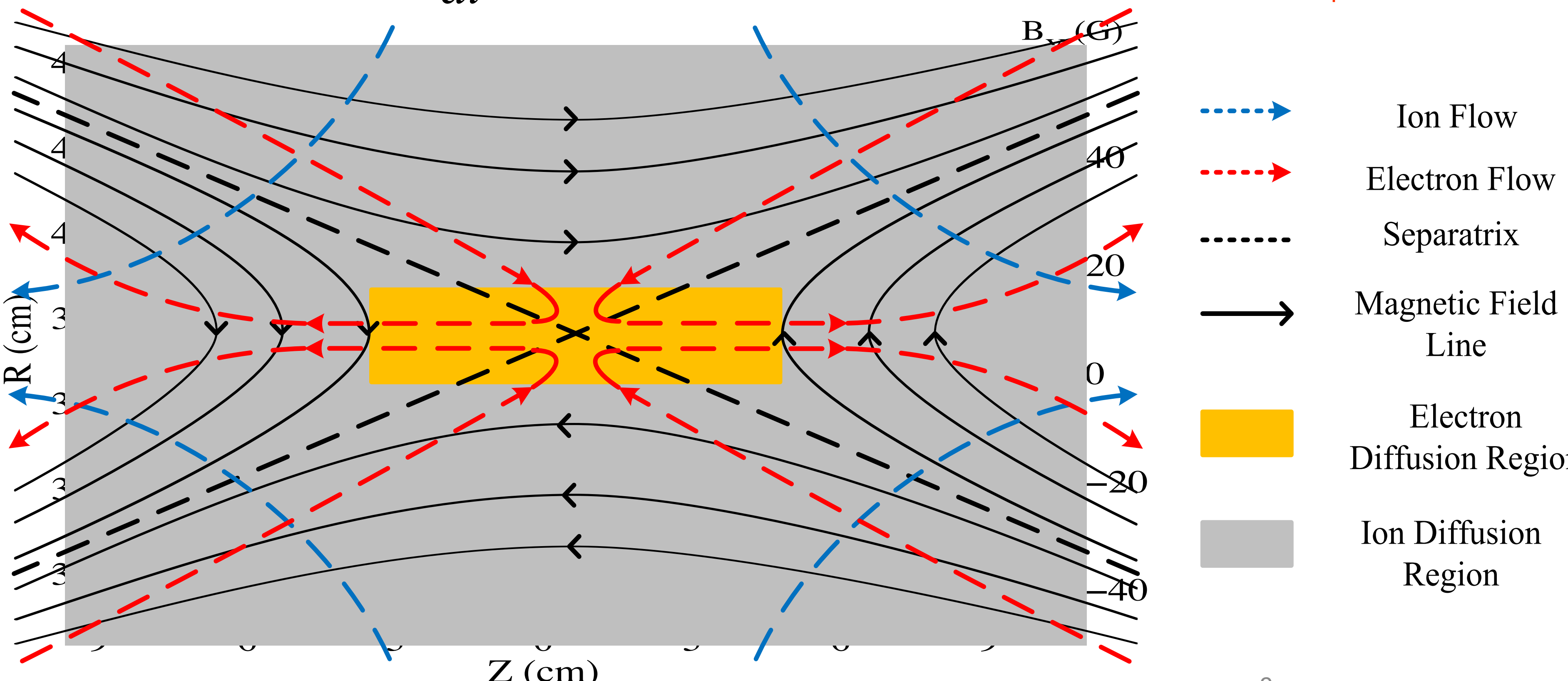
Particle dynamics of the two-fluid reconnection layer

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

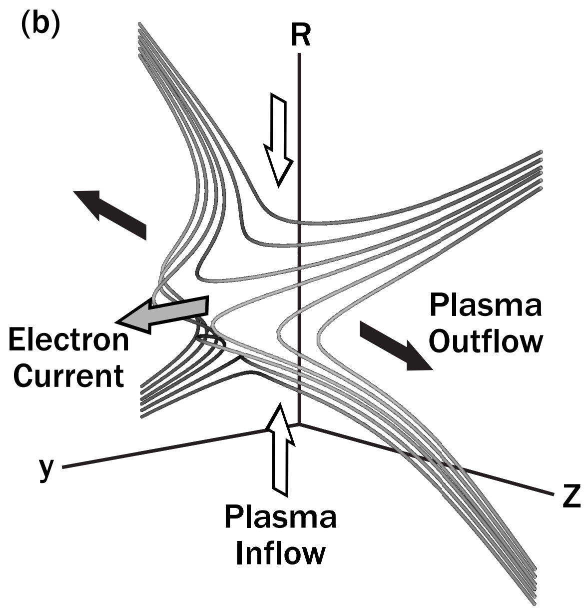
$$E_{rec} + V_{in} \times B_{rec} = 0 + \frac{\delta_i}{\Delta}\frac{j_{in} \times B_{rec}}{n} - \frac{\delta_e^2}{\Delta^2}\frac{1}{n}\frac{dj_{rec}}{dt} + \frac{\delta_i}{\Delta}\frac{(\nabla \cdot P_e)_{off}}{n}$$

Hall term | Electron inertia term | Electron pressure term

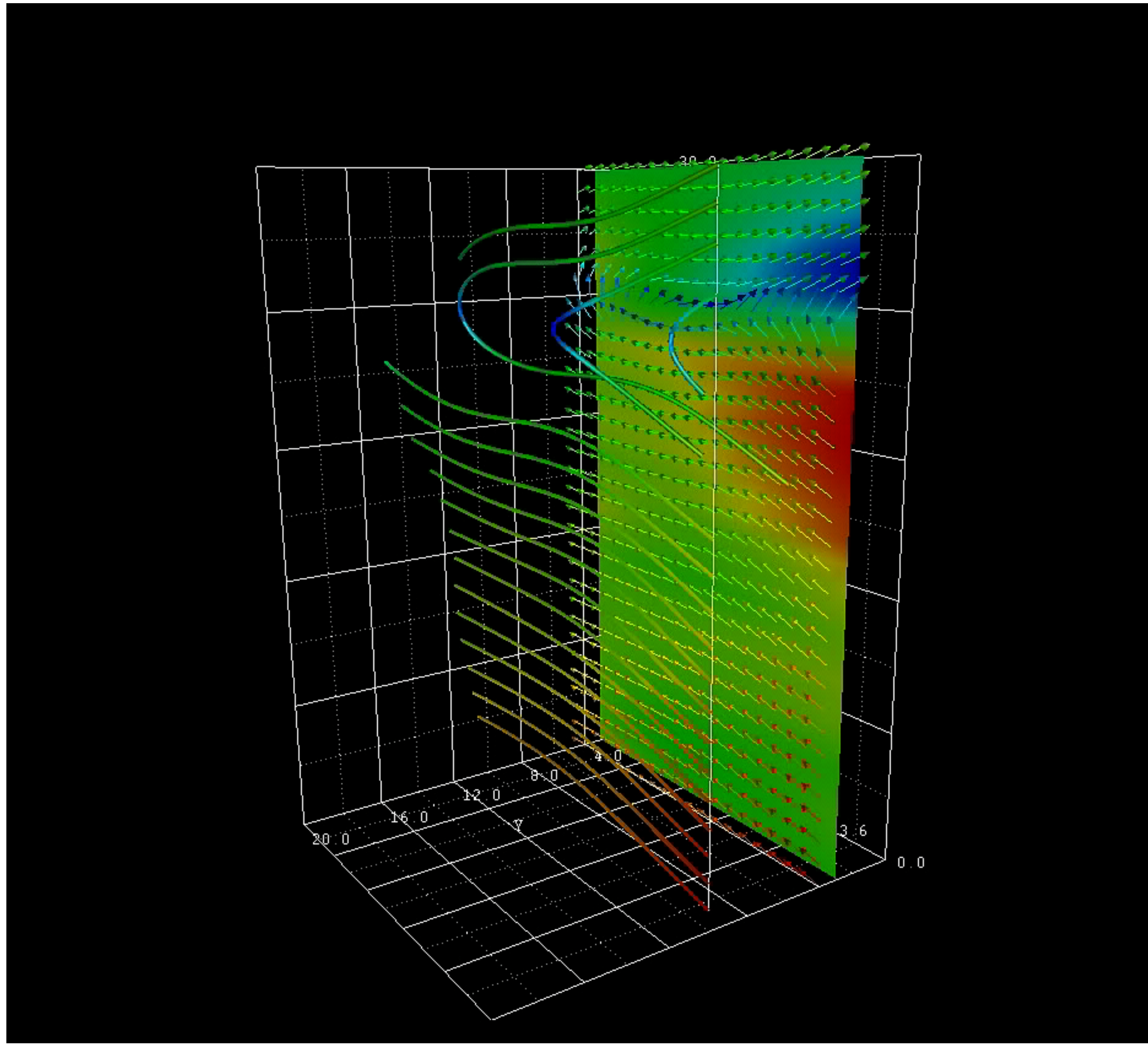
$$V_e \times B_{rec} \approx E_{rec} \approx \frac{d\Psi}{dt}$$



Evolution of magnetic field lines during reconnection in MRX



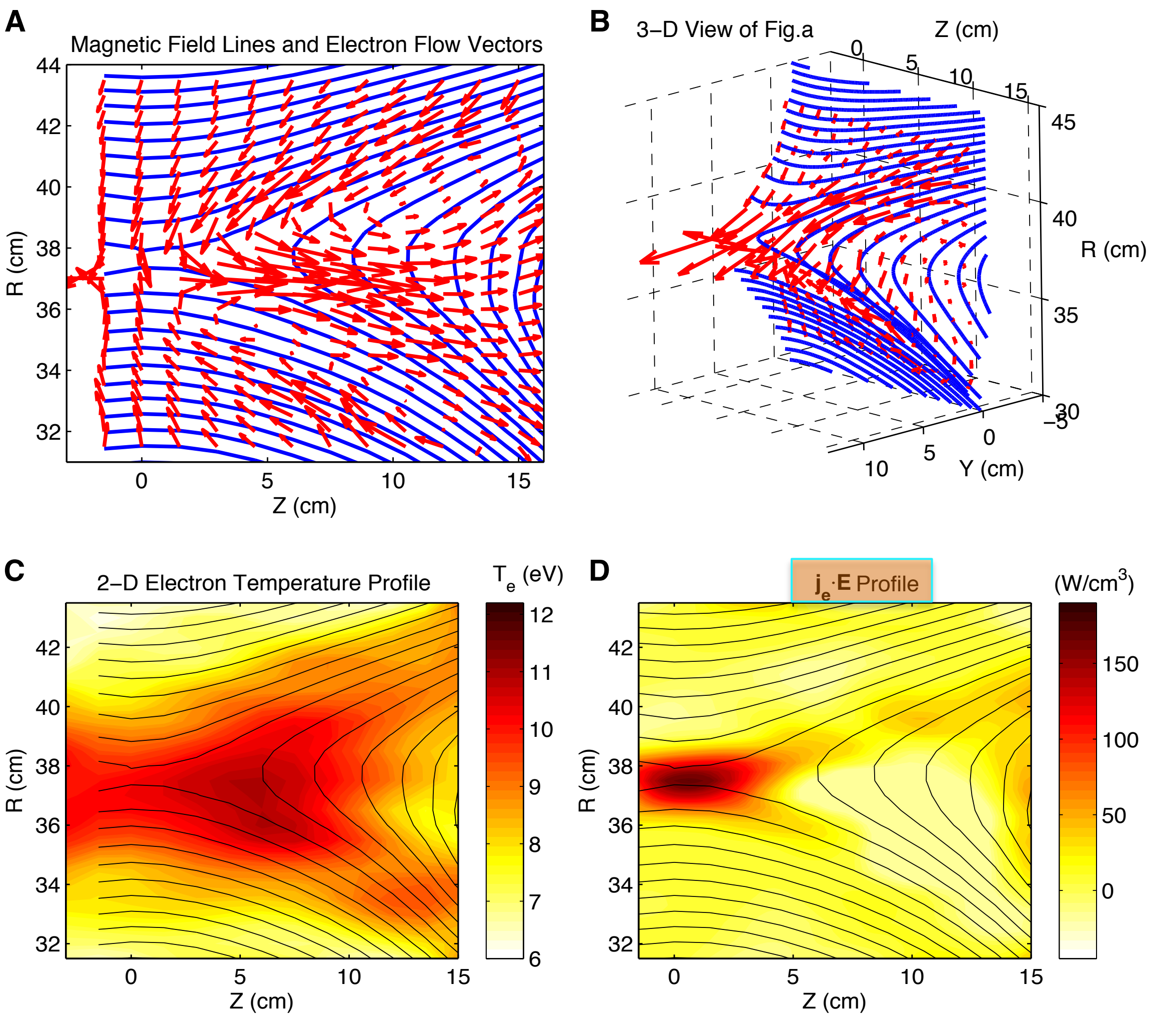
Electron flow pulls field lines



A half of reconnection region measured

Yamada.APS.15

Electron dynamics and electron heating in MRX



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

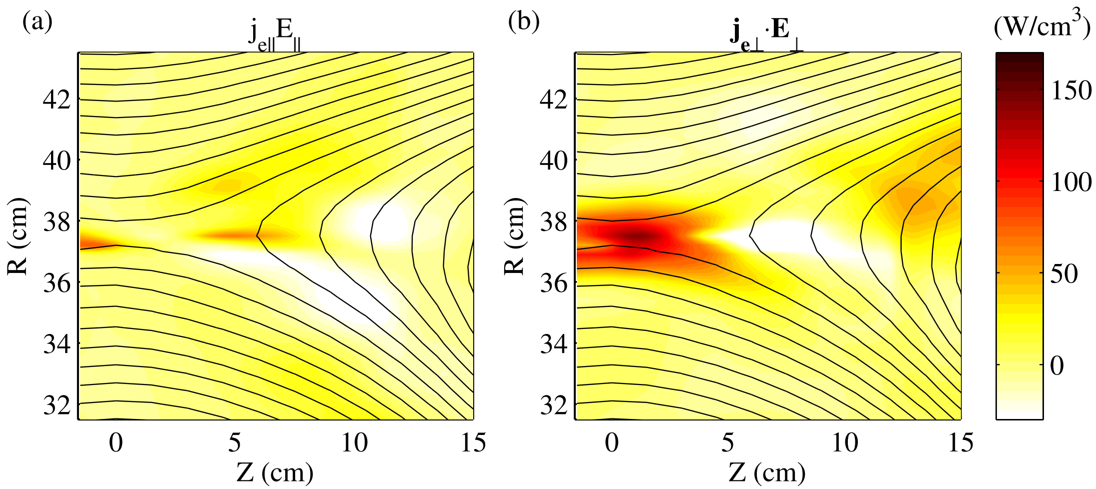
Electron gain energy by E_y

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

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

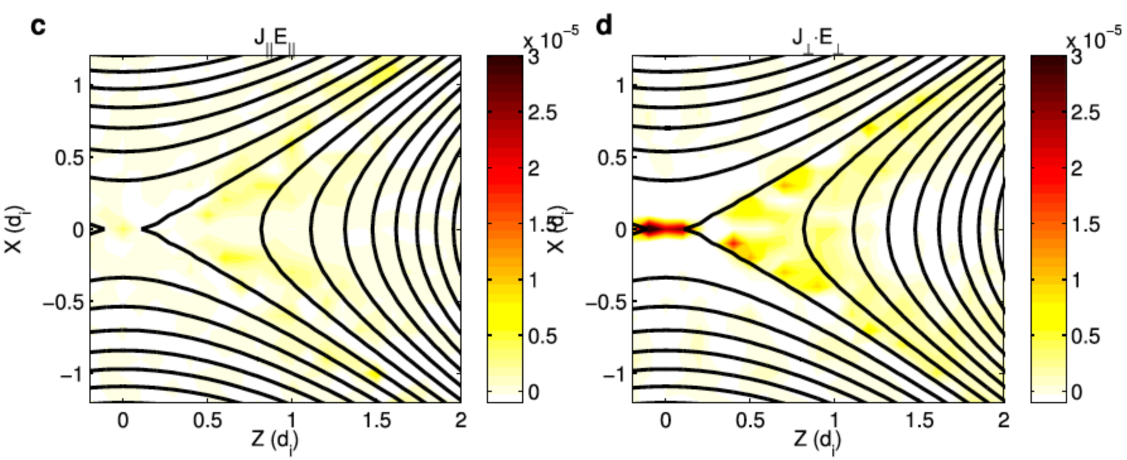
The physics of the high energy deposition rate is not yet resolsved.

Energy deposition to electrons in both symmetric and asymmeric reconnection MRX



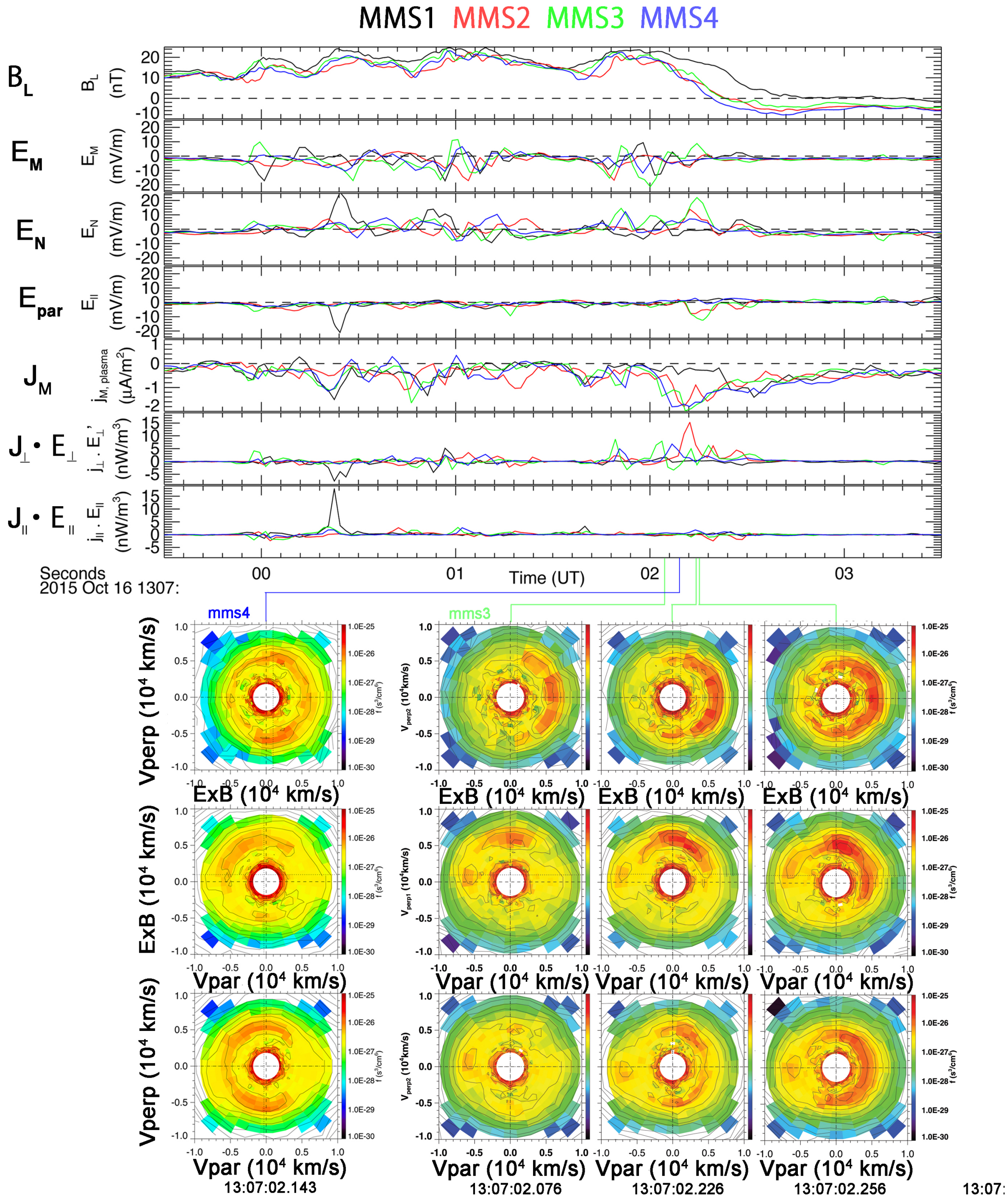
MRX results

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



Simulation results

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

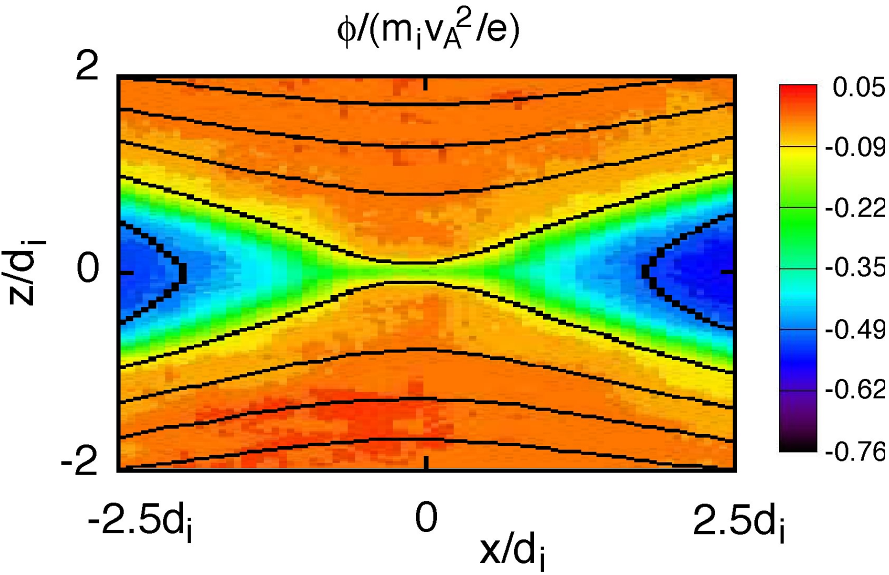


4 seconds of data

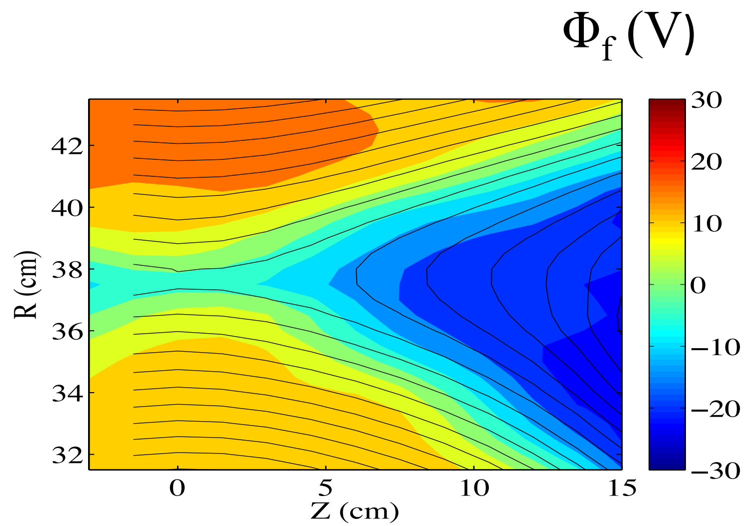
MMS4 southward of X-line

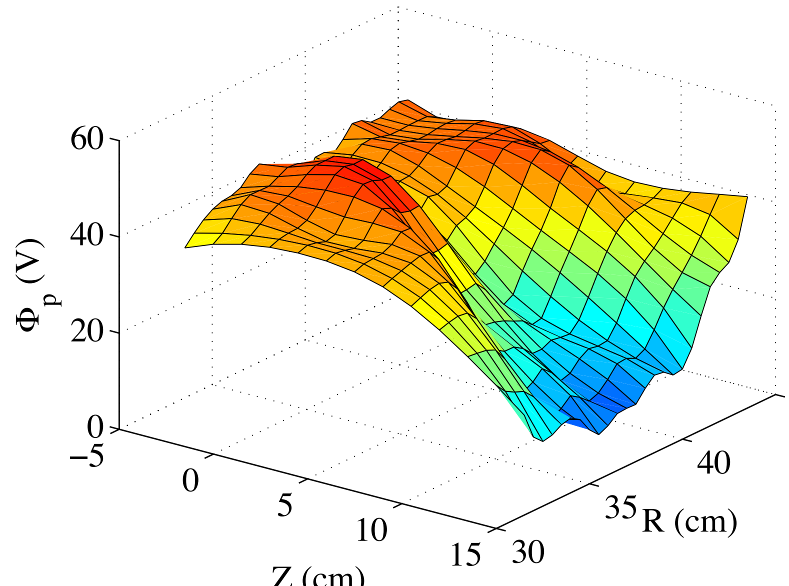
MMS3 northward of X-line

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



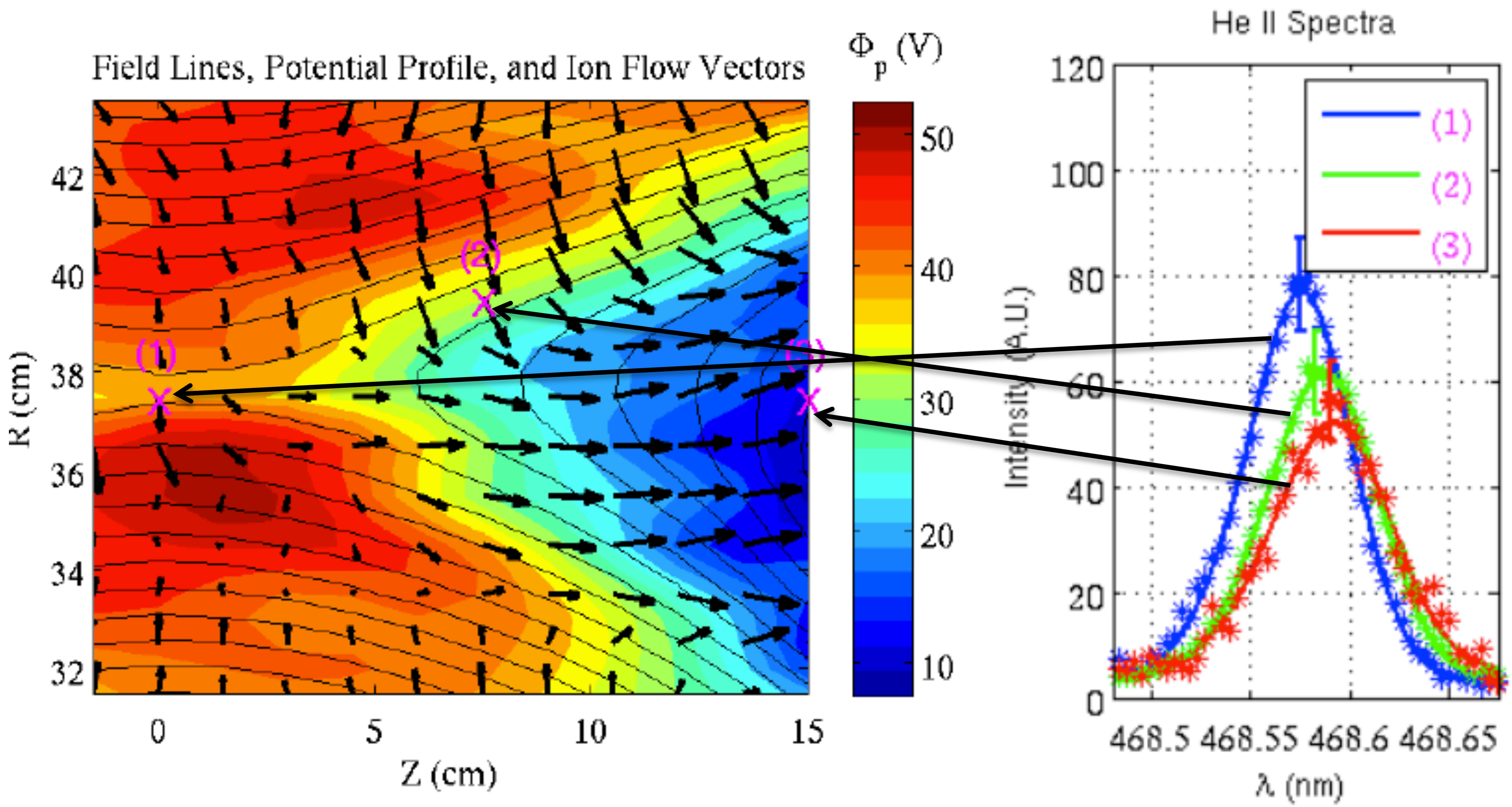
L-J. Chen *et al*, 2008





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

Ion acceleration and heating in the reconnection layer

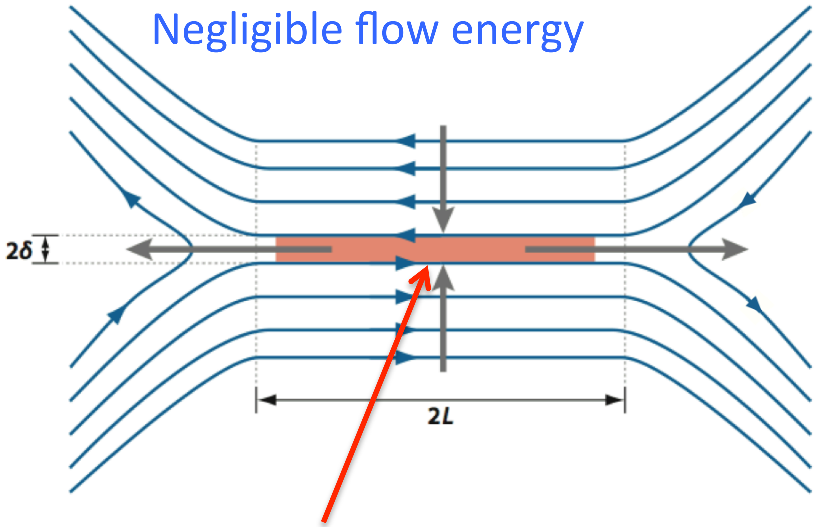


Ion heating is attributed to re-magnetization of accelerated ions

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

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

<u>2-D, resistive MHD model</u>

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

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

A. Analysis of energy flow in MHD formulation

The overall energy conversion in the single-fluid (MHD) model can be examined with the following energy transport equation:[41]

$$\frac{\partial}{\partial t}\left(\frac{B^2}{2\mu_0}+\frac{\epsilon_0 E^2}{2}+u+\frac{\rho}{2}V^2\right)+\nabla\cdot(\mathbf{S}+\mathbf{H}+\mathbf{K})=0, \quad (8)$$

where $u=(3/2)p$ is the internal energy density, $p=n_e T_e + n_i T_i$ is the pressure, $\rho = m_e n_e + m_i n_i$ is the mass density, $\mathbf{V}$ is the single-fluid velocity, $\mathbf{S}=(\mathbf{E}\times\mathbf{B})/\mu_0$ is the Poynting flux, $\mathbf{H}=(u+p)\mathbf{V}$ is the enthalpy flux, and $\mathbf{K}=(\rho/2)V^2\mathbf{V}$ is the flow energy flux.

Magnetic energy inflow is equally divided to changes of energy of plasma enthalpy and flow.

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

$W_H \sim W_K \sim \frac{1}{2} W_M$: J. Yoo (2013)

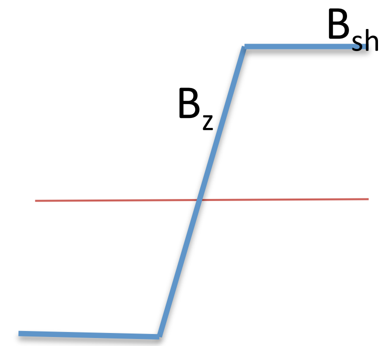
B. Analysis of energy flow in the two-fluid formulation

For two-fluid dynamics, Eq. (8) is modified to include the microscopic heat flux, $\mathbf{q}$, and the scalar pressure, p, which is generalized to the total pressure tensor, $\mathbf{P}$:

$$\frac{\partial}{\partial t}\left[\frac{B^2}{2\mu_0}+\sum_{s=e,i}\left(u_s+\frac{\rho_s}{2}V_s^2\right)\right] + \nabla\cdot\left[\mathbf{S}+\sum_{s=e,i}(\mathbf{H}_s+\mathbf{K}_s+\mathbf{q}_s)\right]=0. \qquad (20)$$

Here, u_s, the internal energy of species s, is derived from the pressure tensor, $u_s = \mathrm{Tr}(\mathbf{P}_s)/2$, and $\mathbf{H}_s = u_s\mathbf{V}_s + \mathbf{P}_s\cdot\mathbf{V}_s$ is the enthalpy flux for species s.

Yamada et al, PoP (2016)



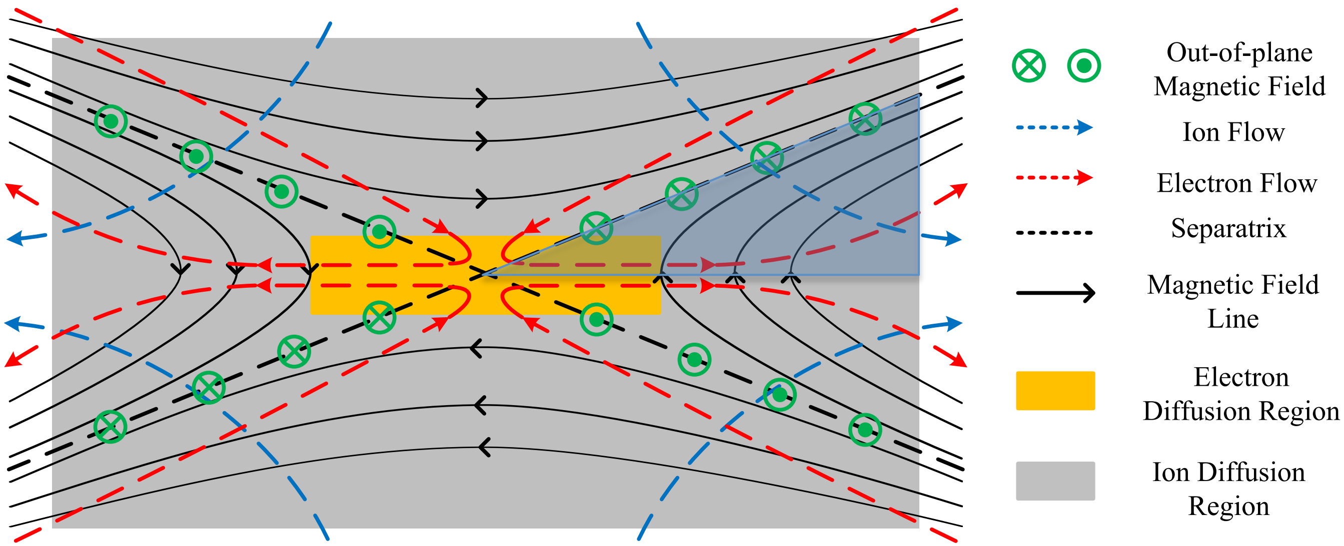
$$E_R \approx V_{ey}B_Z - \frac{1}{en_e}\frac{\partial p_e}{\partial R} \qquad (1)$$

Equation of motion for electrons

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

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

Energy Conversion in Two-fluid Reconnection:
Ions gains energy primarily on the separatrices



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

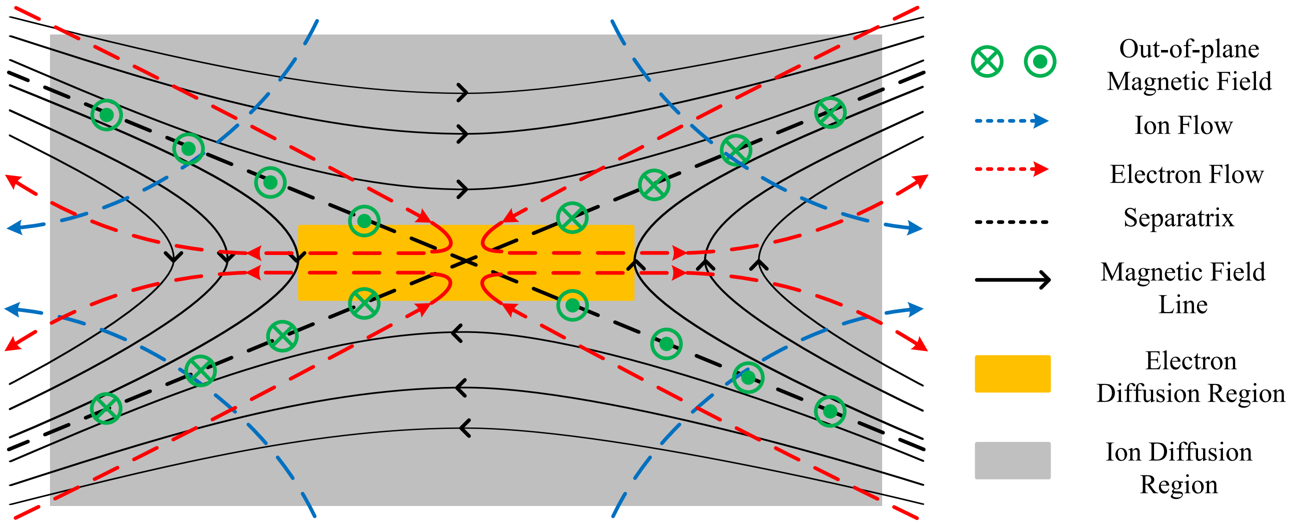
$$W_M \sim L_i V_{in} \frac{B_{sh}^2}{\mu_0}$$

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

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

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

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

$$\Rightarrow \quad \frac{W_e}{W_M} \sim \frac{L_e}{L_i}$$

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

Summary

- Energy partitioning are quantitatively analyzed in the MRX reconnection layer
  - Outgoing magnetic energy (~ 50%)
  - ~50 % of incoming magnetic energy goes to plasma particles
    2/3: to ions
    1/3: to electrons

- 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