Fundamentals for energy partitioning in the reconnection layer

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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 $T_i$
- $\lambda_{mfp,e} \geq c/\omega_{pi} > \delta_{CS} (~2\text{cm})$
Measurement of energy inventory in MRX

Changes in energy enclosed in the volume

• Energy transport equation:

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

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

- Energy deposition rate to ions:
  - 0.37 ± 0.07

- Change of flow energy:
  - 0.07 ± 0.02

- Change of thermal energy:
  - Energy loss rate (Conduction, radiation): 0.08 ± 0.04
  - Energy loss rate (Conduction, neutrals): ≤ 0.16

Yamada et al, Nature Communications (2014)
MRX data is compared with simulations and space data

<table>
<thead>
<tr>
<th></th>
<th>Magnetic energy Inflow</th>
<th>Magnetic Energy outflow rate</th>
<th>Energy deposition to ions</th>
<th>Energy deposition to electrons</th>
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</thead>
<tbody>
<tr>
<td>MRX Data</td>
<td>1.0</td>
<td>0.45</td>
<td>0.35</td>
<td>0.20</td>
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<tr>
<td>Numerical simulation</td>
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<td>0.34</td>
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<tr>
<td>Magnetotail data</td>
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<td>0.39</td>
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<td>(Eastwood)</td>
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</tbody>
</table>

- 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’, => \( T_i >> T_e \)
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 \( x/\Delta \to x, \ V/V_A \to V, \ B/B_0 \to B \)

\[
E_{\text{rec}} + V_{\text{in}} \times B_{\text{rec}} = 0 + \frac{\delta_i}{\Delta} \frac{j_{\text{in}} \times B_{\text{rec}}}{n} - \frac{\delta_e}{\Delta^2} \frac{1}{n} \frac{dj_{\text{rec}}}{dt} + \frac{\delta_i}{\Delta} \frac{\nabla \cdot P_e}{n}
\]

- Hall term
- Electron inertia term
- Electron pressure term

\[
V_e \times B_{\text{rec}} \approx E_{\text{rec}} \approx \frac{d\Psi}{dt}
\]

\[
E_{\text{Hall}} \times B_{\text{rec}} \approx -E_{\text{rec}} \Rightarrow E_{\text{rec}} \approx \frac{d\Psi}{dt}
\]

\[
V_{\text{in}} \times B_{\text{rec}} \approx \frac{d\Psi}{dt}
\]

---

**Legend:**
- Ion Flow
- Electron Flow
- Separatrix
- Magnetic Field Line
- Electron Diffusion Region
- Ion Diffusion Region
Evolution of magnetic field lines during reconnection in MRX

(b)  
Electron Current

Plasma Inflow

Electron flow pulls field lines

A half of reconnection region measured

Yamada.APS.15
Electron dynamics and electron heating in MRX

\[ j = \text{Curl}\ B, \ V_e = j_e / n_e \]

Electron gain energy by \( E_y \)

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

\[ j \perp E \perp >> j \parallel E \parallel \]

The physics of the high energy deposition rate is not yet resolved.
Energy deposition to electrons in both symmetric and asymmetric reconnection MRX

MRX results

\[ j_\perp E_\perp \gg j_\parallel E_\parallel \]

Simulation results

\[ j_\perp E_\perp \gg j_\parallel E_\parallel \]
MMS4 southward of X-line

MMS3 northward of X-line

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 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

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

\[ \frac{B_{in}^2}{\mu_0} \rightarrow W_p + \frac{\rho}{2} V_s^2 \]
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:

$$\frac{\partial}{\partial t} \left( \frac{B^2}{2\mu_0} + \frac{\varepsilon_0 E^2}{2} + u + \frac{\rho}{2} V^2 \right) + \nabla \cdot (S + H + K) = 0,$$

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, $V$ is the single-fluid velocity, $S = (E \times B)/\mu_0$ is the Poynting flux, $H = (u + p)V$ is the enthalpy flux, and $K = (\rho/2)V^2 V$ 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, \( q \), and the scalar pressure, \( p \), which is generalized to the total pressure tensor, \( P \):

\[
\frac{\partial}{\partial t} \left[ \frac{B^2}{2\mu_0} + \sum_{s=e,i} \left( u_s + \frac{\rho_s}{2} V_s^2 \right) \right] + \nabla \cdot \left[ S + \sum_{s=e,i} (H_s + K_s + q_s) \right] = 0. \tag{20}
\]

Here, \( u_s \), the internal energy of species \( s \), is derived from the pressure tensor, \( u_s = \text{Tr}(P_s)/2 \), and \( H_s = u_s V_s + P_s \cdot V_s \) is the enthalpy flux for species \( s \).

\[
E_R \approx V_{ey} B_Z - \frac{1}{en_e} \frac{\partial p_e}{\partial R} \tag{1}
\]

Equation of motion for electrons

\[
\Delta \Phi_p \approx \frac{B_{sh}^2}{2\mu_0 e \langle n_e \rangle} - \Delta T_e. \tag{2}
\]

After integrating (1) w.r.t. \( R \)
Energy Conversion in Two-fluid Reconnection: Ions gains energy primarily on the separatrices

![Diagram showing reconnection process with separatrices and flow lines.]  

\[ W_{ion} \sim L_i V_{in} n_e e^{\delta \Phi} \sim L_i V_{in} \frac{B_{sh}^2}{2 \mu_0} \]

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

\[ \frac{W_{ion}}{W_M} \sim \frac{1}{2} \]

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

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

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

\[
\Rightarrow \frac{W_e}{W_M} \sim \frac{L_e}{L_i}
\]

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