Gyrokinetic magnetic reconnection

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Outline

1. Introduction
2. Gyrokentic magnetic reconnection
3. Reversible magnetic reconnection
4. Summary
Magnetic reconnection is considered to be a key mechanism causing explosive conversion of magnetic energy into kinetic energy.
Magnetic reconnection

• Plasma beta is close to unity.

Magnetic field lines

Current density

A. Ishizawa, PRL, 2005
Reconnection in torus plasma: Sawtooth

- Plasma beta is much smaller than unity.

![Diagram](image1)

The contours of the helical flux function at various points during the nonlinear evolution of the semicollisional \( m = 1 \) mode, the growth rate of which is shown in Fig. 15.1

![Graph](image2)

The growth rate as a function of time for an \( m = 1 \) mode that starts in the semicollisional regime and exhibits a dramatic increase in its growth rate, becoming collisionless during its nonlinear evolution. Time and the growth rate are normalized to the poloidal Alfvén time. The arrows point to approximate points in time where the flux function and current density contours are shown in subsequent figures [source: Aydemir (1991, 1992)].

![Diagram](image3)

The current density contours for the semicollisional \( m = 1 \) mode, showing the change in the geometry of the current sheet from a flat ribbon (Y-layer) to a well-defined X-point.
Fundamental of magnetic reconnection

\[
E = -v \times B - \frac{d_e^2}{d_i} \left( \frac{\partial v_e}{\partial t} + v_e \cdot \nabla v_e \right) + \frac{d_i}{n} J \times B + \frac{d_i}{n} \nabla p_e + \frac{d_i}{n} \nabla \cdot \pi_e + \frac{1}{S} J
\]

- Reconnection electric field (electric field at the reconnection point)

\[
E = - \frac{d_e^2}{d_i} \frac{\partial v_e}{\partial t} - \frac{d_i}{n} \nabla \cdot \pi_e + \frac{1}{S} J
\]

- Electron inertia, non-diagonal part of pressure tensor, and resistivity (electron ion collision) can produce reconnection electric field.
Production of reconnection electric field

Electron momentum equation at the reconnection point

\[ E = -\frac{d_e^2}{d_i} \frac{\partial v_e}{\partial t} - \frac{d_i}{n} \nabla \cdot \pi_e + \frac{1}{S} J \]

- ① Resistive diffusion \( S^{-\alpha} \)
  - Resistive MHD
- ② Non-diagonal terms of pressure tensor \( \rho_i / L \)
  - Collisionless reconnection in beta~1 plasmas \( \rho_e / L \)
- ③ Electron inertia
  - Collisionless reconnection in beta<<1 plasmas \( d_e / L \)

Effects of turbulence are not discussed here.
Magnetic reconnection in magnetized plasmas

• In magnetic fusion and solar corona, plasmas are subjected to an ambient magnetic field.
• Electron inertia is the only mechanism of reconnection
Gyrokinetic simulations of reconnection in strongly magnetized plasmas

• Collisionless reconnection in cylinder (PIC)
  – Naitou, Phys. Plasmas 1995
    • Secondary reconnection

• Weakly collisional slab plasma (Eulerian)
  – Pueschel, Phys. Plasmas 2011
    • Recover fluid simulation results by Aydemir.
  – Numata, Phys. Plasmas 2011
    • Transition between collisional and collisionless regimes is studied.

• Collisionless slab plasma (Eulerian)
  – Ishizawa, Phys. Plasmas 2013
    • Reversible reconnection
Gyrokinetic equations

\[
\frac{\partial \delta f^g_{sk}}{\partial t} - \frac{F_{Ms}}{T_s} q_s v_{Ts} v_{//} E_{//k} + [\left( \phi - v_{Ts} v_{//} A_{//} \right) e^{-b_{sk}/2}, \delta f^g_{sk}]_k = 0
\]

\[
\lambda_{Di}^2 k_{\perp}^2 \phi_k = \sum_s \left( q_s \int dv_{//} \delta f^g_{sk} e^{-b_{sk}/2} - \tau_s [1 - \Gamma_0(b_{sk})] \phi_k \right)
\]

\[
k_{\perp}^2 A_{//k} = \beta_i \sum_s q_s v_{Ts} \int dv_{//} v_{//} \delta f^h_{sk} e^{-b_{sk}/2}
\]

Invariant for time-reversal

Gyro-center distribution function

\[
\delta f^g_{sk}(v_{//}, v_{\perp}) = \delta f^g_{sk}(v_{//}) F_{Ms}(v_{\perp})
\]

\[
E_{//k} = -\frac{\partial A_{//k}}{\partial t} e^{-b_{sk}/2} + [A_{//} e^{-b_{sk}/2}, \phi e^{-b_{sk}/2}]_k \quad [f, g]_k = -\sum_{k', k''} \delta_{k', k''} b \cdot k' \times k'' f_{k'} g_{k''}
\]

\[
\Gamma_0(b_{sk}) = \exp(-b_{sk}) I_0(b_{sk}) \quad b_{sk} = \frac{M_s}{\tau_s} k_{\perp}^2
\]

\[
v_{Ts} = \sqrt{\frac{T_s}{T_i} m_s / m_i} \quad M_s = m_s / m_i \quad \tau_s = T_s / T_e \quad F_{SM} = \frac{1}{\sqrt{2\pi}} e^{-v_{\phi}^2/2}
\]
Time forwarded reconnection
Collisionless reconnection

Magnetic field lines

Current density

Streamlines
Acceleration of reconnection with cross shaped structure

Magnetic field lines

Current density

Cross shaped structure formation

Reconnection electric field

$t \nu_{Ti}/L$
Current layer width

- Gyrokinetic beta<<1,
  
  PIC beta~1

Reversed reconnection

t -> -t

or

v -> -v
Reversed reconnection

- The collisionless reconnection process proceeds inversely leading to the initial state

Current density

- Current density is also goes back to the initial state.
ExB stream lines
Energy

- Energy of each Fourier mode goes back to the initial value.
Energy conversion

\[
\frac{d}{dt} \left( \sum_s \delta S_s^g + W_{es} + W_{es} \right) = 0
\]

\[
W_{es} = \sum_k \left( \lambda_{Dk} k^2 - \sum_s q_s^2 \tau_s [1 - \Gamma_0(b_{sk})] \right) \frac{\phi_k^2}{2}
\]

\[
W_{em} = \sum_k \frac{k^2 |A_{\parallel k}|^2}{2\beta_i} \quad \delta S_s^g = \sum_k \int d\nu_{\parallel} \frac{T_s |\delta \phi_{sk}^g|^2}{2 F_{Ms}}
\]

- During the reversed reconnection the kinetic energy is reconverted into the original magnetic field energy.
Stability of reversed reconnection with cross shaped structure

- The accelerated reconnection with cross shaped structure is reversible with the transformation of the kinetic energy to the magnetic energy, when the perturbations are small.
Time reversibility

• Aspect ratio of diffusion region is close to one.
  – Fast magnetic reconnection
  – Time reversible

• Aspect ratio of diffusion region is large.
  – Not time reversible
Summary

- Reversible magnetic reconnection is demonstrated by means of gyrokinetic simulation.
- A reversed simulation manifests that the reconnection process proceeds inversely leading to the initial state.
- A cross shaped current density causes the acceleration of magnetic reconnection.
- The cross shaped structure has up-/down-stream symmetry that allows a reversible reconnection with energy transfer from kinetic to magnetic energy.