Hinode-7 Nov 12-15, 2013, Takayama

Analysis on Mechanisms of Reconnection Rate Enhancement in 3D MHD simulation of a Current Sheet

WANG Shuoyang[1], YOKOYAMA Takaaki[1], ISOBE Hiroaki[2]

[1] The University of Tokyo, [2] Kyoto University

Abstract

The main purpose of this study is to investigate three-dimensional current sheet evolution under a guide field, initially with stochastically located diffusivity. Many solar activities, especially the impulsive eruptions, demand rapid energy conversion. Recent studies could achieve a fast magnetic reconnection if localized resistivity is applied, with assumption of uniformity on the direction perpendicular to the reconnection plane. When a time-dependent third component is added to the environment, 2-D parallel reconnection is generalized into "component reconnection".

In our simulation results, due to the periodic boundary condition, we found a quickly developing resonance netlike pattern. Small current sheets mainly reside in a thin sheet between safety factors q = 1 and q = -1 and form a zigzag chain. Outflow from one current sheet is fed into a nearby current sheet and accelerate the engine. In the later phase, the reconnection rate increases by a few times compared with Sweet-Parker model. Slow-mode shocks develop eventually on both sides of the upstream and downstream extend from individual current sheet. Thus we have achieved quicker reconnection without permanent localized resistivity in a more universal idea.

Introduction

Many models are raised to explain the tremendous energy release on the Sun. It seems that the large scale of the diffusion region and fast energy conversion rate could not be satisfied simultaneously. Moreover, the extremely small diffusivity in solar environment is another obstacle.

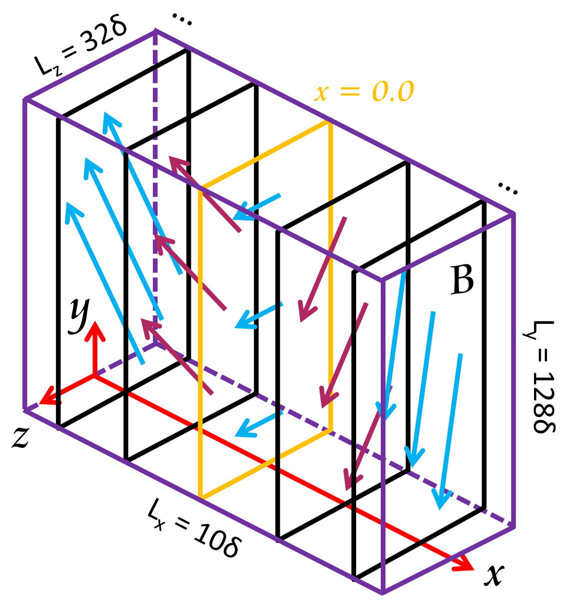
Shibata et al. (2001) considered a way to reach a faster reconnection by strengthen the inflow regardless of the resistivity. This idea is also clear in the double tearing mode which consists of two current sheets that could supply magnetic flux to each other. Enlightened by these, our goal is to find a general resistivity-independent fast reconnection from a large current sheet which is composed by a chain of small diffusion region. This work is the successive study of Yokoyama and Isobe (2010). They explore the 3D turbulent reconnection structure and found that the global reconnection rate is enhanced by the guide field. Based on their findings, we examine the physical mechanisms of this enhancement in detail and propose a "shock-evoking positive feedback model".

Simulation Model and Method

- Equations: 3D resistive MHD equations without viscosity, gravity or heat conduction;
- Simulation code: CIP-MOCCT with artificial viscosity of Lapidus form;
- Box size: $10\times128\times32$, which is normalized by the current sheet width δ;
- Grid number: $192\times1024\times252$; grid size: $\Delta x \geq 0.02$ (non-uniform), $\Delta y = 0.125$, $\Delta z \sim 0.125$;
- Boundary condition: periodic on either side;
- Time scale: normalized by Alfvén velocity, which is calculated as: $v_{A0} = \sqrt{\left(B_0^2 + B_{z0}^2\right)/4\pi\rho_0}$;
- $\beta \sim 0.2$ at initial phase outside of the current sheet; Initial density ρ_0 is uniform;
- Magnetic field set-up:

$$\vec{B} = B_y\hat{y} + B_z\hat{z} \begin{cases} B_y = B_0 \tanh\left(\dfrac{x}{0.5}\right)\left\{\dfrac{1}{2}\left[\tanh\left(\dfrac{|x|-4}{0.5}\right)-1\right]\right\} \\ B_{z0} = 0.1B_0 \ (uniform) \end{cases}$$

- Diffusivity:
  - ✓ t ≤ 1.63: random diffusivity with $0.00016 \leq \tilde{\eta} \leq 0.00048$
  - ✓ t > 1.63: uniform diffusivity with $\tilde{\eta} = 0.00032$



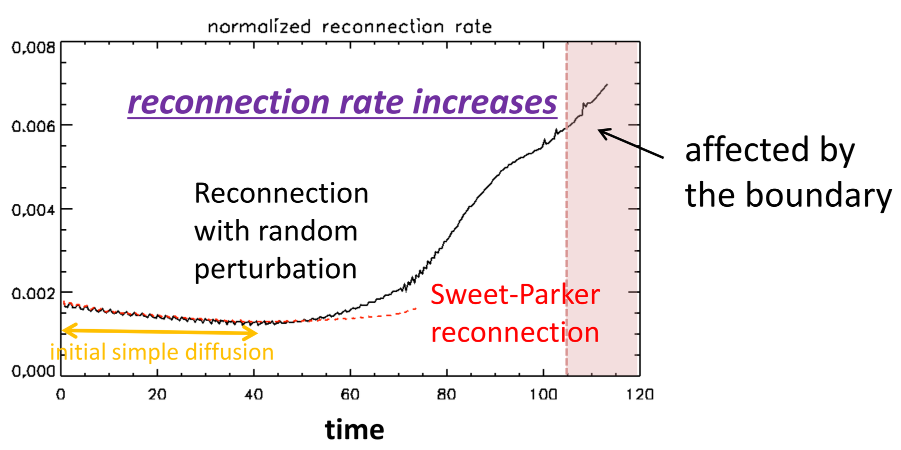
Result

- Reconnection rate:

Reconnection rate is calculated through:

$$rate = \left|\frac{dE_m}{dt}\right| \Big/ \left(2S\frac{B^2}{4\pi}v_{A0}\right)$$

E_m: total magnetic energy in box
S: surface on Z-Y plane
B: $B = \sqrt{B_0^2 + B_{z0}^2}$

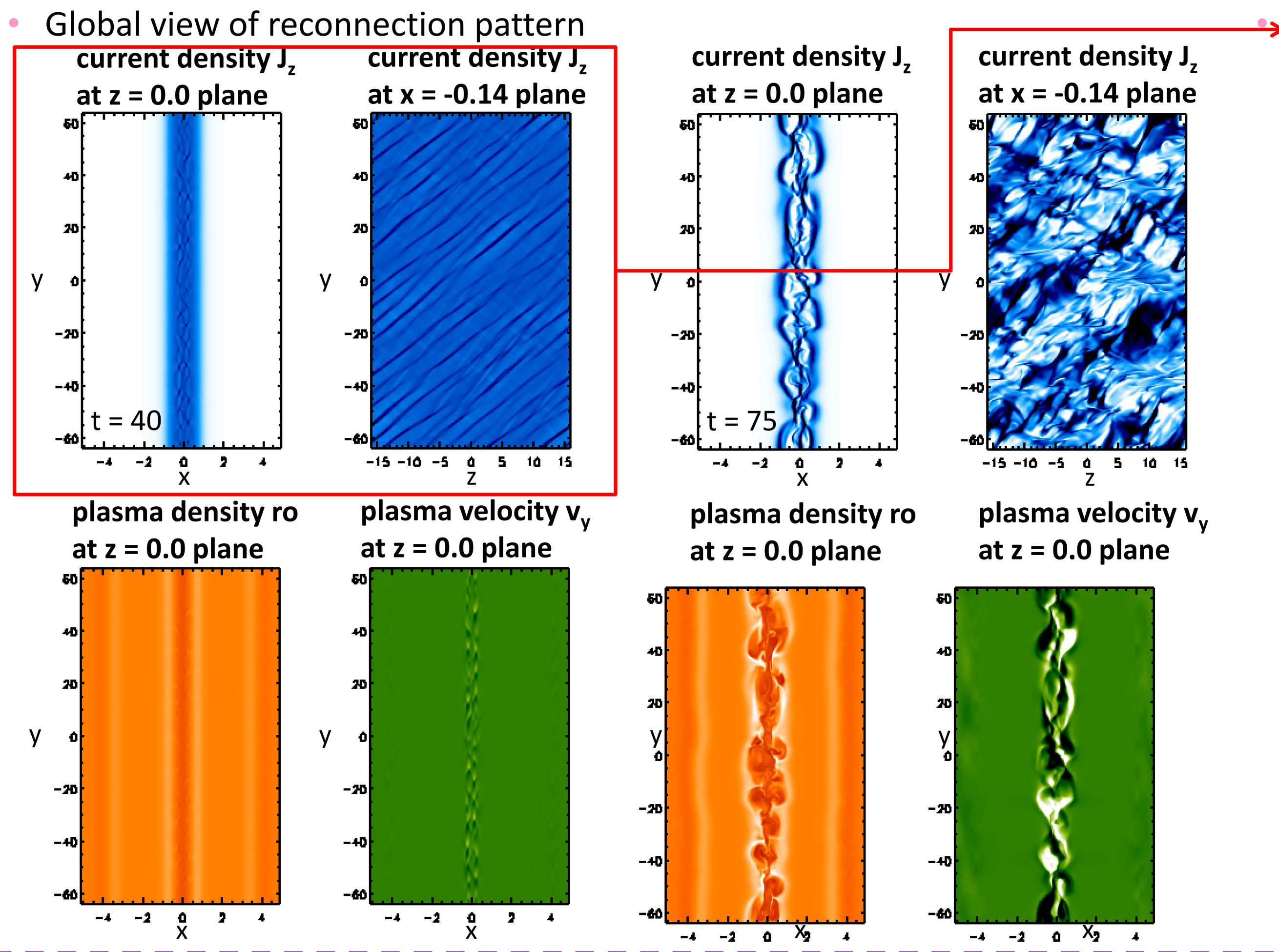


The global Reynolds number could be estimated as:

$R_m = \dfrac{v_A L_y}{2\tilde{\eta}} \approx 2\times10^5 > 10^4$, L_y is the box size on y-direction

Apply this to the Sweet-Parker model, we get reconnection rate is ~ 0.002, which coincides with the simulation.

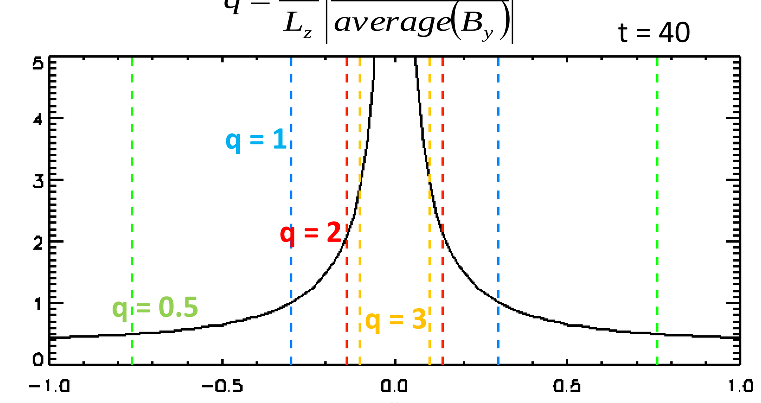
- Global view of reconnection pattern



Resonance pattern

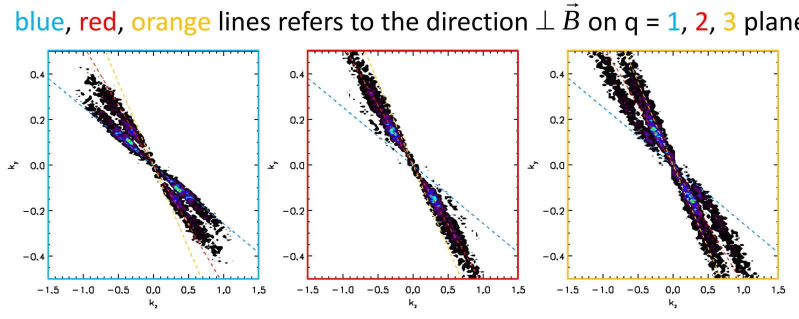
The pattern could be explained with safety factor q:

$$q = \frac{L_y}{L_z}\left|\frac{average(B_z)}{average(B_y)}\right|$$



Fourier Transformation of q = 1, 2, 3 plane

blue, red, orange lines refers to the direction ⊥ $\vec{B}$ on q = 1, 2, 3 plane

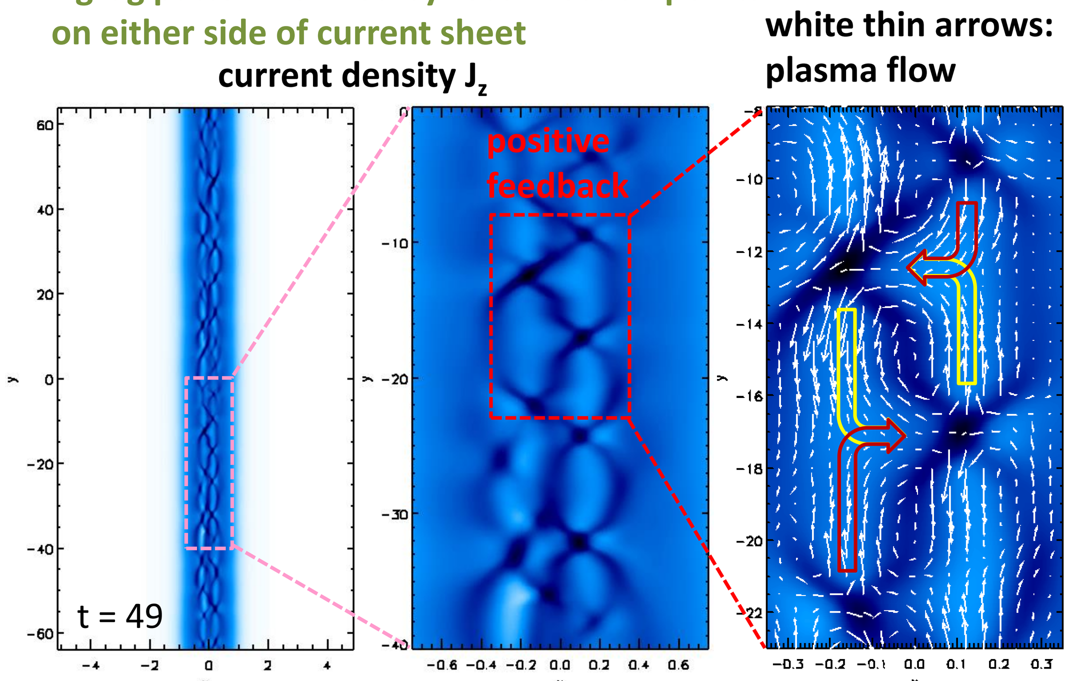


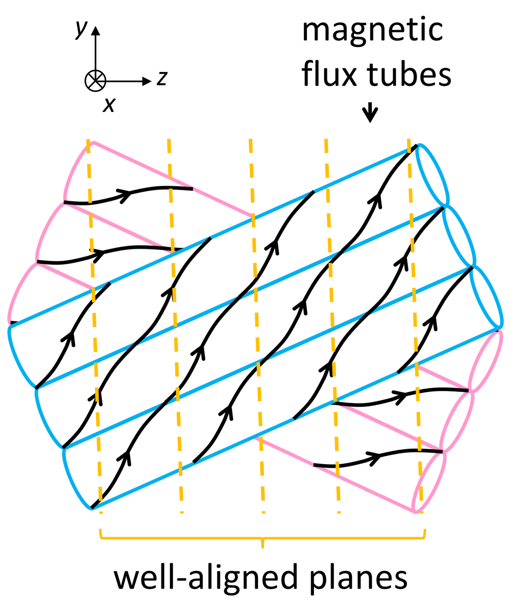
q = 2 is the strongest mode and penetrates into every layer.

Discussion

- Why the reconnection rate increases in "turbulent" case? → "shock-evoking positive feedback model"
  - ✓ Positive feedback of the flow and magnetic flux

zigzag pattern formed by reconnection points on either side of current sheet





Obviously, the structure has less efficiency than double-tearing mode.

- How to explain the current sheet organization? We believe it is due to the **tearing mode.**

The tearing mode time scale is calculated through: $\tau_{tearing} = \sqrt{\tau_A \tau_\eta} \approx 56$ while diffusion time is ~ 3100. In our model, the initial diffusion time is ~ 40. Afterwards, the tearing mode dominates.

Variables show a nicely organized diagonal pattern on Z-Y plane. Intervals between adjacent lines should be the wavelength of the tearing mode. We make the Fourier transformation of this structure and calculate the averaged wavelength in the manner of:

$$\bar{k} = \frac{\sum I(k_z,k_y)\sqrt{k_z^2 + k_y^2}}{\sum I(k_z,k_y)}$$

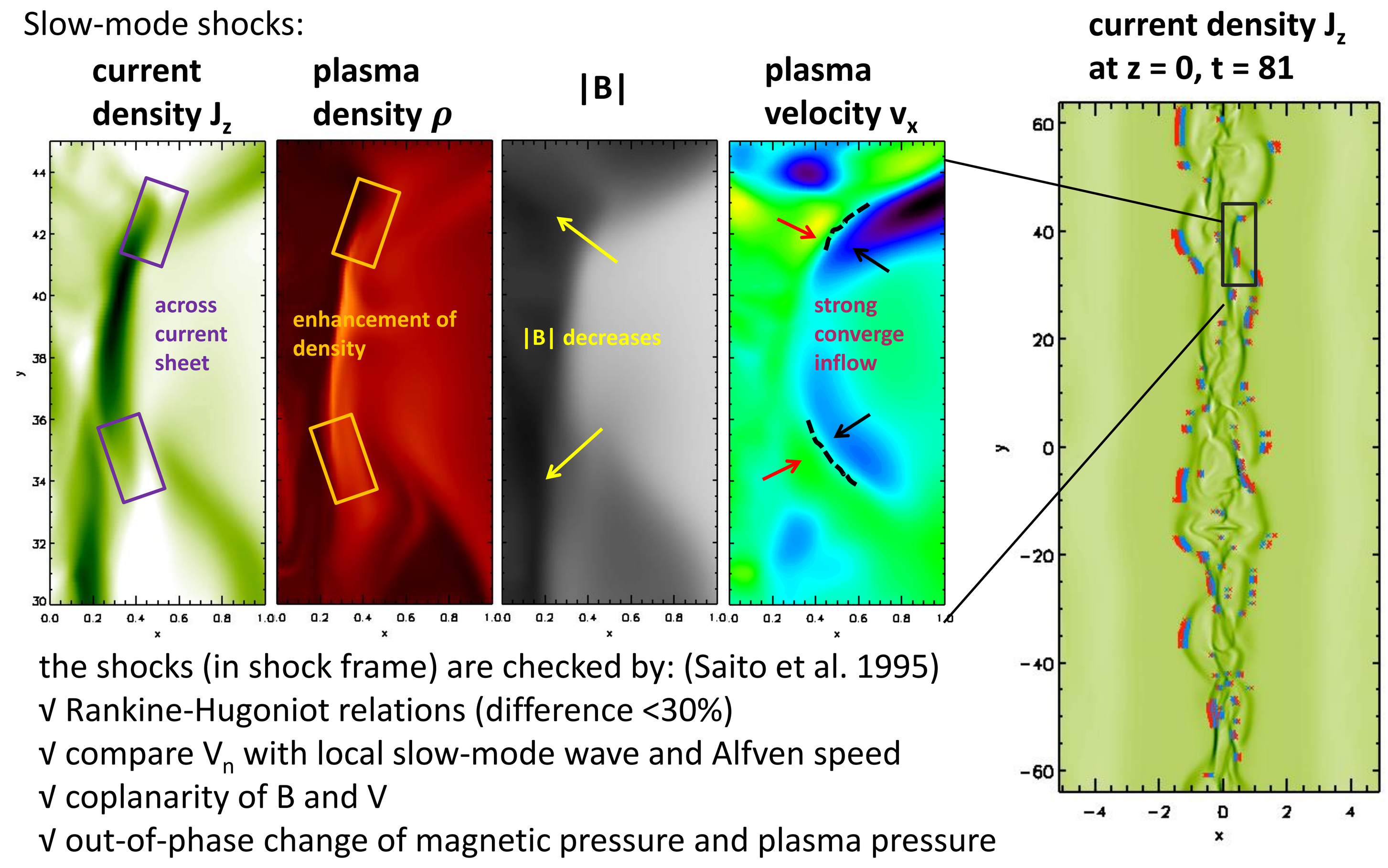
, where $I(k_z,k_y)$ is the signal intensity at each point in phase space (k_z,k_y)

We calculate the pattern in q = 2 plane at t = 30 when the pattern is already well presented. The obtained wavelength is 2.5. According to Furth et al. (1963), the tearing mode wavelength could be calculated via:

$$R_{mt} = \frac{v_A(\delta/2)}{\tilde{\eta}} \approx 1545, \quad \lambda_c \sim 0.65\times2\pi\times\delta R_{mt}^{\frac{1}{4}} = 13$$

Our wavenumber is consistent with the theoretical one by a factor of 5. As time goes by, diverging inflow is strengthened by "positive feedback" mechanism and extends the current sheets length. The global structure gets sparse and distorted due to the vertical interactions, then finally becomes chaotic.

- ✓ Slow-mode shocks:



the shocks (in shock frame) are checked by: (Saito et al. 1995)

√ Rankine-Hugoniot relations (difference <30%)
√ compare V_n with local slow-mode wave and Alfven speed
√ coplanarity of B and V
√ out-of-phase change of magnetic pressure and plasma pressure

Red crosses in the upper right panel represent upstream of slow-mode shocks while the blue crosses are downstream. These slow-mode shocks are induces by inflows which are enhanced due to positive feedback mechanisms thus further converts the magnetic energy into thermal and kinetic energy.

- Compare with the real Sun

We calculate the averaged global inflow outside the current sheet at x = 2.0 and x = -2.0 and the corresponding reconnection rate is: $v_{in}/v_A \approx 0.0035$. According to Yokoyama et al. (2001), the detected reconnection rate in corona is about M_A = 0.001~0.03. So our relative fast model without local enhanced resistivity is applicable in the solar environment.

Since we have only one model until now, whether the reconnection rate would change with increasing Reynolds number is still unclear. In various study of 2D reconnection (e.g. Loureiro et al. 2012), the reconnection rate becomes independent of Reynolds number when $R_m > 10^4$. Our fast reconnection rate is basically determined by the current sheet structure which comes from the tearing mode. Then the inflow pattern dominates. In other words, the reset of the box size, current sheet width etc. might change the reconnection rate other than the resistivity.

Summary and Future Work

- Reconnection points with "zigzag" layout can help each other and form a positive feedback thus accelerate the reconnection rate;
- In the later phase, enhancement of inflow will gradually compress the gas and shock appears. As a result, the energy transverse is more effective due to the heating mechanism of the slow shocks;
- We need more parameter surveys to investigate more of this model. For example, magnetic θ, resistivity, magnitude of B_z component;
- q = 2 mode seems to be dominant in the whole structure thus it is the mode with largest growth rate. Analytic exploration is needed.

References: Shibata et al. 2001, EPS, **53**, 473-482; Saito et al. 1995, JGR, VOL. 100, No. A12, 23,567-23,581; Furth et al. 1963, Phys. Fluids **6**, 459; Yokoyama et al. 2001, APJ, 546: L69-L72; Loureiro et al. 2012, Phys. Plasmas **19**, 042303