Dependence of Reconnection Rate and Energy Conversion on the Initial Current Sheet Thickness

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1. Abstract

Magnetic reconnection is an explosive phenomenon occurring in the space environment, where the magnetic topology is altered and the energy is converted to the plasma. It can account for certain physical processes involved with rapid and massive energy transfer, such as the ones in solar flares and substorm. The term, ***Reconnection Rate***, is adopted to quantitively estimate the evolution progress of the reconnection. A higher reconnection rate corresponds to a faster reconnection as well as the energy conversion burst. ***The reconnection rate is sensitive to current sheet configurations and plasma properties, such as the current sheet thickness***. In this study, we attempt to uncover this relevance by performing theoretical analysis and a series of particle-in-cell (PIC) simulations. Particularly, we focus on the peak reconnection rate as it can reflect the maximum energy conversion rate during the reconnection process. Two types of scaling laws of peak reconnection rate with the current sheet thickness are found, when this thickness increases from the electron-scale to the ion-scale.

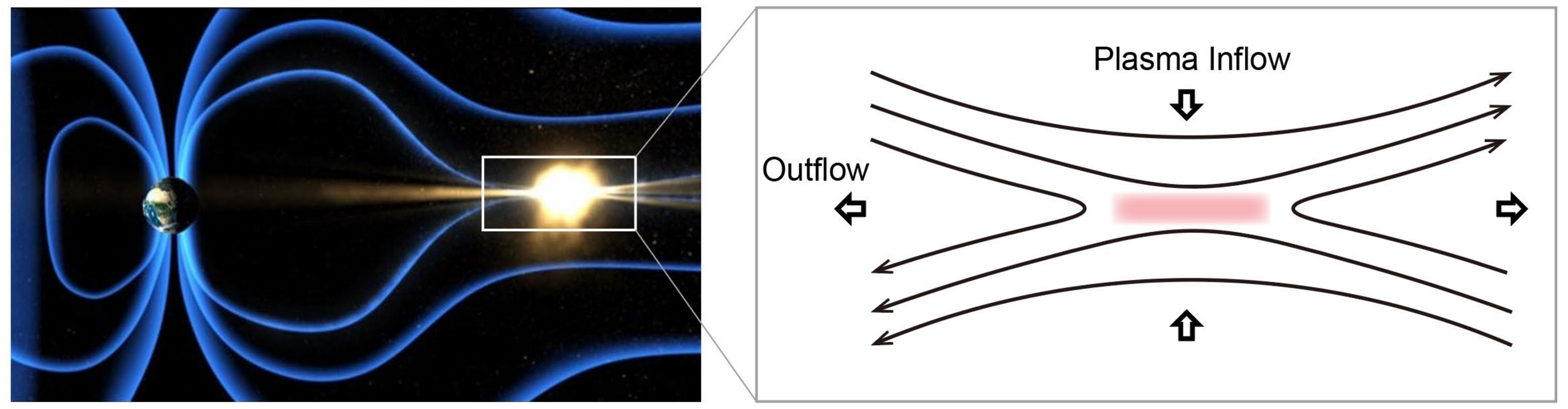

Figure 1. Sketch of magnetic reconnection in terrestrial magnetotail and its physical model.

2. PIC Simulation Setup

Harris Model:

$B_x(z) = B_0\, tanh(z/\delta)$

$n(z) = n_0\, sech^2(z/\delta) + n_b$

Run Number	$\delta\ [d_i]$
1	0.05
2	0.10
3	0.20
4	0.50
5	0.80

Other Parameters:

Grids: 1024×4096

Particle-per-Cell: 400

Mass ratio: $m_i/m_e = 400$

Ion Inertial Length: $d_i = 100$

Temperature Ratio: $T_i/T_e = 4$

Frequency Ratio: $\omega_{pe}/\omega_{ce} = 3$

Guide Field: $B_g = 0$

Background Particle: $n_b/n_0 = 0.2$

3. Results Overview

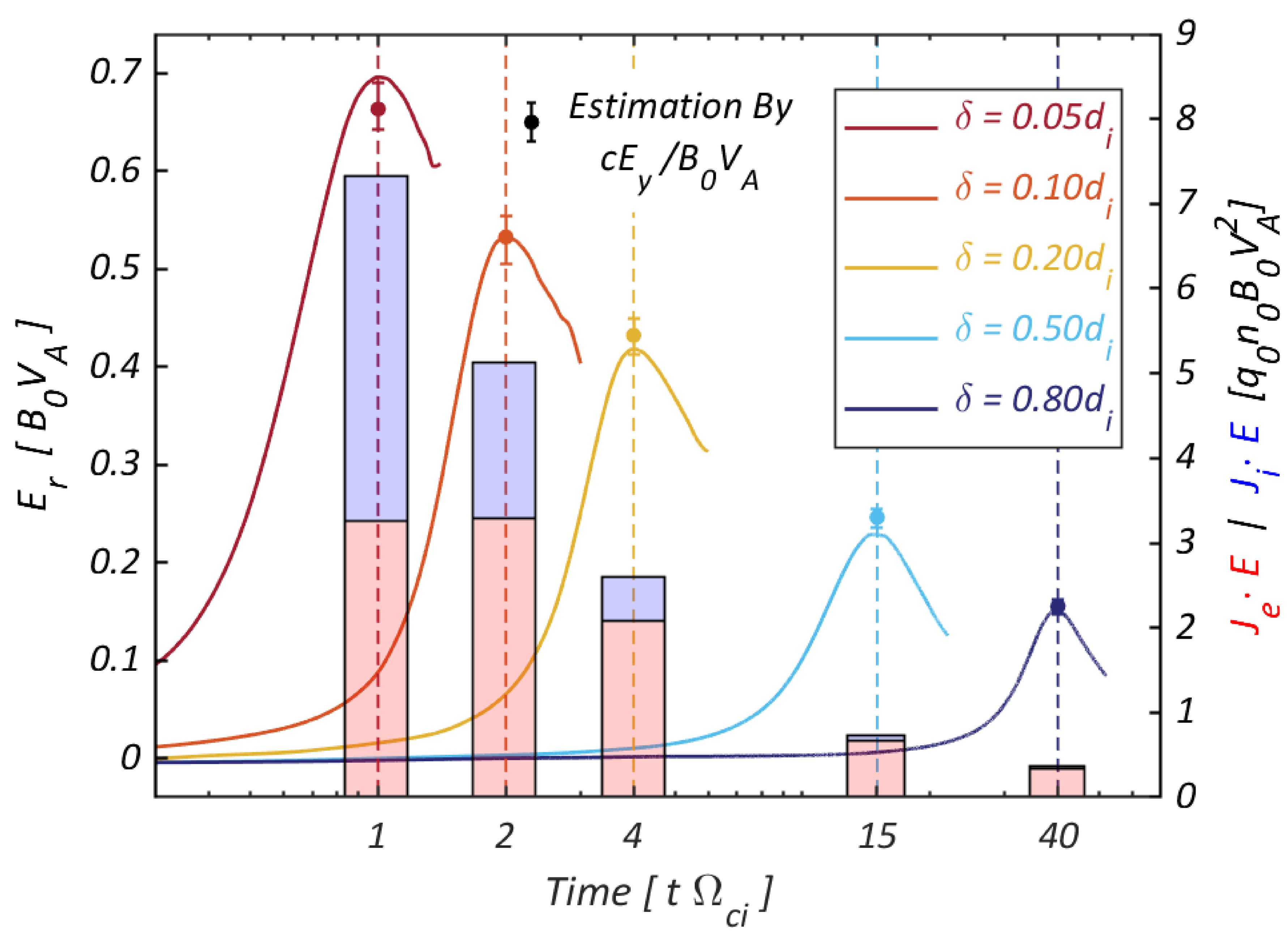

Figure 2. Colored Curvatures belong to the left axis, and they represent the normalized reconnection rates varying with time in different runs. The colored dots with error bar are the reconnection electric field around reconnection site. The vertical dashed lines mark the time of peak reconnection rate in each run. The red and blue histograms represent the energy conversion rate of electrons and ions around the reconnection site, and they belong to the right axis.

4. Modeling Peak Reconnection Rate

Eigenmode Equation of Magnetic Potential Vector:

$$\nabla^2 A_y + \frac{2}{\delta^2}\mathrm{sech}^2\left(\frac{z}{\delta}\right)A_y = -\frac{4\pi}{c}j_y^n \longleftarrow \boxed{\nabla \times \boldsymbol{A} = \boldsymbol{B} \qquad \nabla \times \boldsymbol{B} = \frac{4\pi}{c}\boldsymbol{J} \qquad \nabla^2 A_y = -\frac{4\pi}{c}J_y}$$

$$\frac{d^2A_y}{dz^2} + \left[-(k_x)^2 + \frac{2}{\delta^2}\mathrm{sech}^2\left(\frac{z}{\delta}\right)\right]A_y = -\frac{4\pi}{c}j_y^n$$

Conditions of Current Sheet (Fastest Growing Mode): $E_R = cE_y^{peak} \propto \gamma^f/k_x^f$

Thin Current Sheet:
$$\frac{d^2A_y}{dz^2} + \left[-\left(k_x^f\right)^2 + \frac{2}{\delta^2}\mathrm{sech}^2\left(\frac{z}{\delta}\right)\right]A_y = \frac{\omega_{pe}^2\sqrt{\pi}\gamma^f}{c^2k_x^f v_{th,e}}A_y \qquad \left(j_y^n = f(\gamma^f)\right)$$

Thick Current Sheet:
$$\frac{d^2A_y}{dz^2} + \left[-\left(k_x^f\right)^2 + \frac{2}{\delta^2}\mathrm{sech}^2\left(\frac{z}{\delta}\right)\right]A_y = -\frac{\omega_{pe}^2\sqrt{\pi}}{c^2}A_y \qquad \left(j_y^n \Rightarrow CA_y\right)$$

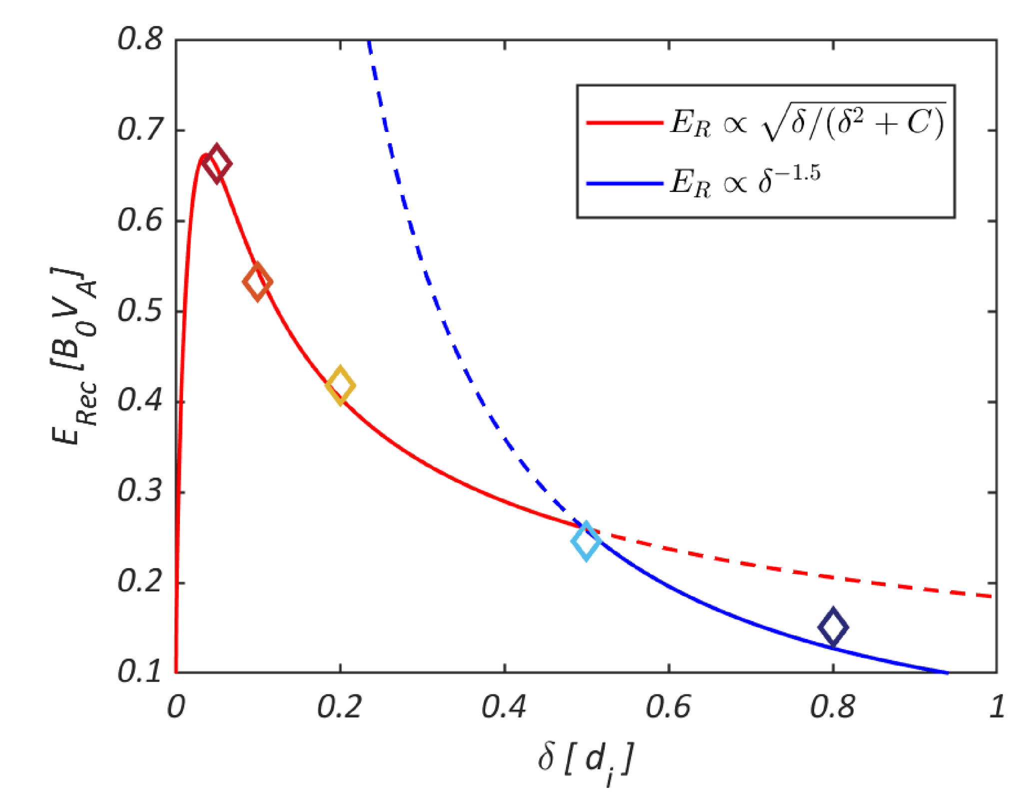

Figure 3. Colored diamonds represent peak reconnection rates in different runs. The magenta and cyan curves are the model results for thin and thick current sheets.

Thin Current Sheet:

$E_R \propto \gamma^f \propto \sqrt{\delta/(C+\delta^2)}$

Thick Current Sheet:

$E_R \propto \gamma^f \propto \delta^{-1.5}$

5. Energy Conversion Contribution

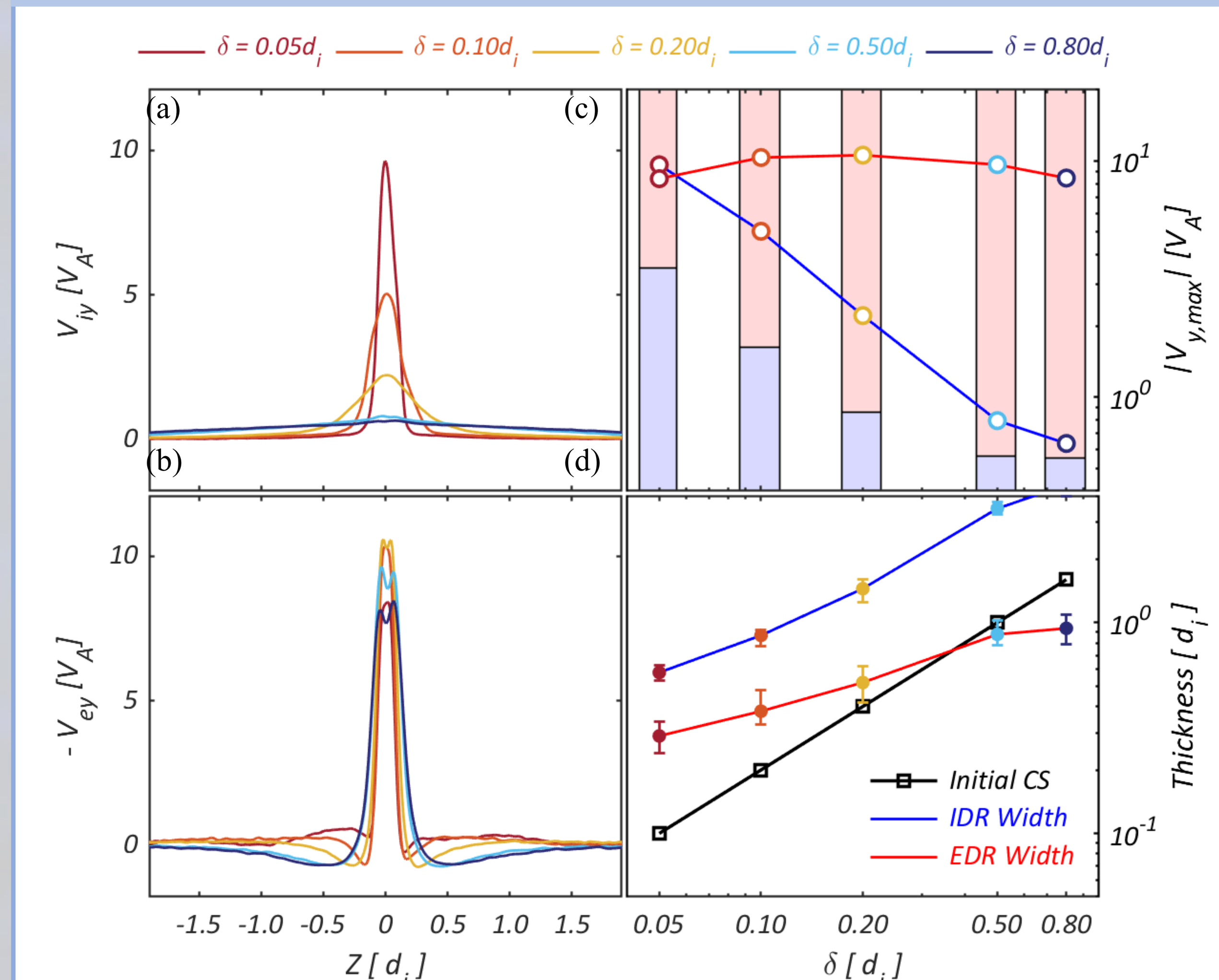

Figure 4.
(a-b) 1D cuts of ion and electron Y component bulk velocity at the time of peak reconnection rate in each run. The cuts are along Z direction across the current sheet .
(c) Red and blue lines: Absolute value of maximum Vy obtained from (a) and (b). The histograms are the energy conversion rate contribution percentage of each species. The red bar represents the electron and the blue one represents the ion.
(d) Current sheet thickness (black line), IDR width (blue line), and EDR width (red line) at the time of peak reconnection rate.

6. Conclusions

- The reconnection rate highly depends on the current sheet thickness, and the peak reconnection rate follows two scaling laws for the thin and thick current sheet.
- The energy conversion rate around reconnection site also depends on the current sheet thickness. As the thickness grows, the contribution from the ions significantly decreases. The Harris model maybe the fundamental reason accounting for this phenomenon.

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