The role of the Weibel instability in $e^- - e^+$ reconnection

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Kinetic Modeling of Astrophysical Plasmas
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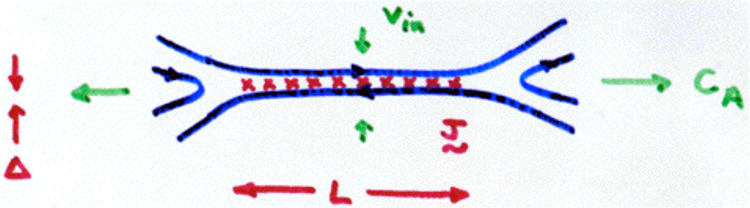
Summary

- Pair reconnection is fast, $v_{\text{in}} \sim \mathcal{O}(0.1)v_A$. The Hall term is sufficient, but not necessary, for fast reconnection,



- The Weibel instability, feeding on the temperature anisotropy in the reconnection outflow, keeps reconnection fast.

Generalized Ohm's Law

Rewrite the fluid momenta equations:

$$\begin{aligned}(1+\mu)\,\mathbf{E} = &- \frac{1+\mu}{c}\mathbf{v}\times\mathbf{B}\\ &+ \frac{1-\mu}{nec}\mathbf{J}\times\mathbf{B}\\ &- \frac{1}{ne}\,\nabla\cdot\left(\mathrm{P}_e-\mu\mathrm{P}_i\right)\\ &+ \frac{m_e}{ne^2}\left[\frac{\partial\mathbf{J}}{\partial t}+\nabla\cdot\left(\mathbf{Jv}+\mathbf{vJ}-\frac{1}{ne}\frac{1-\mu}{1+\mu}\mathbf{JJ}\right)\right]\end{aligned}$$

- $\mu = m_e/m_i$
- $\mathbf{v} = (m_e\mathbf{v_e}+m_i\mathbf{v_i})/(m_e+m_i)$
- P is the pressure tensor
- $n_i = n_e = n$, $q_i = -q_e = 1$

Generalized Ohm's Law in Pair Plasmas

In pair plasmas $\mu = 1$:

$$\begin{aligned}\mathbf{E} = &-\frac{1}{c}\mathbf{v}\times\mathbf{B}\\ &-\frac{1}{2ne}\,\nabla\cdot(\mathrm{P}_e-\mathrm{P}_i)\\ &+\frac{m_e}{2ne^2}\left[\frac{\partial\mathbf{J}}{\partial t}+\nabla\cdot(\mathbf{J}\mathbf{v}+\mathbf{v}\mathbf{J})\right]\end{aligned}$$

- Mass symmetry eliminates the Hall term
- Also removes the usual dispersive modes such as the whistler and kinetic Alfvén waves.
- Does fast reconnection then occur?

PIC Simulations

- Large 2.5D kinetic simulations
  - 800 × 200 inertial lengths
  - 1000 ω_{ce}^{-1}
  - 1000+ processors
- But ... astrophysically small
  - Length: Inertial length

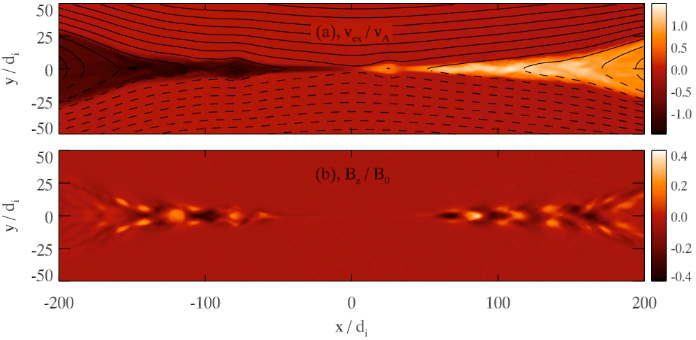
$$\frac{c}{\omega_p} = 5 \left(\frac{1\ \mathrm{cm}^{-3}}{n} \right)^{0.5} \ \mathrm{km}$$

  - Time: Inverse cyclotron frequency

$$\omega_c^{-1} = 0.06 \left(\frac{1 \mu\mathrm{G}}{B} \right) \ \mathrm{s}$$

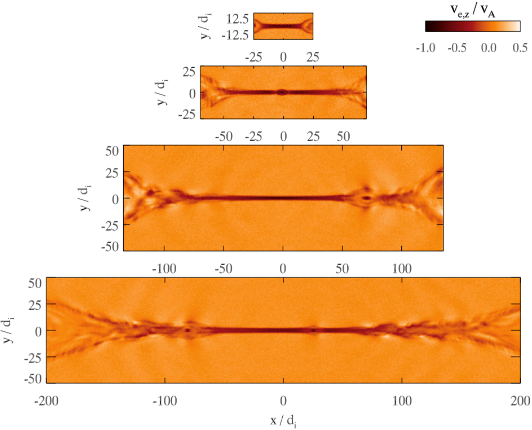
- Non-relativistic: $c/v_A = 5$

Pair Reconnection Synopsis



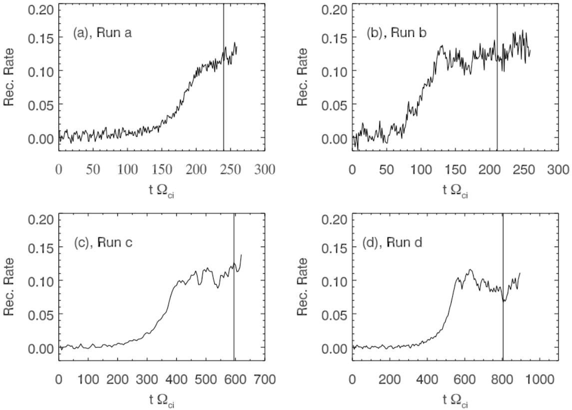
- Top: v_{ex} overplotted with magnetic field lines. Solid & dashed lines indicate opposite signs of reconnecting field.
- Bottom: Out-of-plane B. Note the lack of a quadrupole.

Current Layer Comparison



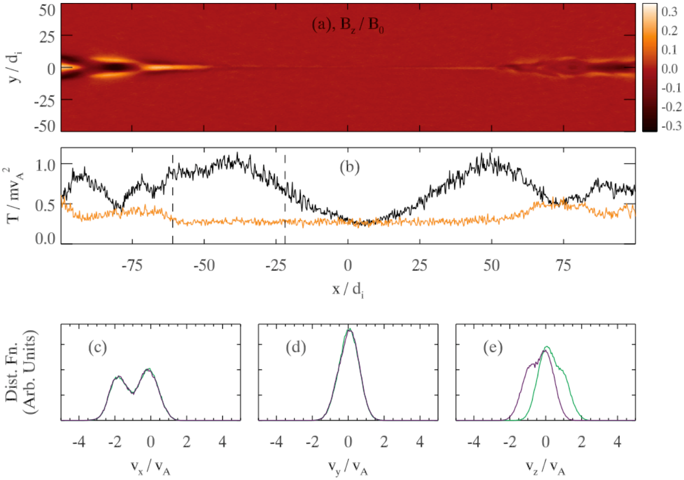
- Out-of-plane electron velocities.
- Top panels: System-size current layers.
- Bottom panels: Current layer length about constant.
- Instability development stops growth.

Reconnection Rate



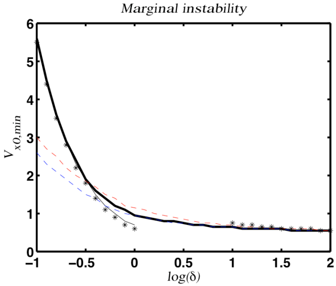
- Minimal variation with box size.
- In general: rate $\equiv v_{\text{in}}/v_{\text{out}} = (\Delta/L)(n_{\text{out}}/n_{\text{in}})$.

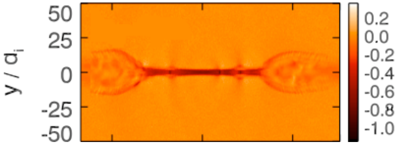
Why Weibel?



- Top: Out-of-plane *B*. Middle: Positron T_{xx} and T_{yy}.
- Bottom: Distributions. Electrons are green, positrons blue.

Extensions and Implications

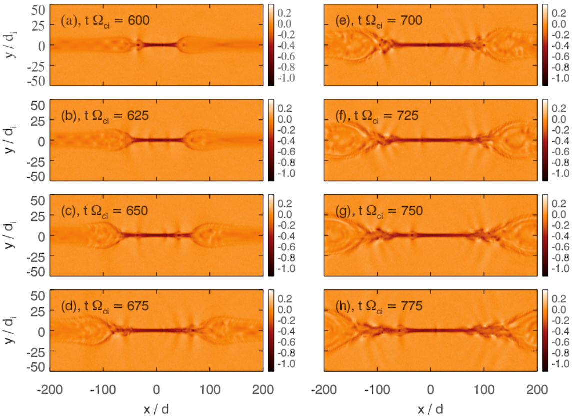




- Top: Marginal instability of Weibel within a current layer.
- Bottom: Weibel in a 1600 × 400 box with B_z suppressed. Longer current layer, lower reconnection rate.

Role of Secondary Islands

Alternate theory of fast pair reconnection.



- v_{ez} at $\delta t = 25$ beginning at $t = 600$ for run d.
- Secondary islands remain modestly sized and convect downstream. They have little effect on the overall structure of the current layer.

Summary

- Pair reconnection is fast, $v_{\text{in}} \sim \mathcal{O}(0.1)v_A$. The Hall term is sufficient, but not necessary, for fast reconnection,
- For small systems ($\lesssim 200d_i$) the current layer is system size. For larger systems the Weibel instability keeps the layer short.
- Open questions: Why should the reconnection rate be 0.1 across multiple systems? Would suppression of this instability lead to slow pair reconnection?
- See Swisdak, Liu, and Drake, *ApJ*, 680, 2, 999, 2008.

Simulations

Table: Simulation parameters.

Run Label	Domain Size	Gridpoints
a	100×50	512×256
b	200×100	1024×512
c	400×200	2048×1024
d	800×200	4096×1024

Table: Parameters during steady reconnection.

Run Label	n_{in}	n_{out}	2δ	2Δ	v_{out}	$v_{\mathrm{in,meas}}$	$v_{\mathrm{in,calc}}$
a	0.16	0.27	4.0	35	0.5	0.13	0.10
b	0.12	0.32	4.0	80	0.8	0.15	0.11
c	0.13	0.33	4.5	120	1.3	0.16	0.12
d	0.13	0.30	5.0	135	1.3	0.13	0.11