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

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Kinetic Modeling of Astrophysical Plasmas
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Pair reconnection is fast, $v_{in} \sim O(0.1)v_A$. 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:

\[(1 + \mu) \mathbf{E} = -\frac{1 + \mu}{c} \mathbf{v} \times \mathbf{B} \]
\[+ \frac{1 - \mu}{ne} \mathbf{J} \times \mathbf{B} \]
\[- \frac{1}{ne} \nabla \cdot (P_e - \mu P_i) \]
\[+ \frac{m_e}{ne^2} \left[ \frac{\partial \mathbf{J}}{\partial t} + \nabla \cdot \left( \mathbf{J} \mathbf{v} + \mathbf{v} \mathbf{J} - \frac{1}{ne} \frac{1 - \mu}{1 + \mu} \mathbf{J} \mathbf{J} \right) \right] \]

- \( \mu = \frac{m_e}{m_i} \)
- \( \mathbf{v} = \frac{(m_e \mathbf{v}_e + m_i \mathbf{v}_i)}{(m_e + m_i)} \)
- \( P \) is the pressure tensor
- \( n_i = n_e = n, q_i = -q_e = 1 \)
In pair plasmas $\mu = 1$:

$$
E = - \frac{1}{c} \mathbf{v} \times \mathbf{B} \\
- \frac{1}{2ne} \nabla \cdot (P_e - P_i) \\
+ \frac{m_e}{2ne^2} \left( \frac{\partial \mathbf{J}}{\partial t} + \nabla \cdot (\mathbf{Jv} + \mathbf{vJ}) \right)
$$

- 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?**
Large 2.5D kinetic simulations
- 800 × 200 inertial lengths
- $1000 \omega_{ce}^{-1}$
- 1000+ processors

But ... astrophysically small
- Length: Inertial length
  \[ \frac{c}{\omega_p} = 5 \left( \frac{1 \text{ cm}^{-3}}{n} \right)^{0.5} \text{ km} \]

- Time: Inverse cyclotron frequency
  \[ \omega_c^{-1} = 0.06 \left( \frac{1 \mu \text{G}}{B} \right) \text{ s} \]

Non-relativistic: $c/v_A = 5$
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.
Minimal variation with box size.

In general: rate $\equiv \nu_{\text{in}}/\nu_{\text{out}} = (\Delta/L)(n_{\text{out}}/n_{\text{in}})$. 

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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 $1600 \times 400$ 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.
Pair reconnection is fast, $\nu_{in} \sim \mathcal{O}(0.1)\nu_A$. 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?

### Table: Simulation parameters.

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<thead>
<tr>
<th>Run Label</th>
<th>Domain Size</th>
<th>Gridpoints</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>100 × 50</td>
<td>512 × 256</td>
</tr>
<tr>
<td>b</td>
<td>200 × 100</td>
<td>1024 × 512</td>
</tr>
<tr>
<td>c</td>
<td>400 × 200</td>
<td>2048 × 1024</td>
</tr>
<tr>
<td>d</td>
<td>800 × 200</td>
<td>4096 × 1024</td>
</tr>
</tbody>
</table>

### Table: Parameters during steady reconnection.

<table>
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<tr>
<th>Run Label</th>
<th>$n_{in}$</th>
<th>$n_{out}$</th>
<th>$2\delta$</th>
<th>$2\Delta$</th>
<th>$v_{out}$</th>
<th>$v_{in,meas}$</th>
<th>$v_{in,calc}$</th>
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<td>4.0</td>
<td>35</td>
<td>0.5</td>
<td>0.13</td>
<td>0.10</td>
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<tr>
<td>b</td>
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<td>0.32</td>
<td>4.0</td>
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<td>0.15</td>
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<tr>
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<td>1.3</td>
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<td>0.12</td>
</tr>
<tr>
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<td>0.30</td>
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<td>135</td>
<td>1.3</td>
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<td>0.11</td>
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