Magnetic Reconnection in laser-driven HEDP: recent experiments & hybrid simulations

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Magnetic reconnection in Accretion Disk

Thin current sheets perpendicular to the accretion disk:

⇒ Magnetic reconnection could produce Relativistic Jet
Magnetic reconnection in Planetary Magnetospheres

The location of thin current sheets depend on the IMF direction:

⇒ Could be responsible of Aurora (also seen on Jupiter)
Laser beam impinging a solid target

Because of the gradient geometries, \( \partial_t \mathbf{B} = -\frac{1}{n^2} \nabla n \times \nabla T_e + \ldots \)

⇒ A Magnetic field is generated by Biermann-Battery effect
## Comparison of dimensionless parameters (MKSA)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>HEDP</th>
<th>MØ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field</td>
<td>$B_0$</td>
<td>$6 \times 10^{-8}$</td>
</tr>
<tr>
<td>density</td>
<td>$n_0$</td>
<td>$5 \times 10^7$</td>
</tr>
<tr>
<td>Proton Temperature (eV)</td>
<td>$T_p$</td>
<td>200</td>
</tr>
<tr>
<td>Resistivity (Spitzer)</td>
<td>$\eta$</td>
<td>0</td>
</tr>
<tr>
<td>Lundqvist Numb.</td>
<td>$S$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>Beta parameter</td>
<td>$\beta$</td>
<td>1</td>
</tr>
<tr>
<td>Proton cyclotron freq.</td>
<td>$\Omega_p$</td>
<td>$1.7 \times 10^9$</td>
</tr>
<tr>
<td>Proton skin depth</td>
<td>$d_p$</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>Alfvén speed</td>
<td>$V_A$</td>
<td>$2 \times 10^4$</td>
</tr>
<tr>
<td>Sound speed</td>
<td>$C_s$</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>Protonon thermal speed</td>
<td>$V_{th}$</td>
<td>$2 \times 10^5$</td>
</tr>
</tbody>
</table>
Beta value from FCI2

at 1.5 ns

→ Strongly depends on where we are!
Hybrid simulations

Can hybrid code handle magnetic reconnection in HEDP?

Physical hypotheses:

- Quasi-neutrality: \( n_e \sim n_i \) (but \( \nabla \cdot \mathbf{E} \neq 0 \))
- Electrons mobility \( \rightarrow \infty \): \( \mathbf{V}_e \) is such as \( \mathbf{J} = n_e(\mathbf{V}_i - \mathbf{V}_e) = \nabla \times \mathbf{B} \)
- Closure equation for electrons: isotherm or adiabatic
- Neglect transverse component of displacement current
- Hence, needs an Ohm's law:

\[
\mathbf{E} = -\mathbf{V} \times \mathbf{B} + N^{-1}(\mathbf{J} \times \mathbf{B} - \nabla \cdot \mathbf{P}_e) + \eta \mathbf{J} - \eta' \Delta \mathbf{J}
\]

\( \Rightarrow \) Can solve \( kd_i \lesssim 1, \omega/\Omega_i \gg 1 \), but no electron scales (neither spatial, nor temporal), and no plasma frequencies. Well suited if \( \omega_P/\Omega \gg 1 \) (1000 in the solar wind).
What is needed for reconnection?

To trigger a reconnecting instability, one needs an electric field such as $\nabla \times E_\parallel \neq 0$

$\Rightarrow$ If we are not interested in the onset (at electron scales), small (numerical) resistivity or hyperviscosity can do the job.

For collisionless & $\beta \sim 1$ plasmas, GEM challenge (Birn et al., JGR 2001) showed that when the Hall effect is considered, the reconnection rate does not depend on the formalism.

$\Rightarrow$ What about HEDP?

Nernst and Righi-Leduc effects are not considered (see eg Joglekar et al., PRL 2014)... neither non-locality. Collisions will soon be included.
Initial profiles

Initial set up, very close to Fox et al., PRL 2011:

⇒ 2 bubbles plus a background to avoid vacuum problems:

- Can handle asymmetries on $B$, $n$, $V$, $T$...
- Can handle non-coplanar configurations: set a given angle of rotation around the 2 directions of the target plane.

⇒ Plus few cautions to get $\nabla \cdot B = 0$ and periodic boundary conditions.
Initial profiles

2D simulations, but manage the out-of-plane dynamics:
Coplannar reconnection

- Hall $E_{XY}$ electric field associated to $J_Z$ just out of each shell → If purely radial, no associated $B_Z$  
- $J_Z$ grows at the tip of each shells when colliding → quadrupolar $B_Z$ grows because $E_{XY}$ is no more curl-free  
- $J_{XY}$ is associated to this out-of-plane magnetic field → Carried by electrons (protons are demagnetized)
Coplanar Hybrid simulation
Non-Coplanar Hybrid simulation : t=0
Non-Coplanar Hybrid simulation: \( t=16 \)
Reconnected flux

- $B_Z$ develops prior the reconnection onset ($t=16$)
- Same reconnection rate at each loci (slope of $A_Z$)
- Time lag between the 2 onsets of reconnection
The slope of the reconnected flux is the reconnection rate: 

\[ E_Z = -\partial_t A_Z \]

Reach the “holly” value of 0.16... 

→ The outflow speed is around 0.2 times the (upstream) Alfvén speed
Out-of-plane quadrupolar Magnetic Field

Sometime also called the “Hall” magnetic field

- Its value clearly increases prior the reconnection onset → Can not be a consequence of the reconnection process
- Double hump structure like the one of the $E_Z$ component → Close connection between these two components?
On the origin of the time lag $\Delta T$

- $\Delta T$ increases with $\Psi$ & constant reconnection rate → The larger the “anti-Hall”, the longer to remove it
- For $\Psi > 16^\circ$, $\Delta T$ is meaningless & reconnection rate decreases → Just because the initial squeeze is to small
Reconnected flux for $\Psi = 24^\circ$

The reconnected rate is clearly decreasing for larger $\Psi$ angles:

$\Rightarrow$ The initial “anti-Hall” magnetic field drives an electric field reverse to the reconnection one.
On the relation between $E_Z$ and $B_Z$

*Smets et al., PoP 2014*

Clear correlation between the Hall magnetic field and the reconnection rate

The organic link being the in-plane current associated to $B_Z$ that drives the reconnection rate
Principle of measurements of magnetic reconnection

blue: short-pulse intense laser for proton radiography

green: high power laser beam to create $B$ field on target surface
Experimental results from GSI

GSI: 2 beams with 25 J & 1.8 ns each

→ Limited by the beam duration which did not allow to maintain long enough $B$ fields
Experimental results from LULI2000

LULI2000 : 2 beams with 200 J & 4.0 ns each - Plane targets

→ The 2 magnetic shells get compressed and get flat

→ On the reconnection sheet, protons are weakly scattered
Experimental results from LULI2000

LULI2000: 2 beams with 200 J & 4.0 ns each - “anti-Hall” targets

→ No more flat sheet between the 2 shells
Experimental results from LULI2000

LULI2000: post-processing - proton radiography (coplanar targets)

→ Strong deflection before reconnection (Large $B$ field)
→ Weak deflection during reconnection (Smaller $B$ field)
Future experiment on LMJ/PETAL (2017)

Using 4 Quads would allow us to multiplex 2 measurements on one shot
Energy budget in PIC simulations

Aunai et al., PoP 2011

Outflow enthalpy flux is larger than bulk kinetic energy flux
Proposal at PETAL/LMJ shots

With appropriate diagnostics:

- Proton radiography
  → Get $E$ & $B$ fields at different times

- DP1 X-ray imager (12 images with a resolution of 130 ps)
  → a sequence of 2D images

- DMX Spectrometer measuring the spectra of emitted x-rays resolved in time
  → measure the black-body spectrum of $T \sim 100$ eV plasma
Concluding remarks

- The out-of-plane magnetic field is not a consequence of the magnetic reconnection process.
- The out-of-plane magnetic field and the reconnection process are both consequences of thin non-flat current sheet (for $kd_p \sim 1$).
- This can be of interest for ICF with direct (anti-Hall) or indirect (pro-Hall) attack for the stability of the confinement.