Particle Acceleration Due to Magnetically Driven Reconnection using Laser-Powered Capacitor Coils

H. Ji\textsuperscript{1}, L. Gao\textsuperscript{2}, A. Chien\textsuperscript{1}, K. Hill\textsuperscript{2}, B. Kraus\textsuperscript{1}, P. Efthimion\textsuperscript{2}

\textsuperscript{1}Department of Astrophysical Sciences
\textsuperscript{2}Princeton Plasma Physics Laboratory
Princeton University

G. Fiksel
University of Michigan

E. Blackman, P. M. Nilson
Laboratory for Laser Energetics
University of Rochester

Q.-M. Lu, K. Huang
University of Science and Technology of China
Magnetically driven reconnection by laser-powered capacitor coils has been studied on OMEGA EP.

- Improved target design results in ~2x improvement in magnetic field strength from capacitor coils.

- Proton radiography data shows agreement with reconnection-motivated electromagnetic fields.

- Evidence of energetic electrons from reconnection is observed with OU-ESM.

- We are working on PIC simulations to compare with experimental data for both electromagnetic fields and energetic particle spectrum.

- Future experiments will characterize plasma parameters.

- Plasma parameters, reconnection parameters, and geometry will be varied to understand mechanisms of particle acceleration.
Magnetic reconnection is a fundamental process in magnetized plasmas.

- Topological rearrangement of magnetic field lines
- Magnetic energy from reconnection field lines is converted to:
  - Bulk flow (outflows)
  - Plasma heating (thermal)
  - Particle acceleration (nonthermal)
Collisionless magnetic reconnection is the basis for many astrophysical phenomena, but particle acceleration is not well understood.

- Ubiquitous process responsible for many astrophysical phenomena:
  - solar flares
  - coronal mass ejections
  - Earth magnetosphere interaction with interplanetary magnetic field

- Astrophysical magnetic reconnection typically is collisionless, low-$\beta$

Magnetic reconnection on the surface of the sun.
(source: nasa.gov)

Krucker et al. (2010)
Laser-powered capacitor coils provide a good platform for direct measurement of particle acceleration in low-\(\beta\), magnetically-driven reconnection.

<table>
<thead>
<tr>
<th></th>
<th>RHESSI (solar)</th>
<th>MMS (space)</th>
<th>MRX / FLARE</th>
<th>Laser-Powered Capacitor Coils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Field (B)</td>
<td>0.02 T</td>
<td>20-100 nT</td>
<td>0.02 T / 0.1 T</td>
<td>100 T</td>
</tr>
<tr>
<td>System Size (L)</td>
<td>(10^4) km</td>
<td>(10^4) km</td>
<td>(0.4) m / (1.6) m</td>
<td>1 mm</td>
</tr>
<tr>
<td>Ion skin depth ((d_i))</td>
<td>1-10 m</td>
<td>10 km</td>
<td>0.04 m</td>
<td>few (10^{-4}) m</td>
</tr>
<tr>
<td>Lundquist number</td>
<td>(10^{13})</td>
<td>(10^{14})</td>
<td>(10^3 / 10^5)</td>
<td>(10^{3-4})</td>
</tr>
<tr>
<td>Normalized Size (L/(d_i))</td>
<td>(10^{6-7})</td>
<td>(10^3)</td>
<td>(10^1 / 10^2)</td>
<td>2-20</td>
</tr>
<tr>
<td>Electron MFP ((\lambda_{\text{MFP, e}}))</td>
<td>100 km</td>
<td>(10^{4-5}) km</td>
<td>5 cm</td>
<td>2-15 mm</td>
</tr>
<tr>
<td>Debye Length ((\lambda_D))</td>
<td>2 mm</td>
<td>2-4 km</td>
<td>1 mm</td>
<td>2-40 (\mu)m</td>
</tr>
<tr>
<td>In-situ Detector Size (L_{\text{in-situ}})</td>
<td>---</td>
<td>1 m</td>
<td>5 mm</td>
<td>---</td>
</tr>
<tr>
<td>Plasma (\beta)</td>
<td>0.01</td>
<td>0.04-6</td>
<td>0.1</td>
<td>0.003-0.1</td>
</tr>
<tr>
<td>Control</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>In-situ measurements</td>
<td>No</td>
<td>Yes</td>
<td>Difficult</td>
<td>No</td>
</tr>
<tr>
<td>Ex-situ measurements</td>
<td>Yes (photon)</td>
<td>No</td>
<td>No</td>
<td>Yes (electrons)</td>
</tr>
</tbody>
</table>
Many previous experiments on magnetic reconnection in laser plasmas have been flow-driven and broadly high-$\beta$.

### Self-generated magnetic fields

![Diagram of self-generated magnetic fields](image)

### External magnetic fields

![Diagram of external magnetic fields](image)

<table>
<thead>
<tr>
<th>Flow-Driven</th>
<th>Magnetically-Driven</th>
</tr>
</thead>
<tbody>
<tr>
<td>• L. Willingale et al., PoP 17, 043104 (2010)</td>
<td>• H. Ji, L. Gao, A. Chien</td>
</tr>
<tr>
<td>• J. Zhong et al., Nature Phys. 6, 984 (2010)</td>
<td></td>
</tr>
<tr>
<td>• G. Fiksel et al., PRL 113, 105003 (2014)</td>
<td></td>
</tr>
<tr>
<td>• A. E. Raymond et al., PRE 98, 043207 (2018)</td>
<td></td>
</tr>
</tbody>
</table>
A novel technique for creating strong external magnetic fields was demonstrated as a result of our NLUF award in FY14.

L. Gao et al., PoP 23, 043106 (2016)
Our campaign in 2017-2018 aimed to measure particle acceleration by magnetically driven axisymmetric reconnection.

TNSA Proton Radiography:
- Characterize electromagnetic field structure.
- Fast protons (up to $60 \, \text{MeV}$) deflected by local electromagnetic fields onto a film pack.

Osaka University – Electron Spectrometer (OU-ESM):
- Time-integrated electron spectrum measurement based on $\vec{v} \times \vec{B}$ deflection.
- Energy range: $20 \, \text{keV} \rightarrow 2 \, \text{MeV}$
Proton radiograph measurements show prolate voids and center bubble structure.

\[ E_p = 24.7 \text{ MeV} \]
Comparisons of “prolate void” feature in radiographs imply maximum coil current of 56 kA at t=1 ns, or maximum B~110 T at coil center.

~2x increase in coil current compared to Gao et al., 2016 are achieved due to improved target design.
Proton radiograph measurements show prolate voids and center bubble structure.

\[ t = 3.158 \text{ ns} \]
\[ t = 4.149 \text{ ns} \]
\[ t = 6.137 \text{ ns} \]

\[ E_p = 24.7 \text{ MeV} \]
Center feature in proton radiography images can be analyzed with respect to magnetic reconnection-motivated fields.

1. In-Plane Electric Field

\[ E_{in} \sim \nu_{ez}B_x = \frac{j_{ez}B_x}{en_e} \]

\[ E_{in} \sim \nu_{e,A} \times 0.1B_y \sim 9 \times 10^8 \text{ V/m} \]

2. Out-of-plane Current

\[ J_{out} \sim \frac{B_{coil}}{\mu_0 \delta} \]

\[ I_{out} \sim J_{out}(\delta)(L) \sim \frac{B_{coil}d_i}{\mu_0} \sim 16 \text{ kA} \]
In-plane electric field reproduces shape of center structure; required artificial field strength is \(~20\) times larger than estimate.

Estimated $E_{in} \sim 9 \times 10^8 \text{ V/m}$
Out-of-plane current is another strong candidate with inferred $I_{out} = 28 \, kA$; feature shape is strongly affected by current sheet geometry.

Estimated $I_{out} \sim 16 \, kA$

Center feature shape is strongly affected by current sheet geometry and dimensions.
Evidence of energetic electrons generated by the reconnecting targets is observed.
Evidence of energetic electrons generated by the reconnecting targets is observed.
Conclusions

Magnetically driven reconnection by laser-powered capacitor coils has been studied on OMEGA EP.

- Improved target design results in ~2x improvement in magnetic field strength from capacitor coils.

- Proton radiography data shows agreement with reconnection-motivated electromagnetic fields.

- Evidence of energetic electrons from reconnection is observed with OU-ESM.

- We are working on PIC simulations to compare with experimental data for both electromagnetic fields and energetic particle spectrum.

- Future experiments will characterize plasma parameters.

- Plasma parameters, reconnection parameters, and geometry will be varied to understand mechanisms of particle acceleration.
Questions?