RELATIVISTIC RECONNECTION USING OMEGA EP

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Outline

- Magnetic reconnection with lasers
  laboratory astrophysics

- Relativistic reconnection

- Asymmetric geometry (short pulse/long pulse)
Laser Radiation sources at CUOS

Laser wakefield acceleration
Schumaker (PRL 2013)
He (Nat. Comm. 2015)

Table-top x-ray and γ ray sources
Kneip (Nat. Phys. 2010)
Sarri (PRL 2014)

Positron beams
Sarri (PRL 2013)
Sarri (Nat. Comm. 2015)

Directional high energy neutron beams
Zulick (APL 2014)

Laser acceleration of ions
Dollar (PRL 2011,2012)
Dollar (APL 2103)

High Order Harmonic pulse generation
Dollar (PRL 2013)
Easter (NJP 2013)
CUOS laser systems

Hercules
10J, 30fs, 800nm
$2 \times 10^{22} \text{ Wcm}^{-2}$

T-cubed
10J, 400fs, 1.053μm
$5 \times 10^{19} \text{ Wcm}^{-2}$

λ³ (500Hz)
12mJ, 30fs, 800nm
$5 \times 10^{18} \text{ Wcm}^{-2}$

Omega
<1000J, 1-10ps, 1.053μm
$1 \times 10^{19} \text{ Wcm}^{-2}$

Titan
<300J, 1-10ps, 1.053μm

Gemini
2×15J, 30 fs, 800nm
$\sim 10^{21} \text{ Wcm}^{-2}$
Relativistic Laser Systems: OMEGA EP

- Laboratory for Laser Energetics at University of Rochester

- Four beamlines of kilojoule energy with long and short pulse capabilities - to both form and interact with plasma targets, respectively
Laboratory Astrophysics - Magnetic Reconnection:
Topology changes that converts magnetic energy into plasma kinetic energy
Magnetic reconnection

- Anti-parallel magnetic field lines are driven together, the field lines break and reconnect within the reconnection layer.
- Magnetic energy is released as plasma kinetic energy.

- Sweet-Parker model \( \rightarrow \) incompressible MHD: A neutral current sheet forms so field lines can slip from plasma and diffuse across the reconnection layer.
- Reconnection rate estimates are orders of magnitude too slow!
Magnetic reconnection

- Relativistic electron fluid Ohm’s law:

\[ \mathbf{E} + \mathbf{C} \times \mathbf{B} - \frac{\mathbf{J} \times \mathbf{B}}{en_e} + \frac{1}{en_e} \nabla \cdot \mathbf{P}_e + \frac{m_e}{e} \left( \frac{\partial U_e}{\partial t} + \mathbf{V}_e \cdot \nabla U_e \right) = \eta \mathbf{J}, \]

- Length scales < ion inertial length, ions decouple and B-field frozen to the electrons
  - length of the current sheet, L, is comparable to the mean-free-path of electrons
  - electric field in the reconnection layer is supported by pressure tensor, and by the Hall term in the surrounding region

→ allows fast, collisionless (Hall) reconnection
Experimental characterization of this regime has included:

**Magnetic field measurements:**


**Density measurements:**


**Temperature measurements:**


**Jet formation observations:**


These experiments used nanosecond duration, moderate intensity laser pulses.
Relativistic magnetic reconnection

• The energy density of the reconnecting fields, $B^2/2\mu_0$, exceeds the rest mass energy density, $n_e m_e c^2$, or:

$$\sigma = \frac{B^2}{\mu_0 n_e m_e c^2} > 1$$

• Nanosecond laser driven reconnection: $\sigma < 0.01$

• High-intensity laser driven reconnection: $\sigma \sim ?$
Magnetic field generation from a relativistic intensity interaction

- Electrons are heated to MeV energies
- Electron cloud expands into vacuum
- Large space-charge field is formed
  - confines the majority of the hot electrons to the target surface
  - Hot electron current spreads radially out along the target surface
  - Cold electron return current in bulk target
  - Azimuthal magnetic field is associated with these surface

Relativistic Electron Driven Magnetic Reconnection

The azimuthal magnetic fields are in the same configuration, but the magnetic field lines are driven together at \( \sim c \).
Experimental set up – 2 short pulse beams

**Hercules**
Parabola cut in half with half on a translation stage. Deformable mirror required.

\( \lambda = 800 \text{ nm} \)
2 J
40 fs
2 \( \times 10^{19} \) Wcm\(^{-2} \)
Normal angle of incidence

**OMEGA EP**
Two separate 20 ps beam lines. Co-timed to +/- 5ps.

\( \lambda = 1.053 \mu\text{m} \)
500 J or 1000 J, 20 ps
(1.2 – 2.5) \( \times 10^{18} \) Wcm\(^{-2} \)
45° angle of incidence
Mid-plane signal enhancement is due to reconnection fields.

- (a) face on
- Magnetic field lines
- Relativistic electrons
- Focal spot 1
- Focal spot 2
- Reconnection layer

- (b) side on
- $\frac{\partial E}{\partial t}$
- B-field 1
- Laser pulse 1
- B-field 1
- Out-of-plane E-field
- B-field 2
- Laser pulse 2
- B-field 2

Image of a simulation showing the enhancement of signal with reconnection fields.
Omega EP Experimental configuration

5-channel electron spectrometer
54.3° - 60.0°

Copper target

Target Rear Normal

X-ray detector or streak camera slit

Copper Kα spherical crystal imager (8.048 keV)
Omega EP copper K$_{\alpha}$ imaging
Electron spectra measurements

5-channel electron spectrometer
54.3° - 60.0°

Copper target
Copper Kα spherical crystal imager (8.048 keV)

Target
Rear
Normal

X-ray detector

100 ps Delay

\[ \frac{dN}{dE} (\text{#/MeV}) \]

Energy (MeV)
Electron spectra measurements

- 5-channel electron spectrometer
- Copper target
- Copper Kα spherical crystal imager (8.048 keV)
- X-ray detector
- Non-thermal electron population appears

Graph showing dN/dE vs. Energy (MeV) for different pulses with and without delay.
3D OSIRIS Simulation
(using 34,848 nodes of the NASA Pleiades supercomputer)

- \((x_1, x_2, x_3) = (23 \, \mu m, 50 \, \mu m, 99 \, \mu m)\)
- 40 cells per \(\lambda\)
- 3 x 3 x 3 particles per cell
- \(n_{\text{max}} = 30 \, n_c\)
- Plasma scalelength of \(\lambda\)
- Stationary ions
- Single pulse with periodic boundary create an effective spot separation of 50 \(\mu m\)
3D simulation results: time averaged $j_1 \cdot E_1$

Simulation $\vartheta/L \approx 0.35$

Hercules
3D simulation results

Nonthermal spectral component develops: power law fit

Consistent with relativistic reconnection

\[ \frac{dN}{d\gamma} \propto \gamma^{-1.6} \]

Temporal evolution of the energy in nonthermal electrons and magnetic potential energy
• Simulations indicate **relativistic reconnection**: (40%) of $\sigma > 1$ on target surface
• **Hall-like** features observed
• Reconnection rate is **fast**, comparable to experimental results and magnetic energy conversion time is
• **Suprathermal electrons** injected into the midplane
Asymmetric B-fields - OMEGA EP setup

- UV long pulse: 1250J, 1ns, $2 \times 10^{14}$ W/cm²
- IR short pulse: 500J, 10ps, $10^{19}$ W/cm²
- IR short pulse: 300J, 1ps, $5 \times 10^{19}$ W/cm²
- Radiochromic film (RCF) stack
- Cu target
Proton radiography of the relativistic interaction

Protons

Target

RCF Stack

t = 0 ps

6.47 ps

11.3 ps

18.1 ps

23.0 ps

27.1 ps
Proton radiography of the relativistic interaction

Ring Expansion

Time (ps)

Radius (mm)

Expansion velocity (c)

0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1
1.2
1.4

0 10 20 30 40
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 1

0 1 2 3 4 0

t = 0 ps
6.47 ps
11.3 ps
18.1 ps
23.0 ps
27.1 ps

1 mm
Long pulse - short pulse interaction

Spot separation – 750μm
Short pulse delay – ~ 500ps

UV long pulse

IR short pulse

UV spot

L. Gao et al. PRL (2015)
Long pulse B-structure depends on material

- Proton radiography of magnetic field generation by a UV long pulse \((E = 1250 \text{ J}, \, t_p = 1 \text{ ns}, \, d = 0.8 \text{ mm})\) on different target materials at OMEGA EP.

- Each proton radiograph was taken at \(t = t_o + 750 \text{ ps}\), where \(t_o\) is the arrival time of the main interaction laser.
Long pulse - short pulse interaction

Spot separation – 750μm
Short pulse delay – 500ps

UV long pulse

IR short pulse

750μm

UV spot

short pulse arrival

1 mm

16.5 ps

20.7 ps

25.7 ps
Long pulse - short pulse interaction

Spot separation – 1250 µm
Short pulse delay – 750ps

UV long pulse

IR short pulse

1250µm

1 mm

16.5 ps 20.7 ps 25.7 ps

11.7 ps

4.8 ps

0 ps
Plastic target comparison

t = 0 ps

0 ps

11.3 ps

6 ps

2.9 ps

9.1 ps

14 ps

22.3 ps

16.8 ps
Preliminary 2D simulations

Electron Density at $t = 0 \, 1/\omega_p$

$E_y$ at $t = 0 \, 1/\omega_p$

$B_z$ at $t = 0 \, 1/\omega_p$

$E_y$ at $t = 70 \, 1/\omega_p$

Sheath field

Self-generated $B$-field

$E_y$ at $t = 140 \, 1/\omega_p$

$B_z$ at $t = 140 \, 1/\omega_p$

Stagnation and pile-up
Summary

- Relativistic reconnection characterized

- Both long pulse and short pulse fields depend on material

- Interaction of long pulse/short pulse fields give rise to new dynamics

- Numerical modeling is underway
END