Dynamics of Magnetic Fields in Laser-Driven High-Energy-Density Plasmas for Fusion and Astrophysics

Rayleigh-Taylor Instability

Magnetic Reconnection

Magnetized Jet

Proton radiograph

$t = t_0 + 2.6 \text{ ns}$

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PPPL SULI program
August 3, 2017
Outline

• Introduction
  – High energy density (HED) physics
  – Laser-driven HED systems
  – Rayleigh-Taylor (RT) instability

• Nonlinear RT instability experiments
  – Magnetic field generation and evolution

• Ongoing and future work relevant to astrophysics
  – Dynamo
  – Magnetic reconnection
  – Magnetized jet

• Advanced diagnostics development for HED systems
  – High-resolution x-ray spectrometer

• Summary and conclusions
High energy density (HED) physics concerns the study of matter at high densities and extreme temperatures.

Laboratory for laser energetics (LLE) at University of Rochester operates two of the world’s largest lasers for HED physics research.

**OMEGA Laser System**
- Operating at LLE since 1995
- Up to 1500 shots/year
- Fully instrumented
- 60 beams
- >30-kj UV on target
- 1% to 2% irradiation nonuniformity
- Flexible pulse shaping
- Short shot cycle (1 h)

**OMEGA EP Laser System**
- Completed 25 April 2008
- Four NIF-like beamlines; 6.5-kj UV (10 ns)
- Two beams can be high-energy petawatt
  - 2.6-kj IR in 10 ps
  - can propagate to the OMEGA or OMEGA EP target chamber

More than half of OMEGA’s shots are for external users.
The National Ignition Facility (NIF) at LLNL aims at demonstrating fusion ignition.

- The NIF is a 1.8-MJ laser system (60× OMEGA’s energy); NIF is a $3.5 billion facility completed in 2009.
- The NIF is performing experiments with the goal of achieving ignition.

The achievement of ignition—a national “grand challenge”—on the NIF will change the fusion landscape.
Ablation is used to generate the extreme pressures required to compress a fusion capsule to ignition.

\[ \text{Gain (G)} = \frac{E_{\text{neutron}}}{E_{\text{laser}}} \]

Ignition = \( G \geq 1 \)

“Hot-spot” ignition requires the core temperature to be at least 5 keV and the core fuel areal density to exceed \( \sim 300 \text{ mg/cm}^2 \).
Both direct and indirect (x-ray) drive are being used to implode the inertial confinement fusion capsules.
Intense lasers create HED conditions in the laboratory through ablation.

\[ P_{\text{abl}}^{*} (\text{Mbar}) = 40 \left[ \frac{I(10^{15} \text{ W/cm}^2)}{\lambda(\mu\text{m})} \right]^{2/3} \]

at \( I = 10^{15}, \lambda = 0.35 \mu\text{m}, P_{\text{abl}} = 80 \text{ Mbar} \)

*J. D. Lindl, Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive (Springer-Verlag, New York, 1998).*
The laser-driven target is subjected to the Rayleigh-Taylor (RT) instability.
The RT instability has linear and nonlinear stages

- **Linear regime (classical)**:
  \[ \eta = \eta_0 e^{rt} \]
  \[ \gamma = \sqrt{AKg}, \quad A = \frac{\rho_h - \rho_l}{\rho_h + \rho_l} \]

- **Linear regime (ablateive)**:
  \[ \gamma = \alpha \sqrt{\frac{Kg}{1 + \varepsilon KL}} - \beta KV \]

- **Nonlinear regime**: \( \eta \geq 0.1\lambda \)
  - Slower growth
  - Bubbles and spikes
  - Bubble competition and merger


**J. D. Kilkenny et al., Phys. Plasmas 1, 1379 (1994).**

Magnetic fields are generated by the Biermann battery mechanism

\[ \mathbf{E} = -\frac{\nabla P_e}{\varepsilon n_e} \]
\[ \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \sim -\frac{\nabla n_e \times \nabla T_e}{\varepsilon n_e} \]

R. G. Evans, Plasma Phys. Control. Fusion., 28, 1021 (1986);
A strong magnetic field may modify the heat transport

- Hall parameter $\chi \equiv \omega_{ce} \tau_{ei}$
- $\kappa_\perp \approx \kappa_\parallel / \chi^2$ for large $\chi \gg 1$
- The heat flux is reduced
- Plasma dynamic is altered

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*S. Braginskii, Review of Plasma Physics (1965).*
The growth rate for RT instability in laser-driven targets has been inferred with x-ray radiography.

\[ \frac{\rho_h}{\rho_l} \]

Bubbles

Spikes

Acceleration

X-ray photons are sensitive to density modulations.

\[ t = 1.9 \text{ ns} \]
\[ t = 2.3 \text{ ns} \]
\[ t = 2.4 \text{ ns} \]

X-ray radiography

\[ 100 \mu m \]

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Target Normal Sheath Acceleration (TNSA)* generates MeV proton beams in intense (>10^{18} W/cm^2) laser-solid interactions

- Hot electrons escape from the rear side of the target
- An electrostatic field is built up, with a field gradient of the order of MeV/\mu m
- Protons are accelerated to tens of MeV

Laser-driven protons are ultra bright, extremely collimated, and have high peak energy (58 MeV) and short burst duration (picosecond scale).

Magnetic-field generation has been studied in side-on and face-on geometries using the acceleration of planar plastic targets.
25-μm-thick CH targets were unbroken by instability formation
Proton radiography of 15-μm-thick foils reveals magnetic field generation and its evolution*

MG-level magnetic fields are predicted in a broken 15-μm-thick CH foil using 2-D magnetohydrodynamic (MHD) *DRACO* simulation.

![Density and Magnetic Induction Contours](image)

- **Density (g/cm³)**
  - 1 mm
  - $t = t_0 + 2.1$ ns

- **Magnetic induction (toroidal component) (Gauss)**
  - Black line: density contour at 0.05 g/cm³

Face-on geometry

Face-on probing reveals magnetic field generation by the RT instability

Proton radiograph

$4 \text{ kJ, 2.5 ns}$

$4 \times 10^{14} \text{ W/cm}^2$

$0.3 \text{ kJ, 1 ps}$

$1.5 \times 10^{19} \text{ W/cm}^2$

$1 \text{ mm}$

$8 \text{ mm}$

$80 \text{ mm}$

$500 \mu\text{m}$

$t = t_0 + 2.6 \text{ ns}$
The magnetic-field spatial distribution was characterized using the watershed algorithm.
The number of magnetic cells decreases and the magnetic cell diameter increases with time.
The normalized magnetic-field spatial distribution evolves self-similarly.
The evolution of the magnetic-field spatial distribution is consistent with an RT bubble competition and merger model.*

\[ N(t) \propto (\omega \sqrt{2D(t)} + 2C)^{-4} \]

\[ \langle \lambda \rangle(t) \propto \omega^2 D(t) \]

Target: 15 \( \mu \)m CH

\( \omega_{CH} = 0.79 \pm 0.06 \)**

*O. Sadot et al., Phys. Rev. Lett. 95, 265001 (2005);
D. Oron et al., Phys. Plasmas 8, 2883 (2001);

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The origin and amplification of the magnetic field in the universe is a central astrophysical problem.

- Sources of magnetic fields
- Amplification by the dynamo process
- Flow-dominated systems are common in astrophysics
- Particle acceleration, non-thermal emission
Two classes of experiments are proposed towards the first realization of a full MHD turbulence and dynamo in the HED systems using the NIF.

**Single RT plume**
- Proton Detector
  - WRF & SRF
  - DIM (0,0)
- Drive beams: 240 kJ, 10 ns
- Scandium foil
- 14.7 MeV / 3 MeV Protons
- Proton generation beams: 40 kJ, 0.7 ns

**Colliding RT plumes**
- Proton Detector
  - WRF & SRF
  - DIM (0,0)
- Drive beams: 450 kJ, 20 ns
- CH foil
- CH foil
- 14.7 MeV / 3 MeV Protons
- Proton generation beams: 40 kJ, 0.7 ns

**3D MHD simulation for the colliding case:**
- log($E_k$)
- log($E_B$)
A novel technique has been developed to generate 100s of Tesla magnetic fields using powerful lasers. 

We are studying particle acceleration due to efficient axisymmetric magnetic reconnection.
A strong, fast propagating, magnetized jet has been created at the OMEGA Laser Facility.

**Magnetized Jet and the Collisionless Shock**

- Collisionless shocks are believed to sites for cosmic ray acceleration
- A magnetized, supersonic jet has been successfully demonstrated in the FY16 campaign, in collaboration with Rice, LLE and MIT
- The next goal is to collide the jets for collisionless shock
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High-resolution x-ray spectroscopy is well-established on Tokamaks for measuring plasma conditions.

**Enabling Principles**
- Astigmatism of a spherical reflector
- Bragg relation
- Rotational symmetry of a spherical reflector about the normal axis, CO

Can obtain spatial resolution for small sources if the source is located on the sagittal focal line at Bs.

\[
\frac{1}{p_m} + \frac{1}{q_m} = \frac{2}{R \sin \theta}
\]

\[
\frac{1}{p_s} + \frac{1}{q_s} = \frac{2 \sin \theta}{R}
\]

**Bragg relation**

\[n \lambda = 2 d \sin \theta\]
High-resolution x-ray spectroscopy is well-established on Tokamaks for measuring plasma conditions.

**X-ray Crystal Spectrometer Makes Debut at C-Mod**

*New Technique a Major Advance for ITER*

A PPPL/Alcator C-Mod collaboration has resulted in the demonstration of a greatly improved X-ray crystal spectrometer for application to ITER and fusion reactors. Experiments conducted by a PPPL/MIT team in April mark the beginning of a new era in the ability of such devices to determine radial profiles of the ion temperature and the rotational velocity of high-temperature plasmas without the need for diagnostic beams. Their success will benefit substantially ITER and other advanced fusion energy systems.

From the left are: Alex Ince-Cushman, MIT; Ken Hill, PPPL; Manfred Bitter, PPPL; John Rice, MIT; and Christian Broennimann of the Paul Scherrer Institute in Switzerland.

Impurity by the pattern of frequencies, or spectrum, of the light emitted and they can determine the
PPPL designed high-resolution x-ray spectrometer has been identified as one of the 8 National Transformative Diagnostics.
NIF DIM-based high-resolution x-ray spectrometer (dHIRES)

- Three crystals are fit in the same plane inside a cassette, covering a large range of x-ray energies
- Detectors are the DISC streak camera and image plate: measure time-resolved and -integrated spectra simultaneously
- dHIRES will be used to measure $n_e$ and $T_e$ in implosion and benchmark $n_e$ and $T_e$ derived from neutrons

*K. W. Hill et al., 26th IAEA Fusion Energy Conference, Kyoto, Japan, 2016*
dHIRES is being calibrated at the x-ray lab at PPPL (L123)

K. Hill and L. Gao

dHIERS crystals

Sample spectra

- Alignment
- Energy calibration
- Throughput
- Filter

dHIRES will be shipped to NIF in the week of August 14, and deployed on NIF for experiments on Sept. 27, 2017
The nonlinear phase of the RT instability generates magnetic fields that could be of astrophysics importance*

A strong, fast propagating, magnetized jet has been demonstrated ready for astrophysics applications**

A novel axisymmetric reconnection platform based on a strong external magnetic field source generated by high-power lasers is being pursued***

The NIF high-resolution spectrometer will be fielded on NIF for actual shot end of September****

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**L. Gao et al., in preparation.
****K. W. Hill et al., 26th IAEA Fusion Energy Conference, Kyoto, Japan, 2016