White Paper for *Frontiers of Plasma Science Panel*

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• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	S
• Interactions of plasmas and waves	S
• Plasma self-organization	P
• Statistical mechanics of plasmas	

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Oral	X
Poster	
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Title:	Opportunities using High Energy Density Laser Facilities for Basic Plasma Physics and Plasma Astrophysics
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(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)

This white paper describes recent and future contributions *of laser-driven high-energy-density* (HED) experiments to problems in basic plasma physics and astrophysics.

Understanding the physics of plasmas is key to unlocking a number of important problems in astrophysics. These questions include, how are cosmic rays accelerated? How do magnetic explosions work? How are magnetic fields generated and amplified? How astronomical jets are launched from accretion disks? What is the role of hydrodynamic instabilities in supernovae explosions and interstellar clouds? Can relativistic electron-positron plasmas explain gamma ray bursts? The plasma physics processes that likely lie at the root of these questions are the physics of magnetic reconnection, collisionless shocks, hydrodynamics, radiative transfer, and dynamos. These questions and others were reviewed for example, in the recent *Workshop on Opportunities in Plasma Astrophysics (WOPA)* [1], and have also received significant discussion in previous NRC [2] and ReNeW Reports [3]. The WOPA report was the work of a broad collection of both laboratory plasma physicists, fusion physicists, and plasma astrophysicists and developed a list of a number of research topics and questions for which significant progress can be envisioned through a concerted effort of laboratory experiments, observation, and theory.

Recent experiments on high power laser facilities, including the DOE facilities OMEGA, OMEGA EP, the Matter in Extreme Conditions (MEC) experiment at LCLS, and soon, NIF [4], have demonstrated significant progress in addressing many of these questions. These experiments leverage ICF-class lasers to produce high-temperature and energy, low dissipation plasmas suitable to studying these questions. The exploration of *magnetized* HED plasma phenomena is now possible, either fields self-generated in expanding plasmas, or by coupling a pulsed-power B-field generator to laser-driven targets.

These problems are united by a requirement that the most interesting, astrophysically relevant regimes are characterized by large system size (measured in fundamental plasma units such as the ion skin depth or gyroradius) and high temperature (allowing low dissipation, and high corresponding parameters such as Lundquist number or magnetic Reynolds number). Together these imply a large separation from macroscopic to dissipation scales and collisionless plasma behavior. Obtaining these regimes can be directly translated to requirements on plasma **energy;** thus motivating experiments at larger laser power on systems including the NIF to obtain the interesting self-organized regimes.

We finally note that the physics of magnetized laser-produced plasmas, including reconnection, and shocks, and Rayleigh Taylor instability, are also basic ingredients of laser-plasma coupling in both hohlraums or in directly driven inertial fusion energy targets. Magnetic field generation by expanding plumes alters heat transport, and furthermore the formation of shocks and reconnection could accelerate particles and thereby contribute to deleterious capsule pre-heat.

This work cuts across many sub-areas within FES, including General Plasma Science, High-energy-density physics, Plasma Theory, and Advanced computing. These experiments are directly aligned with the FES goals of understanding high energy density plasma and increasing the fundamental understanding of basic plasmas and astrophysical plasmas.

Major astrophysical topics under study in recent HED experiments:

1. Magnetic Reconnection: Magnetic reconnection [5] is a ubiquitous process in magnetized plasmas and it allows the fast release of stored magnetic energy, and release of magnetic tension forces that can accelerate bulk plasma flows and accelerate particles to high energy. Indeed magnetic reconnection is proposed to be the source of particle energization in many astrophysical environments, ranging from the Earth's magnetotail[6] to solar flares[7] and extragalactic jets[8].

Many important questions in reconnection research remain; here we touch on a few interesting ones where we see that laser-driven experiments can shine. These are: how is fast reconnection obtained at very large system size and in low-dissipation regimes? Such regimes characterize reconnection in most astrophysical contexts, and recent work has proposed that fast reconnection is obtained through a turbulent case driven by the tearing or plasmoid instability [9]. Second, what are the mechanisms and what is the efficiency of particle acceleration by reconnection? Recent theory posits that the interaction of energized particles with this same self-driven reconnection turbulence generates a first-order Fermi mechanism and is responsible for the spectrum of highest energy particles from reconnection [10].

Recent results in high-energy-density plasmas have demonstrated significant progress in developing this new platform for magnetic reconnection study. Experiments have been conducted where the magnetic field is generated by the "Biermann battery" effect in the expansion of a plasma plume, and have observed magnetic field annihilation, jets, and particle acceleration [11]. Most recently a new set of experiments has demonstrated controlled magnetization with an externally applied magnetic field and subsequent driven magnetic reconnection [12]. Recent simulations indicate that these experiments can achieve fast reconnection via the plasmoid instability, opening a new avenue to observe this physics experimentally for the first time [13]. In terms of fusion applications, recent theory has proposed how

magnetic reconnection can operate under hohlraum conditions driven by novel heat flux (Nernst) effects[14].

2. Collisionless shocks: Shocks are driven where super-sonic or super-Alfvenic plasma flows collide, often energized by astrophysical explosions, and are sites where this kinetic energy is thermalized, in a number of space and astrophysical systems including the Earth's bow shock, heliosphere termination shock. Shock formation in collisionless astrophysical plasmas requires mediation by magnetic fields, either compressed from the up- stream plasma in magnetized shocks, or self generated by processes such as the Weibel instability or Bell instability [15]. Shocks have long-been proposed as the sites of astrophysical particle acceleration [16]; but only recently have measurements directly demonstrated acceleration of cosmic ray protons in supernova remnant shocks, via observations of characteristic pion-decay signals in the gamma-ray spectra from the shocks [17].

Significant questions for collisionless shocks include, What is the efficiency of the Weibel mechanism vs. compression of upstream magnetic field? Can the Fermi or DSA process be verified and if so what is its efficiency? How does this depend on the parameters and magnetization of the shock?

Recent experiments and associated modeling have demonstrated magnetic field generation by the ion-driven Weibel instability between colliding flows for the first time [18]. This is the first ingredient required to form a Weibel mediated shock and indicates that at sufficiently large and high temperature it may indeed be possible to demonstrate it in the lab. Recent experiments have also demonstrated magnetized shock formation. [19]

3. MHD turbulence and dynamos: Magnetic field amplification by MHD dynamos in a turbulent flow is believed to play an important role for amplifying weak initial seed fields to present day values in many astrophysical systems. [20] Significant experimental questions include: can this turbulent magnetic field amplification process be observed in the laboratory, and how efficient is this dynamo in various parameter regimes. Interesting first steps to study these problems have been achieved in recent experiments. MG-level magnetic fields generated by the Rayleigh-Taylor (RT) instability have been measured in a laser-driven HED system, where the cellular magnetic field structures encircling RT bubbles and spikes evolve self-similarly in the nonlinear growth phase [21]. With a more intense and longer laser drive like the NIF, a full MHD turbulence can be realized to obtain turbulent dynamo amplification of seed magnetic fields.

4. Radiative shocks and reconnection: Radiative shocks occur where radiative energy flux exceeds incoming material energy flux [22]. These are important to many astrophysical shocks, including supernova and accretion shocks. Recently radiative reconnection has been proposed to play a role in many astrophysical situations [23], such as pulsar magnetospheres, black hole accretion-disk coronae, jets, gamma-ray bursts, and magnetar flares. The proposed radiation effects include radiative cooling, radiation pressure, and photon-drag resistivity and strongly affect reconnection and the consequent particle acceleration. Experiments on both shocks and reconnection at large system size and using efficient radiating materials may attain these radiative regimes and test predictions of the theories.

Some research needs:

The experiments discussed in this white paper are largely carried out on DOE/NNSA User facilities (funded outside of FES resources), which represent an incredible investment of national resources. FES, by funding researchers to conduct experiments and accompanying theory, can leverage enormous benefits for plasma physics. In addition to continued support for the experiments and associated modeling and theory, we ask for support for the development of improved and comprehensive diagnostics of measuring plasma conditions, including multiple complementary techniques for measuring magnetic fields and energized particles.

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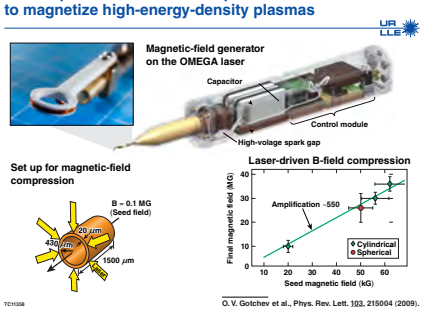
Figures (maximum 1 page)

Pulsed-power devices are coupled to lasers to magnetize high-energy-density plasmas



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Opportunities

- generate magnetized collisionless shocks relevant to astrophysical particle acceleration

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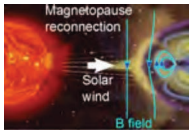
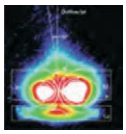
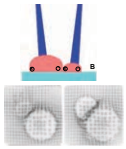
Magnetic reconnection studied in laser-plasma experiments with colliding, magnetized plumes

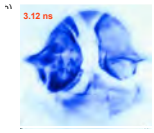




outflow jets and particle energization (Zhong *et al* Nature Phys 2010, Dong et al PRL 2012)



Reconnection between asymmetric plasmas (M. Rosenberg Nature Comm 2014)



Reconnection between externally-magnetized plasmas (G. Fiksel PRL 2014)

Opportunities

- astrophysical particle energization by reconnection vs. shocks
- multiple island reconnection at large system size
- Radiative cooling effects in reconnection

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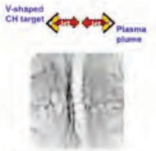
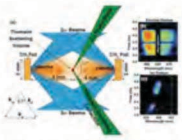
Colliding plume experiments study physics of astrophysical collisionless shocks and jets

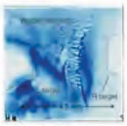
Supernova remnant and Gamma ray burst shocks, sites of cosmic ray acceleration



Radiography of colliding plasma jets (C.K. Li PRL 2013)



Anomalous ion and electron heating in colliding plumes by electrostatic instabilities (J.S. Ross PRL 2013)



Observation of ion-driven Weibel instability (Fox PRL 2013, Huntington Nature Phys 2015)

Opportunities

- Detailed benchmarking of Weibel instability and associated shock physics
- Create a fully-formed collisionless shock with large energy (proposed for the NIF)

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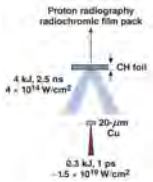
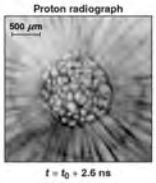
Magnetic field generation by Rayleigh-Taylor instability has been studied, opening the door for possible magnetized turbulence and dynamo studies





MG-level magnetic fields during the non-linear growth phase were measured for the first time* The structural evolution was found to be self-similar and consistent with a bubble competition and merger model**

*L. Gao *et al.*, Phys. Rev. Lett. 109, 115001 (2012).
**O. Sadot *et al.*, Phys. Rev. Lett. 95, 265001 (2012).
***L. Gao *et al.*, Phys. Rev. Lett. 110, 185003 (2013);
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Opportunities: study self-organized turbulent state driven by many overlapping plumes, astrophysical magnetic field generation, and dynamos

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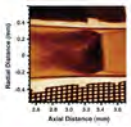
Laser experiments can study physics of systems where radiation can play a role



1. **Radiative shocks** occur when Radiative energy flux exceeds incoming material energy flux. Leads to high compression (~20) of material by the radiative shock. Material ahead of the shock is heated by radiation
Relevant to many astrophysical shocks, including supernova and accretion shocks

(A radiative shock in Xe, Drake, HEDP, 2011)

2. Radiative reconnection: in many ***astrophysical*** situations **radiation** strongly affects reconnection processes
(pulsar magnetospheres, black hole accretion-disk coronae/jets, gamma-ray bursts, and magnetar flares).
Important radiative effects on reconnection:
radiative cooling; radiation pressure; photon-drag resistivity.
(Uzdensky 2011, for review)

Opportunities

- Create radiation-*pressure* dominated regimes for shocks relevant to star formation and stellar interiors
- Use radiative shocks to create a dense, compressed shell susceptible to instabilities that could explain clumpy structure in SNR
- Detailed theory and simulation of feedback effects of radiation on magnetic reconnection in relevant systems. Experimental demonstration with HED facilities

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