Laboratory astrophysics and basic plasma physics with high-energy-density, laser-produced plasmas

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This white paper highlights some recent results and exciting possible contributions of laser-driven high-energy-density (HED) experiments to basic plasma physics and plasma astrophysics. Research on these topics fall squarely within the Discovery Science category of the new FES budget divisions.

The authors of this white paper represent a broad collection of plasma physics researchers, encompassing Laboratory and University, both Experimental and Theoretical, and from Fusion to Plasma Astrophysicists. At the same time, the work highlighted here is but a small collection of the overall exciting physics done on these facilities, and is meant to be illustrative and not exclusive.

We summarize the recommendations here first:

- The FES should continue strong support for this physics research area, as experiments on these facilities are well-aligned with two out of four the FES mission in plasma physics and fusion research, and significant accomplishments can be foreseen in the next decade with support maintained.

- The experiments discussed in this white paper are largely carried out on DOE 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.

- As a general Recommendation, FES should maintain strong and stable support of HEDP physics to undertake the physics research both experimental and theoretical. In recent years this SC support for this research has come through NSF/DOE Joint Program, General Plasma Science at the Laboratories, and, most significantly, the Joint SC/NNSA HEDP program. A continual strong level of funding is recommended (e.g. in FY12 and 13, the SC/NNSA program was $10-12M/yr and supports on the order of 20-30 research groups.)

- As a separate Initiative, significant run time is now available on two new machines, MEC and the NIF, which is soliciting experimental proposals for Discovery Science shots (18 days for FY16). In the case of NIF, FES should partner with NNSA to find a model to support researchers who obtain shots on this facility, so as to extract the maximum possible scientific benefit.
Context of Recent Reports

The exciting fields of high-energy-density physics and plasma astrophysics have been reviewed in a number of community-generated reports.


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. The HEDP reports reviewed and presented recommendations on a broad range of topics of high-energy-density physics, from plasma astrophysics to stockpile stewardship.

As reviewed in all these reports, a number of important astrophysics questions are also fundamental plasma physics questions and can be tackled with HEDP laser facilities. These 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? How does radiation play a role in controlling shocks and magnetic reconnection in certain high-energy-density astrophysical plasmas? 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.

Research topics are aligned with the plasma physics missions of FES

These research topics are well-aligned with two of the four primary missions of FES:

Pursue scientific opportunities and grand challenges in high energy density plasma science to explore the feasibility of the inertial confinement approach as a fusion energy source, to better understand our universe, and to enhance national security and economic competitiveness;

The experiments and topics discussed here use laser-produced plasmas. Therefore, in the process of tackling these problems in basic plasma physics and astrophysics, significant insight will also be gained about the behavior of HED plasmas.
Increase the fundamental understanding of basic plasma science, including both burning plasma and low temperature plasma science and engineering, to enhance economic competitiveness, and to create opportunities for a broader range of science-based applications.

The experiments and topics proposed here involve the most basic plasma physics processes, including turbulence, shocks, magnetic reconnection, and basic plasma instabilities. These are the building blocks of our general understanding of plasma physics.

Highlights of Recent Progress

Recent experiments on high power laser facilities, including the DOE facilities OMEGA, OMEGA EP, the Matter in Extreme Conditions (MEC) experiment at LCLS, have demonstrated significant progress in addressing many of the research questions listed in the reports. 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 by coupling a pulsed-power B-field generator to laser-driven targets. Recent experiments have observed radiative shocks, fast magnetic reconnection between colliding magnetized plasma plumes, particle energization by reconnection, colliding plasma jets, magnetic flux compression, and the Weibel instability in colliding unmagnetized plumes relevant to astrophysical collisionless shocks. This list is by no means meant to be exhaustive, merely illustrative of the breadth of topics and some of the recent results from these experiments.

An appendix at the end copies slides from our FESAC presentation showing some highlight results in greater detail.

Future opportunities

Continued research in this area over the next decade could yield significant progress towards understanding these astrophysical processes. The appendix slides at the end indicate some exciting possible questions which follow from the recent results.

In addition to continued experiments on OMEGA and OMEGA EP, the new facilities, MEC and the NIF represent qualitatively new ways to conduct the experiments. The MEC facility at LCLS couples a laser-plasma facility to the LCLS free-electron-laser, which provides an unprecedented x-ray laser for probing the plasma.

The NIF, through its significant increase of laser energy (1.8 MJ) over any previous facility, will allow new experiments with significantly hotter plasmas, at larger system size and at lower-dissipation. For example, in the context of dynamos, the hotter plasma can yield significantly larger magnetic Reynolds numbers, crucial for the turbulent dynamo to grow. The larger system size afforded by the greater energy should allow shock experiments with fully formed collisionless shocks, and magnetic reconnection experiments in the “large-system-size” regime (large in units of fundamental plasma units such as the ion skin depth), where current sheet tears into multiple islands.
Funding Landscape

This research has been recently been funded through the following mechanisms -

- By NNSA, at NNSA Laboratories through Laboratory Basic Science-type programs
- By SC, at Universities and Laboratories through competed grants, such as NSF/DOE Joint program, or through Laboratory GPS lines.
- The recent combined SC/NNSA Joint program in High-Energy-Density Physics.

The latter two avenues are very important as they reach collaborators and in particular astrophysicists outside the Laboratories.

An essential component of this research is access to experimental time. OMEGA and OMEGA EP have well-established solicitation processes with external review panels, and managed by the NNSA. The process, called the National Laser User Facility, provides about 14-16 shot-days per year on each of OMEGA and OMEGA EP, supporting 8-12 campaigns on each. This program also provides some funding for researchers to conduct the experiments, basically at a single-investigator-type level.

The MEC facility has an established shot proposal process managed by the greater LCLS facility. Typically 5-6 experimental campaigns are available on each 8-month LCLS cycle.

The NIF has recently announced its own call for Discovery Science proposals [4], in which it was anticipated that up to 18 shot days would be available in FY16, again likely supporting in the range of 8-12 experimental campaigns.

However, neither the MEC nor NIF shot solicitations include any provision for obtaining funding.

Priorities, Recommendations and Initiatives

We do not seek to prioritize within the field of HEDP plasma physics. This document presents a relatively small slice of the exciting work being done on these machines. The best way to fund this field is to continue the open, competitive research grants for shot time and funding.

The experiments discussed in this white paper are largely carried out on DOE User facilities (MEC, OMEGA/EP, NIF). These facilities represent an incredible investment of national resources. FES, by funding researchers to conduct experiments and accompanying theory, can leverage enormous benefits for plasma physics.

As a Recommendation, FES should maintain strong support of HEDP physics to undertake the physics research discussed above. In recent years this SC support for this research has come through NSF/DOE Joint Program, General Plasma Science at the Laboratories, and most significantly the Joint SC/NNSA HEDP program. Unfortunately the latter program has undergone significant funding gyrations in recent years. We recommend naturally a consistent level of funding (e.g. in FY12 and 13, the SC/NNSA program was $10-12M/yr and supports on the order of 20-30 research groups.)

As a separate Initiative, with the conclusion of the National Ignition Campaign at the NIF, significant time is being made available for Discovery Science shots (up to 18 days have recently been announced through a shot-time solicitation for FY16). FES should partner with NNSA to find a model to support researchers who obtain shots on this facility, so as to extract the maximum possible scientific benefit. Similarly, FES should find a model to support FES-relevant experiments on the LCLS/MEC.
References:


Appendix:

The following appendix slides show a gallery of recent results and associated references:
Opportunities

- generate magnetized collisionless shocks relevant to astrophysical particle acceleration

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**

Opportunities: study self-organized turbulent state driven by many overlapping plumes, astrophysical magnetic field generation, and dynamos
Magnetic reconnection studied in laser-plasma experiments with colliding, magnetized plumes

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

Colliding plume experiments study physics of astrophysical collisionless shocks and jets

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