Summary of a Workshop on Opportunities for High Energy Density Laboratory Plasma Science

Conveners: Robert Rosner, ANL, and John C. Browne, LANL – retired

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Executive Summary

There is little question that there is now a gathering storm of scientific interest in the physics of high energy density matter[1]. Based on ongoing work at large and medium-scale national and small university-based HED facilities, and with the imminent opening of forefront large-scale facilities such as NIF (at LLNL), OMEGA/OMEGA EP (at Rochester), Z-R (at Sandia), and LCLS (at SLAC), major assessments have been carried out by the National Academy of Sciences[2] and by an interagency task force focusing on opportunities in HEDLP that broadly cut across scientific disciplines[3]. These assessments give substance to one's untutored impression that a new field of science is on the threshold of emergence. Based partially on these prior studies, the Undersecretary for Science at the Department of Energy chartered a workshop, held at Argonne National Laboratory on May 23-24, 2007, to examine opportunities for frontier experiments on major high energy density science facilities, and to recommend a programmatic path forward. A group of scientists drawn from DOE, the DOE SC and NNSA laboratories, academia, and industry gathered in this workshop to discuss the most exciting HEDLP science and prepare the following overview 'white paper' that may help guide a possible federal government response to the opportunities that are now facing us.

The general conclusion of this workshop is that there are compelling scientific opportunities of high intellectual value across this very broad field of HEDLP that will produce significant and exciting advances at the new and existing HED facilities if a DOE program is developed to support the growth of this science community at their home institutions and as users of the major facilities. Rapid progress will require a balanced approach, making the most efficient use of the various HEDLP facilities. The smaller facilities are superb for training students, doing wide ranging empirical surveys of HED science, and developing creative, new diagnostic techniques. The medium scale facilities can be thought of as the physics "work horses", where real dynamics and integrated experimental concepts are tried and proven. To probe the most extreme states of matter and achieve the most significant scientific progress will require the largest facilities, in particular NIF. We strongly recommend that DOE/SC and NNSA take steps to initiate a program of significant size (~$25-50M). This level of funding would allow this community to perform research at a scale that will begin to realize these exciting opportunities.

The Scientific Ambitions and Challenges of HEDLP

- ***Achieve the grand challenge of fusion energy enabled by high energy density laboratory plasmas – powering the planet.*** The successful development of inertial fusion energy (IFE) will require fundamental understanding of the behavior of high energy density plasmas.

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[1] We will henceforth refer to HED science as High Energy Density Laboratory Plasmas, or HEDLP.
[2] "Frontiers in High Energy Density Physics – The X-Games of Contemporary Science" (NRC Press, 2003); see also "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century" (NRC Press 2003)
[3] "Frontiers for Discovery in High Energy Density Physics" (National Task Force on High Energy Density Physics, 2004)

- A challenge and obligation for humankind is the development of clean energy sources. Developing the science of high energy density plasmas in the laboratory is a cornerstone for a promising approach for such an energy source, inertial fusion. The achievement of ignition at NIF will focus world attention on the potential of IFE. The science of HEDLP will create the basis for interpreting these ignition results and for developing experimental scenarios that extend laboratory fusion's promise beyond ignition and toward fusion power. This science will be grounded in improved knowledge of the equations of state in warm and hot dense matter conditions relevant to fusion, and also relevant to many astrophysical problems such as stellar dynamics and the structure of planetary interiors. The understanding of two-stage ignition processes, in which fusion fuel is first compressed and then ignited by a localized insertion of additional energy as a "spark", holds the practical promise of enabling increased fusion gain and dramatically simplified fusion power plant system architectures. The understanding of ion beams and their interactions with fusion fuel may lead to systems with high fusion gain and allow for the ability to control fundamental plasma instabilities. HEDLP systems with embedded magnetic fields are also of potential importance to the future of fusion energy as it may lead to improved inertial fusion systems. The science issues critical to inertial fusion energy cut across a wide range of HEDLP research thrusts. The grand challenge of inertial fusion energy represents the best of all attributes of scientific research, combining aspirations of the highest and best impact to civilization with multi-scale scientific questions of the richest subtlety and complexity.

- ***Create, probe, and control new states of matter in HEDLP.*** The next generation of experiments puts us at the frontier of a new regime in physics; qualitatively new phenomena emerge when the energy density exceeds roughly a million atmospheres. This leads to deep connections to astrophysical phenomena, ranging from star formation to nucleosynthesis and black hole dynamics, with laboratory experiments providing a direct means of quantitatively probing the vital physics underlying astrophysical processes (and the related enigmatic observations). The key point is that the HEDLP field appears poised to take the step from understanding the underlying physical principles to controlling the detailed plasma physics and unique states of matter.
  - ***Are there already examples of how HEDLP plasmas may be controlled?*** Such control is starting to be observed in laser-plasma based accelerators. Until recently, laser-plasma interactions have generated large numbers of electrons having energies of 100's of MeV, but with an energy spread of nearly 100%. The discovery of the "bubble" interaction regime, which required both theoretical and experimental advances, has enabled multiple groups to generate nearly monoenergetic electron beams in excess of 100 MeV, with one group demonstrating a 1 GeV (10^9 eV) electron beam. It may become feasible that TeV (10^{12} eV) electron beams can be generated, having applications in accelerator physics and simultaneously providing new tools for probing HEDLP systems.
  - ***How do radiation-dominated plasmas behave?*** Particle interactions (such as ion-ion collisions) control the behavior of ordinary plasmas, while in radiation-dominated plasmas, radiation controls heating, cooling, ionization, and pressure. This leads to novel phenomena such as radiative shocks, radiation waves, radiation pressure, and photon-controlled ionization. These laboratory phenomena are in turn connected to frontier areas of research in astrophysics, including black holes, gamma-ray bursts,

star formation, supernovae, molecular cloud destruction, and radiatively collapsed astrophysical shocks.

- ***What happens in high-pressure quantum matter?*** Classical physics describes the behavior of ordinary plasmas, but when high-pressure plasmas become sufficiently dense, quantum mechanics takes over. This leads to regimes that often involve very strong electrical forces and generate a novel interplay between density, pressure, ionization, radiation, and electrical properties. The behavior of this state of matter has relevance to giant planets such as the newly discovered exoplanets and Jupiter (and its associated magnetic bubble, which is bigger than the Sun) and may lead in the long run to innovative electrical and mechanical devices. Forming this state of matter may require the generation of energetic electrons, ions, and photons by processes that are themselves a challenge to understand.
- ***What happens in strong-shock-dominated HED plasmas?*** New laboratory phenomena arise in the presence of very-high-Mach-number shock waves that are strong enough to ionize solids. These include turbulence that overtakes shock waves, plasma jets that surround themselves with cocoons of warm matter that travel with them and bathe them in sound waves, and the turbulent destruction of molecular clouds by blast waves. These phenomena are connected to astrophysical turbulence, protostellar jets, molecular clouds, neutron stars, shock waves and their interactions, and to the dynamics that cause massive stars to turn inside out when they explode.
- ***What happens when plasmas go relativistic?*** When the electron temperature (expressed in energy units) exceeds the rest mass energy of the electron, or in other words when E is bigger than mc^2, the thermal and radiative properties of a plasma change dramatically. Electron-positron pairs are created spontaneously; their formation and annihilation plays a key role in the plasma evolution. The next generation of high energy, ultra-intense laser facilities will have the capability to create such pair-dominated plasmas for the first time in a laboratory setting. Experiments in this regime will allow us to probe physical conditions relevant to gamma ray bursts, accretion disks around massive black holes, and the magnetospheres of radio pulsars.
- ***How are elements made in dense plasmas?*** Ordinary nuclear physics creates reactions in which two chosen particles interact. NIF – by achieving ignition – will produce unprecedented conditions of dense nucleons where the interactions occur in a thermal environment, where interactions involving three particles could occur frequently enough to be studied, and where dense plasma effects such as screening could become important. Such conditions might enable unprecedented nuclear physics experiments investigating rare “multi-hit” events involving reactions from nuclei already in an excited state (from a previous interaction $\sim 10^{-12}$ s earlier), and thermonuclear reactions in dense, Fermi-degenerate plasma, relevant to the formation of heavy elements in exploding stars, stellar evolution, and the solar neutrino problem.
- ***How can one use coherent, nonlinear, collective processes to control HEDLP?*** The nonlinear responses generated by intense fluxes of particles or photons in HED plasmas can be harnessed to create and probe novel, self-organized, low-entropy states and their dynamics. These have applications controlling the HED plasmas and in medicine, chemistry, materials science, particle accelerators, and astrophysics. An example is the use of laser or electron beams to create plasma bubbles that in turn emit beams of electrons of nearly constant energy. The

production, transport, and interaction of these fluxes are all important: the challenge is to use the nonlinear response of the plasma to siphon energy from an incident beam into directed particle or photon fluxes of interest. As an example, ultraintense lasers can produce a “spray” of relativistic electrons that can, in turn, produce directed proton fluxes of use for radiation therapy.

- ***What novel magnetic regimes can be created****?* Most laboratory plasmas either have fast magnetic dissipation or a ratio of particle pressure to magnetic pressure far below one (1). Emerging facilities will be able to produce magnetized plasmas having slow magnetic dissipation and pressure ratios near unity, as does much of the universe. This will enable experiments relevant to the dynamo process that generates the solar magnetic field and to the dynamics of galactic accretion disks and galactic jets. The new facilities will also be able to create enormous magnetic fields more than a billion times as intense as the Earth's magnetic field. Atoms, plasmas, and shock waves all change their behavior significantly in such “astronomically large” fields. This is relevant to phenomena near the surface of neutron stars and the event horizon – the point of no return – around black holes.

❖ ***Ultrafast dynamics – catching reactions in the act***

Modern technology makes possible manipulation of matter on the smallest time and spatial scales, literally controlling atomic motion in molecules and solids. This atomic manipulation requires probing and control of matter under conditions of extreme pressure, temperature, and rates of change. The tools and techniques of HEDLP now open avenues of control and probing of atoms in ways not before possible. Because the time scales of atomic motion in chemistry and solid state physics are often femtoseconds (10^{-15} s) and spatial scales are angstroms, probes on time scales and at wavelengths not before utilized will be needed. HEDLP experiments can now produce the x-ray pulses with durations short enough to freeze frame atomic motion, with the wavelengths necessary to probe atomic spatial scales. In addition, intense lasers coupled with large accelerator-based light sources, such as 3rd generation synchrotrons or 4th generation x-ray free-electron lasers, will enable unprecedented probing of chemical reactions or rearrangement of atoms in technologically important solids. Future breakthroughs may lead to even faster probing, when the relativistic plasma behavior driven by the next generation of petawatt (10^{15} W) lasers makes possible attosecond (10^{-18} s) duration x-ray pulses. At this time scale, the motion of electrons in chemistry and solid state physics can be sampled. Furthermore, the techniques and states accessed with HED physics may lead to ways of modifying matter that are unlike any that can be accessed with current technology. Intense lasers can place several photons per unit cell in a solid or large molecule. This concentration of energy on fast time scales may lead to new phase changes or novel molecular configurations with potentially dramatic and unforeseen consequences. Furthermore, HED plasmas can be used to generate very intense pulses such of magnetic fields, x-rays, electrons, ions or even neutron bursts that can heat or affect matter in unexplored and potentially beneficial ways.

Building the community

Building a robust community of High Energy Density Laboratory Plasma (HEDLP) scientists outside of the NNSA national laboratories is essential for the future of the field of HEDLP. The central role that the intermediate- and large-scale NNSA facilities, built primarily for mission-oriented research and development, can play in advancing the frontiers of HEDLP science is clear. As such, is it important that a vigorous, highly capable user community for these facilities be established, building on the relevant experience and proposal mechanisms developed in established programs in the Office of Science, such as Basic Energy Sciences, Fusion Energy Sciences, High Energy Physics, and the Office of Advanced Scientific Computing Research. At the same time, it is necessary to nurture and expand the capabilities at universities and small businesses to generate and study scientifically exciting high energy density plasmas with smaller-scale laser, pulsed-power, and particle-beam facilities, at which novel ideas and diagnostic concepts can be rapidly tested. The successful ideas and diagnostic concepts can then "move up" to the appropriate larger-scale facility under the leadership of their experienced university/small business developers. Finally, it is important to emphasize that scientists and facilities at Office of Science laboratories such as LBNL and SLAC are also making significant contributions to HEDLP research.

Community-building requires critical support from the Office of Science for "discovery-driven" science through the sponsorship of user programs on the mission-driven facilities with the following characteristics:

1. Relatively stable, group level support at universities based upon experiments to be carried out at intermediate- and large-scale facilities or diagnostic devices that can be developed and fielded on those facilities;
2. Involvement of undergraduate as well as graduate students and postdoctoral associates in high-visibility projects connected to the national laboratory community;
3. Long-term support (subject to appropriate review) that would enable PI's to concentrate more on scientific discovery and less on survival;
4. Closer relationships between national laboratory scientists and the university and small-business scientific community; and
5. The possibility of nurturing and expanding HEDLP research at major research universities, including in physics departments.

While an important new element that is driving the excitement for an Office of Science-supported HEDLP program is the set of new NNSA facilities, community building should not be, and need not be, limited by the available time on the facilities at the national laboratories. The HEDLP community is able to carry out outstanding, exciting, creative HED science with relatively small-scale, flexible facilities at universities that are also very valuable for building a healthy HEDLP community. As such, the training of graduate students, postdoctoral research associates, and undergraduates in the methods of HEDLP, both experimental and computational, and the development of new young faculty members at major research universities in the HEDLP area, can also take place where relatively quick response, hands-on training and versatility are the major benefits, rather than accessing large volumes of the most extreme states of matter.

The workforce development issue raises the point that targeted efforts to facilitate the growth of the HEDLP Community are clearly called for. Such efforts could include, among other initiatives, graduate and postgraduate fellowships, annual HEDP summer schools focusing on the various facets of HED science, and a "Young Investigator" program to bootstrap the efforts of new young staff members (e.g., junior university faculty or laboratory staff).

Facilities, Program Structure, and Program Management

We are at the threshold of a new physics regime that can produce some of the most exciting science in the coming decades. The new NNSA HEDLP facilities, such as NIF, OMEGA EP, and Z-R, will enable this research to enter these new regions of high energy density, but no single facility can address all the scientific challenges presented. At the same time there are new capabilities being developed outside NNSA (e.g., LCLS, petawatt lasers) that also open up new horizons for this type of research. What is needed to make significant advances in this field is to develop a focused scientific program (within OFES) that addresses the most compelling scientific problems while strengthening the HEDLP community in the universities and the national laboratories.

To promote the growth of this community, DOE should hold a series of research workshops in specific HEDLP areas identified in this report. These workshops will allow the DOE to lay out the initial broad elements of a scientific program, including scientific objectives and estimated resource requirements. This can be followed by a national call for proposals in the initial program areas that will allow more detailed program elements to be identified. DOE can utilize its peer review process to identify the best proposals.

In order for HEDLP to thrive, it is essential to build an HEDLP science community, whose workforce 'pipeline' is anchored in universities. Given that academic science is largely based on the work of small collaborative research teams, it is critical that groups of this scale – that can address the important scientific questions and can help attract new students, postdocs, and faculty to this field – are supported by the projected funding levels. The scientific program must cover the needs of such teams for computation, local experimentation, target preparation, and eventual access to the user facilities.

DOE must also create governance models for all the NNSA HEDLP facilities (small scale to large scale) that allow appropriate access for the user community. While access to the facilities should be driven by peer-reviewed scientific merit, and compatibility with facility capabilities, facility directors should be given the flexibility to develop optimized schedules to accomplish all the priorities of the facility.

This approach is new to this field, although some user facilities (e.g., OMEGA) currently exist. The program managers in DOE and the scientists in the laboratories and the universities will have to exert strong leadership to allow this community to realize the tremendous benefits of this approach and take advantage of the new opportunities presented by the HEDLP facility advances.

Workshop Attendees

B. Afeyan (Polymath)
R. Betti (U. Rochester/LLE)
S. Binkley (DOE/SC)
R. Boyd (LLNL)
J. Browne (LANL-retired)
K. Budil (LLNL)
S. Cowley (UCLA)
R. Davidson (PPPL)
T. Ditmire (UT/Austin)
P. Drake (U. Michigan)
R. Falcone (UCB/LBNL)
J. Fernandez (LANL)
R. Fonck (DOE)
D. Hammer (Cornell)
M. Hockaday (LANL)
C. Joshi (UCLA)
S. Kahn (Stanford)
C. Keane (DOE/NNSA)
J. Kilkenny (GA)
J. Lindl (LLNL)
G. Logan (LLNL)
C. Mailhiot (LLNL)
R. McCrory (U. Rochester/LLE)
D. Meyerhofer (U. Rochester/LLE)
E. Moses (LLNL)
J. Peoples (FNAL-retired)
R. Petrasso (MIT)
J. Porter (SNL)
B. Remington (LLNL)
R. Rosner (ANL/UChicago)
R. Siemon (U. Nevada/Reno)
E. Synakowski (LLNL)
F. Thio (DOE/SC)
M. Turner (ANL/UChicago)
A. Velikovich (NRL)
G. Wurden (LANL)