BASIC RESEARCH NEEDS FOR HIGH ENERGY DENSITY LABORATORY PHYSICS

Report of the Workshop on High Energy Density Laboratory Physics Research Needs

November 15-18, 2009

U.S. DEPARTMENT OF ENERGY

The U.S. Department of Energy, Office of Science and National Nuclear Security Administration

On the cover:

Invisible infrared light from the 200-trillion watt Trident Laser enters from the bottom to interact with a one-micrometer thick foil target in the center of the photo. The laser pulse produces a plasma — an ionized gas — many times hotter than the center of the sun, which lasts for a trillionth of a second. During this time some electrons from the foil are accelerated to virtually the speed of light, and some ions are accelerated to energies of tens of millions of volts. In this time-integrated image, one sees many colorful plasmas that result from the collisions of energetic X-rays and particles with nearby surfaces. Various diagnostic devices located around the edge of the image are illuminated by the plasmas. The green light is caused by the second harmonic of the laser, and is produced by a nonlinear process taking place at the laser-plasma interface (see Chapter Four). Bits of debris from the target are seen as orange streaks of light, some of which ricochet from the surrounding environment, and some of which produce a colorful dance of twisted braids as they spin in flight. The Trident laser facility is one of the several nascent intermediate-scale user facilities discussed in Chapter 8.

Image courtesy of Joseph Cowan and Kirk Flippo, Los Alamos National Laboratory.

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Preface

The present report concerns research challenges and opportunities in the emerging field of high energy density laboratory physics, or HEDLP, which in the broadest sense is the physics of matter at ultra-high pressures and temperatures. In the past, such extreme states were produced on Earth mostly in nuclear weapons tests, and the results were classified. Since the moratorium on nuclear weapons testing and the development of the Stockpile Stewardship Program in the early 1990s, though, HEDLP has received broader attention in the United States, primarily due to a willingness on the part of administrators at the National Nuclear Security Administration (NNSA) to open up the science to the academic research world. The increased transparency has led to a concerted effort to make available to the scientific community at large the new experimental facilities originally designed and built for NNSA's stockpile stewardship mission, facilities that are both powerful and unique in the world.

Our report, commissioned by the US Department of Energy's Office of Fusion Energy Science, is known in the trade as a Research Needs Workshop, or ReNeW, report. We focus on defining the current status of HEDLP research, as well as on describing the opportunities and needs of the research community in this new area of physical science. HEDLP has emerged from astrophysics, laser and pulsed-power applications and nuclear weapons research, into an exciting, well-defined discipline of its own, with its own intellectual agenda and deep fundamental questions to answer. An extensive experimental infrastructure is by now in place, largely funded by the NNSA and its predecessor organization, the Defense Programs part of the Department of Energy (DOE). Also involved, however, is the DOE Office of Science, which intends to pursue forefront research in HEDLP and to push the boundaries of the extreme states of matter available for study to levels relevant to understanding the most energetic events in the cosmos.

Like many specialized fields of physics, HEDLP is riddled with jargon. Although it cannot be entirely eliminated, we have attempted to make the Executive Summary, the chapter introductions and illustrative sidebars as "low tech" as the subject allows. The body of each chapter is definitely more technical, but we anticipate that it will be accessible to physicists whose specialties lie outside of the subject matter of this report.

The emergence of a vigorous HEDLP research program is not only intrinsically intellectually exciting, but also enables a new era in which open science drives new areas of technology, especially those of high-power lasers, pulsed-power machines and particle accelerators, and advanced energy systems. Furthermore, the program will help develop the workforce needed for future national defense programs, including the continuation of the Stockpile Stewardship Program as long as it is needed.

A vigorous HEDLP research program that enables this field's promise will require:

- Reasonable competitive access by the academic community to the existing experimental facilities;
- Funding responsive to the proposal pressure now being experienced by the experimental facilities;

- Development of a strategic plan for needed future investments in both facilities and programs; and
- Open competitive access to state-of-the-art computing facilities and reconsideration of national security and export control restrictions on computational modeling, taking into account international HEDLP programs.

Because of HEDLP's historical ties to the US nuclear weapons program, there is an obvious question that deserves our attention: Is HEDLP really an intellectually distinct, fundamental sub-discipline within physics, or is it primarily an applications-driven program? This basic and important question has been addressed in a number of previous reports by the National Academy of Sciences (NAS) and US government agencies, which are listed below on pages v and vi. These reports make it clear that while there are important applications of HEDLP research, including stockpile stewardship, fusion energy and advanced accelerators, there are also many fundamental and intellectually compelling questions that can be addressed by HEDLP research. As such, we have not felt it necessary to be fully comprehensive in our own response to this question. In particular, the most recent HEDLP report (the Fusion Energy Science Advisory Committee's "Betti" report, listed on page vi) sorted through the many research areas within HEDLP and identified six priority areas. Since we fully subscribe to the findings in the Betti report, we feature the same six sub-disciplines of HEDLP in the present work.

We note, however, that because the current report focuses on future opportunities and research needs, rather than on what has already been published, we have included no references in the body of the text, except for a few explicit citations for figures and direct quotes. Numerous bibliographic references can be found in the reports just mentioned, listed on pages v and vi.

Procedural Background

The procedural background for our report is based on its charter[1], which was provided by the DOE's Office of Fusion Energy Science (OFES) Director, Dr. Ed Synakowski, and Director of the Office of Inertial Confinement Fusion and National Ignition Facility Project, Dr. Christopher Deeney. Technical Leads were Dr. Francis Thio for DOE/OFES and Dr. Dillon McDaniel for NNSA. Professors Robert Rosner of the University of Chicago and David Hammer of Cornell University agreed to chair and co-chair the workshop, whose organization and procedures have followed the Research Needs Workshop (ReNeW) concept pioneered by the DOE Office of Science.[2] Once the official charter was received in July 2009, the chair, co-chair and members of the OFES and NNSA technical program offices selected panel leads in early August, and a ReNeW meeting of panel leads took place later in August in Chicago. The entire workshop panel was in place and started its work around October 1, following the plan set out in the Office of Basic Energy Sciences (BES) manual on the ReNeW process.

[1] The charter and list of panel members is appended to this report as Appendix **A**.

[2] http://www.er.doe.gov

The charter specifically suggested that the workshop address the six scientific sub-disciplines identified by the Fusion Energy Science Advisory Committee (FESAC)-HEDLP Panel in 2009:

- High energy density (HED) hydrodynamics,
- Nonlinear optics of plasmas
- Relativistic HED plasma and intense beam physics
- Magnetized HED plasma physics
- Radiation-dominated dynamics and material properties
- Warm dense matter

We also recognized the need for cross-cutting panels in the areas of

- Computing
- Diagnostics
- Research infrastructure
- High-Z multiply ionized HED atomic physics.

The original six sub-disciplines suggested by FESAC plus the four cross-cutting topics led to the formation of 10 sub-panels of our ReNeW.[3]

In order to draw in the open science community as much as possible, we held a town meeting at the American Physical Society Division of Plasma Physics (DPP) meeting in early November 2009. The ReNeW itself was held November 15-18, 2009, in Rockville, Maryland, and we drafted the report from material received from panel leads between November 18, 2009, and February 1, 2010. The first outbrief took place at the FESAC meeting of March 9-10, 2010.

Robert Rosner, Chair

David Hammer, Co-Chair

Tony Rothman, Editor

Previous Reports on HEDLP

National Academy of Science (NAS)/National Research Council (NRC) report (Davidson): *Frontiers in High Energy Density Physics, The X-games of Contemporary Science* (2003).

NSTC - National Task Force on HEDP (Davidson): *Frontiers for Discovery in High Energy Density Physics* (2004).

Department of Energy (DOE)/Office of Science (SC) (Browne-Rosner): Summary of a Workshop on Opportunities for High Energy Density Laboratory Plasma Science (2007).

[3] An eleventh group, on connecting HEDLP research to other areas of physics and science in general, made contributions to all the sub-panels and to the Executive Summary.

NSTC/IWG (Kovar-Keane): Report of the Interagency Task Force on High Energy Density Physics (2007).

NAS/NRC report (Cowley-Peoples): Plasma Science - Advancing Knowledge in the National Interest, Chapter 3 (2007).

Office of Fusion Energy Science (OFES)/Fusion Energy Science Advisory Committee (FESAC) (Betti): *Advancing the Science of High Energy Density Laboratory Plasmas* (2009).

Reports Related to HEDLP Science

DOE/NSF: The Science and Applications of Ultrafast, Ultraintense Lasers: Opportunities in Science and Technology using the Brightest Light Known to Man (2002).

NAS/NRC report (Turner): Connecting Quarks with the Cosmos (2003).

Contents

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Executive Summary

Introduction

> *Plasma—The "fourth state of matter," in which the temperature is high enough that the electrons have been separated from their nuclei, leaving a gas of charged particles. (The atoms are said to be "ionized.") The majority of stars, and hence most of the visible universe, is composed of plasma. It should really be called "the first state of matter."*

We are fortunate to live at a time when rapid advances in physics and technology have allowed researchers to create conditions in Earthbound laboratories that previously existed only in the unattainable interiors of stars and planets. In such extreme environments—temperatures of millions of degrees and pressures of millions of atmospheres—matter displays surprising and exotic properties unknown in more ordinary circumstances. Matter may simultaneously act as both a solid and a gas of charged particles—a plasma—and insulators can be changed into metals. No known theory is fully capable of explaining such behavior. Yet advances in plasma physics, powerful lasers and pulsed-power machines have enabled exciting discoveries and detailed exploration of high energy density (HED) states of matter, and investigators in the nascent field of high energy density laboratory physics (HEDLP) are now capable of manipulating matter and energy at these extremes. In doing so, researchers are indeed able to study physical phenomena heretofore thought to be inaccessible in the laboratory.

The ability to create and control stellar conditions in a terrestrial laboratory establishes the long-sought connection between some of the most energetic events in the universe—such as supernova explosions—and energy production from controlled fusion on Earth. The cosmically extraordinary is connected through HEDLP research to providing a possible clean and inexhaustible energy resource for mankind. It should come as no surprise that a broad range of questions is thus raised in studies of HEDLP. They form a continuum from the most profound, addressing the very laws of nature themselves, to the most practical, dealing with the extraction of useful energy from matter under extreme conditions and with the development of compact, inexpensive sources of radiation for science, industry and medicine. It is truly exciting that we are now on the threshold of an era in which such questions may finally be answered.

I. The Important Questions of High Energy Density Physics

How does the exotic behavior of dense collections of electrons, ions and photons arise?

Exotic behavior abounds when pressures of millions of atmospheres are applied to solids. Such high energy density conditions can cause solids to flow, to change into liquid, gas or plasma. At pressures of millions of atmospheres and temperatures of millions of degrees, the energy density of the photons—particles of light—becomes high enough that they exert the dominant force on the matter. Well-organized structures appear from disorganized initial states. The conduction of heat and electricity changes dramatically. Any description of the behavior of matter under various high energy density regimes may have to take into account not only the effects of intense electric and magnetic fields, but also of relativity, quantum mechanics or statistical physics. To develop solid theoretical understanding, compelling experimental evidence and effective computational models of this regime is a grand challenge for physics of the present century. Moreover, as noted in the Introduction (page 1), exotic phenomena have been long recognized in the astrophysical context but were not heretofore accessible to direct experimental study. Now we can finally ask and hope to answer the question: Are long-established astrophysical models for such phenomena correct?

How does self-organization arise within high energy density matter?

High energy density plasmas—Always characterized by pressures in excess of one hundred thousand atmospheres, HED plasmas may have temperatures ranging from thousands of degrees to billions of degrees. While ordinary plasmas exhibit collective behavior resulting from well-understood electric and magnetic interactions, understanding HED plasmas require additional physics that depends upon the temperature: At low temperatures, HED matter exhibits properties of solids, liquids and gases as well as plasmas. At the high temperature extreme, particle speeds approach the speed of light and matter and energy become interchangeable, requiring the addition of relativistic physics.

Self-organization refers to the propensity of matter to produce well-ordered structures despite the general tendency of systems to become disorganized—the famous increase in entropy. In the presence of a high-power laser beam, these self-organized structures can form in HED plasmas and constantly evolve to sustain themselves. When the laser is turned off, they quickly dissipate. An example of such a structure that was predicted theoretically and has been seen in the laboratory is made up of a mixture of waves that are simply never seen in ordinary plasmas. An intriguing possibility of self-organization would be the “helium rain” that may occur within the hydrogen cores of giant planets. Such states have enormous potential to generate novel practical applications, such as to suppress undesirable waves in fusion-energy devices or to channel energy where needed in a particle accelerator or light source. When present in extreme form in nature, self-organized states may be responsible for unexplained astrophysical phenomena.

Can intense transient flows of energy and particles, unconstrained by conventional material limits, be manipulated and controlled?

A key step beyond understanding the physical principles of HED matter and energy is the control of the detailed plasma and photon physics—that is, manipulation of HED plasmas to produce unique states of matter and energy. We might want to do this to understand fundamental HED plasma physics or to achieve a specific application. In pursuit of fundamental understanding, we could explore how HED plasmas respond to intense fluxes of particles or photons, and as a result investigate whether we can create and control novel, self-organized plasma states. In pursuit of practical applications, we could produce novel energetic particle and light sources brighter than today’s, which are limited by material damage. This limitation exists because intense light degrades mirrors and lenses, and excessive voltages damage metallic structures. Fortunately, the collective action of particles and photons in HED plasmas bypasses those material limits, enabling the direct manipulation of energy and matter at unprecedented intensities. The key is to force the plasma to siphon energy from an incident high-power laser or particle beam into the desired, and possibly even higher-power, particle or photon beam. Such research has already led to doubling the energy of a high-energy electron beam in less than a meter—whereas three kilometers was required previously for the same energy gain. This particular advance is expected to have direct applications in accelerators and high-energy particle physics; it also could lead to a wide range of novel, compact, and inexpensive sources of particles and light for science, industry and medicine.

Can the interactions of matter under extreme conditions be controlled to enable practical inertial fusion energy?

Ion—In plasma physics, an ion is an atom with at least one electron removed. A plasma—an ionized gas—therefore consists of ions and electrons.

An imperative for modern civilization, driven largely by the combination of sharp increases in worldwide consumption of energy resources and concerns regarding global warming, is the development of new energy sources with minimal environmental impact. Developing the science of HED plasmas in the laboratory is a cornerstone for a promising approach to such an energy source, popularly known as laser fusion, but called inertial fusion energy (IFE) within the scientific community.[4] HEDLP research will create the scientific foundation for developing scenarios that could facilitate the transition from laboratory fusion experiments to inertial fusion energy. The science issues critical to inertial fusion energy cut across a wide range of fundamental HEDLP research: We require improved knowledge of the relationship between temperature, pressure and density under a broad range of extreme conditions relevant to fusion; improved knowledge of the effects of embedded magnetic fields; and a better understanding of the properties of ultra-high-intensity ion beams and their interactions with HED matter. This makes HEDLP an outstanding example of the principle that broad fundamental research is an essential component of the effective development of practical technologies.

What can we learn about the cosmos by creating cosmic conditions in the laboratory?

The foundation of astrophysics is the premise that physical laws governing processes on Earth are identical to those elsewhere in the cosmos. Many of the most interesting and exotic astrophysical phenomena, however, from stellar explosions to accretion of matter into black holes to the evolution of planetary interiors, occur under conditions of matter and energy that previously could not be probed in terrestrial laboratories. And so, the fundamental premise of astrophysics could not be fully verified—until now. The new generation of high energy density laboratory plasma experiments places us at the frontier of a new regime in physics: qualitatively new phenomena emerge when the energy density exceeds roughly a million atmospheres. Such conditions establish the deep connections to astrophysical phenomena touched on in the Introduction, from star formation to stellar nucleosynthesis to black hole dynamics. Laboratory

[4] In fact, ion beams and intense X-ray sources from pulsed-power machines are also possible power sources for IFE.

experiments probing such matter will provide direct means of quantitatively probing the physics governing astrophysical processes—processes that have been otherwise inaccessible to experimental study. This confers the ability to develop a vastly improved understanding of the fundamentals of cosmic evolution, including the formation of Earth and other planets.

II. The Special Nature of the Field of High Energy Density Physics

Connections between HED science and other fields of physics

Given its historical development, the discipline of HEDLP has understandably deep connections with a number of other physics sub-disciplines. In the case of ordinary plasma physics, which concerns comparatively lower-energy-density plasmas, connections occur on many levels—a shared vocabulary, related diagnostic and experimental analysis techniques, common theoretical frameworks and methods of analysis, and related computational modeling techniques. But plasma science is not the only closely related physics sub-discipline. Consider these instances in which HEDLP science supports other physics sub-disciplines:

- Warm dense matter (WDM) lies at the juncture of condensed matter and dense plasmas at 100,000 atmospheres or more. The study of WDM has opened new vistas in chemistry under conditions of high temperature and high pressures, and is an enabling basic science underpinning planetary physics.
- Ultra-high-intensity laser-plasma interactions may enable ultra-high-field accelerators, one of the possible routes to decreasing the cost of future generations of accelerators beyond the Large Hadron Collider, for particle physics at high energy.
- HEDLP environments are allowing experimental studies of many phenomena relevant to astrophysics, phenomena that were previously unconstrained by astrophysical observations yet are essential to building astrophysical models.
- The achievement of ignition at the National Ignition Facility (NIF) may lead to a major transformation of the US energy portfolio and affect both national energy policy and strategies.
- The extremely bright neutron source that will result from ignition at NIF will complement the use of heavy ion accelerators by the nuclear physics community to study previously unexplored nuclear reactions and novel isotopes.

In other cases, sister sub-disciplines of physics have served an essential role in building HEDLP science:

- Atomic physics is the fundamental enabler for much of the diagnostics carried on in the HEDLP realm.

- The development of ultra-high-power lasers has played an essential role in building HEDLP. Internationally, the needs of HEDLP are pushing forward the frontiers of these very same lasers.

The elephant in the room: The relationship between HEDLP and the nuclear weapons program

It is possible to see the ultimate origins of HED physics in the research of physicists attempting to explain the internal structure of dying or dead stars in the 1930s, most prominently by Hans Bethe and Subrahmanyan Chandrasekhar. Nevertheless, the majority of advances in HED physics over the past 60 years have emerged from research related to the development of nuclear weapons. The connection has had a number of consequences for the development of HED physics, among which arguably the most important have been the following:

- Until recently, *national security classification of virtually all aspects of this science has resulted in a very significant restriction on the flow of scientific information*. This remains a problem in some areas of HED science in the US, including radiation transport and fundamental properties of matter under HED conditions. The very active HEDLP research community in Europe, which includes active participation by scientists from Asia, is far less constrained by such restrictions, placing US researchers at a significant disadvantage.

- *Significant differences in approach are perceived by the academic community between weapons-related research and open scientific research*. The former is driven by practical needs to accomplish specific missions, while the principal driver of the latter is to achieve a fundamental understanding of natural phenomena.

- *There are also significant differences in how research results are valued*. Such disparities are again rooted in the divergent outlooks of weapons versus open scientific research: "If we can understand things well enough to accomplish our mission, then we have done our job well," in contrast to the search for a fundamental theory sufficient to explain all extant observations.

As a consequence of these three core issues, information exchange between the classified and unclassified HED science programs has been hugely hampered, to the detriment of both branches of the HED science community, as well as to the science itself. The classified programs have made enormous strides on both the experimental and theoretical levels, advances that are only slowly diffusing out to the unclassified HED science community. Unfortunately, the classified HED programs have not benefited from the inventiveness and free-wheeling vigor of unclassified research as practiced in research universities. As a consequence, both sides have suffered from the (obviously needed) barriers imposed by national security concerns.

No one is under the misimpression that a vigorous, unclassified HED program will mean wholesale dismantlement of the current barriers imposed on information flow out of the classified HED programs. We nevertheless believe it is important to recognize that the weapons program, and in particular the Stockpile Stewardship Program of the National Nuclear Security

Administration (NNSA), will likely benefit in a number of ways as a result of the development of a vigorous unclassified HEDLP research program that enhances the Joint High Energy Density Laboratory Plasma Program recently established in the Office of Fusion Energy Sciences. Benefits to NNSA of enhancing this program potentially flow from

- The substantial increase in scientists well-versed in HED science and
- The harnessing of open science capabilities not previously engaged in HED research to attack long-standing barriers in computing, diagnostics and theory.

A potential further complication is that tools important to HEDLP research may at times be subject to export control in the US, even when the international community is already doing more advanced research than the US work that is restricted. In particular, all of the computational methods useful in HED physics that are subject to export control in the US are actively under development or in use by the international scientific community. Export controls also dampen the enthusiasm of the best young university faculty to participate in the research if they can do something else equally exciting. As export control issues are revisited over the next few years, perhaps attention will be given to the extent to which they penalize US HEDLP researchers and research programs, including strategically important ones, while leaving comparable competing research programs abroad unfettered.

Finally, we note the obvious: the discussions in this report do not directly address the needs of the Stockpile Stewardship Program—nor could they, nor should they! The Stockpile Stewardship Program has its own unique technological justification, its own funding stream, and its own review processes and administration, and that is as it should be.

III. The Sub-disciplines of High Energy Density Laboratory Physics

The questions posed in Section I above show that the field of high energy density laboratory physics has a remarkably broad span. It encompasses a number of distinct sub-disciplines driven by their own unique enigmas posed by nature. Each of these subjects is in turn deeply connected to other physical science areas, which are not formally part of HED science, but from which the field of HEDLP originally emerged. It is only in recent years that we have recognized all these sub-disciplines as both distinct and united under the umbrella of HEDLP.

The remainder of this report is devoted to an exposition of these subjects. We

- Report on their current status;
- Detail some of the key new results, as well as the research opportunities and needs that are evident as a consequence; and
- Set each sub-discipline in the context of the importance of these research directions, given the intrinsic interest of the fundamental science, opportunities for applications and connections to other physical sciences.

Before delving into the details in the main body of our report, we provide a brief, high-level overview of each sub-discipline, giving the reader an indication of the exciting science that is only now beginning to be opened up to public scrutiny. The Joint HEDLP Program has the opportunity to substantially broaden the work in progress in all of the HEDLP areas, as we describe briefly here and in more detail in Chapters 1-6.

HED hydrodynamics

How is hydrodynamics altered by the distinct properties of high energy density systems? Can understanding HED hydrodynamics help to control HED plasmas in the laboratory and increase our understanding of cosmic phenomena?

Hydrodynamics—Literally "the dynamics of water," but as scientists use it, the physics of any fluid. Hydrodynamics describes the behavior of fluids under the action of forces, which generally requires calculation of the fluid velocity, density, pressure and related quantities, such as entropy.

In high energy density situations (for instance, stellar interiors and the conditions needed for IFE), plasmas share many of the properties of a fluid, and consequently their behavior is largely encompassed by the science of hydrodynamics—the study of fluids. Understanding the hydrodynamics of HED plasmas is crucial to making inertial fusion a long-term energy source on Earth, as well as to describing the structure of the Sun and the planets in our solar system, the dynamics of stars, supernova explosions and other extremely high energy phenomena in the Milky Way and elsewhere. In short, an understanding of HED hydrodynamics is necessary to explain the most energetic phenomena in the known universe, and the ability to manipulate the dynamics of HED plasmas is essential for achieving a limitless practical energy supply by means of inertial fusion energy.

HED hydrodynamics, however, is far more complex than the hydrodynamics of ordinary plasmas. Solid materials that are subject to one million atmospheres of pressure or more and heated to a few thousand degrees are governed by the laws of condensed matter even as they begin to flow and ionize. When the temperature exceeds one million degrees, the usual electric and magnetic forces are supplemented by the pressure exerted by photons, and plasma motion can be dominated by this radiation pressure. The transport of energy by radiation or particles can become much more complex than the ordinary transport of energy by the bulk motion of matter or the kind of heat conduction that occurs when you heat one end of a piece of metal and the other end becomes hot shortly afterward. Further complexities arise due to the impulsive generation of many interesting HED plasmas, which leads to extremely strong shock waves, and due to the spatial variation of the plasma properties, the behavior of the waves in these plasmas, that normally act like sound and water waves can be substantially altered. To date, our understanding of the complexities of HED hydrodynamics is incomplete.

Magnetized HED plasma physics

How are magnetic fields created, and how do they evolve and affect the properties of HED plasmas?

Magnetic fields are ubiquitous in nature, yet our understanding of their origins and of their interaction with matter remains very limited. We do know that magnetic fields can change the fundamental properties of HED plasmas in ways that bring significant rewards as well as significant challenges. When magnetic fields strongly influence the motion of charged particles, the transport of energy within a plasma can change completely. If strong shock waves are driven into a magnetized plasma, charged particles can be accelerated—this process is thought to be the principal source of cosmic rays, the highest-energy particles known in the universe. Magnetic fields could also facilitate the achievement of ignition and the development of practical IFE by improving the energy and particle confinement in a reacting fuel capsule.

Pulsed-power machines—A class of devices designed to deliver a huge electrical power by discharging up to 27 million amperes of current into a dense plasma load. In the case of Sandia National Laboratories' Z machine, the current is delivered for 100 billionths of a second, creating over 50 trillion watts, 50 times the electrical capacity of the entire US. The large currents produce extremely strong magnetic fields, which in turn implode the plasma, thereby generating HED conditions.

Rapidly increasing magnetic fields can easily produce hot, dense plasmas that consist of high-atomic-number materials, such as tungsten, which are efficient radiators of X-rays. Thus, magnetically driven HED plasmas can be a highly effective method for converting magnetic field energy into X-ray energy. The magnetic forces produced by the latest generation of pulsed-power machines can be large enough to compress a plasma to pressures of millions of atmospheres, a state of matter not found naturally on Earth but seen in many large celestial bodies. Magnetically compressed tungsten plasmas have already become a workhorse, providing an X-ray source for a number of other HED plasma experiments, including measurements of the optical properties of matter, studies of radiation-dominated hydrodynamics, and materials testing. The science of fusion-grade HED magnetized plasmas, laboratory modeling of dynamical astrophysical phenomena and creation of extreme states of matter define the core of magnetized HED plasma science, while simultaneously providing major linkages to other physical science disciplines and to practical applications.

Nonlinear optics of plasmas

How does high-intensity radiation modify the behavior of high energy density plasmas?

High-powered lasers can create ultra-dense plasmas that display many new and novel properties. Laser light is said to be coherent because the wave crests of all of the component waves march in lock-step, in contrast to the random timing of crests in light waves emitted by ordinary light bulbs. Intense coherent light impinging on a plasma not only shapes the plasma, but can cause it to self-organize into states in which the particles execute complex but highly ordered motion.

The plasma in turn can focus, create and steer radiation, indeed producing light at new frequencies. This complicated response of plasmas under the action of coherent light is called the nonlinear optics of plasmas.

Nonlinear—Colloquially, a simple system is linear, while a complex system is nonlinear. More technically, in a linear system the response of the individual components is independent of the input to or the response of the other components. In a nonlinear system, components interact with each other and cannot be treated separately. This makes the treatment of nonlinear systems very difficult. Nonlinear systems can exhibit such properties as chaotic behavior and self-organization.

Meeting the challenges posed by strongly nonlinear HED plasmas requires us to examine phenomena spanning length scales of less than one micrometer to one centimeter, and time scales spanning a millionth of a nanosecond to microseconds. Until recently, such capabilities exceeded technological limits, but laser and diagnostic capabilities now enable researchers to achieve the required resolution. This capability points the way to new experiments, simulations and theories that will provide quantitative understanding, and potential control, of nonlinear optical phenomena in HED plasmas. Apart from the exciting opportunity of simply discovering how nature will allow us to manipulate HED plasmas, such control has practical importance to fields as diverse as the creation of inertial fusion energy, the understanding of astrophysical pulsar and quasar behavior, and the development of new laser and accelerator technologies for science, industry and medicine. Self-organized states could prove to be one of the most fruitful research paths in this field, both because of the novel fundamental science likely to be discovered and its potential applications.

Radiation-dominated hydrodynamics and material properties

How is the behavior of HED plasmas altered in the radiation-dominated regime, and how do HED plasmas alter the propagation of radiation?

Under certain conditions—found in the early universe, the interiors of stars, stellar and nuclear explosions, and terrestrial fusion energy experiments—the energy inherent in radiation may be comparable to or exceed the energy of motion of the matter itself. When the energy of the radiation is so high that it, as opposed to the particle energies, controls the behavior of the system, we say that the dynamics are radiation-dominated. For example, radiative processes are involved in the birth, life and death of stars, notably just before and during supernova explosions, which are responsible for the generation of the chemical elements—a process necessary for life. Studying radiation-matter interactions under such extreme conditions is also central to achieving breakthroughs in fusion energy research, and once fusion ignition is achieved, it will in turn offer the promise of creating even more energetic environments for HED experiments. It is in this sub-discipline of HEDLP that the limited availability of open-source simulation tools, a situation exacerbated by the export control issues discussed above, combined with restricted access to large computers, has had the most significant impact on scientific progress within the US.

Relativistic HED plasma physics and intense beam physics

How do plasmas dominated by relativistic effects behave?

When particles travel at nearly the speed of light, we know that the traditional physics of Newton is inadequate to describe their behavior. Instead, one must invoke Einstein's theory of relativity for a proper accounting. Modern laser facilities commonly create such high temperatures that the plasma particles become relativistic. An extremely intense particle beam from an accelerator directed onto a plasma will also cause it to become relativistic. When relativistic effects dominate the behavior of a plasma, they lead to substantial changes in the relationship among the temperature, pressure and density that would normally hold in ordinary, nonrelativistic matter.

Relativistic effects can also lead to conditions in which the plasma is far from equilibrium, a state that is inherently subject to rapid change in complex ways. The physics of far-from-equilibrium plasmas is incompletely understood, both because of the complex behavior and because researchers have just scratched the surface in this area of research. Nevertheless, a more complete understanding is critical to the many applications that may in the future flow from this subject area. Among the practical applications are ultra-intense particle-beam and light sources, and the novel approach to fusion energy known as fast ignition (see Chapter 5). Progress in the area of HED relativistic plasmas will also improve our understanding of the extreme physical conditions observed in the high-energy universe, particularly of the various mechanisms by which high-energy particle beams are generated and accelerated. With the advent of new, much more powerful lasers, we expect to create extreme relativistic plasmas that display conditions never before encountered. Comprehending observed phenomena under those conditions, whether predicted by existing theoretical and computational capabilities or not, will be a challenge.

Intellectually, the most exciting prospect may be that at the highest laser intensities we will be able to probe the interaction between light and the quantum vacuum through which it often propagates. In ordinary circumstances photons do not interact with each other or with the vacuum in any observable way. However, the fundamental theory of interaction between light and matter, quantum electrodynamics, predicts that at extreme laser intensities such interactions should manifest themselves in the form of the creation of matter—electron-positron pairs—seemingly out of nothing. It will be an exciting journey to see what surprises are in store for us as we try to reach such high intensities.

Warm dense matter

What are the material and transport properties of warm dense matter?

The study of warm dense matter—matter that is neither solid, gas, liquid nor plasma, but can have properties of all four—lies at the heart of questions raised about the nature of our planets: What physics underlies the formation of planets? Why is Saturn so warm, and why does Jupiter have such a large magnetic field? Can we relate the birth of a star to the path to fusion in the laboratory? What new chemistry emerges when high pressures and temperatures force electrons from inner orbits onto outer orbitals where they may interact with other atoms? Other interesting questions relate to fundamental properties of matter at millions of atmospheres of pressure: How does an insulator, in which electrons are bound to a nucleus, become a metal, in which electrons are free to travel from one nucleus to another? What new phenomena emerge when nuclei, free electrons, and photons are compressed so highly that they have energy densities comparable with those of molecules and atoms? While planetary science is a natural and grand backdrop for discussions of WDM, the same conditions are found during the implosion of inertial confinement fusion capsules, in industrial applications such as laser drilling of metals, and in a wide range of HED laboratory experiments.

Like much of HED science, WDM science is defined by a departure from well-established disciplines, and as a consequence, the boundaries of WDM are far from sharp. Depending on the materials involved, one must take into account not only the classical electric forces that bind atoms to one another in solids and liquids, but so-called degeneracy pressure, a purely quantum mechanical phenomenon that arises when matter is compressed to high densities. At the same time, temperatures are high enough in WDM that electrons are on the verge of separating from their nuclei, creating a plasma. Because all these effects are equally significant, generating an accurate model of warm dense matter is a difficult task. Substantial progress has been made in our understanding during the roughly ten years since WDM was identified as a field in its own right. The emergence of new experimental platforms, the continuing development of more capable computers and the fertility of the computational and theoretical landscape, all suggest that the next generation of WDM research will be very fruitful.

IV. Cross-cutting Subjects of High Energy Density Laboratory Physics

Aside from the core sub-disciplines of HEDLP just discussed, the success of the nascent field of HEDLP involves infrastructure (experimental and computational facilities) and diagnostic instrumentation, as well as developments in other physical science areas—atomic physics, computational physics and nuclear physics. The health and vibrancy of these areas, while essential to HEDLP, are not solely determined by progress in HEDLP. For this reason, we discuss the essential cross-cutting elements for HEDLP's future separately.

High-Z atomic physics

As its name implies, atomic physics is the fundamental science that concerns the physics of atoms as a whole; in particular, it concerns the behavior of the electrons orbiting the nucleus and their interactions with the nucleus itself. Bulk properties of materials are largely determined by atomic physics, as is the interaction of radiation with atoms. The theoretical framework for atomic physics is quantum theory, which accounts for atomic properties; indeed, the observed behavior of atoms served as the earliest tests of quantum mechanics. A great many of the most interesting HEDLP experiments are carried out at least in part with high-atomic-number, or "high-Z," materials.[5] This is certainly the case for the intense radiation sources employed in the

[5] "Z" is the standard abbreviation for atomic number.

so-called "indirect drive" ignition campaign now under way at NIF. The complicated nature of high-Z atoms at extreme densities makes their atomic physics and application to HEDLP a unique and complex sub-discipline. Achieving an understanding of high-Z atomic physics is essential to designing "well-posed" HEDLP experiments and diagnostic instruments, and to analyzing the data obtained from them. This is equally true of HED plasmas produced by lasers, pulsed-power machines and intense heavy-ion beams.

On a more fundamental level, understanding high-density high-Z atomic physics will allow us to describe a wide range of phenomena, from accretion disks around black holes to laboratory X-ray lasers to the plasmas that may one day yield unlimited clean fusion energy. Other potential applications include therapeutic and diagnostic applications of intense pulsed plasma X-ray sources in medicine, improvements to plasma televisions, and the use of bursts of radiation from high-Z materials in the manufacture of future generations of electronic components.

Direct vs. indirect drive—The "direct drive" approach to inertial fusion energy utilizes lasers or heavy ions to implode the fusion fuel capsule by directly irradiating its surface. A very high degree of beam uniformity is required in this approach. In order to ease the uniformity requirements, "indirect drive" IFE involves first converting the energy from a large number of lasers or ion beams into a uniform bath of X-rays inside a small cylinder made of high-Z material. The X-rays, in turn, irradiate a spherical fusion fuel capsule so that it implodes symmetrically. In both approaches the resulting high density and temperature ignites fusion reactions, which yield much more energy than the incident laser beams supplied.

Experimental infrastructure

To fulfill the promise of HEDLP to provide great science and attract some of the best young research scientists to the field requires a healthy and vigorous research program that takes full advantage of the world-class experimental facilities available in the US. This suite of facilities ranges from university-scale laser and pulsed-power machines up to the largest power and energy facilities in both of these categories in the world: NIF (an NNSA facility at Lawrence Livermore National Laboratory) and the Z-machine (an NNSA facility at Sandia National Laboratories, Albuquerque). The laser facilities also include the brightest X-ray free-electron laser facility in the world, the Linac Coherent Light Source (at the Department of Energy's SLAC National Accelerator Center), a user facility soon to have an end-station dedicated to HEDLP experiments. Only one of the many NNSA-HEDLP facilities is currently operated as a user facility, the OMEGA laser at the University of Rochester. Assuring access to even the largest facilities, as well as providing sufficient resources in the Joint HEDLP Program to enable their use for a broad range of HED physics experiments, is essential to the long-term productivity of the field and the development of a new generation of HED scientists. The HEDLP field would greatly benefit from developing user facilities at as many of the intermediate- and large-scale NNSA facilities as possible. A successful HEDLP facility also requires dedicated computational facilities for HEDLP experimental design and analysis (see Computing, below) and a full suite of diagnostic capabilities (see Diagnostics, below). Finally, we note that the power and intensity required to explore the most interesting physics regimes are always a factor of ten or one hundred beyond what can be produced at the current moment. Therefore, it is important to develop a prioritized program plan, based upon predicted research opportunities, for the design and construction of future facilities.

Diagnostics

Because of the extraordinary physical conditions encountered in HED physics experiments, the design and deployment of appropriate diagnostic instrumentation and the development of new measurement techniques face challenges that are no less extraordinary. In the HED environment, experiment and diagnostics merge: the design of the experiment and the measurements to be made, the interpretation of the diagnostic data and the physics revealed by the experiment, must all be considered in an integrated way. What we can observe and measure is often several steps removed from the underlying mechanisms of interest, and the steps must be filled in with computer simulations that are themselves at the edge of our capabilities. Making sense of the measurements depends on our ability to model the complex physical interactions at these extreme conditions—and at the same time, development and validation of the computer simulations depends on the measurements! High value is thus conferred on diagnostics that act independently of simulations but, usually, validation and deployment of diagnostics is necessarily an iterative process. For example, if one wishes to determine the properties of a plasma by its emitted X-ray spectrum, one must design the experiment so that the plasma will allow the X-rays to escape. When the data are actually collected, one must determine whether the inferred conditions in the plasma are consistent with the assumptions made in the experimental design. If not, the conditions must be recalculated in an iterative process until the observed spectrum and the inferred plasma properties are self-consistent.

In spite of such difficulties, diagnostics remain the heart and soul of scientific discovery. From the earliest spectrometers, which break sunlight into its component parts, to the most advanced gamma-ray detectors, diagnostic instruments have revealed a universe far beyond what human imagination had contemplated. Not surprisingly, HED diagnostics are revealing with each improvement new regimes of matter and new enigmas posed to us by nature, just as new generations of telescopes have time and time again revealed new phenomena in the universe. Because we carry out this work in the laboratory, and have control over the experimental conditions, we are able to manipulate and probe nature in ways that astronomers and astrophysicists cannot. We can also repeat experiments again and again. The diagnostic challenge for HED laboratory physics is nevertheless enormous: As mentioned in "Nonlinear Optics" above, we deal with an extraordinary range of spatial and time scales. The temperatures and densities also span many orders of magnitude. Existing diagnostic tools are often incapable of encompassing such wide ranges and, consequently, some phenomena we believe to be important for understanding macroscopic behavior of HED plasmas have as yet escaped our grasp. In order to enable HEDLP to fulfill the potential established by the facilities described above, it is important to proactively support the community-driven development of novel and advanced diagnostics.

Computing

The design, analysis and interpretation of experiments, as well as developing predictive theory of high energy density physics, depend critically on computer modeling and simulations. As is the case in many other physical sciences, computations have become a powerful symbiotic tool, complementing both theory and experiments: Simulations allow the "virtual" exploration of complex theoretical models, while theory guides the development of the computational tools that form the basis for simulations. By the same token, simulations steer the design of experiments, while experiments inform and direct the design of simulations that should have the greatest impact on the field. Computer modeling and simulations also drive discovery—they test new theories and can be used to explore physical phenomena in regimes that are difficult, and at times impossible, to access experimentally.

Simulation programs and computing platforms have become an essential aspect of the HEDLP support infrastructure. However, a complication has been that much of the infrastructure supporting academic computing—from support for applied mathematics and computational science to advanced computer hardware—is managed and funded through federal program offices that do not have a direct link to HED science, while computer-based modeling of HED plasmas—in both the open science and the classified realms—has been primarily managed and funded by the weapons program. As a result, building a sustainable open-source computational science infrastructure for HED science that matches the research culture prevalent in academia is proving to be a challenge. Close and careful coordination between open science and scientifically related classified programs will be essential to make substantial progress in this area.

Chapter 1: High Energy Density (HED) Hydrodynamics

How is hydrodynamics altered by the distinct properties of high energy density systems? Can understanding HED hydrodynamics help to control HED plasmas in the laboratory and increase our understanding of cosmic phenomena?

Introduction

How can we understand and create the power of the stars in the laboratory? Can we develop inertial fusion energy to turn that achievement into a limitless practical energy supply for Earth? What are the conditions in the interiors of the largest planets in our solar system, Jupiter and Saturn? The answer to each of these questions requires understanding the behavior of ionized gases—plasmas—at pressures in excess of one hundred thousand atmospheres and temperatures ranging from thousands to billions of degrees. In other words, we need to understand and learn how to manipulate the dynamics of high energy density (HED) plasmas.

To a large extent, plasmas behave as ionized fluids, and therefore understanding the hydrodynamics—the physics of fluids—of HED plasmas is crucial not only to making fusion into a long-term energy source on Earth, but also for describing the state of matter and the dynamics of the Sun, the planets, the stars, supernova explosions and other extremely high-energy phenomena that we observe in the Milky Way and other galaxies. The hydrodynamics of HED plasmas underpins many of the other topics of this report.

Grand Challenge for HED Hydrodynamics: How Do We Understand and Recreate the Power of the Stars in the Laboratory in Order to Provide Limitless Energy?

To see more vividly how HED hydrodynamics figures in the quest for fusion, as well as the challenges facing the endeavor, imagine taking the output of the entire global power grid for a few billionths of a second and focusing it in the form of a laser beam onto the surface of a hollow capsule no larger than a pea. Next, imagine filling the capsule with the fuel of fusion reactions, the two heavy isotopes of hydrogen (namely, deuterium and tritium), and then sitting back to "watch the action." Under the intense laser light, the capsule implodes at velocities of up to one 400 kilometers per second. At peak compression, the capsule's core achieves temperatures of 100 million degrees Centigrade and the fuel density reaches 160 times that of water, with pressures approaching 500 billion atmospheres. Such enormous pressures, equivalent to the weight of five hundred aircraft carriers balanced on a finger tip, exceed those found at the center of the Sun. Matter at such high pressures is confined for less than one billionth of a second by its own inertia, hence the terms "inertial confinement" and "inertial confinement fusion" (ICF) for this approach to creating fusion energy. Not surprisingly, the outcome of the violent compression is a "microsun" that within a few billionths of a second releases a large amount of fusion energy in an explosion equivalent to a few hundred pounds of dynamite. At least, that is the outcome if we can understand and control the hydrodynamics of the implosion and avoid dangerous hydrodynamic instabilities that would disrupt the process before fusion takes place.

Harnessing fusion energy in the laboratory has been a scientific quest since the 1950s. Most research has focused on use of magnetic fields to confine a low density, hot plasma in a donut-shaped chamber called a "tokamak." In contrast to magnetic confinement, the HED approach to fusion, as we have just illustrated, exploits inertial forces in order to recreate for a brief moment the stellar energy source itself. This is the challenge of the ICF program in the United States. It provides the focus for a great variety of fundamental research, with the hope and expectation that it will prove to be the basis for a clean and unlimited energy source. The half-century quest for a laboratory demonstration of controlled fusion energy is expected to reach the major milestone of ignition within the next few years at the National Ignition Facility (NIF). Ignition in the ICF case means that the ratio of fusion energy released to laser energy absorbed in the "hohlraum" (see sidebar, page 17) equals or exceeds unity.[6] This will be a profound scientific achievement because it will take matter from near absolute zero temperature and solid density to conditions hotter and denser than those at the center of the Sun.

An understanding of extreme states of matter is equally crucial for exploring violent phenomena occurring in the distant universe. Consider the fate of a star five times more massive than the Sun. After living a recklessly "fast-paced" life that lasts less than one percent the life of stars like our Sun, the central core, by then rich with heavy elements like iron because of fusion reactions, gravitationally collapses to form a neutron star in a matter of seconds. Like a super-strong rubber ball springing back after having been squeezed to a tiny fraction of its original radius, the core rebounds and triggers an unimaginably strong shock wave that blows the star apart in an explosive fireball. A supernova has just been created. Today, fundamental supernova physics can be studied in the laboratory because the laws of hydrodynamics governing the "very big" and the "very small" allow physicists to scale the astrophysical environment to laboratory experiments. We call this field of scaled HED laboratory astrophysics "LabAstro." Developing properly scaled LabAstro experiments is one of the challenges of HED hydrodynamics.

How does HED hydrodynamics differ from ordinary hydrodynamics? Hydrodynamics, the science of the mechanics of fluids, has been studied since the ancient Greeks and was formalized in 1883 by Osborne Reynolds in his landmark work on turbulence. The fluids that Reynolds' treatment encompassed—ordinary liquids and gases commonly encountered in both the laboratory and the terrestrial surface environment—tend to have constant or slowly varying density, are typically not ionized (i.e., are neutral), and have constitutive properties such as viscosity and thermal conductivity that vary smoothly with the fluid's physical properties.

The hydrodynamics of HED plasmas, however, involves vastly more extensive and complex physics. The flows of plasma are often formed by strong shock waves that can easily ionize the gas. Large surface pressures can accelerate the plasma to supersonic velocities, and it can have huge spatial variations in density. Perhaps most seriously, HED plasmas are also susceptible to rapidly growing hydrodynamic instabilities, alluded to in the description of inertial confinement fusion above, that can shred the plasma into narrow filaments or generate small-scale turbulence that violently mixes the constituents. Bizarre regimes exist in which the material is still solid, yet

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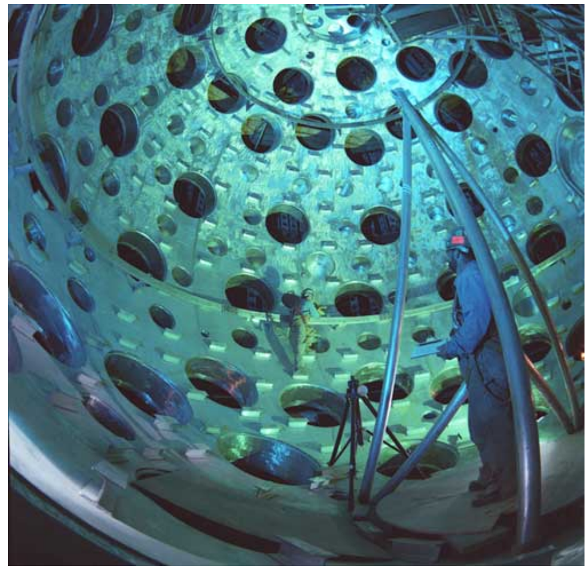
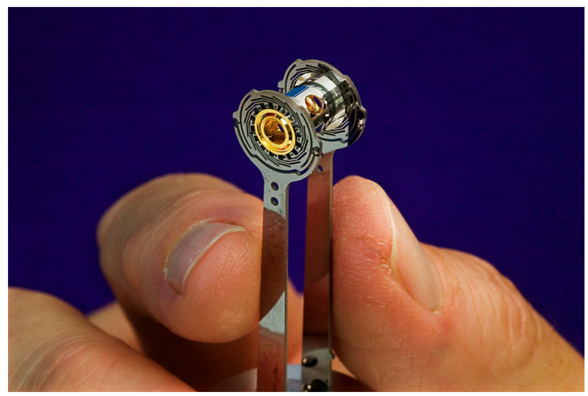
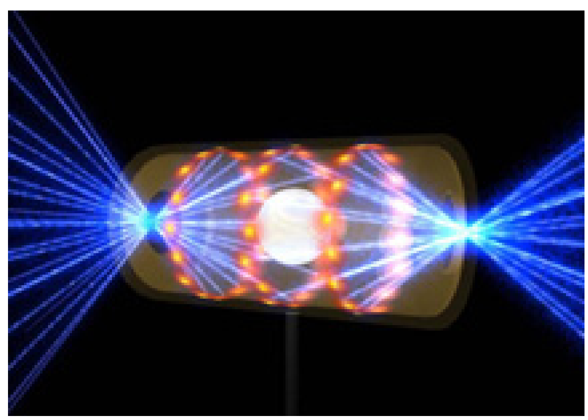
[6] Note that the definition of "ignition" for ICF differs from that employed by the magnetic fusion energy (MFE) community. In the latter case, "ignition" is usually taken to mean that the plasma temperature is sustained by fusion-reaction heating for a significant duration, while in ICF "ignition" describes a single burst of energy, analogous to the energy release in a car engine when the fuel is ignited by the spark plug.

Drive toward fusion at NIF

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory houses the world's most powerful laser system. The initial laser pulse is divided into 192 "beamlets," which are amplified to deliver a peak power of 500 trillion watts to a ten-meter-diameter target chamber (top photo). In the "indirect-drive" approach to inertial-confinement fusion, the 192 laser beams deliver a focused pulse of light a few nanoseconds long on a "hohlraum" (second photo), a tiny metallic chamber containing the deuterium-tritium fuel capsule. As the hohlraum is vaporized, it emits a uniform bath of X-rays that are absorbed by the fuel capsule, whose surface material blows off at high velocity. The rocket reaction then drives the implosion, which stagnates for about ten trillionths of a second at the center ("inertial confinement") and ignites the fuel (bottom simulation). In a "direct-drive" approach (discussed more fully in Chapter 5), the lasers would themselves ignite the fuel, but this requires extremely precise timing and focusing of the 192 beams. The uniform bath of X-rays produced by the hohlraum relaxes this requirement but is not as efficient as a direct-drive approach. To produce deuterium-tritium ignition is the immediate objective of the National Nuclear Security Administration-sponsored inertial confinement fusion (ICF) program now under way at NIF.







flowing. As a result, basic properties that affect material flows, such as viscosity—the friction usually associated with fluid motion—are governed by complex mechanisms that are difficult to calculate. The fact that HED systems can be ionized affects the energy transport and the bulk hydrodynamics. In some cases, the length over which fluid properties change becomes as short as the distance over which particles collide. At that point, the fluid ceases to behave like a traditional fluid, and both thermal and radiation energy can be transported over large distances. There are also classes of HED phenomena in which electromagnetic fields strongly affect the nature of the hydrodynamic flows. Such phenomena make the understanding, simulation and control of HED hydrodynamics a challenging scientific discipline.

I. Status

HED hydrodynamics has applications to a wide range of phenomena, and a large fraction of the research in progress is in pursuit of these applications. Examples include supernova and astrophysical jets, flyer-plate[7] acceleration for equation-of-state studies, and the high-gain target ignition that will ultimately lead to inertial fusion energy production (see figure 1-1). The quest for ignition at NIF is bringing the emergent field of HEDLP onto center stage and propelling all of these applications to the forefront. While ignition is expected to be first achieved with an *indirect drive* involving lasers to heat the hohlraum (see Executive Summary, page 12, and sidebar, page 17), the higher performance required for true IFE will probably require a different approach. This might be direct irradiation of the fuel capsule by the lasers (*direct drive)*, possibly assisted by a spark from fast or shock ignition, to be discussed below, or powered by another type of driver, such as a heavy-ion beam or a Z-pinch. In the last case, extremely large current transients through a plasma lead to its radial collapse, which in turn produces a magnetized HED plasma, the topic of Chapter 2. The hydrodynamics of HED fluids thus forms the bedrock of much of the rest of high energy density physics—from fundamental science to applications—and it is therefore not surprising that HED hydrodynamics is presently the most developed of the HED subdisciplines. Indeed, much of the development effort in HED facilities and computational tools to date has focused on HED hydrodynamics. These efforts have aimed to

- Produce and control the conditions of HED matter;
- Develop the diagnostic tools that allow one to determine physical conditions in HED matter while it is being experimentally manipulated; and
- Develop the computational tools that allow one to understand, in conjunction with the experimental facilities, the great variety of physical processes that are uniquely associated with the HED physical state.

Perhaps the most critical advance that has occurred over the past two decades relates to *our ability to produce and control HED matter*. From the most general perspective, HED matter can be produced by using powerful lasers or ion beams, or transient strong magnetic fields, to compress and heat matter to HED conditions. In each of these cases, modern facilities that

[7] Flyer plates are typically metallic disks that can be accelerated to extremely high speeds by means of magnetic forces, and then used in turn to literally push the materials to be studied to high density, pressure and temperature.

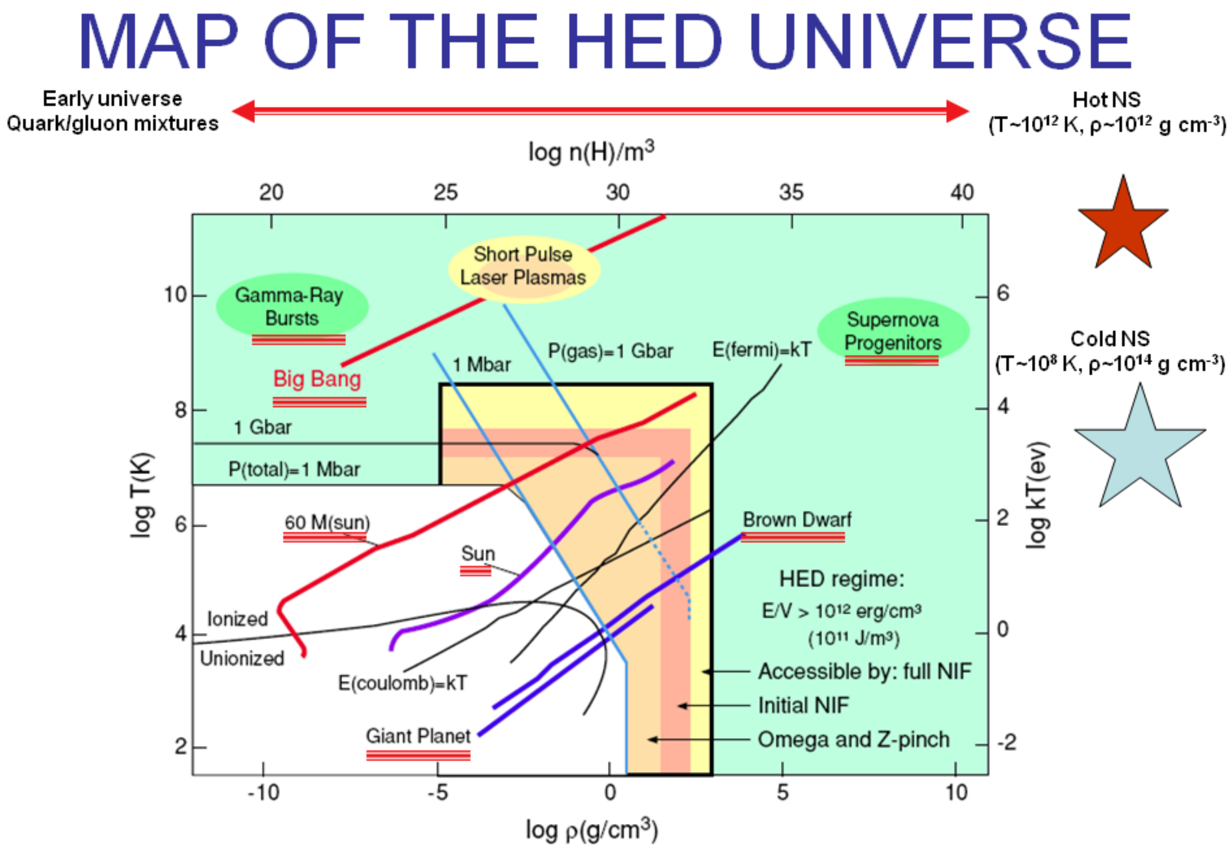


Figure 1-1. The HED universe is displayed in this plot of temperature versus density, which illustrates the wide range of physical processes spanned by HED physics in both naturally occurring and laboratory plasmas. Many of the phenomena indicated here are discussed in greater detail in the following chapters. Note that the diagonal blue lines running northwest to southeast indicate one million and one billion atmospheres pressure. The line E(Fermi) = kT roughly indicates the boundary between nondegenerate and degenerate matter, where quantum effects become important. Within the yellow rectangle are the regimes expected to be attained by the Z Facility, OMEGA, “initial NIF” (region accessible by lasers alone) and “full NIF” (region accessible assuming ignition is obtained). Notice that the conditions shown on the plot include those found in the core of the Sun, neutron stars (NS) and cores of giant planets, such as Jupiter.

exemplify how these techniques have been optimized over time already exist or are under construction: OMEGA at the University of Rochester and NIF at Lawrence Livermore National Laboratory (LLNL) in the case of laser-based HED facilities; the Neutralized Drift Compression eXperiment, or NDCX-II, to be built at Lawrence Berkeley National Laboratory (LBNL); and the Z Facility at Sandia National Laboratories for magnetically driven pulsed-power HED.

The challenges: Success in the application of HED hydrodynamics is closely tied to success in overcoming a number of fundamental technical hurdles on both the experimental and theoretical fronts. Here we provide a few illustrations of the kinds of challenges that have already been addressed and, though not in all cases fully resolved, have seen enormous progress over the past decade:

- *Material compression.* Effective compression of materials that are initially “cold” (cryogenically so or roughly at ordinary laboratory temperature and pressure conditions) to HED conditions always requires a high degree of symmetry (e.g., either spherically or cylindrically symmetric). For example, achieving adequate symmetry for ICF ignition at NIF involves both sophisticated optical smoothing techniques in order to provide uniform laser beams and further improvement of the symmetry by the indirect drive approach described in the sidebar (page 17). Thus, a spatially uniform bath of X-rays within the hohlraum is produced to uniformly implode the fuel capsule. This is a work in progress.

- *Plasma heating.* While capsule compression is closely associated with (adiabatic) heating of the capsule interior materials, instabilities at the periphery of the compressed capsule tend to mix in colder external material, thus reducing the efficacy of the adiabatic heating. Extensive work that employs a combination of optimized laser pulsing and careful shell layering of the capsule material ingredients has attempted to minimize this kind of mixing during heating phases; this remains a major research activity today.

- *Modeling implosion physics.* Accurately modeling the spherically and cylindrically converging flows when generating HED matter has long been understood as a major challenge for computational hydrodynamics; this is especially the case for the extreme degrees of compression needed for ICF. For this reason, much effort has been devoted to developing computational algorithms that can deal with the complex physics and singularities associated with strongly converging flows. Substantial progress has been achieved, largely as a result of the National Nuclear Security Administration’s (NNSA’s) science-based Stockpile Stewardship Program, via its Advanced Simulation & Computation (ASC) initiative. By and large the program succeeded in producing numerical hydrodynamics simulation tools for the design and analysis of HED compression experiments.

II. Research Opportunities and Needs

(1) How can we understand and create the extreme conditions of stellar temperatures, pressures and densities in the laboratory?

One of the fundamental principles of astrophysics is that the laws of physics governing the cosmos are the same as those governing the behavior of matter and energy here on Earth. This principle has served astronomers well since the dawn of astrophysics during the 19th Century, when atomic spectroscopy was deployed to demonstrate that elements well-known here on Earth were also found in the surface layers of the Sun and other stars. Thus, laboratory experiments and theoretical understanding of them have helped astrophysicists develop an understanding of the workings of stars.

Of course, such an approach has limitations: although we can readily recreate in terrestrial laboratories conditions on the surface of the Sun, until recently it has been impossible to duplicate the physical conditions within the Sun's core, where the temperatures rise to 10^7 K or more, and densities reach values on the order of 1-16 × 10^4 kg m^{-3}. As a consequence, current models of the Sun and other stars have relied primarily on theory for describing the nuclear fusion reactions and the convective and radiative transport in the solar and stellar interiors. One of the key intellectual ambitions of HEDLP is to address this fundamental limitation of astrophysics: create conditions in the laboratory that resemble those encountered under extreme cosmic circumstances, and carry out the experimental tests necessary to reach an understanding of the physics involved.

Why is it important? It is a unique human conceit to expect to understand the workings of nature around us, and the evolution of science since the Renaissance has taught us that reaching such understanding requires the intimate interaction of theory and experiment. Theories are built on observations that are in turn used to predict the behavior of natural systems. The theories are then considered validated if these predictions are consistent with observations. As indicated above, astrophysics has been severely handicapped by the absence of the iterative link between theory and observations on the one hand and experimental testing on the other. It is the broad ambition of HEDLP to broaden the reach of laboratory physics as an explanatory tool for understanding the cosmos we inhabit.

The challenge: Producing matter with temperatures, densities and pressures that approach or exceed those found in the center of the Sun requires us to accelerate matter so that it gains the required energy density as directed kinetic energy, and then to cause the matter to stagnate, or stop, on itself. The challenge is to achieve the desired temperatures, densities and temperatures in a controlled manner through a spherical or cylindrical implosion. To reach solar core energy densities, implosion velocities must exceed 300 kilometers per second. Such speeds are produced by impulsively compressing this matter with about 100 million atmospheres of pressure.

What's new? To achieve such conditions is exactly the aim of NNSA's large-scale experimental facilities. The HEDLP community is currently being encouraged to use them for a variety of purposes, including fundamental science.

What's needed? The creation of stellar conditions in the laboratory requires major experimental and theoretical programs aimed at achieving a deep understanding of such physical phenomena as:

- The mixing instabilities encountered during the compression phase, which as already mentioned, mixes hot and cold material, tending to degrade the ultimate temperatures attained;
- The efficient coupling of the driver (e.g., the laser light or the magnetic-field-associated forces) to the matter during acceleration and compression; and
- The constitutive properties of the heterogeneous matter under compression, as these directly affect the efficacy of the compression process.

Connections: The intellectual goals of HEDLP as applied to the astrophysics realm are fundamentally shared with virtually all of the other application areas of HEDLP, including achieving ICF ignition in deuterium-tritium plasmas, a key step to developing practical inertial fusion energy. Both domains require computing and measuring opacities (Chapter 4), computing and measuring equations of state for degenerate matter (Chapter 6) and so forth. These connections carry over to the diagnostic devices and tools employed by astrophysicists to image emissions from the most energetic objects in the universe by using the entire electromagnetic spectrum, from radio waves through infrared and visible light to X-rays. Finally, the computational tools resemble one another sufficiently that astrophysics and HEDLP have traditionally shared computational approaches, and even the simulation codes themselves. As a consequence, there has traditionally been substantial intellectual interchange between these two fields. It has also been commonplace to find astrophysicists working within the HEDLP-focused laboratories; thus, astrophysics has traditionally provided a ready manpower resource for the various HED physics sub-disciplines, serving as a significant training ground for HED physics that would otherwise be much more sparsely represented within the academic community and the national laboratories.

(2) Can we achieve controlled ignition of inertially confined fusion plasmas in the laboratory?

One of the "holy grails" of HEDP is the achievement of ICF ignition, defined as the point at which more energy is released from a compressed fusion fuel capsule than is delivered to the capsule (or to the hohlraum in the case of indirect drive) by the impinging laser beams.

Why is it important? In the "open science" arena, ignition is a prerequisite to achieving the ultimate goal of fusion energy production. This eventual practical application of ICF is clearly the dominant justification driving this science direction. In addition to paving the way to IFE, ICF ignition will give access to otherwise unreachable regimes of pressure and temperature; it will demonstrate knowledge of material properties in this exotic regime and lead to unique radiation sources. Furthermore, the work and success of ICF will rapidly expand the knowledge base of HED hydrodynamics concerning X-ray energy coupling to matter; control of fuel capsule material properties during implosion through precise control of the laser pulse shape; and mitigation of the hydrodynamic instabilities that can disrupt the imploding capsule and spoil its symmetry.

What's needed? Understanding the implosions in ICF experiments will require experimental diagnosis of the imploding fuel and its final state, together with relevant high-resolution 3-D computer simulations that address phenomena characterized by a multiplicity of scales. Once ignition is achieved, the next step in ICF target physics is the demonstration of high-energy gain. For a viable fusion energy power plant, the product of the driver efficiency and the target gain[8] should exceed 7 (i.e*.,* a 10% efficient driver requires a target gain of 70). It is unlikely that such

[8] Driver efficiency is defined as the ratio (energy delivered by the driver to target)/("wall plug" energy required to run the driver). A typical driver efficiency may be 0.1-0.4. The target gain is defined as the ratio (fusion energy produced)/(energy input on target).

high gain will be achieved in a laser-driven, indirect-drive configuration with the laser energies available at NIF. Either a larger driver or an alternative approach will be required.

Connections: The 3-D hydrodynamic codes required to simulate imploding capsules, which will be benchmarked against ICF experiments, will find application in other HED plasma physics problems, especially in astrophysics, as has been discussed above.

(3) How can plasmas be assembled to maximize system performance for inertial fusion energy?

There are various ways to compress and heat matter to the conditions required for fusion energy production. High system performance demands both high driver efficiency and effective use of the driver energy to produce hot, dense fusion fuel, whether the driver is a laser, heavy-ion beam or pulsed power; whether or not there is a pre-existing magnetic field in the plasma; and whether the approach is indirect drive or direct drive (sidebar, page 17). With any of these choices, there are possible variations aimed at improving system performance. *Fast ignition*, discussed in detail in Chapter 5, is a two-step process in which one laser or ion beam compresses the fuel and then a second ultra-intense laser pulse of only a few picoseconds duration ignites a small region within the compressed deuterium-tritium fuel. *Shock ignition* utilizes a slowly rising pulse for compression with a billion-atmosphere spike at the tail-end of the compression pulse that is timed to ignite the fuel by shock-wave-induced heating at the instant of maximum compression. By contrast, in the *hot-spot ignition* scheme, the baseline approach presently being followed at NIF, the compression of the fuel by itself is sufficient to heat a relatively low-density central "hot spot" (the commonly used phrase to denote the hot, central core) to the point of ignition. Both fast ignition and shock ignition are projected to be more efficient than hot-spot ignition, but much more is known about hot-spot ignition, both experimentally and theoretically, at present.

Why is it important? In order to develop an economically viable IFE power plant, there is a need to develop one or more of the variations discussed above to verify and quantify their efficiency advantages over hot-spot ignition.

What's new? Facilities on which relevant experiments can be carried out are now, or will soon be, available. Many, but not all, of these experiments require the largest-scale NNSA facilities, which are largely used for stockpile stewardship tasks, but which are expected to be available for a significant fraction of their time for the novel experiments required to investigate the alternative IFE schemes described above. On the theoretical side, computer simulations suggest that if fast or shock ignition is used to spark a two-stage ignition design, the total energy and implosion symmetry requirements are likely to be relaxed compared to those for hot-spot ignition. In addition, lower implosion velocities are needed in two-stage ignition, and so the target should be more stable. These developments imply that substantial advances should be possible with existing facilitites or already planned upgrades.

The challenges: Results from recent acceleration and implosion experiments employing conventional direct drive with lasers indicate that ablatively driven compression remains problematic because of hydrodynamically unstable ablation and generation of hot electrons due to nonlinear laser plasma interactions (see Chapter 3, on nonlinear optics). These experiments clearly point out important challenges in achieving direct-drive IFE: the laser deposition profile, the nonlocal transport processes (electrons and radiation), instabilities at the ablation front, etc. The importance of those processes varies with laser pulse profile and ablator material, each of which changes the ablation front structure, and hence the effectiveness of reaching high compression of the target.

The major new challenge for shock ignition arises from the addition of the ignitor pulse. This strong, spherically converging shock introduces new physics as well as technical questions: Can such a strong shock driven by a few-hundred-picoseconds pulse be produced? Does the production of the ignitor pulse require a separate set of driver beamlines, or can the compression and ignitor pulses be co-generated by the same beamlines? How well can the driver energy be coupled to the capsule exterior surface layers at high irradiation intensities (approximately 10^{16} W/cm^2)? What is the role of laser-driven instabilities during the driver-capsule interaction, and can they help rather than degrade the drive (i.e., the compression)? How uniform must the ignitor shock be? How does this shock interact with the inhomogeneities in the density and velocity previously generated in the assembled fuel? How do the compression and ignitor pulses separately contribute to the energies in the cold fuel and ignition of the hot spot? To what degree are the effects of the two pulses coupled?

What's needed? Experiments at large-scale facilities to examine both fast- and shock-ignition concepts are in their infancy and must move forward rapidly to inform the choice of paths forward for IFE once ignition is achieved at NIF. Fast- and shock-ignition experiments with sufficient laser intensity to attain ignition almost certainly require NIF itself. Experiments at the OMEGA facility, on the other hand, can test the necessary conditions for driver and target uniformity to achieve high compression, as well as test the impact of laser-plasma instabilities on the compression. The Z Facility can also examine similar issues when the large magnetic drive is coupled to a short-pulse laser at implosion. At present, the nonlinear laser-plasma interaction levels and behavior for various ignition target designs are theoretically and experimentally unknown. However, it is known that laser-plasma instabilities generate energetic ("fast") electrons that may be helpful in driving the ignitor shock. Whether or not this occurs will depend on the energy spectrum of the electrons and their spatial distribution, which are unknown. Plasma instabilities might limit the compression pulse intensity (pressure) and thus may affect the basic hydrodynamic stability of the imploding pellet. For further discussion of laser-plasma instabilities and of research needs to control them, see Chapter 3. Experiments with state-of-the-art heavy-ion facilities are also needed to evaluate physics and technology projections for that approach to IFE and are discussed here. However, fast ignition and an approach involving magnetic fields are discussed in detail in Chapters 5 and 2, respectively.

For shock ignition, ignitor shock strength and dynamics experiments are needed at realistic intensities in the range 5×10^{15} to 2×10^{16} W/cm^2 in long-scale-length plasmas. Research must address the role of hot electrons in driving the ignitor shock, as well as their contribution to the hydrodynamic evolution. Since shock ignition achieves high gain through the shock-induced compression of a central hot spot, the effects of non-uniformities transferred from the ignitor shock to the hot spot must be investigated through experiments and multidimensional simulations. Shock ignition might also be investigated in experiments at NIF, using alternative schemes for aiming the laser pulses in a direct-drive configuration (where, for example, the laser beams are not all targeted to converge at the capsule center).

For high-gain direct drive, gain of 70-100 or even more, multidimensional simulations are needed to identify target designs that are resistant to hydrodynamic instabilities and suitable for IFE. According to hydrodynamic simulations, the optimal ablator for laser IFE is a wetted plastic-foam shell saturated with deuterium; this offers the best performance with respect to laser-energy absorption and hydrodynamic stability. However, pure deuterium-tritium ablators have performed poorly with respect to the final compression. Therefore, research is needed to develop and test, through experiments and hydrodynamic simulations, alternative high-gain target designs fashioned from different ablators, or to employ different laser wavelengths that improve laser-energy coupling and hydrodynamic stability properties during the implosion process.

For heavy-ion direct drive, upon completion of the new ion-beam accelerator NDCX-II, the HED community will be in a position to undertake planar hydrodynamics experiments involving ion deposition, ablation, acceleration, and stability at energy densities of interest to HED-hydro and IFE. Energy densities will be high enough for optical measurements of hydromotion via tracer-dopant emission lines but low enough to neglect radiation transport. Ion beams have an advantage over optical beams in that they have relatively small intensity variations that are on the length scale of the beam radius. The effect of these variations on the ablation and acceleration of a planar target can be explored. If necessary, proposed mitigation strategies, such as "wobbling" the beam with controlled amplitude radio-frequency perturbations, should be verified experimentally. Since energy deposition from ion beams is volumetric, ablation effects may be quite different than with lasers. Therefore, experiments that examine acceleration of planar target layers are needed. Experiments with imprinted density variations will make it possible to study hydrodynamic instabilities (see next question) under a variety of experimental situations.

Connections: To maximize system performance of ignition for fusion energy applications will require a close coupling between diagnostics, theory and simulations. Only in this way can one understand and optimize fast or shock ignition, improve target designs for high gain, and determine the viability of heavy ion fusion in spherical geometry. The knowledge and experience gained in this endeavor will impact the stockpile stewardship mission of NNSA. Furthermore, student interest in the "holy grail" of IFE will, as it has in the past, provide ready expertise for the Nation to draw upon to maintain its capabilities in national defense.

(4) How do we understand and control the hydrodynamic instabilities that can limit the pressures and densities achievable in the laboratory?

HED plasmas, whether formed in planar, cylindrical or spherical targets with lasers, particle beams or pulsed-power machines in the laboratory, or in ejecta from supernovae, display developing structure on multiple spatial and temporal scales due to hydrodynamic instabilities. Classic examples include the Rayleigh-Taylor instability, prevalent when a heavy fluid is supported by a lighter one; the Richtmyer-Meshkov instability, in which inhomogeneities between different materials are amplified by passing shock waves; and the Kelvin-Helmholtz instability, which arises from adjacent fluids streaming at different velocities. All these instabilities can arise in ideal fluids, but in an HED plasma the phenomena are complicated by steep entropy and density gradients, non-ideal equations of state, and nonlocal energy transport by energetic particles or radiation. It is important to understand the development of hydrodynamic instabilities because they strongly affect the flows. Moreover, it is essential to control the growth of instabilities in inertial confinement experiments, which require uniform compression.

What's new? Phenomenological and sub-grid models have been successfully constructed for many flows that are not high energy density. They describe the dynamics from the initiating instabilities into the fully nonlinear, turbulent regime. An analogous approach is under development for HED flows to describe the full range of scales and mixing. Some of the models have been validated against simple experiments and simulations. Advances in computer architecture and parallel processing are permitting ever greater spatial resolution in hydrodynamic codes. The increased speed of computer systems allows inclusion of more complex phenomena, such as nonlocal thermodynamic equilibrium (non-LTE) radiation or nonlocal heat transport. For near-solid HED flows, fundamental molecular dynamics simulations can be employed to obtain the behavior of material stress and strain under dynamic conditions, from which improved sub-grid models can be developed.

We anticipate that significant advances in understanding instability initiation and growth will emerge from advances in diagnostics. Spectroscopic techniques can provide space- and time-resolved images of the evolving plasma or emission line spectra from highly ionized constituent species. Such data can be used as constraints on simulation models to match the observed structure and radiation features. An example is the observed Doppler-broadened line widths of optically thin emission lines, which have been interpreted as indicative of transonic turbulence in an imploding plasma. High-energy X-ray backlighting and radiography with subatomic particles have both undergone significant development in the past decade. The spatial resolution of these diagnostics continues to be refined, and they can now address small-scale structure in HED plasmas. Accelerated planar targets are particularly fruitful for the study of instabilities because they allow simultaneous face- and side-on diagnostics, both spectroscopic and backlit shadowgraphy.

The Reynolds number separates smooth, laminar flow from turbulent, unstable flow. Low Reynolds number characterizes smooth flows that are dominated by viscous effects, whereas a high Reynolds number characterizes turbulent systems that tend to be dominated by instabilities, and in which the fluid transport properties become independent of microscopic fluid properties, such as viscosity and thermal diffusivity.

The challenge: In HED plasmas, the flows range in conditions between two limiting extremes. In the low-temperature (and low-Reynolds-number) regime, bizarre phenomena exist, such as that of flowing, yet near-solid, materials. Basic properties, such as mass diffusivity and viscosity, arise from complex mechanisms and are difficult to calculate but may be determined from well-designed hydrodynamic experiments. Also, such materials exhibit mechanical strength and damage that alters growth rates of instabilities. In the high-temperature plasma regime, the flow is nearly inviscid, such that the Reynolds number is very high. Both regimes can be simulated numerically, but with different limitations. Due to memory and speed limitations, high Reynolds flows cannot be simulated at all physically important scales with current computers; models of varying sophistication—such as large eddy simulations—must be used to describe the hydrodynamics at the unresolved, "sub-grid" spatial scales. Furthermore, diagnostics of dynamically unstable plasmas require high space and temporal resolution. The high strain rates of materials in HED experiments are not encompassed by standard engineering descriptions of material properties, and the material state may not even be in thermodynamic equilibrium. Thus, new phenomenological models must be introduced in order to describe the full range of scales, and these must be validated with simple simulations and experiments.

Specifically for ICF research, understanding how instabilities are created by the steep entropy and density gradients produced during capsule compression can provide insight into their generation and give clues on how to control them. In this context, it is particularly important to understand the role played by the non-ideal equations of state typically encountered under such conditions, as well as to understand the role played by nonlocal energy transport resulting from energetic (long-mean-free-path) electrons and radiation. The instabilities in question cause the entropy to increase and hot and cold fuel layers to mix. Therefore, they will limit the compression of thermonuclear material. Furthermore, accurately treating convergent flows in cylindrical and spherical systems still remains a challenge for large compression ratios.

What's needed? There are three outstanding directions to the advancement of improved models for initiation and growth of hydrodynamic instabilities in HED flows. First, the role of initial perturbations on the late time evolution of the flow must be understood and quantified. In particular, the dependence of the nonlinear turbulent spectrum on the initial conditions is of interest. In the ICF context, these conditions would include laser or particle beam non-uniformities and target imperfections.

Second, there is a need for experimental and numerical data on how turbulence evolves in dynamically convergent, strongly compressed systems. Understanding the properties of fully turbulent flows in imploding capsules requires highly resolved, validated, three-dimensional simulations as well as dedicated, well-diagnosed experiments that are matched to the simulations by design.

Third, the evolution and impact of strong shocks, or even transonic flow, in a turbulent medium is almost completely unknown and hence is a topic with significant growth potential. HED experiments provide a unique environment for studies of such physics. Thus, the effects of distorted shock fronts on hot-spot formation can be studied through 2-D and 3-D hydrodynamic simulations and implosion experiments at large-scale facilities. The rate of mixing at the ablator-fuel and cold-fuel/hot-fuel interfaces in fusion-target implosions can be studied through integrated implosion experiments at existing facilities. Pulsed-power machines can be used to carry out experiments on how hydrodynamic instabilities alter current flow in HED plasmas.

A major limitation to understanding the effects of turbulent mixing in ICF implosions is the relative scarcity of well-developed diagnostic techniques. New concepts are needed, and their development is a high priority research need. Well-diagnosed, controlled experiments on regular fluids (liquids and gases) in non-HED conditions can study the transition to turbulence and the dependence on initial conditions. An outstanding uncertainty that should be addressed is whether the properties of materials at HED conditions will modify the understanding developed from non-HED experiments. To the extent it makes sense theoretically, both low and high energy density experimental platforms should be used to study the transition to turbulence.

Connections: The understanding and control of instabilities is directly related to achieving efficient ignition in targets designed for inertial confinement fusion. It is thought that turbulent mixing during the deceleration phase of an ICF implosion is a primary cause of degradation of hot-spot parameters. The experience acquired from the interplay of theory, simulation and experiments will lead to improved target design for eventual application to inertial fusion energy. An exploding supernova is the inverse phenomenon to an imploding fuel capsule, but the two systems are similar in that they both accelerate a heavy fluid by a lighter one and are thus hydrodynamically unstable. Understanding the outstanding issues will benefit other applications as well. For instance, hydrodynamic instabilities are believed to play a major role in the nucleosynthesis of high-atomic-number elements during supernova explosions. Also of interest for astrophysics is the interaction of shock waves with molecular clouds and other density clumps. This process plays an important role in forming the distribution of stellar masses (the so-called "initial mass function") that determines galactic evolution and the formation and evolution of exoplanetary systems.

(5) How do hydrodynamic flows change as a result of the additional physical complexity and the multiscale nature of HED plasmas?

HED flows have unique properties compared to conventional hydrodynamic flows because the former are compressible in the extreme, are potentially highly supersonic, and can have complex material evolution and their ionization state can vary strongly with time. HED flows are relevant to laboratory experiments, exploding stars, stellar birth dynamics, accreting black holes, and catastrophic meteor or asteroid impact dynamics. Compression can be greatly increased by radiative energy loss, which produces thin layers of very dense flowing material. The "established laws" of hydrodynamics are largely empirical and result from observations of weakly compressible systems. The natural question is whether these "laws" are altered in the HED regime. Observations to date have revealed mixing of material layers (the mechanism for which is not understood), evidence of material erosion by turbulent motion, and mixing rates strongly affected by the strength and proximity of strong shocks at high compression. Finally, it is noteworthy that it may be possible to use hydrodynamic flows to probe the unique properties of HED media (for example, through the evolution of instabilities).

What's new? A promising multiscale approach to understanding HED plasma properties, which spans angstrom to millimeter scales, starts with quantum mechanical interatomic potentials that are inserted into molecular dynamics simulations; these simulations are passed upward to dislocation dynamics that ultimately connect to continuum code simulations at the macroscopic scale. The multiscale, multistep approach can work only if the individual components can be checked via validation and verification experiments. The result could be a powerful probe of material properties at extreme HED conditions, which would be relevant to such diverse phenomena as catastrophic asteroid impacts and hypervelocity micrometer-scale dust-dust collision dynamics, which plays a significant role in the evolution of the young solar nebula and its stellar counterparts.

The challenge: The challenge and research opportunity here is to devise and develop experiments and models of hydrodynamic flows from which the viscosity, thermal conductivity or other properties of dense, HED matter can be inferred as conditions become more and more high-energy-density. Developing appropriate diagnostics is a major part of this challenge. Creative innovation may enable relevant work on sub-kilojoule, nanosecond lasers or Joule-scale ultra-fast lasers as well as on the larger-scale facilities. Solid-state flows are particularly difficult to model because uncertainties abound in fundamental properties, such as in the equation of state, ductility, shear modulus and so forth. At the other extreme, plasma flows at high Mach number involve ionization and excitation states that are not in local thermodynamic equilibrium. Such microphysics takes place at the atomic scale but, due to the long-range Coulomb interactions, affects the transport coefficients for heat and viscosity. At high densities, strong coupling occurs, in which the plasma thermal energy is on the order of the interionic Coulomb potential. In this case, pressure ionization can shift previously bound states into the continuum.

What's needed? The research opportunity is to devise experiments and models that can reveal the properties of HED matter, including flowing solid-state matter at extreme pressures and ultrahigh deformation rates. In the plasma state, diagnostic capabilities are needed to understand the exchange and flow of internal energy. Flows can be set up that would be hydrodynamically stable in the absence of thermal-heat conduction, and for which the degree of instability is a function of the thermal conductivity. Measurements of the instability growth rate would then probe the thermal conductivity of the matter. Similarly, hydrodynamic flows involving instabilities could be designed to be sensitive to viscosity. In a turbulent flow with eddies, for example, one might ask how the microscopic equilibration process between the ion and electron temperatures is affected by the multiscale energy cascade of the eddy's kinetic motion. An opportunity in HED laboratory plasma experiments exists to validate within the next few years advanced models of transonic turbulence and the associated multi-faceted dissipation processes.

Connections: Understanding the properties of HED matter is relevant to a wide variety of scientific focus areas, such as the dynamics of accreting white dwarfs and other compact astrophysical objects. High-rate plastic flows[9] are relevant to a fundamental understanding of deformation dynamics in solid-state matter at extreme pressures and shear stresses; hypervelocity impact dynamics and cratering; interplanetary and interstellar dust dynamics; and improved durability of space hardware against micro- and nano-dust particle impacts at extreme velocities (10 to 100 km/s). Creative innovation may enable relevant work on intermediate and university-scale systems.

(6) How can we use HED hydrodynamic experiments to clarify the behavior of astrophysical flows?

The task of modern astronomers and astrophysicists is to apply astronomical observations, astrophysical theory and simulations toward an understanding of the structures and evolution of the universe. Astronomical observations themselves are the principal guideposts in this endeavor, providing many examples of HED hydrodynamics in action: As shown in figures 1-2 and 1-3, supernovae and young stellar objects produce shock waves and eject high-velocity matter into the interstellar medium.

[9] "Plastic" flows typically occur when solid materials are deformed to the point that a critical stress value is reached (the "yield" stress), after which the material flows; in such cases, the material behaves like a very viscous fluid and will not return to its original shape when the stress is removed.

What's new? In a LabAstro experiment using state-of-the-art HED facilities, a strong shock or high-Mach-number flow can be generated from well-controlled initial conditions, and the subsequent evolution can be measured from multiple diagnostic perspectives. Hydrodynamic-scaling theory and methodologies can then be applied to match the lab results to the astrophysical phenomena. In short, the ability to test key aspects of large-scale, complex astrophysical simulations and their underlying assumptions experimentally is now on the table. LabAstro opens up the potential to examine aspects of some of the most extreme and violent phenomena of the universe, including supernova explosions, photo-evaporation (ablation) front dynamics of molecular clouds in stellar "nurseries," hypervelocity asteroid impact dynamics, plasma jets produced by young stars, accretion flows around neutron stars and black holes, galactic outflows, and strong shocks in the interstellar medium.

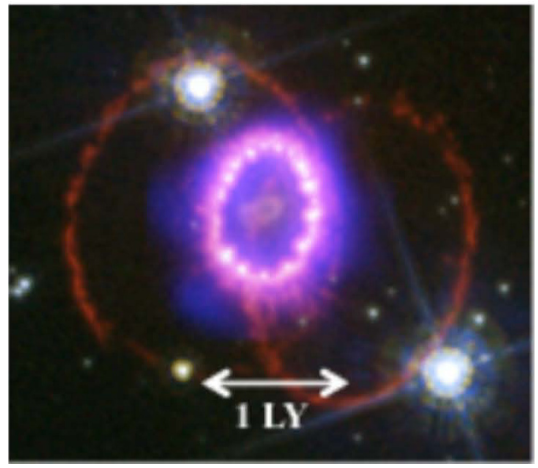


Figure 1-2. The remnant from Supernova SN1987A, observed in 2003 (16 years after the stellar explosion was first detected). The distance to this supernova is about 170,000 light years; diameter of the inner, clumpy circumstellar ring is about 1 light year.

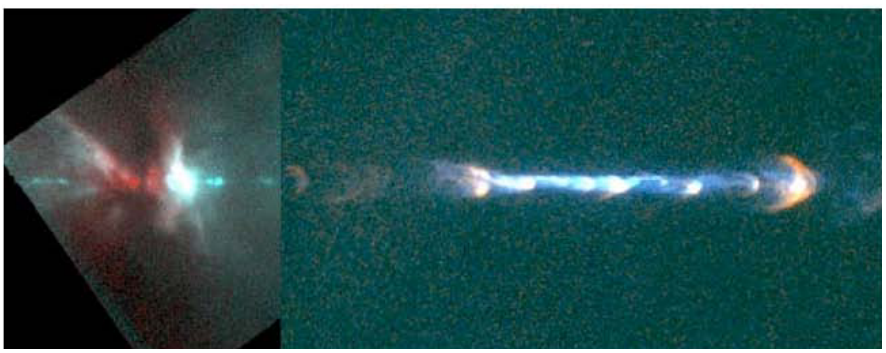


Figure 1-3. A montage of pictures showing a strong plasma jet (Herbig-Haro object HH111) ejected by a young star into the interstellar medium. The jet is moving toward the right. Both objects display HED hydrodynamics in action.

A radiating shock is one in which the post-shock plasma radiates away the internal energy generated in the shock front, thereby generating a thin, dense shell of plasma following the front. A laboratory example of the phenomenon has recently been generated in the form of a piston with Mach number of about 20 traveling through a tube filled with xenon gas (see Chapter 4, figure 4-2). The strong radiative characteristics of this gas produced a collapsed post-shock gas shell that was directly diagnosed with X-ray radiography. Although xenon is not abundant in the interstellar medium, shock waves that radiate away most of their internal energy and form thin, dense shells are common in astrophysical systems. The experiments thus observe an analogous dynamical evolution, and their data can be used to validate simulation codes.

The challenge: Astrophysicists strive to reproduce supernova observations with large-scale simulations of exploding stars. The simulations are enormously complex, however, and the data used to constrain them are sparse, given that we are limited to telescopic observations and have no control over the initial conditions. The challenge is to isolate specific astrophysical processes in Earthbound experiments that satisfy a scaling relation between the laboratory and the astrophysical event and employ them to validate the physical models contained in the simulations.

What's needed? The regions of validity for the hydrodynamical scaling just discussed must be established theoretically. The impact of HED experiments on astrophysics and planetary physics rests, in part, on how carefully and thoroughly such assessments are done. Experimental data can then be used to check and validate sophisticated multidimensional numerical codes that are used to simulate observed astrophysical phenomena. Research in this category will involve a combination of experiments, diagnostic development, simulations, theory and target development. Relevant work should become possible on a wide range of facilities within the next few years.

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Chapter 2: Magnetized High Energy Density Plasma

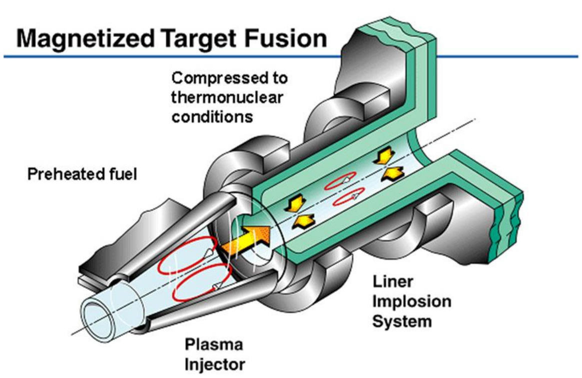
How are magnetic fields created and how do they affect the properties of high energy density plasmas? Can magnetic fields reduce the power and energy needed to initiate fusion reactions in dense plasmas?

Introduction

Magnetic fields change the fundamental properties of high energy density plasmas in ways that bring significant rewards as well as significant challenges. The interaction of charged particles with a magnetic field completely alters the transport of energy within a plasma. For example, when a strong shock wave is driven into magnetized plasma, charged particles accelerate across the shock front many times. This process is thought to be the principal source of energetic cosmic rays, the highest-energy particles known in the universe. In the case of imploded plasmas for inertial confinement fusion, magnetic fields could facilitate ignition through the suppression of heat loss from the burning region via an approach to fusion known as magneto-inertial fusion (see sidebar, below and next page).

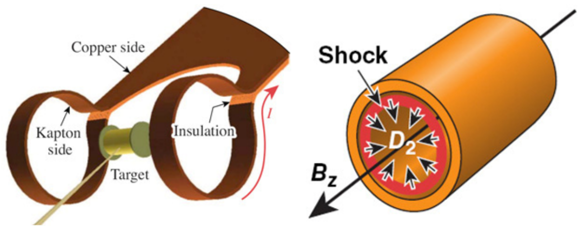
Magneto-inertial fusion: A hybrid of magnetic and inertial confinement fusion

Magneto-inertial fusion (MIF) concepts combine attractive features of inertial confinement fusion (ICF) and magnetic confinement fusion (MCF) to make an alternative pathway to fusion energy. MIF can achieve much higher densities and magnetic fields than traditional MCF, and by employing more compact and lower-power lasers or particle beams, it can potentially reach the conditions necessary for fusion reactions more easily than conventional ICF. All proposed MIF methods involve high energy density laboratory plasma systems that compress plasma targets within a conducting shell. Four distinct approaches give time scales ranging from 1 nanosecond to 10 microseconds. All four methods include permeating the plasma with a strong magnetic field of 100 to 10,000 teslas. The thermal insulation provided by the magnetic field allows the target to be compressed over a longer time scale and with less stringent requirements on compression than in conventional approaches to inertial confinement fusion. Lower compression ratios mean reduced stability requirements on the imploding, conducting shell. Exciting fusion yields may be possible on existing facilities in the next several years. The four MIF approaches presently being tested are illustrated and described in figure 2-1 on page 39 and below.



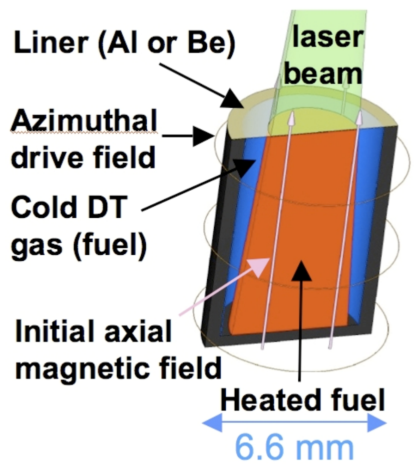
a) The 10-microsecond variant of MIF utilizes the magnetic pressure produced by a 12-MA current to implode a cylindrical metallic liner (green). A magnetically confined plasma formed outside the liner (red ellipses to the left of liner) is injected into the liner as it is imploding. This plasma is compressed and heated to fusion conditions by the time the imploding liner stagnates against the plasma. (AFRL/LANL collaboration)

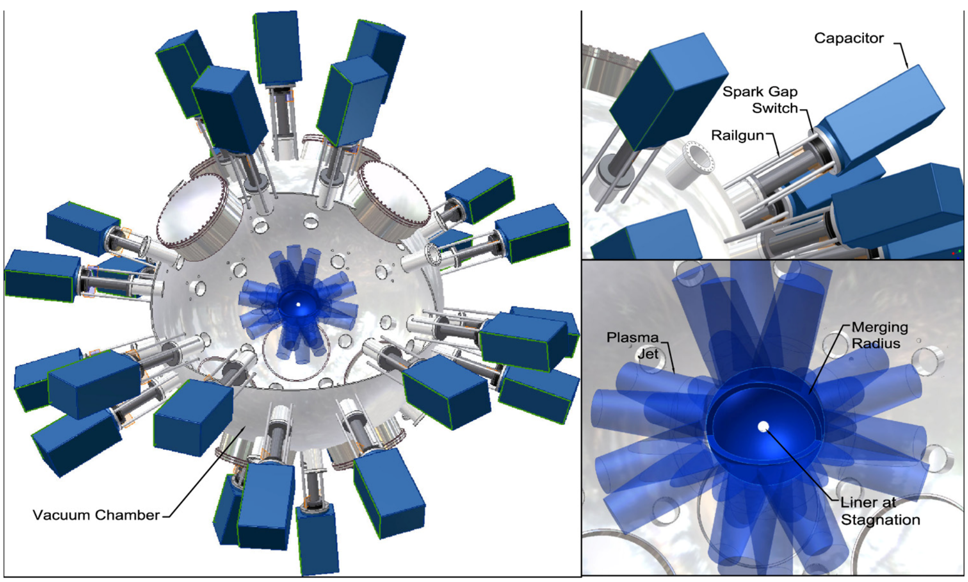
Magneto-inertial fusion: A hybrid of magnetic and inertial confinement fusion (Cont.)



b) In this one-nanosecond variant of MIF, a target containing fusion fuel is contained in a cylindrical tube (labeled "target"). A magnetic field is applied along the axis of the cylinder by the copper coil, and the target is then imploded by laser ablation. A shock wave launched into the fuel ionizes and heats it, and the target implosion compresses the plasma to fusion conditions. (LLE, Univ. of Rochester)

c) In this 100-nanosecond variant of MIF, a cold deuterium-tritium (DT) gas (blue) contained within a beryllium or aluminum cylinder (black) is preheated with a laser (green) and magnetized with an axial magnetic field. A fast-rising current of 25 MA is then applied, which produces an azimuthal magnetic field that implodes the metal cylinder, compressing the DT plasma to fusion conditions. (Sandia National Laboratories)





d) In this one-microsecond realization of MIF, many cold dense plasma jets are launched by plasma guns (blue rectangular boxes) toward the center of a 2.7-m-diameter sphere, where they merge to form a continuous plasma liner that continues to implode toward the center. A pulsed laser (not shown) generates a seed magnetic field in fusion fuel at the center of the sphere. The eventual goal is for the plasma liner compression to amplify the seed magnetic field and heat the plasma to fusion conditions. (Los Alamos National Laboratory)

Magnetic fields can apply substantial forces to HED plasmas. In many astrophysical objects, magnetic forces in fact dominate the observed behavior. In fusion research, the latest generation of pulsed-power machines can provide magnetic pressure forces that match the pressure of a fusion-grade HED plasma. Furthermore, when magnetic forces are used to compress a plasma that loses energy by radiation, they can provide a highly efficient mechanism for extracting energy from the magnetic field and generating X-rays. This X-ray source is already a workhorse for a number of other HED plasma experiments, such as materials testing, measurements of the optical properties of matter and radiation hydrodynamics. Moreover, by concentrating a large electrical current into a plasma of small dimensions, the magnetic forces become great enough to compress the plasma to pressures of billions of atmospheres, a state of matter not found naturally on Earth but ubiquitous in large celestial bodies (see sidebar, below and next page).

X-pinches: Exploring the frontier of extreme states of matter

Magnetic fields found in the atmospheres of neutron stars are billions of times stronger than that of the Earth (see figure 1). Determining the star's surface density, temperature and magnetic field strength requires a detailed knowledge of how such a magnetic field changes the structure and binding energies of atoms and matter and hence their emission spectrum.

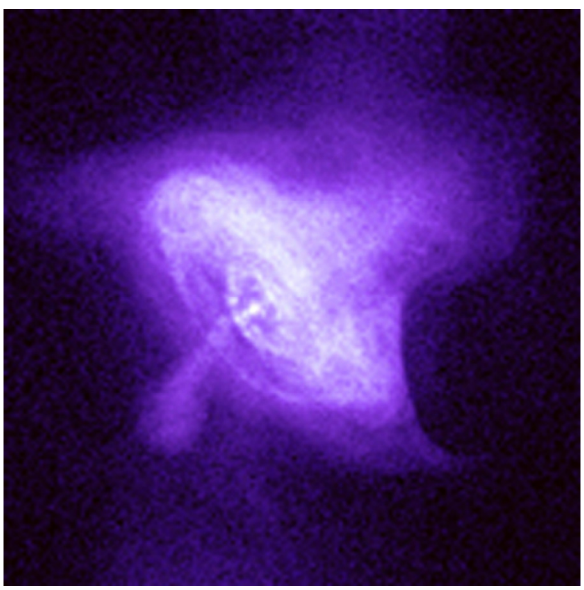


Figure 1. X-ray view of the Crab Nebula supernova remnant, as seen with the Chandra X-Ray Observatory. The bright spot in the center of the image is a pulsar (a highly magnetized, rotating neutron star), which powers intense jets from the stellar poles and winds from the equator. (NASA/Smithsonian Astrophysical Observatory)

One possible way to create similar conditions in the laboratory would be to make use of the high energy densities that can be reached by concentrating a large current in a narrow plasma channel. An example is the so-called X-pinch, an X-ray image of which is shown on the right of figure 2. A 50-nanosecond, 200,000-ampere current pulse is injected into two thin metal wires that cross and touch at a single point to form an "X." The high current converts the wire into plasma and generates a magnetic field that in turn compresses the plasma. The magnetic pressure, which is largest where the wires touch, becomes increasingly strong as the plasma contracts. Intense emission of X-rays cools the plasma, which triggers a rapid collapse to very high densities (figure 2, left). In experiments with a 200,000-ampere current pulse delivered to two molybdenum wires, a transient plasma lasting 100 trillionths of a second produced 1 billion watts of X-rays from a source 1 millionth of a meter across.

X-pinches: Exploring the frontier of extreme states of matter (Cont.)

Measuring the spectrum of X-ray emission from the 200,000-ampere X-pinch reveals that the transient plasma reaches a temperature in excess of 10 million degrees and more than ten percent of the density of solids. The conditions correspond to a plasma pressure of a billion atmospheres and are consistent with a magnetic field hundreds of millions of times greater than the Earth's magnetic field. Extending the same technique to the highest current levels available (26 mega-amperes) suggests that far higher energy densities and magnetic fields can be achieved.

Such intense bursts of X-ray emission from microscopic point sources also provide a method of high-resolution radiographic imaging, but with lower photon energies than a medical X-ray. As a result, X-pinch X-rays are capable of imaging the exoskeleton and internal organs of the common housefly and other lightweight biological samples (see figure 3). Alternatively, the short duration of the burst can be used to reveal the structure of rapidly moving plasmas, such as an exploding twisted pair of wires (also shown in figure 3).

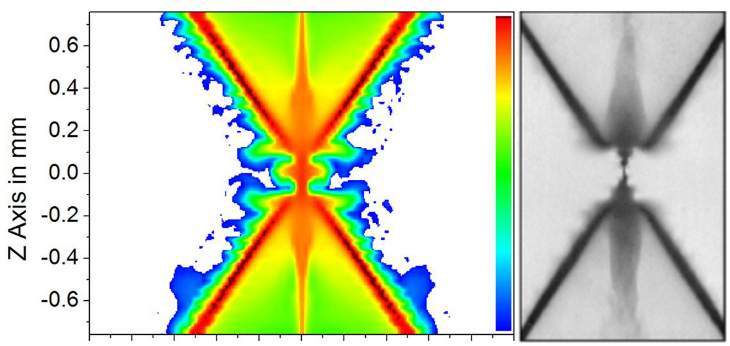


Figure 2. At left, a slice through a 3-D simulation of an imploding X-pinch reveals the formation of a narrow plasma column where the wires cross. At right, a flash of X-rays from one X-pinch (not shown) is used to capture the instant when the center of a second X-pinch collapses to a few millionths of a meter. (Left image, Imperial College; right image, Cornell University)

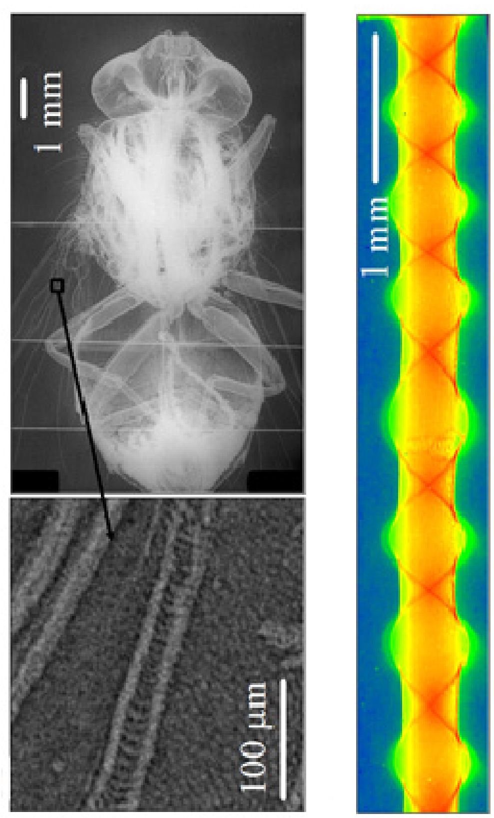


Figure 3. The common housefly, as seen using the high resolution afforded by the microscopic X-ray source of an X-pinch, is shown (left), including a greatly expanded portion of the radiograph that shows the intricate structure of the wing (below). The short duration also allows the X-pinch to image rapidly evolving plasma experiments, such as the exploding pair of twisted wires (right). (Cornell University)

The diversity of these phenomena and their possible applications makes this area of research extremely attractive for young talent and very promising for major breakthroughs in fusion energy and astrophysics over the next five to ten years. The remainder of this chapter is organized around three areas of high priority: 1) The science of fusion-grade, magnetized HED (MHED) plasmas; 2) laboratory modeling of dynamical astrophysical phenomena; and 3) extreme states of matter. Although these three areas are closely related to one another, as well as to broader HEDLP research, there are also significant differences in the objects studied and final applications.

I. Status

Magnetic fields have been successfully employed for confining low density, hot fusion plasmas in quasi-steady-state devices such as tokamaks. In HED plasmas, which are at much higher densities, both introducing the magnetic field into the plasma and predicting plasma behavior become more difficult, but the expected favorable effect on the performance of these pulsed fusion systems can be equally dramatic. Progress in theoretical and experimental research during the last ten to fifteen years has brought us to the position where we can anticipate major breakthroughs in magnetized HED fusion plasmas within the next few years.

Driven largely by the National Nuclear Security Administration's (NNSA's) interest in nuclear weapons stockpile stewardship and other related applications, a unique suite of facilities for generating HED plasmas was created that is also suitable for controlled fusion research for power production and a broad range of basic science research. Included are NNSA's large-scale "pulsed-power generators" and high-power and -energy lasers (see box on page 8 of Executive Summary), which are complemented by more modest, university-scale facilities (see Appendix B). This suite provides a foundation for rapid progress in magnetized HEDLP for fundamental science as well as for major applications.

Four concepts have been proposed to produce fusion-grade magnetized HED plasmas (see sidebar, pages 33-34). All take advantage of the ability of magnetic fields to inhibit particle and heat loss across the field lines in magnetized plasmas. The infrastructure is ready: existing NNSA multi-mega-ampere "pulsed-power generators" and high-current capacitor banks, as well as extremely high-power lasers, have brought us to the point at which experiments could test all four concepts in the very near future, as we shall discuss shortly.

One example of the basic physics research enabled by pulsed-power facilities is topic 2 listed above: laboratory modeling of astrophysical phenomena, commonly known as LabAstro. LabAstro consists of investigations believed to be relevant to understanding objects observed in the cosmos. During the past decade, experimental tools have been developed that allow the creation of dynamically evolving plasmas that are morphologically similar to objects observed in the universe. We distinguish this "dynamical" simulation of astrophysical objects from the more established branch of LabAstro associated with providing data on atomic cross-sections, equations of state, opacities, etc. What makes *magnetized* LabAstro particularly interesting and exciting is the fact that the universe is permeated by magnetic fields that range from nanoteslas in the interstellar medium to many gigateslas in the vicinity of black holes and magnetars. These fields play a critical role in a wide array of astrophysical phenomena, from cosmic-ray generation and transport to the processes of star formation and evolution. The behavior of such objects as astrophysical jets, accretion discs, stellar convective zones and dense molecular clouds is intimately related to the presence of magnetic fields.

In addition to addressing magnetized HEDLP science, pulsed-power devices can produce extreme states of matter (topic 3 above) through the generation of high magnetic pressure. Pulsed-power generators at university scale routinely produce 0.5 -1.5 million ampere (MA) current pulses, and the largest such device produces up to 26 MA. At the 26-MA level, the magnetic pressure that can be produced in 1-cm-wide, closely spaced conductors can reach one million atmospheres. If that pressure is used to accelerate a low mass conductor, such as a thin aluminum disk, the disk can be accelerated to very high velocity—hence, the disk is termed a "flyer plate." The conversion of large amounts of electrical energy into mechanical energy through the intermediate step of generating very high magnetic pressure enables precise materials science experiments. The impact of the flyer plate on a sample compresses it to extremely high densities in a controlled way, which serves to determine the equation of state (EOS)—that is, the relationship among the temperature, density and pressure—of the material under HED conditions. An equally important method for determining the EOS of materials, first developed in pulsed-power facilities, is a shockless compression of the material using a carefully designed, slowly increasing magnetic pressure drive. Such "isentropic-compression experiments" (ICE) provide a different trajectory through the material phases, which complements the data obtained in flyer-plate experiments. Precision measurements of the EOS of hydrogen and other materials have been carried out by these methods. High accuracy can be obtained due to the relatively large energies (and therefore large sample sizes) available in experiments carried out with pulsed-power machines.

Another common application of pulsed-power facilities is the efficient generation of short, very intense pulses of soft X-rays (a few hundred electron-volts up through perhaps 10 keV). The radiation thus produced can be used for indirect-drive inertial confinement fusion studies, as discussed in Chapter 1. It can also be used for studies of radiation effects on materials; for opacity measurements of importance to many applications, including astrophysics; and for driving astrophysically relevant experiments (e.g., on photo-evaporated molecular clouds). The soft X-ray generation technique relies on coupling large pulsed currents to thin metallic wires (see sidebar, page 36). The use of such techniques requires us to understand and model the physics of dynamical phase transitions of the wire materials into dense plasmas, an aspect of warm dense matter studies, which will be taken up in Chapter 6.

II. Research Opportunities

(1) How can dynamic magnetic fields be used to enable inertial fusion energy?

Why is it important? The key research opportunity in topic 1, fusion-energy-related MHED plasma physics, is to explore and demonstrate the attainability of fusion breakeven conditions for pulsed HED plasmas with magnetic fields. In the magneto-inertial fusion (MIF) approach to fusion, a magnetic field in a high density fusion plasma is expected to both reduce heat loss from the plasma and increase the deposition within the plasma of energy carried by charged particle fusion reaction products. These effects could significantly reduce the power and energy requirements for compressing and heating a plasma to conditions where interesting fusion energy gains are possible. The reduced power requirement allows the use of heavy and relatively slow conducting "liners," or shells, which are imploded by pulsed power in order to compress a magnetized "target" plasma (sidebar, pages 33-34). Detailed experimental data and validated computational tools in this area are rapidly becoming available. The status of this work, combined with the predicted favorable performance of these pulsed magnetized HED fusion systems, makes MIF a compelling area of study.

Specific approaches that could use existing pulsed-power and laser facilities to realize major breakthroughs in MIF within the next five-to-ten years include the following:

1. Compression of pre-magnetized plasmas by magnetic pressure on a 100-ns time scale can be tested today. A thin cylindrical shell with an initial scale of approximately 1 cm can be imploded by magnetic pressure produced by currents of up to 26 MA, as illustrated in figure 2-1, below. Calculations suggest that plasma temperatures and densities close to those required for fusion energy applications could be achieved. The approach provides a direct path to creating fusion-grade plasmas employing the kind of conceptually simple target that would be desirable for IFE. The present availability of the necessary pulsed-power machine makes the time scale for major breakthroughs in this area 3-5 years.

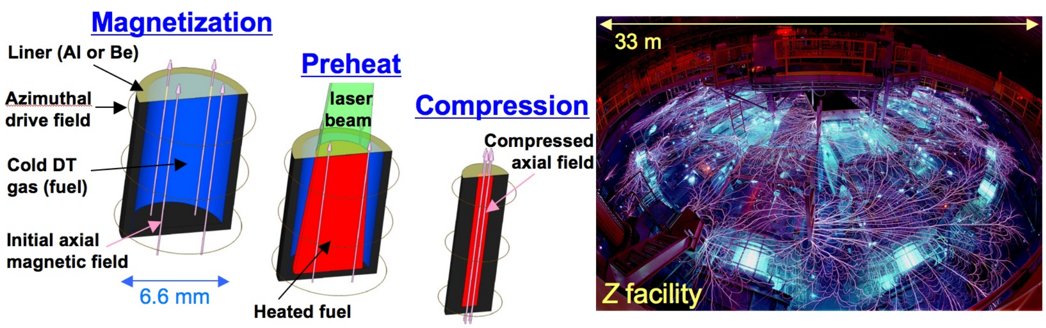


Figure 2-1. An approach to magneto-intertial fusion (MIF) based on the use of rapidly rising mega-ampere currents available on the pulsed-power Z Facility: (1) a cylindrical capsule with a gas pre-fill is magnetized; (2) a laser pulse heats and ionizes the gas in a few nanoseconds; (3) a current driven through the metal cylinder produces an azimuthal magnetic field that implodes the shell, compressing the plasma to fusion conditions. The Z Facility itself, shown at right, is operated by Sandia National Laboratories and is the world's largest X-ray generator. Visible in the photo are the arcs that form during a shot on the machine; each shot may produce up to 290 terawatts of X-ray power for a few nanoseconds. (Sandia National Laboratories)

2. Pre-magnetization of a laser-driven fuel capsule, and subsequent compression of the fuel with the embedded magnetic field, could reduce heat loss from the plasma core and facilitate ignition. The configuration is illustrated in the sidebar on pages 33-34. Much preparatory work has been done on this to develop both a pre-magnetization technique and adequate diagnostics. Exciting results can be obtained within 2-3 years.

3. Relatively slow compression of a pre-formed magnetized plasma with initial dimensions on the order of 10 cm can be achieved with a thin imploding metallic liner. The magnetically confined plasma can be created outside the liner and then transported into it once the liner implosion has begun, as illustrated in the sidebar on pages 33-34. The high degree of uniformity obtained with solid liner implosions leads to effective magnetic flux compression, which in turn is predicted to compress the magnetized plasma to fusion conditions. This research effort is relatively advanced and could achieve a major breakthrough within 1-2 years.

4. Other innovative MIF approaches with potentially high payoff, which also utilize pulsed-power technology for generating and compressing magnetized plasma, have received attention. One possibility relies on an imploding plasma liner generated by converging dense plasma jets. Techniques for magnetizing the compressed plasma, such as laser generated beat-wave current drive, are being explored. This concept is illustrated in the sidebar on pages 33-34. Exploratory opportunities such as this one could bear fruit on the time-scale of 5-10 years.

In addition to opening new avenues to inertial fusion, magnetized HEDLP research would bring the physics of magnetized plasmas to unexplored domains of high collision rates and small mean free paths, non-ideal plasma states, sharp gradients in plasma composition (hydrogen plasma "leaning" on a wall of plasma of medium-to-high atomic numbers) and magnetized nonthermal particles (e.g., energetic alpha particles) "bathed" in a collisional dense plasma. This naturally blends magnetized-HED-related fusion energy research with discovery science, enabling great potential for the emergence of new concepts and unanticipated applications.

(2) What can scaled magnetized HEDLP experiments tell us about the evolution of astrophysical systems?

Why is it important? Dynamical LabAstro experienced a rapid development from the first, somewhat naïve attempts to reproduce as a whole observed astrophysical phenomena, to much more pointed exercises in scalable experiments that focused only on specific, well-defined components of the whole process. In particular, an ongoing collaboration funded by the European Union, which includes both astrophysicists and HEDLP scientists (and came to be known as the JetSet), has utilized pulsed-power facilities to investigate various stages of formation and propagation of magnetized, radiating plasma jets (figure 2-2).

The possibility to change at will the input parameters in laboratory experiments and track the evolution of the system over a dynamically significant time interval makes LabAstro experiments a powerful tool for the validation and verification of codes developed to help astrophysicists understand observations. It is likely that, during the next 5-10 years, the contribution of scaled laboratory experiments will dramatically increase our ability to numerically model astrophysical phenomena.

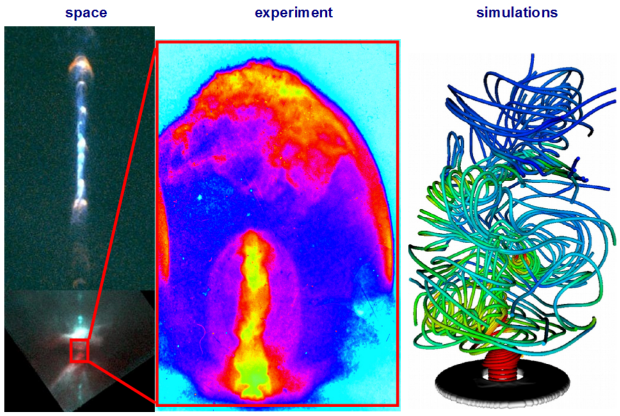


Figure 2-2. Scaled experiments (center) combined with high-performance computer simulations that include magnetic field evolution (right) aid in understanding the nature of launch regions of astrophysical jets (left) that are too small to be clearly observed. The launch region is represented by just 2 cm in the experiment, but the physics at work is believed to be the same as in solar-system-sized jets from young stars. (NASA/Imperial College/Paris Observatoire)

Exciting new opportunities have been recently identified in meaningful laboratory replication of such astrophysical phenomena as collisionless shocks driven by point explosions, accretion discs and jets, and magnetized, photoevaporated clouds ("star nurseries"). It is important to note that relevant experiments can be performed on university-scale facilities (both pulsed-power and laser drivers), which provide reasonably high shot rates. Access to national facilities, including the Z machine at Sandia National Laboratories, Albuquerque, is needed in order to extend parameter space and obtain a better scaling to astrophysical objects. Progress in this area will be largely determined by funding and available machine time, as the intellectual and technological potential accumulated in the past decade is sufficient to enable the field to advance rapidly.

The time is opportune to start new and enhance ongoing experiments in magnetized LabAstro to capitalize on significant investments made in astrophysical observational tools, including the James Webb Space Telescope, the Atacama Large Millimeter Array, the Very Large Telescope Interferometer, the Solar Dynamics Observatory and others. The astrophysical community should be encouraged to exploit the great opportunities of magnetized LabAstro by participating in joint teams, transforming the experimental design process, and suggesting new observations as well as new ways of looking at existing observations.

(3) What are the most extreme states of condensed matter we can create in the laboratory?

Why is it important? By means of rapid implosions, either laser- or current-driven, magnetic fields approaching 10,000 T will be generated in volumes of 0.1 to 1 mm^3. Such fields have significant effects on the atomic properties of matter. If increased tenfold, they would approach the fields existing on the surface of pulsars.

> Z-pinch—In a Z-pinch, a large current is passed through a conductor in the vertical or "z" direction, which generates an azimuthal magnetic field. The field in turn produces a radial compression, as in figure 2-1 on page 39.

It may be possible to produce quantum-degenerate, magnetized matter in magnetically-driven implosions. One possible method of reaching this state is the collapse induced by radiation cooling within hot spots formed at the intersection point of two or more wires (i.e., an X-pinch). On university-scale pulsed-power generators, X-pinches are routinely used as point sources of X-rays for point-projection radiography to image other HED plasmas or other objects (see sidebar, page 36). The challenge here is to measure plasma properties that are indicative of the degenerate state in the tiny hot plasma at the cross point.

Studies of extreme states of matter: On the largest pulsed-power generator, up to 26 MA of current can be used to maximize the photon energy range, the peak soft X-ray power and total X-ray yield achievable from wire-array Z-pinch implosions. Improvements in our ability to numerically model tungsten-wire-array Z-pinches with various configurations of hundreds of wires has led to an ability to design and control the radiation pulse shape. The resulting soft X-ray pulse can itself be used to achieve very high density and temperature conditions through spherical or cylindrical implosions, such as for indirect-drive inertial confinement fusion.

Supported by the progress in diagnostic tools and computer simulations that took place in the last ten years, generation of Z-pinch and X-pinch plasmas has proven to be an enabling technology for experiments in the areas of LabAstro, condensed matter physics, biological imaging, stockpile stewardship and homeland security, to name a few. Great potential exists for break-throughs in all of these areas, which may have transformational effects on our understanding of astrophysical phenomena, on inertial fusion energy and in the national security arena.

III. Research Needs

All three areas of magnetized HEDLP have similar needs:

Availability of experimental time: MHED experiments can be performed on a number of facilities, both in universities and national laboratories. They include both laser and pulsed-power facilities (Appendix B). The largest pulsed-power facility, the Z machine, typically generates HED plasmas at a rate of one "shot" per day at currents in excess of 20 MA. The university-scale facilities produce currents on the order of 1 MA and make 3-5 shots a day. The uniqueness of the Z machine, in terms of the achievable current and the extensive suite of sophisticated diagnostics, makes it extremely valuable for basic science and the academic community. The Z Facility can also be used as a radiation source for driving a number of other experiments that are likely to be of interest to other areas of HEDLP research. Examples include measurements of opacity of materials or creation of photo-ionized plasmas. The OMEGA laser facility at the University of Rochester currently has a vigorous National Laser User Facility program (NLUF) funded through DOE, which permits access to external users through a proposal and review process. A similar program for the Z machine would be extremely valuable to the HEDLP science community, especially those interested in MHED plasmas. A study by Z Facility scientists shows that it may be possible to operate the facility at up to 10 MA at a shot rate of two per day, doubling the data return and lowering the average facility labor cost per shot. Such an operating point would provide a significant intermediate step between testing a concept at the university scale of 1-2 MA and the 26 MA at the Z machine. In addition, the large, modern diagnostic infrastructure on Z, including the Z-Beamlet laser and Z-PW laser, will enable significant and cost-effective advances.

During the coming 3-4 years, highly productive magnetized HEDLP research can be performed on existing facilities. A focus on realizing to the fullest extent the tremendous potential of these facilities in the three research areas identified in Section II above, with added diagnostic and computational capabilities, is very appropriate. At the end of this initial period, optimal next-step facility/facilities for fundamental magnetized HED science and the major applications can be determined.

Diagnostics: An obvious critical issue for magnetized HED plasma experiments is measuring the magnetic field strength, both outside and within the plasma. One challenging example is to make a local measurement of the field near the boundary of a transient, dense plasma (e.g., to measure the peak magnetic field just outside a Z-pinch plasma that has imploded to a radius of about 10 μm and a particle number density of about 10^{28} m^{-3} and which lasts for less than a nanosecond). Active probing techniques with visible or UV lasers (e.g., Faraday rotation) cannot be used, and traditional passive emission diagnostics (e.g., Zeeman splitting) must compete with other effects (Doppler and Stark broadening). Novel techniques under development today could be further developed in the next 5 years to help address problems like this one; examples include proton deflectometry, detailed spectroscopic line shape measurements of different fine-structure components of multiplets, or diagnostics based on coherent XUV/VUV sources capable of penetrating denser plasma. It is unlikely that there will be a one-size-fits-all-plasmas solution, and this is a critical area of research for the field.

The experiments described in this chapter will also require a wide range of other diagnostics, including measurements of fusion products, plasma temperature and density, imaging of the plasma, etc. (see also Chapter 9 on diagnostics). Many instruments and methods to measure these parameters are in use on various facilities and can support experiments within the next few years. However, there will be a need for continuous innovation in their implementation as plasma densities and temperatures increase and the plasma evolution times become shorter. In some cases, the diagnostics may not exist at a particular facility that might be most suitable for a given experiment in other respects, and so funding to duplicate or move diagnostics will be important as well.

Computing: The computational treatment of MHED plasmas typically relies upon a combination of magneto-hydrodynamic (MHD) models, which simulate the motion of the plasma as a whole, and electromagnetic particle-in-cell (PIC) codes, which treat the effect of the fields upon the behavior of individual charged particles.

MHD simulations of experiments are complex calculations that need to resolve many different physical effects, including changes in the atomic populations and equations of state of the plasma, the flow of radiation, the penetration of magnetic flux and the coupling of energy from a driving circuit. They also need to be able to resolve the three-dimensional motion at a fine scale, which leads to large-scale parallel computing of up to 10^9 computational elements (see figure 2-3). Considerable progress has recently been made in the ability of these calculations to predict and reproduce the behavior of experiments. In order to meet the scientific objectives outlined for MHED physics, there would clearly be benefit in making 3-D MHD source code more freely available to groups wishing to propose or design novel experiments, or to improve physics models in the code. This could be achieved either through the release of an unclassified code based on those used at the national laboratories or by a concerted effort by the academic community to develop such a capability without repercussions related to export control, as discussed in Chapter 10.

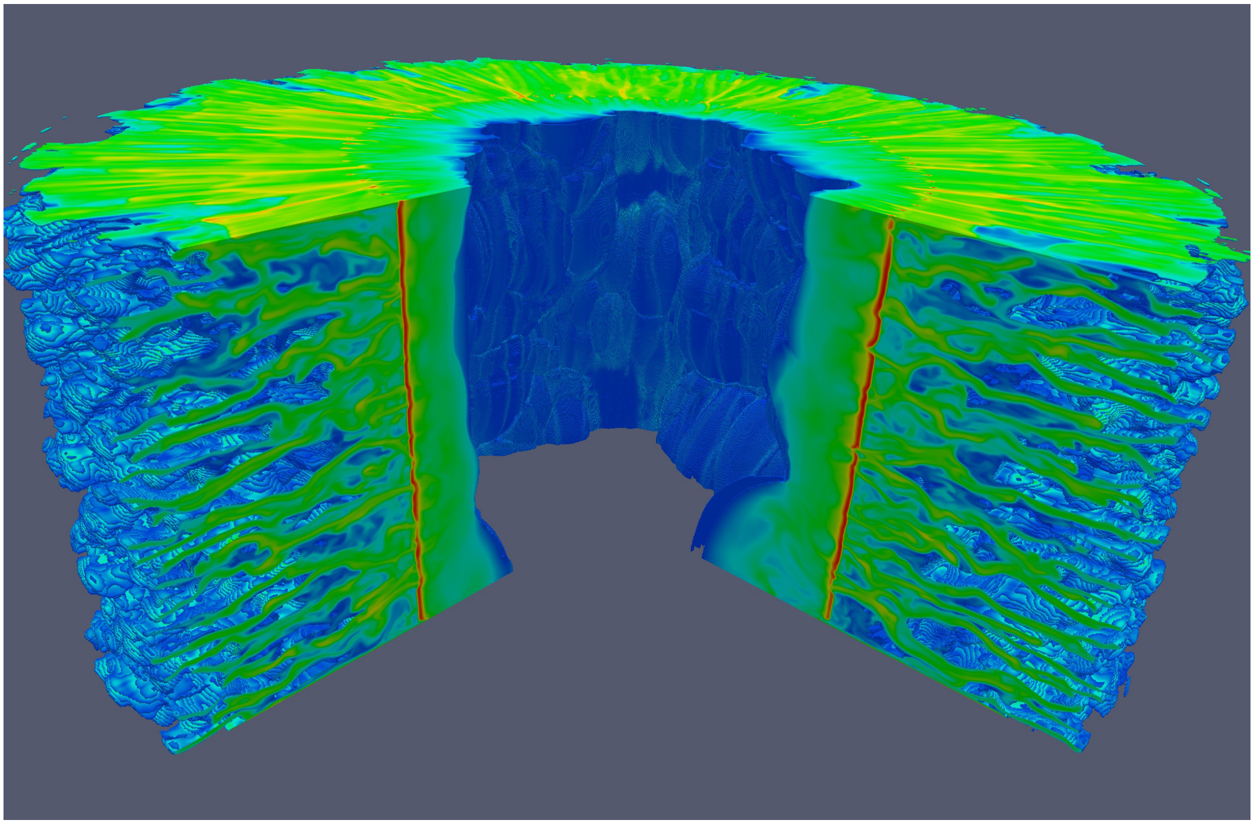


Figure 2-3. A simulation of a nested wire array Z-pinch using a 3-D MHD code with 700 million computational elements. (J. Chittenden, Imperial College, London)

There is also a need to pursue more accurate computational algorithms that focus on maximizing the resolution of fine-scale structures and overcoming numerical limits to the effective magnetic Reynolds numbers that can be represented currently. This is best achieved by collaboration between groups developing the next generation of AMR (adaptive mesh refinement) and ALE (arbitrary Lagrangian-Eulerian) laboratory MHD codes with university groups working on ideal MHD simulations of astrophysical objects.

Development of specialized PIC models will also be needed to address such specific issues as particle acceleration in magnetized shocks and fusion fuel heating by magnetized alpha particles, where the mean free path is comparable to the size of the plasma.

Chapter 3: Nonlinear Optics of Plasmas

How does intense coherent radiation alter the behavior of high energy density plasmas, and how do plasmas modify coherent radiation?

Introduction

Plasmas comprise nearly all the visible universe and exhibit a rich variety of states that arise from the complex interactions between the plasma's constituents and electromagnetic forces and radiation. In the laboratory, the intense laser radiation that creates dense plasmas also strongly shapes them and provides the ability to fashion and understand a broad variety of plasma states. This shaping of plasma configurations and the resulting optics of laser light is termed "the nonlinear optics of plasmas," referring to the typically complicated behavior of high-intensity, coherent electromagnetic radiation in the plasma. Examples of nonlinear laser-plasma interaction in high density plasmas include the creation of plasma waves that, in turn, scatter the laser beam, exchange energy, couple with particles, and may even self-organize into states in which particle positions and velocities execute complex and sometimes chaotic paths. In turn, the plasma can focus, steer and even create light at new frequencies (see sidebars, pages 46 and 47). Other important nonlinear laser plasma interactions include the generation of extremely energetic particle beams and the focusing and amplification of the laser beam.

Meeting the challenges posed by strongly nonlinear physics will provide insight into a broad range of plasma behavior. To do so requires us to follow the evolving plasma structures and their effects on the laser pulses propagating through them on ultra-short time and space scales. In HED plasmas, these scales range in length from less than one micrometer to one centimeter and in time from a millionth of a nanosecond to nanoseconds. Although until recently such resolution was technically impossible, new experiments have begun achieving that capability, pointing the way to further investigations and theories, which could provide quantitative understanding of these phenomena. In addition to the exciting opportunity of simply discovering to what extent nature will allow us to manipulate HED plasmas, strategic control of such plasmas has practical importance to fields as diverse as generating inertial fusion energy, understanding pulsar and quasar behavior and developing new laser and accelerator technologies.

Grand Challenge for Nonlinear Optics of Plasmas:
How Can We Control and Manipulate the Intense Flow of Energy and Matter in Extreme States?

I. Status

For many years, plasma physicists have been investigating the mechanisms by which laser beams interact with plasmas—work that is generally catalogued under the name "laser-plasma interaction" (LPI). Beyond such single-particle interactions as Thomson scattering, which has

Nonlinear optical processes—now you see it, now you don't

Imagine looking at a red light bulb through a clear crystal. Everyday experience tells us that the light will remain red after it passes through the crystal. But if you take an intense infrared light beam, such as one produced by a high-power infrared laser, and shine it through the same crystal, something unexpected happens—green light emerges. Two photons of infrared light have joined within the crystal to make one photon of green light! This is just one of the many surprising, peculiar and very important results that occur in nonlinear optics (figure 1).

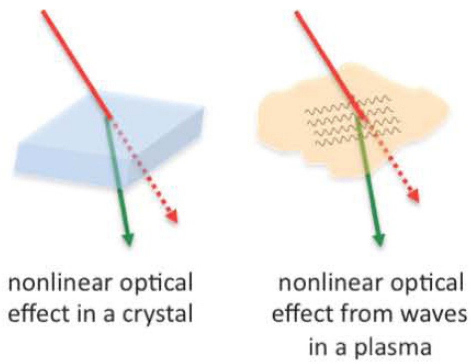
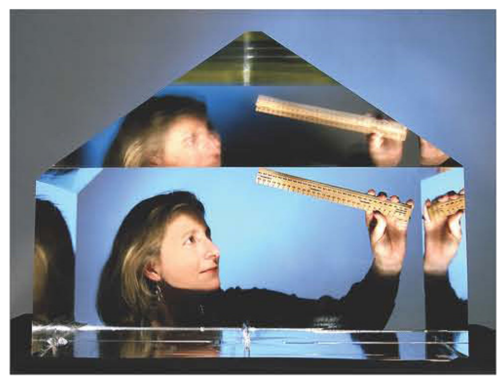


Figure 1. Laser beams passing through crystals and plasma.

Figure 2. Crystals, such as the one shown here, are used to convert infrared light from the National Ignition Facility (NIF) laser to ultraviolet light before it is focused on the target. The nearly perfect crystals must be very large so that they will not be damaged by NIF's high laser energy.

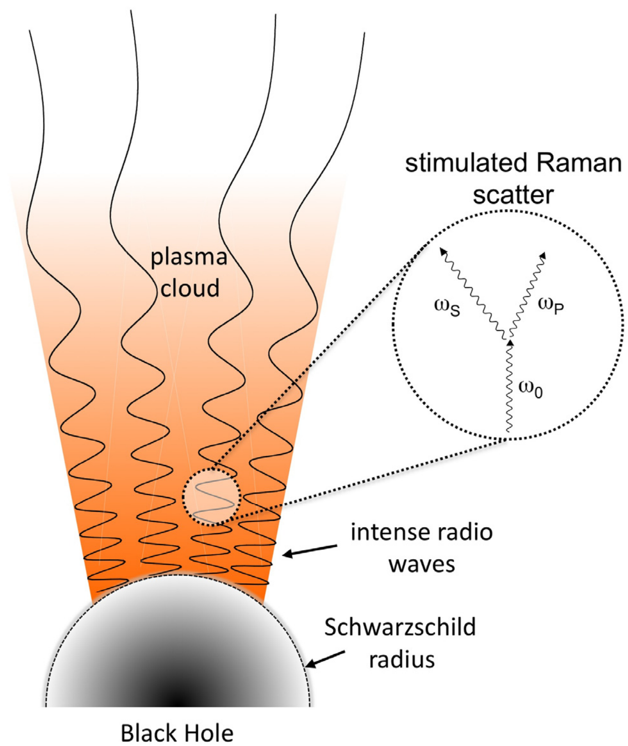


How has the crystal merged two photons? Under sufficiently intense light, the crystal does not allow the light to pass through "unimpeded," as it normally would. Instead, the vibrations of atomic bonds in the material become so large that they synchronously mix their electric fields with those of the light wave. The result is a light wave with increased energy, or a green photon rather than an infrared one. Nonlinear optical processes in ordinary matter are well understood by now, and are commonly used to fashion devices that quickly redirect or refocus light (in less than a trillionth of a second) or change its color. Such devices are often used together with fiber optics for telecommunications purposes. If the light is too intense, however, it will damage or even break the material. To avoid this problem, the crystals used to double or triple the frequency of the powerful infrared beams for ICF research at NIF must be very large, spreading the power over a large area (see figure 2).

HEDLP scientists have discovered that plasmas also produce nonlinear optical effects. When intense light passes through a plasma, the light's electromagnetic pressure can produce waves that scatter the light. As in the crystal, nonlinear optical processes can quickly convert laser beam energy from one frequency to another or deflect the beam. Since plasma is made of a collection of free electrons and ions, the laser can also rapidly transfer its energy to intense beams of particles. The HED plasma itself can transfer intense power flows among light beams and matter. In the future, HEDLP researchers hope this approach will enable the next generation of ultra-powerful lasers, or produce compact sources of intense particle beams. Furthermore, the interaction among many such nonlinear processes will lead to discoveries concerning the self-organization of matter far from equilibrium, which may have ramifications in all fields of science.

Nonlinear optical processes in quasar plasmas

In quasar plasmas, intense radio waves with frequency ω_0 propagate through the surrounding plasma. These waves can produce large amplitude electron plasma waves (at frequency ω_P) via a process called stimulated Raman scattering. The process also produces intense scattered radio waves (at frequency ω_S) that are shifted in frequency from ω_0 by an amount equal to the plasma wave frequency. Such nonlinear processes are thought to be responsible for the important aspects of quasar emission spectra. They are directly analogous to those produced in laser-driven HED plasmas. Theories for the origin of quasar radiation and for radiation from other astrophysical systems can be rigorously tested using data and modeling obtained from nonlinear optics experiments in laser-driven HED plasmas.



been used for diagnostic purposes in plasmas for over four decades now, many effects that involve plasma waves have received a great deal of scrutiny, such as the scattering of laser beams from electron plasma waves and ion acoustic waves (see Section II, below). Most of the work involving nonlinear LPI that was carried out until recently was intended to understand it well enough to avoid the unfavorable effects of the nonlinear interactions, such as the break-up of a laser beam into filaments (which makes it much more difficult to focus). An exception to the desire to avoid nonlinearities is the three-decade-long effort to use intense lasers propagating through dense plasmas as a means to accelerate particles to high energy in a much shorter distance than conventional accelerators; this subject will be discussed in Chapter 5, on relativistic HED plasmas.

In addition to filamentation of the laser beam, many different nonlinear optical processes have recently been predicted in computer simulations and observed in LPI experiments. Among them are "self-focusing" of an intense laser beam by the plasma channel created by the light's electromagnetic pressure, as well as stimulated scattering of the beam from electron plasma waves or ion sound waves. Computer simulations and theory have helped identify important signatures of such processes and predicted key experimental trends as functions of laser intensity and plasma conditions. A fascinating interplay—nonlinear interaction among these nonlinear optical processes—has been observed, as we will discuss shortly. Various beam smoothing techniques, as well as manipulation of plasma composition, have been used to provide some control of LPI in regimes of moderate laser intensity and modest plasma sizes.

Laser-plasma interaction processes are modeled with a variety of simulation tools, ranging from kinetic "particle in cell" (PIC) simulations to various simplified descriptions that have enabled simulations using realistic laser beams propagating in plasmas with scale lengths as large as 3-5 millimeters. These simulations use highly simplified models for the nonlinear optical processes and need to include improved models of non-paraxial wave propagation, the coupling between laser beams that cross, and unstable plasma wave growth when it slows down due to nonlinear effects. The possibility that laser energy might be dissipated through acceleration of a small fraction of plasma electrons to high energy, as is seen in PIC simulations, should also be included in the simplified model simulations.

Several important and novel aspects of the nonlinear evolution of plasma waves have also been observed in recent experiments and simulations. In HED plasmas through which an intense laser beam propagates, simulations predicted—and subsequent experiments showed—the formation of strong, persistent, nonstationary structures that defy description using ordinary linear perturbative theories. These recent discoveries and our deepened understanding of the underlying physics of the nonlinear optics of plasmas, coupled with advances in high-performance computing and revolutions in diagnostic techniques, open the door for tremendous new opportunities for future progress.

II. Research Opportunities and Needs

(1) How does coherent radiation drive self-organized states in plasmas?

Why is it important? One of the more remarkable properties of plasmas is their ability to support many different kinds of waves. For instance, in the absence of externally applied magnetic fields, plasmas transmit electromagnetic waves with frequencies above the electron plasma frequency, and they can support two kinds of electrostatic waves: electron density disturbances (which are loosely called plasma waves) and waves involving the motion of the ions (which are analogous to sound waves and so are called ion acoustic waves). Such waves are the plasma's response to small perturbations of various kinds; they can be flexibly excited and probed by intense lasers, providing unique insight. The various small-amplitude waves in plasmas have been catalogued and studied for over fifty years, but quantitative understanding of their creation, and especially their interactions with each other when amplitudes become large, and with nonlinear kinetic plasma states, remains crucial both to basic plasma science and to applications.

Game changers: A recent discovery has shown that intense lasers can excite structures in plasma that are similar to electron plasma waves, except that they have no small-amplitude or stationary limit. Such waves form only when a threshold in disturbance size is surpassed in the plasma and the frequency-wavelength relation of the disturbance differs from any ordinary wave supported by the plasma. First observed in simulations, they have now been excited and detected in a growing number of experiments. An example, known as a "Kinetic Electrostatic Electron Nonlinear" (KEEN) wave, is shown in figure 3-1.

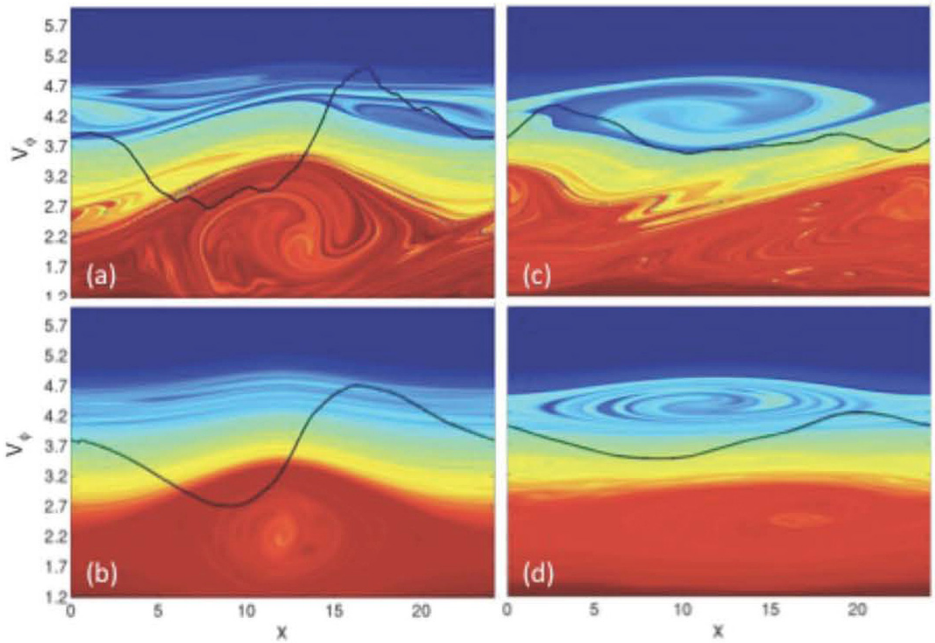


Figure 3-1. A nonlinear electrostatic wave driven by high-power laser beams, dubbed a "Kinetic Electrostatic Electron Nonlinear" (KEEN) wave, can be seen in the two left panels as a swirling red vortex. The plots display the position (x) and velocity (V) of electrons in a simulation in which the plasma is transferring energy between intersecting laser beams. The vortex indicates that the electrons are confined within certain ranges of motion. Panels (a) and (b) show the time evolution of a KEEN wave with the same wavelength as an electron plasma wave, shown in blue, but exactly half the frequency (phase velocity V near 2 in panels (a) and (b)). The KEEN wave in panels (a) and (b) does not allow the formation of fully trapped electrons in the electron plasma wave's electric field, and thus that wave never forms its own vortex structure. This is illustrated by the fact that the blue vortex near V = 4 dies off between panels (a) and (b). The relative overall electric field, indicated by the black curve, represents a resonance between the first two harmonics of the KEEN wave and the single harmonic plasma wave. Panels (c) and (d) show the same time evolution as before, but with the frequency of the KEEN wave slightly higher than in the first two panels and off resonance. In this case, the plasma wave successfully forms and slightly alters what would have been a smaller KEEN wave. This sort of phenomenon enables non-local interference in velocity space, which is a fascinating new research area in HED plasmas.

The KEEN wave is an example of plasma self-organization in which two intense laser beams with precise angle and frequency relationships can be crossed in the presence of an intermediary plasma wave to create long-lived but inherently nonlinear and nonstationary excitations. Such excitations have the potential to control optical scattering and to modify the propagation of the laser beams in the plasma. In the process of generating and maintaining these states, the usual plasma response to a perturbation can even be suppressed under some circumstances, as shown in figure 3-1. The fundamental questions we need to answer are: Can we use these nonlinear structures as tools to redistribute energy in the plasma and otherwise manipulate it? How can we characterize such states in the laboratory and compare their features with the predictions of computer simulations? Are they representatives of a wider class of structures that can be generated by means other than the crossing of laser beams?

***What's needed*?** In the laboratory, the necessary tools to answer these questions are pairs of tunable-wavelength lasers. Optical mixing of the two beams in the plasma provides the driving force to create nonlinear wave structures under various plasma conditions. In addition, a sub-picosecond high frequency probe laser is required to map the evolution of the structures via Thomson scattering.

On the simulation side, 2-D and 3-D PIC and Vlasov (kinetic) simulations, which present and future computer capabilities make increasingly practical, are required to assess the effect of the finite transverse extent of the nonlinear waves, such as that shown in figure 3-1. To date, these processes have been investigated mostly by using 1-D Vlasov-Poisson and Vlasov-Maxwell simulations. Of course, their experimental detection has been in full 3-D.

Connections: An understanding of self-organized states may shed light on the persistence of coherent structures in far-from-equilibrium systems, such as the processes of galaxy formation and turbulence in magneto-hydrodynamic and 2-D Euler systems.

(2) How can we control and tailor nonlinear optical processes in high energy density laboratory plasmas?

Why is it important? Many present and envisioned applications that employ intense lasers to interact with matter require the control of nonlinear optical processes as well as the structures they produce in dense plasmas. Controlling these processes demands an understanding of their onset, growth, and other underlying factors that determine wave growth and structure development. With such understanding, scientists will be equipped to control the propagation and energy transfer processes of intense beams in plasmas. This will enable the creation and study of extreme states of HED matter using lasers, and ultimately enable robust approaches to high-gain IFE.

Leaping beyond simple control of nonlinear processes, a far-reaching goal is the ability to tailor and manipulate these processes for revolutionary applications. Nonlinear optics in solid, low-temperature matter is commonly used to convert a laser beam to other useful forms of light or to a laser beam at a different frequency (see sidebar, page 46). By contrast, researchers envision that manipulating nonlinear optical processes in HED matter will allow the design of compact radiation and particle beam sources with extreme intensities that lie beyond the limits of current solid-state optics or accelerator technologies. Laser amplifiers based on HED plasmas could one day transform the laser beams of today into ultra-powerful, ultra-intense light sources that would be impossible with solid-state amplifiers because plasmas can tolerate much higher power densities than solids.

Game changers: The ability to control and manipulate nonlinear optical processes in HED plasmas is underpinned by a deepened understanding of many of the important physical processes and an ability to predict them, as well as the discovery of nonlinear, kinetic self-organized states in plasmas. At the same time, technology, computing and diagnostic methods have advanced sufficiently to enable research to control and manipulate nonlinear optical processes in HED plasma. The ability to vary the power and spatial profile of laser beams on time scales that are comparable to the growth times of laser-plasma instabilities is a potential game-changer for success in this arena. So is the implementation of flexible optical mixing techniques to transfer energy from one laser beam to another in plasmas. Revolutionary advances will be enabled by experiments using sub-picosecond creation, detection and visualization of plasma waves and structures. The ability to model the physics with a full 3-D kinetic description covering the time and space scales of experimental interest will be equally revolutionary.

What's needed? In the near term, three to five years, dedicated research at small- and intermediate-scale laser facilities is required to develop experimental platforms with sub-picosecond diagnostic methods and tunable-wavelength picosecond lasers (for optical mixing) to provide fundamental understanding of nonlinear optical processes in dense plasmas. The ability to design and implement extreme time-variation in laser-pulses on picosecond time scales should be tested experimentally as a means to control laser-plasma instabilities on the time scale of their growth and decay in the presence of a plasma-modified distribution of intense laser hot spots. This approach could provide a means not only to control, but also to precisely manipulate, nonlinear optical processes in HED plasmas. Multi-scale models of the kinetic, nonlinear evolution of laser-plasma processes will also be needed in conjunction with the experimental data. Experiments are needed to explore multi-speckle laser-plasma interaction at increasingly longer time scales, and theoretical models of nonlinear optical evolution would be required to compare with the data generated by the experiments. On the five-to-ten-year horizon, dedicated experiments with detailed diagnostic methods are required that measure the evolution of the plasma wave properties and their effects on the plasma velocity distribution functions. On the seven-to-ten-year horizon, research needs would entail moving these capabilities to large-scale laser systems to explore compelling applications, such as IFE and producing the next generation of ultra-powerful, short-pulse lasers.

Connections: Laboratory nonlinear optics research in plasmas would connect to astrophysics through nonlinear optical processes that occur in plasmas surrounding quasars and pulsars. Such research would also validate our understanding of how intense neutrino fluxes deposit their energy via strongly driven plasma waves in dense plasmas during the core collapse of a supernova. Research into nonlinear optics of plasmas would push the boundaries of high-performance computing, and it also has ties to the study of high-dimensional nonlinear dynamical systems. Furthermore, it will lay the foundation for applications such as advanced accelerators, plasma-based nonlinear optics, and revolutionary ultra-high-intensity light sources.

(3) How do multiple nonlinear processes co-evolve? How do overlapping laser pulses interact via common plasma modes?

Why is it important? A dramatic property of plasma driven by high-intensity light is the tendency for incident photons to decay into a scattered photon plus a plasma wave. These three-wave processes represent the easiest-to-excite resonant instabilities of light waves in plasma, and they can rapidly erupt and redirect the flow of optical energy. Such instabilities are the primary limitation to the coupling and driving of HED matter with lasers, but they may also offer a unique means to control the properties of the HED plasma and "engineer" complex plasma states. A recent series of experiments and simulations with laser beams in HED plasma demonstrated a technique to control the energy flow of beams so intense that they would destroy solid matter. The building blocks to accomplish this feat are ordinary plasma waves in a geometry determined by the wave vectors and frequencies of the incident laser beams. The building blocks can be formed into optical devices that are essentially 3-D lattices of charged particles which scatter light and shift frequencies with high precision (for example, from one intense laser beam into the other).

Game changers: Control of energy flow in a plasma has been demonstrated by experiments in which large-amplitude ion acoustic waves driven by intense coherent light suppressed stimulated scattering by electron plasma waves.
Specifically, researchers studying the coupling of laser energy to inertial fusion targets found that the coupling efficiency can be controlled by selecting target materials and beam properties that favor the growth of the ion acoustic plasma wave over the electron plasma wave. The observed reduction of the laser beam scattering by the electron plasma wave confirmed the expectation that the nonlinear interaction between plasma waves can control both the scattered energy and the energy eventually coupled to the target. More recent studies of scattering from electron and acoustic waves confirm the rapid time scales of their nonlinear interactions, as shown in figure 3-2. By operating away from the threshold for the abrupt growth of either electron or ion waves, the same process could amplify one laser beam by scattering energy into it from a second laser beam. To accomplish this, careful control of the plasma conditions is essential in order to ensure the presence of the necessary acoustic wave, and the geometry of the interacting laser beams must meet the resonance conditions between the two electromagnetic waves and the acoustic wave. The results of this work call for research in which precisely located ion acoustic waves produced by the optical mixing of intersecting laser beams can suppress scattering from electron plasma waves that would otherwise become unstable at the same location.

Power transferred between crossing laser beams via ion acoustic waves has also been used to make precise adjustments to the power deposition profile in hohlraum targets (see

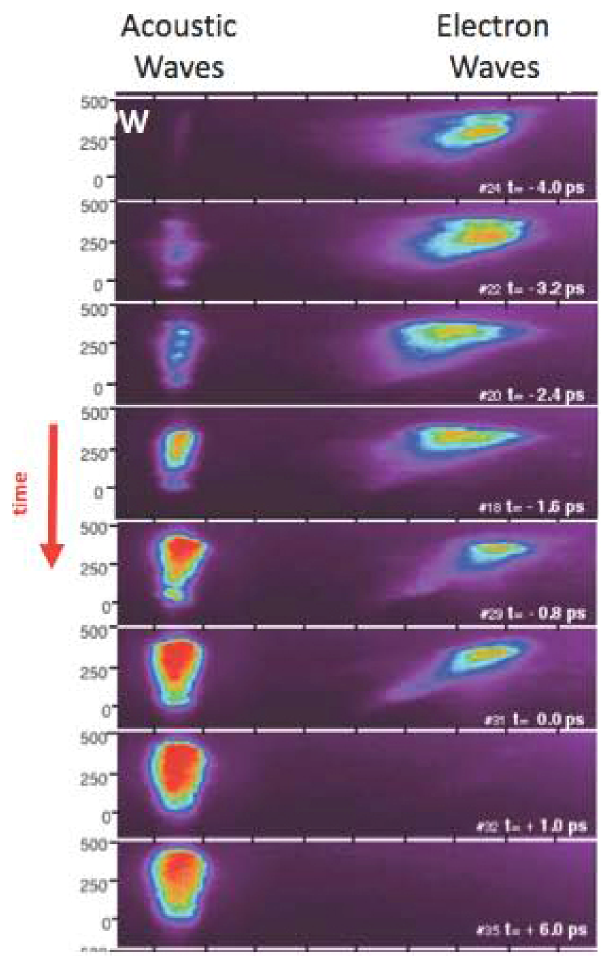


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Figure 3-2. Studies using snapshots of light scattered from electron plasma waves and ion acoustic waves driven by intense laser beams show that the electron wave is dying out while the acoustic wave is growing. This is an indication that the laser light is mediating the energy transfer between the waves. Such processes can one day be developed to control the flow of energy in HED plasmas.

Chapter 1) studied for inertial fusion at the National Ignition Facility. This was accomplished in recent experiments by frequency-tuning the incident lasers, enabling improved implosion symmetry over a range of input laser energies up to 1.05 megajoules. Detailed understanding of the observations will require new experiments where the energy transfer properties of pairs of crossing beams in carefully prepared plasmas are studied in isolation in a geometry allowing a full complement of diagnostics.

What's needed? The processes just described are in a good position to be rapidly advanced with the help of multi-scale high-performance computing to point out the best regions of plasma and laser parameter space to investigate. The expanding experimental database from NIF, if coupled with an extensive series of well-diagnosed experiments at smaller facilities, can be used to inform development of a non-paraxial, computational model to describe these phenomena in depth. This work will require dedicated computation effort, as well as the development of advanced diagnostics to image the plasma wave profiles on ultra-short time scales.

Connections: Optical mixing control and optimization of plasma instabilities will advance applications in IFE and HEDLP experiments, and will connect with understanding dissipative classical field theory, pattern formation and chaos control, which are studied in the context of turbulence in ordinary media.

(4) How do we develop predictive capability using multi-scale models that include nonlinear kinetic behavior?

Why is it important? The ability to predict how complex, nonlinear phenomena evolve underpins the success of IFE. The challenge of HED science, including laser-driven IFE, the development of next-generation laser-particle accelerators and the production of extreme states of matter, is to couple energy into plasma in a very short time but in a *controlled* fashion. Predictive capability will enable control.

Game changers: Recently developed computational models have demonstrated the ability to bridge *all* length scales in HED plasmas: from "micro-scale" (where intricate wave-particle dynamics occur), to "meso-scale" (where laser refraction, diffraction and laser-plasma coupling become manifest), to the "macro-scale" of radiation flow and hydrodynamics. With one-petaflop (a million billion operations per second) supercomputers, micro-scale simulations can now capture the complex physics contained below the computational grid size of a meso-scale simulation. Similarly, studies of the entire laser beam at the meso-scale can model new physics arising from laser-plasma interaction at the macro-scale. Indeed, in some instances, such as short-pulse LPI studies, it is now possible to model the *entire* physical domain at all length and time scales, as illustrated in figure 3-3.

What's needed? Development of robust, validated physical models for nonlinear and kinetic processes in plasma, involving a combination of improved micro- and meso-scale models, is essential. In micro-scale simulations, physics model improvements must include efficient modeling of collisions of relativistic particles, inclusion of atomic and radiation physics, new algorithms to treat quantum effects where necessary, and more. At the highest intensities, the drag on charged particles as they oscillate and radiate in intense laser fields must be included,

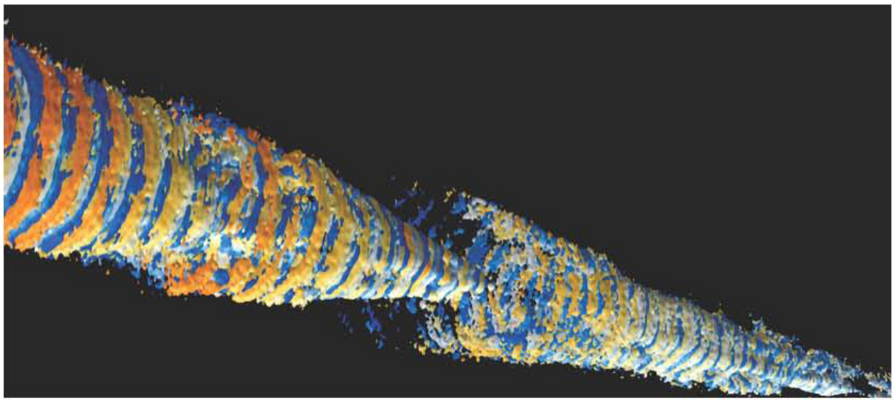

Figure 3-3. 3-D kinetic modeling of electron density waves driven by an intense laser in a plasma shows changes in their detailed spatial structure and reveals the micro-scale physics that must be accurately captured in multi-scale models. The width of the large tube-like structures is about 5 micrometers.

perhaps along with the effects of matter-antimatter pair production (see Chapter 5 on relativistic hydrodynamics). Improvement in algorithms is needed to enable simulations to span time scales ten to one hundred times longer than is presently possible. Injection and application of new ideas, such as techniques for improved efficiency and noise control, along with adaptive, implicit and multi-scale modeling techniques, will enable computer simulations to continue to aid in the discovery process in nonlinear-optics physics.

Meso-scale simulation models must capture the rich assortment of processes manifest in IFE and HED experiments, including multi-wave, multi-mode nonlinearity, and plasma-wave interactions near the critical region, where the local plasma frequency matches the laser frequency. These models must go beyond the paraxial approximation for laser beam propagation, which is a dramatic simplification that evolves wave envelopes, and instead follow the dynamics of the intense electromagnetic waves in nonlinear media.

Success will hinge on access to and effective use of the largest supercomputers. The landscape is complicated by the likelihood that the next generation of supercomputers will be much different from today's and will require different algorithms. This work, which will benefit from engaging the applied mathematics, computational science, and high-performance computing communities, represents a clear cross-disciplinary opportunity.

Connections: Because high-intensity lasers are central to HEDLP, predictive modeling of laser-plasma coupling will benefit the HED community as a whole and spur development of applications such as IFE. By its nature, this work has natural ties to high-performance computing. Coupling with the plasma experimental and diagnostics development communities will also be essential, since direct comparison with experiments will provide the ultimate validation of the hierarchy of numerical models.

(5) How can we develop a self-consistent description using wave-kinetic models for laser-matter interactions that bridge the gap between classical, quantum and relativistic regimes?

Why is it important? Meaningful theoretical models that can capture the physics of multiple interacting waves must go beyond a simplistic, coupled rate equation description in order to capture slowly evolving nonlinearities, inhomogeneities, and stochasticities. A technique ideally suited to the task is the use of wave-kinetic models, in which space and spatial scales, as well as time and frequency, are treated on an equal footing in phase space. In addition, wave-kinetic descriptions permit the incorporation of quantum and relativistic effects in a single formalism that is applicable to both waves and particles. Also, radiation sources of wide-frequency content and their interactions are naturally included in such models. The challenges in this research are that complex non-local models must be judiciously simplified to produce computationally efficient local descriptions that must be tested in computer simulations against the original precise models for validation and guidance. Any such approach requires the preservation of causality, gauge invariance, and maintaining positivity of probability densities to the extent possible.

What's needed? Brute force approaches to full-scale multi-physics calculations are prohibitively expensive, scaling with the number of resolution elements as N^4 in the two dimensions transverse to the laser beam propagation direction. The ability to perform sparse sampling of rays in phase space for the efficient construction of semi-classical descriptions would lead to a breakthrough in extending the range of validity of wave-kinetic models. Also, non-local interactions must be described without ghosts of interference effects obscuring the underlying fundamental physical processes. Incorporating weakly nonlinear and stochastic effects, as well as inhomogeneity and anisotropy in space and time, is the most likely approach to capture the self-consistent dynamics of these far-from-equilibrium nonlinear systems.

Unification of techniques in advanced harmonic analysis (wavelets, curvelets, exploiting sparsity) with stochastic averaging techniques, and incorporation of rare but significant random events, order statistics and the statistics of extremes, could lead to major theoretical and computational advances for HEDLP.

Connections: Quantum statistical mechanics, weak turbulence theory, quantum optics, the study of quantum chaos and wave chaos would all benefit from the development of these modeling methods.

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Chapter 4: Radiation-Dominated Dynamics and Material Properties

How is the behavior of HED plasmas altered in the radiation-dominated regime, and how do HED plasmas alter the propagation of radiation? How does the resulting energy flow affect cosmic phenomena and the evolution of the universe?

Introduction

Fusion energy, the birth and death of stars, the structure of galaxies—all depend intimately on how radiation propagates through matter. In stellar interiors, nuclear explosions, terrestrial fusion-energy experiments and the early universe, the energy inherent in radiation may be comparable to or exceed the energy of motion of the matter itself. When the density of radiation is so high that it, rather than the particle interactions, controls the behavior of the system, we say that the dynamics are radiation-dominated. Under these conditions, electrons are stripped from their parent atoms, leaving behind positively charged ions. The life cycle of stars, and with it the generation of the elements in the universe—many of which are necessary for life—all involve the propagation of radiation through ionized media. Discoveries helping to shed light on longstanding mysteries in this arena are becoming possible through new capabilities in high energy density laboratory physics. Through the use of high-power lasers or huge pulses of electric current from pulsed-power machines, it is now possible to make and study in the laboratory macroscopic amounts of star-like material—matter with the composition, temperature, and density of that found in stars. These laboratory systems utilize bursts of radiation so intense that they are able to heat and compress matter to conditions that mimic those found in stellar interiors or in the vicinity of exotic astrophysical objects such as black holes or quasars. Studying radiation-matter interactions is also likely to lead to breakthrough advances in inertial fusion energy research, the success of which in turn offers the promise of creating even more powerful HED physics platforms.

I. Status

The key role that radiation-dominated dynamics and HED material properties play in astrophysics has been recognized for at least 80 years. Stride after stride in progress has occurred by combining astronomical observations and computer simulations with terrestrial research, relying where possible on limited-availability experimental benchmarks. Early laser and electrical discharge experiments were found to reach temperatures that rivaled the stars, but these results were not entirely suitable for detailed studies that could form a foundation for astrophysical and fundamental HEDLP research. Beginning in the 1970s, the need for fundamental HED physics knowledge in radiation-dominated plasmas was shared with astrophysicists by scientists involved in inertial confinement fusion (ICF) research. For both the astrophysics and ICF applications, there were two main problems that had to be solved to make laboratory experiments on radiation-matter interaction scientifically useful: the production of relatively uniform HED matter of adequate size and long enough lifetime to enable detailed study, and the establishment of diagnostic methods that could characterize that matter after

Making "star stuff" in the laboratory

Astronomers have often said that we are made of "star stuff," atoms created in the interiors of stars and then expelled into space to be incorporated into later stars and the planets around them. New developments in HEDLP research are enabling the creation of macroscopic quantities of stellar matter in our laboratories on Earth. The amounts are still small, ranging from the size of a grain of sand up to a cubic centimeter. The duration is still short, only a few billionths of a second. But extraordinary instruments developed in HED research can record snapshots even ten times shorter and with spatial resolution smaller than a human hair. Detailed measurements of matter like that which exists inside of stars are within sight and will transform astrophysics from a science of passive observations linked with simulations to a new experimental branch in HED physics.

How are such experiments done? The ability to create the temperatures and densities found in stars has in fact existed for about 30 years, but the process has been inadequate for scientific purposes because of the difficulty of producing uniform conditions. Only now, with the advent of the National Nuclear Security Administration's two largest facilities, NIF and Z, is the ability to create uniform conditions that mimic stellar interiors a reality. Typically, a laser or electrical discharge creates a hot plasma; the X-rays emitted from that plasma illuminate and heat the sample in a uniform way to the required temperature, as illustrated in figure 1.

Opacity, the property of matter that prevents passage of X-rays (see footnote to page 60), has been studied experimentally for over two decades and is advocated here as a high-impact topic for future research. Opacity measurements on a sample are performed by using a spectrometer to view an X-ray source directly through the sample, thus measuring the X-ray transmission as a function of photon energy (see figure 2). Such measurements are a powerful way to test and validate sophisticated quantum models of atoms in hot HED conditions as well as to determine the conditions inside the plasma.

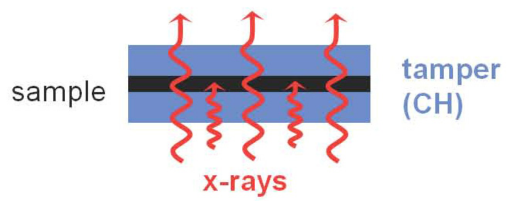


Figure 1. X-rays stream through a sample and heat it uniformly over its volume. Uniformity is key because it enables comparison with models for X-ray transmission that assume a single temperature and density throughout the material. Transmission is measured by positioning an X-ray source below the sample and recording the transmission spectrum, an example of which is shown in figure 2, with a spectrometer positioned above the sample.

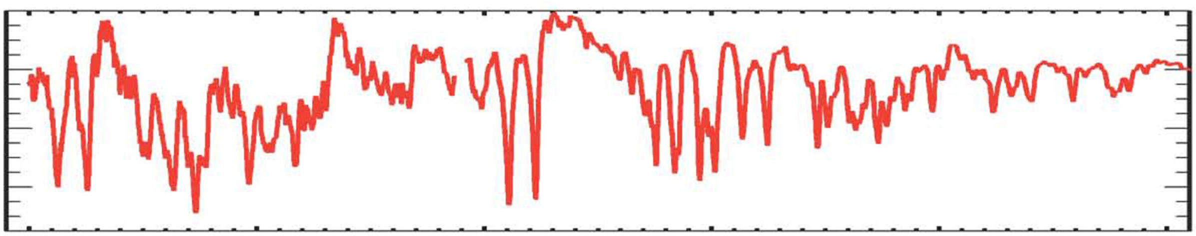
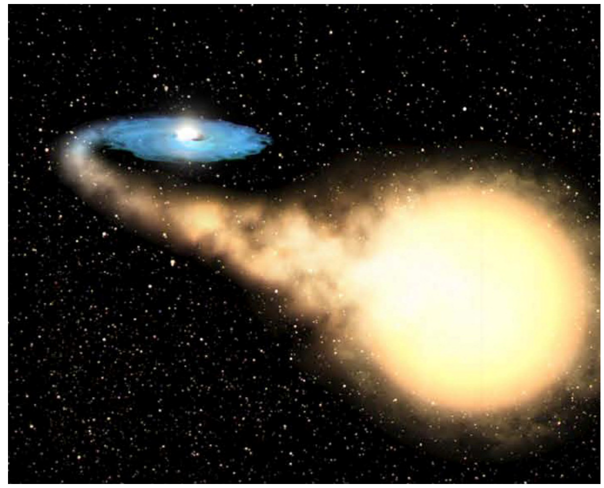


Figure 2. Transmitted intensity versus wavelength - transmission spectrum for iron heated to 1.8 million degrees. The peaks and valleys of the data carry a wealth of information about the different electronic states iron atoms take in the plasma, such as in the interior of a star. This type of data can be used to test quantum mechanical models of iron opacity.

Black holes up close

Black holes are arguably the most tantalizing objects in the sky, and the sites at which the weakest force in nature—gravity—prevails over all other forces. Paradoxically, the immediate vicinities of these dark objects constitute the brightest persistent sources in the universe by virtue of the immense energy released as matter swirls down into the black hole. Black holes come in two general mass classes: stellar-size black holes (which are found in X-ray binaries, as illustrated in the figure), and supermassive black holes millions to billions of times more massive than the Sun, which reside in the centers of galaxies. The radiation emanating from these powerful sources creates radiation-dominated plasma conditions in any ambient matter, whether it is the stellar wind in an X-ray binary or the outflow of radiation from a galactic black hole that is actively gaining new matter. Intense laboratory HED radiation sources can be harnessed to produce similar conditions in laboratory plasmas that, in turn, help scientists study the nature of black hole sources. In fact, the diagnostics developed for these astrophysical sources are based on, and very similar to, methods developed in the laboratory, such as X-ray spectroscopy.



Artist's impression of an accreting stellar black hole in a binary system.

subjecting it to a powerful energy source. These problems are interrelated, as the required size and duration depend on the diagnostics. The theoretical sophistication and computational horsepower needed to interpret the raw results, the importance of which should not be underestimated, is now developing.

The conjunction of several progress streams has positioned radiation-dominated HED research well for breakthroughs in many areas over the next decade. The scale of laboratory experiments has grown until it now encompasses megajoule-class facilities capable of producing true testbed HED samples. Diagnostics have evolved so that they can provide reliable, accurate measurements of plasma conditions. Sufficiently sophisticated diagnostics can enable progress in fundamental understanding even with more modestly scaled facilities. Theoretical models and computer simulation codes, including radiative energy transport models, are available and are rapidly becoming more powerful. Astrophysical observations have grown in accuracy until the measurements recorded by space-borne instruments rival or surpass the accuracy that can be achieved in Earthbound observatories. Moreover, inertial fusion ignition is drawing ever closer (see Chapters 1 and 5), providing added incentive for experiments on radiation-dominated matter to elucidate the fundamental physics. Finally, scientists' thinking about HED research has matured. The context for this report is set by the incremental progress in dozens of topical areas that together set the stage for transformational, or in some cases revolutionary, progress in the future.

II. Research Opportunities and Needs

We suggest three areas that are ripe for progress in the near term in the area of radiation-dominated dynamics, plus a fourth area of such high potential impact that it should be pursued for the long term: nuclear burning plasma.

(1) How does the Sun work?

Why is it important? Understanding solar structure is a compelling goal by itself, but it also has broad ramifications far beyond the curiosity of solar specialists. The Sun provides the "gold standard" for models used to describe nearly every star we see.

A high-priority research opportunity is to measure and theoretically analyze more precisely the radiative properties of the elements that regulate the structure and energy flow within the Sun and other stars. Through such research we can hope to improve the detailed understanding of how stars work, how old they are, and what they are made of. Our own Sun, if well enough understood, would serve as a precision laboratory for neutrino physics, which might in turn give key insights into new fundamental physics beyond the standard solar model. The internal structure and life span of stars depends on the opacity,[10] equation of state and plasma dynamics of stellar matter. A path forward here is to create on Earth a *macroscopic quantity* of stellar-interior matter, measure the frequency-dependent transmission of photons, compare with and advance the theoretical physics of atoms in plasmas, then connect these advances back to the Sun for an improved knowledge of solar physics and interior structure, such as the exact location of the boundary between the radiative zone and convection zone. While this research might be motivated by understanding the Sun and stars, at a more fundamental level, knowledge of the opacity, equation of state and plasma dynamics is a cornerstone of HED physics and affects virtually every HED experiment involving radiation. Furthermore, IFE target designs depend on accurate determination of these properties.

In greater detail, the outstanding puzzles of solar structure are rooted in our imperfect understanding of the properties of HED matter. For example, the energy liberated in fusion reactions at the center of the Sun is transported outwards by radiation over the central seventy percent or so of its radius, known as the radiative zone. Outside the radiative zone, radiation transport becomes inefficient and convection takes over. Radiation transport is driven by the temperature gradient and is hindered by the absorption, or opacity. The absorption depends on the elemental composition of the star, as well as the frequency dependence of the opacity of each element. Different elements contribute different amounts of opacity, and it is generally true that higher-atomic-number elements contribute much more absorption per atom, since they retain some of their bound electrons even under the extreme conditions inside a star. Thus, there is an intimate connection between elemental abundances, elemental opacities, and the success or failure of any stellar model to reproduce all available observations. Today, theoretical models for the X-ray opacity of stellar material have reached a mature level of sophistication, but they have

[10] Opacity describes the degree to which radiation traversing a medium is absorbed by it. The HED plasmas of interest in this report range up to densities high enough that light, and even X-rays, emitted by highly stripped ions near the center of the plasma, are highly likely to be absorbed before escaping the plasma.

yet to be tested in the conditions that exist within a star. The rapidly advancing ability for HED experiments to replicate and study stellar matter may soon help to resolve such basic questions.

In addition, the compositions of all stars and many other astrophysical objects are calibrated by solar models. Thus, the total oxygen inventory available to form water (H_2O) in the universe is estimated in part by solar research. The abundances used in solar models are, in turn, estimated from the composition of meteorites (which provide the input for the initial elemental composition of solar models for relatively non-volatile elements) and from spectra that emerge from the solar photosphere (which define the current composition of the convective outer envelope of the Sun). The data must be interpreted with a spectral synthesis model, based on spectrally resolved observations of the solar photosphere. These models have become increasingly sophisticated since the early versions developed in the 1950s and 60s, and today they have, for example, begun to account for departures from local thermodynamic equilibrium. Because of observational limitations—principally related to an inability to fully spatially resolve plasma structures and flows at the photospheric level—the newer models still parameterize such phenomena. Unresolved flows are treated by so-called micro- and macro-turbulence models whose physical connection with the actual flows remains a major open question. This situation will continue as long as lack of observations limits our ability to validate the models.

Recent research that removed some of these approximations led to a major revision of the solar abundances, including a 50% reduction in the amount of oxygen. Solar models constructed with these new abundances now disagree significantly with helioseismology, the most powerful tool brought to bear in solar interior studies. Helioseismology has employed extraordinarily accurate measurements of tiny oscillations in the solar surface to determine the sound profile, and hence structure, within the Sun. These measurements together with others have shown that the basic picture of solar structure is sound. Therefore, it is appropriate to ask if the current discrepancy is due to the fact that even the most refined photosphere models are in error. Is it because the theoretical opacity models lack sufficient accuracy? Or is it because the physical approximations used in the solar models—especially those describing the solar surface—do not capture all the essential science?

Game changers: Laboratory research can now provide a solid basis for resolving these questions. Progress in experimental techniques could enable the first opacity measurements at conditions corresponding to the boundary of the radiative and convection zones. The temperature of two million degrees, densities of ten percent that of solids and the difficulty of producing enough matter at these conditions to permit accurate measurements precluded taking such data in the past. However, the availability of large-scale HED facilities is a game-changing capability for this research. Validation and refinement of opacity models through new experiments on these facilities will further constrain stellar abundance estimates, since the abundance estimates and opacity models are so intimately connected. On a longer time scale, HED experiments could more directly constrain the abundances by testing the non-LTE models used to interpret the photospheric spectra and by measuring the equation-of-state characteristics employed to interpret and leverage helioseismological observations.

What's needed? In the near term, opacities should be measured for the most important elements, oxygen, iron, and neon, at conditions corresponding to the base of the solar convection zone. The change in the pure element opacities when they are embedded as minor constituents in a mostly hydrogen plasma should also be determined. A simultaneous effort to improve opacity models and to make them fully available to the astrophysics and HED communities should also be undertaken in order to fully exploit the measurements. In the longer term, measurements of the opacities of those three elements should be extended to temperatures and densities corresponding to conditions deeper within the Sun. This will likely require innovations in experimental techniques. It will be very valuable to develop as soon as possible two other experimental platforms: one capable of validating the non-LTE model used to interpret photosphere spectra and the other aimed at validating EOS models used in the solar convection zone. The teams responsible for this research should be interdisciplinary, including astrophysicists and inertial fusion researchers as fully participating team members, in order to guide the research in the most useful directions and to maximize the utilization of the improved knowledge.

Connections: The knowledge gained in addressing the solar problem will be directly applicable to many other terrestrial and astrophysical situations. For example, inertial fusion energy involves the transport of radiation through HED matter. The materials and conditions vary depending on the exact approach envisioned, but the need for experimentally benchmarked opacity, equation-of-state, and plasma dynamics models is universal. Refinements in opacity and equation-of-state models will also have immediate applications to stellar modeling in general. On a longer time scale, improved and benchmarked abundance estimates will strengthen investigations of all other stars. Improvements to astronomical observation techniques provided by missions such as *Kepler* and *Gaia* make such information even more urgent. Seismic techniques (asteroseismology) are beginning to be feasible for remote stars, and the quality and quantity of photosphere spectra from remote stars is growing rapidly. The value of this new information, and the ability to avoid erroneous interpretations, rests on the foundation provided by our knowledge of HED material properties.

(2) How does matter respond to super-intense radiation?

Why is it important? Astrophysical objects often generate radiation so intense that photon-driven processes, rather than collisions between electrons and atoms, dominate the motion and ionization of the surrounding medium. One of the most exotic examples is matter falling onto supermassive black holes (the power source for quasars) and the ensuing fast outflows that, in turn, form galactic-scale winds and jets. These winds, occasionally referred to by cosmologists as galactic feedback, are believed to bear intimately on galaxy evolution, star formation, and heating and enriching the intergalactic medium. They also provide an indirect probe of the poorly understood accretion process onto the black hole. Hot stellar winds and their violent eruptions, as well as planetary nebulae that form when low-mass stars like the Sun run out of their nuclear fuel, are other spectacular examples of radiation-driven matter (see figure 4-1). The widely recognized and universally inspiring Eagle Nebula, the so-called “Pillars of Creation,” is an example of a star-forming “nursery” that violently irradiates its ambient molecular cloud. Scientific uncertainties reside in how radiation couples to and drives the nonlinear flows observed in this nebula. At the opposite end of stellar life, super-intense radiation helps determine how matter synthesized in stellar cores is expelled to enrich the galaxies with the elements required for life.

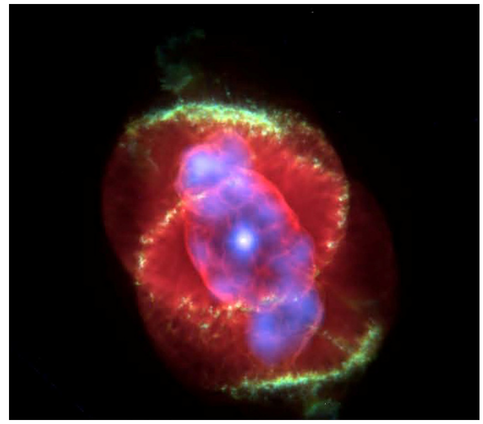


Figure 4-1. A radiation-driven wind in a planetary nebula.

The path forward to investigate the effect of super-intense radiation on matter is to employ flexible, radiation-dominated plasma testbeds using Z-pinch, laser, and X-ray laser radiation. Such a capability can improve models for the physical properties of matter that are incorporated into astrophysical pictures. Of equal importance, our ability to evaluate the accuracy of astrophysical descriptions relies on the interpretation of spectroscopic observations, and these interpretations depend in turn on how well we understand the material properties of the medium. For the longer term, studies of photoionized plasma emission may provide a glimpse at matter entrained deep in a black hole accretion disk and provide tests in the regime where effects of Einstein's general relativity are significant. At a more applied level, X-ray lasers and K-shell radiation sources involve rapidly developing ideas and modeling techniques in non-LTE physics and are also used widely as diagnostic tools (e.g., X-ray radiography) for high energy density and, particularly, ICF experiments.

What's new? Intense radiation sources and the resulting photoionized gases, such as those just discussed, do not naturally occur anywhere in the solar system. Now, however, powerful HEDLP facilities are able to produce such extreme conditions in the laboratory, where they can be studied in great detail. The high-power radiation source mimics a bright quasar or stellar source, while the irradiated matter plays the role of galactic outflow. In a manner similar to the way astronomers measure absorption and emission spectra of quasar flows, the laboratory experiments enable the matter's radiation emission and absorption properties to be studied. Spectral details as well as radiation transfer in these systems can be carefully addressed by such laboratory experiments.

In the past decade or so, with the advent of modern ground and space telescopes such as *Keck*, *Hubble* and *Chandra*, astronomers are acquiring data with such high spectral resolution that laboratory experiments are now challenged to match it. These remarkable observations enable spectroscopic interpretations with ever-increasing detail, but exploiting this capability requires a commensurate increase in the accuracy of the spectral synthesis models that are used. A challenge in this regard is that by virtue of the vastly smaller scales, higher densities, and shorter lifetimes of laboratory experiments, certain properties of radiation-dominated matter in the laboratory differ by orders of magnitude from those of genuine astrophysical situations. Other properties, however, can match those of astrophysical sources (e.g., the ionization distribution and the column density). Appropriate scaling, together with the ability to isolate and control different aspects of the complex system, allows HEDLP experiments to access unique regimes where our understanding of radiation-dominated astrophysical flows can be tested. Laboratory spectra from such sources can now be used to test and benchmark spectral models used by astrophysicists that to this date have relied solely on theory.

Radiative shocks are extremely common in the universe and represent another situation where the response of HED matter to intense radiation must be understood. The structure of the density and temperature profiles of a radiative shock is strongly influenced by the large radiative fluxes.

These shocks occur in interstellar clouds, giant stars, supernovae and stellar evolution scenarios. The effects of radiative shocks on astrophysical systems can be substantial: the radiative shock in a supernova remnant may be responsible for the complex structure of these objects. Material behind the shock cools rapidly and collapses into a thin shell, which is then susceptible to thin-shell instabilities and may account for the clumpy structure of a supernova remnant. A radiograph of a radiative shock created in the laboratory is shown in figure 4-2. In that experiment, a high-energy laser was used to accelerate a thin beryllium disk into xenon gas, resulting in a radiative shock moving at about 150 km/s. Further laboratory experiments are needed to study different types of radiative shocks, how a radiative shock affects a hydrodynamically unstable interface, and the consequences of radiative shocks in a radiation-pressure-dominated system.

***What's needed*?** There are many uncertainties in our understanding of how matter responds to super-intense radiation. Understanding radiating shocks, complex spectral line shapes, ionization distributions, and radiation-dominated ionization rates will require intense theoretical and computational effort from atomic physicists. It also will require experimental data to constrain

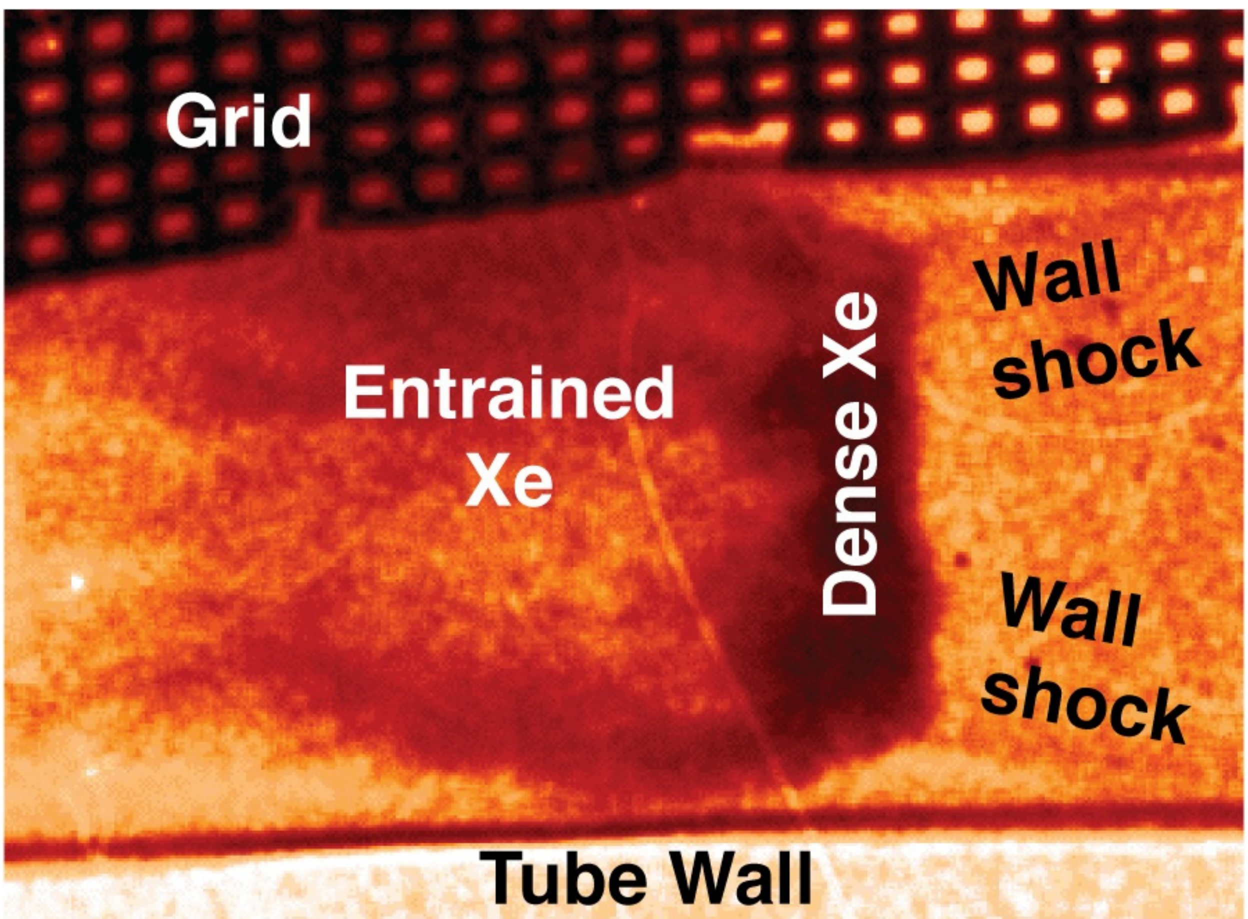


Figure 4-2. An X-ray radiograph of a radiative shock imaged 14 nanoseconds after high-energy laser beams irradiated a thin beryllium disk. The shock is moving to the right in this image into the unshocked xenon gas. The xenon gas is swept up by the shock, creating the dark structure in the image.

models, validate codes and reduce uncertainties. This will, in turn, require flexible radiation-dominated experimental plasma testbeds employing all available high-intensity and high-energy experimental facilities.

Connections: The fundamental problems posed by observations of and laboratory experiments on radiation-dominated gases are bringing together observational astronomers, laboratory and theoretical physicists and computational experts. These diverse collaborations are essential to making headway on sifting through the prevailing models of matter-radiation interaction in such fascinating systems as accretion flows around black holes, galactic winds and molecular clouds in stellar nurseries, as well as aspects of inertial fusion.

(3) How old are the oldest stars?

Why is it important? The universe can be no younger than the stars in it. The age and history of our galaxy is written in the oldest stars, the white dwarfs, and estimates of their ages constrain the age of the universe. To reliably date white dwarfs depends on our ability to infer their mass and temperature from observed spectra. The present accuracy of this method, however, is limited because of our incomplete understanding of matter at densities so high that the electronic structure of the atoms is distorted, thereby changing the spectra. To improve the accuracy of the age estimates requires development of techniques to create in the laboratory conditions similar to a white dwarf photosphere, measure spectral emission and absorption under those conditions, and then compare and improve state-of-the-art spectral-synthesis models. Only recently has all this become possible. Moreover, new theoretical approaches to understanding atoms in plasmas and unprecedented astrophysical observations make this an opportune time to focus new effort on this question. As density and correlations between atoms increase, however, the difficulty of developing accurate theoretical models also increases. Advances in understanding here will translate to more credible estimates of the ages of the oldest stars and will also have broad impact on inertial fusion. At a more fundamental level, this research will test the physics of atoms and plasmas under intermediate and strong coupling conditions, leading to improved diagnostics for plasmas, from dense laboratory plasmas to atmospheres of compact stellar objects, as well as improved understanding of broadly applicable atomic and many-body physics.

In greater detail, more than 98% of all stars become white dwarfs, and their ages serve to calibrate the ages of the other structural components of our galaxy. White dwarfs are supported by electron degeneracy pressure; their evolution is determined by their cooling rate. Thus white dwarfs with lower temperature are generally older, and so their ages can be inferred if one can determine the mass and temperature of the star by observing the spectral emission and absorption from the photosphere and then interpreting the spectra with the aid of an atmospheric model. The sensitivity of the spectra to mass arises mainly because the mass determines the surface gravity, which in turn determines the atmospheric density and hence spectral line widths. The temperature largely determines the continuum shape and relative spectral line intensities. Therefore the accuracy of our knowledge of white-dwarf ages depends on how accurately we can interpret observed photosphere spectra.

Unfortunately, when this approach is applied to a catalog of white dwarfs, the inferred masses systematically increase for stars with lower temperatures. Researchers generally consider this trend to be unphysical, and the leading hypothesis to explain it is inadequate accuracy in the spectral line broadening models. Spectral line broadening calculations are a problem for complex ions with more than one or two bound electrons, but there are difficulties even with simple atoms: hydrogen, helium and carbon. A further challenge is determining how much of the detailed line profile needs to be incorporated into opacity models and developing computationally feasible ways to include that detail. Currently, experimental tests of broadening models under HED conditions are rare and plagued by problems of independent determination of the temperature and density in the laboratory plasma.

What's new? Modern facilities give us the ability to create HED plasmas in macroscopic amounts with conditions uniform enough to test models, while new diagnostics (such as X-ray Thomson scattering) permit *independent* determination of the plasma conditions. Large-scale computational models and molecular dynamics approaches to calculating line broadening under HED conditions are now feasible but not yet widely applied.

In astrophysics, the availability of unprecedented numbers of objects through large-scale surveys, such as the Sloan Digital Sky Survey, and high-quality spectra obtained from the latest generation of telescopes are making the study of line profiles possible for intrinsically faint objects. This raises the possibility of mapping the formation history of ever more remote segments of the universe. However, taking advantage of these new observations requires reliable models tested as completely as possible with terrestrial research.

***What's needed*?** To address white dwarf issues, the first challenge is to generate uniform experimental testbed plasmas under conditions of interest, which span a wide range: Plasmas with densities of roughly 10^{17} ions/cm^3 at temperatures of 1 eV are interesting for low-atomic-number elements found in white dwarf atmospheres, while densities of 10^{24}-10^{26} ions/cm^3 at temperatures of several hundred eV are interesting for neutron star atmospheres, as well as the equations of state and opacities of white dwarf envelopes and other stellar plasmas. Production methods span a range as wide as the conditions: relatively straightforward radiation heating could generate low temperature plasmas, while inertial fusion-type implosions (either cylindrical or spherical) would be needed to reach higher temperatures. Innovative systems using short-pulse laser-generated particle beams or X-ray lasers could also be investigated. Thus, HEDLP can be seen as an integral part of the larger intellectual mission of understanding the extraordinary breadth of physical conditions and phenomena encountered in astrophysics.

A second challenge will be to characterize the testbed plasmas in advance of enlisting them in the study of spectral-line broadening. This must be accomplished by means of independent diagnostics, such as X-ray Thomson scattering, radiography and perhaps other spectroscopic methods. We must measure absorption or emission spectra to determine the profiles of spectral lines influenced by the correlations. This will also require the development of new theoretical approaches to calculate the spectral-line profiles that arise under strong-coupling conditions, using as many state-of-the-art models as possible, and compare with the measurements.

As with the other topics in this chapter, these research topics are best carried out by teams, including astrophysicists and fusion scientists, to ensure that the new physics insights are quickly incorporated into all relevant applications.

Connections: The interiors of white dwarf stars provide an important laboratory for extreme physics. The ratio of Coulomb energy to thermal energy at the onset of crystallization in dense Coulomb plasmas can be determined from the observations of white dwarfs. A subset of white dwarfs pulsates, which permits us to use asteroseismology to study all regions below the surface in detail. Asteroseismology allows direct detection of the white dwarf cooling rate through observed changes in pulsation periods. The resulting ages serve as a calibration of cosmochronology. The dominant cooling mechanism in white dwarfs is via the escape of neutrinos and antineutrinos, which are produced by the decay of plasma photons (known as "plasmons"). Plasmon decay is possible because the white dwarf core has a nonzero index of refraction and therefore, according to electroweak theory, the photon has picked up an effective mass. The energy carried off by the neutrinos depends upon both the star's density and temperature. The density enters because as it increases, it increases the photon effective mass and hence the energy available to the neutrino-antineutrino pair. The temperature enters because it determines the density of the plasmons, and hence the number of neutrinos produced. Consequently, the cooling rate of white dwarfs provides a constraint on electroweak theory. Furthermore, once conditions are established for the core of white dwarfs, models can be devised that give the production rate of axions, a proposed component of dark matter. Those production rates, together with terrestrial detection limits, can then be used to test and constrain theoretical models of axions as dark-matter components.

All of the above applications are either inaccurate or impossible without the accurate mass and temperature determinations facilitated by new laboratory experiments.

(4) What are the equation of state and transport of energy, matter and radiation in a burning fusion plasma?

Why is it important? Understanding the properties of matter and radiation in a plasma undergoing nuclear fusion burning is essential to the development of inertial fusion as a clean, efficient energy source on Earth. This is a long-term effort with potential impact that is very high, both from a fundamental physics point of view and from the practical fusion-energy point of view. Once a burning plasma experimental testbed has been created, studies of radiation flow through turbulent plasmas with localized density enhancements, and the feedback on the burn wave itself, are frontier areas of research with obvious connections to IFE and to studies of novae and Type-Ia supernovae. In general, burning plasmas will be directly applicable as even more powerful experimental radiation sources than are available from current lasers and pulsed-power machines.

What's needed? The development of fusion sources as experimental platforms for HEDLP research will not only be a theoretical and design challenge, but also an experimental one. The fact that such sources will be significantly more powerful than current HED plasmas will require diagnostic innovations for the efficient collection of X-rays and charged particles and the shielding of detectors from high radiation and neutron fluxes. Three specific examples (not an exhaustive list!) of research opportunities and challenges in the study and exploitation of fusion burning experimental platforms are:

1. *Applying high-Z doped ablators and eventually fuels in burning plasmas to provide a local spectroscopic diagnostic of the temperatures and densities of the burning assembly, and to enable the study of parasitic nuclear reaction rates.* The experimental study of the flow of intense radiation in highly compressed burning fuel capsules in ICF experiments will teach us much about the emission spectra of many astrophysical sources. Well-characterized doped inertial fusion plasmas are needed to understand properties in detail of branches of the pp chain that powers the Sun, and the CNO cycle in heavier stars.

2. *Developing an improved understanding of the microphysics of burning and applying it to HEDLP studies.* Such improvements could lead to new burn configurations yielding far higher radiation fluxes to drive HED experiments. A challenge is that present models for burning plasma rely on a fluid description. However, these models have known limitations, and a kinetic transport description may be necessary for the understanding needed to consider other burn modes.

3. *Improving prospects for advanced fuels and for achieving even more extreme conditions.* Looking farther to the future, achieving ICF ignition will allow the opportunity to study the physics required to move to the higher-temperature HED conditions required for burning tritium-poor DT or even pure deuterium. How far this can be studied experimentally on current facilities is an open question. Pure deuterium burning is plainly important in energy generation (by reducing the neutron flux) but also has implications for scientific experiments, because the conditions generated appear to allow laboratory investigation of intense broadband radiation fields of extraordinary intensity. For DT burning at NIF, the peak intensity will be on the order of 10^{20} W cm^{-2}, whereas for pure deuterium burning capsules the intensity would be greater than 10^{22} W cm^{-2}, which is comparable to that delivered by the highest-intensity laser today. Because the radiation would be broadband and quasi-isotropic, the physical situation is expected to be very different from that of a laser propagating in a plasma. At these intensities electron-positron pairs are produced in both cases. For the burning plasma case, the pairs are produced by photon-photon annihilation (the dominant mechanism in astrophysics), whereas with high-intensity lasers it is the fast electrons that result from laser-plasma interaction that produce electron-positron pairs through interaction with nuclei.

Connections: The demonstration of fusion burning and its development as a versatile experimental platform for radiation-dominated HEDLP research will enable the investigation of such astrophysical questions as the study of photo-ionized accretion disk plasmas at fluxes very close to black holes, opacities and EOS at the very core of a star, and the effects of plasma screening on nucleosynthesis reaction pathways.

The highest temperature and density fusion burn plasmas have the potential to take us so far from present HEDLP experience that we must be prepared to address new physics never before seen in the laboratory. Success in this endeavor will require not only new theoretical models, but also target innovations and diagnostic advances. However, the payoff in pushing the frontiers of science, as well as developing practical inertial fusion energy, would be enormous.

Chapter 5: Relativistic HED Plasmas and Intense Beam Physics

How do plasmas dominated by relativistic effects behave?

Introduction

When particles travel near the speed of light, the traditional physics of Newton is inadequate to describe their behavior. Instead, for a proper accounting one must invoke Einstein's theory of relativity. Modern laser facilities commonly create such high temperatures that the plasma electrons become relativistic. Intense particle beams injected at high energy from an accelerator can also cause relativistic effects. If such effects dominate a plasma's behavior, they lead to substantial changes in the relationship among the temperature, pressure and density that would normally hold in ordinary, nonrelativistic matter. Any plasma in which relativistic effects dominate is termed relativistic for short.

Many of the high energy density plasmas causing excitement in the HEDLP research community are relativistic, and these plasmas often have potentially important applications. The field of HED relativistic plasmas includes the dynamics of high-temperature plasmas, relativistic particle beams in plasmas and intense photon beam and particle beam interactions with plasma. Relativistic effects can lead to conditions in which the plasma is far from equilibrium, a state that is inherently subject to rapid change in complex ways. The physics of far-from-equilibrium plasmas is incompletely understood, both because of the complex behavior and because researchers have just scratched the surface in this area of research. A more complete understanding is critical to the many future applications that may flow from this subject area.

A quantitative understanding of the interactions of intense energetic particle and photon beams with matter and the study of very-high-temperature plasmas will lead to important practical applications as well as blazing new trails in HED plasma physics. Among the practical applications are ultra-intense light sources and fusion energy through the approach known as fast ignition (see sidebars, pages 70-72). Progress in this research area will also improve our understanding of extreme physical conditions observed in the high-energy universe, particularly of the various mechanisms by which high-energy particle beams are generated and accelerated.

Laser intensities may increase rapidly during the next decade via the nonlinear optical methods discussed in Chapter 3. With the advent of new, much more powerful lasers, we expect to create extreme relativistic plasmas that display conditions farther and farther away from those achieved in experiments to date. The farther we move away from experimental regimes for which HED computer codes have been validated, the less we can trust their predictions of phenomena we will see in future experiments. It will nevertheless be essential to understand the conditions created by the development of higher- and higher-power lasers in order to evaluate the potential effectiveness of fast ignition of highly compressed fusion fuel. An understanding of such conditions is also crucial for the development of ultra-high-field particle accelerators, and simply to comprehend novel phenomena that will inevitably arise in experiments—predicted

Plasma tolerance for high fields enables devices beyond material limits

When an applied electric field becomes stronger than the typical atomic field binding electrons to the nucleus (a few electron volts, eV, per atomic size), it can essentially rip the electrons from the atoms and cause material failure in any solid. Such failure sets a natural upper limit for allowable field strengths in ordinary particle accelerators and ultra-intense light sources and, consequently, limits the possible acceleration or intensity of light, respectively. Plasmas, already containing freely moving electrons, do not suffer this limitation, and they are able to support traveling waves whose amplitudes are limited only by the density of the plasma itself. This tolerance of high fields, if controlled carefully, enables the realization of powerful acceleration mechanisms for electrons, ions and ultimately other charged particles, and also enables for powerful coherent light sources ranging from the optical to the ultraviolet and X-ray, and possibly even to the gamma-ray regime.

Ultra-high gradient compact accelerator: High electric fields and accelerations in plasmas can be created through the production of a plasma wave in the wake of a short, intense laser or electron beam pulse. This effect lends its name to the wakefield accelerator. In much the same way as a surfer is quickly accelerated toward shore by synchronizing himself or herself with the face of a large, fast-moving water wave, charged particles can be accelerated to very high energies by riding just ahead of the crest of a large, fast-moving plasma wave. Such plasma wakefields moving close to the speed of light in moderate density plasmas can produce acceleration fields exceeding 100 gigavolts per meter (GV/m), many times larger than the field at CERN's Large Hadron Collider (see figure 1, below). Recent experiments have generated accelerating fields in excess of 50 GV/m over meter-long distances, using electron pulses to produce the wakefield. The energy of some of the electrons accelerated by this plasma wave was doubled from 42 to 84 GeV in less than 1 meter. Such wakefields have also been excited by intense laser pulses whereby mono-energetic electron bunches at 1 GeV have been created.

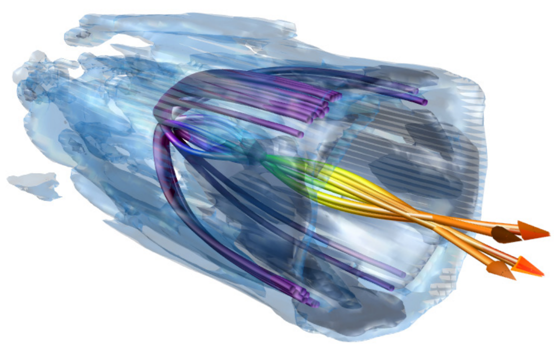


Figure 1. Computer simulation shows electrons being trapped and accelerated in a "bubble" (blue-grey cup-like structure) from a laser wakefield accelerator. Particle tracks are also shown for electrons successfully trapped by the wake. The color of the tracks, from purple to red, shows the increase in electron energy along the track. (Image: W.B. Mori and L.O. Silva)

Ultra-high intensity light source: The highest-intensity light sources at present are short-pulse lasers, whose maximum intensities are limited by the highest electric field that can be tolerated by the final optical element, such as a diffraction grating in the apparatus used to produce the laser beams. The intensity produced by such lasers on the grating is about a trillion watts (1 terawatt) per square centimeter. That limitation can be removed using a plasma-based process called Raman compression (figure 2, next page). A high-quality, short-pulse laser beam, the seed beam, is set up to propagate against a longer-pulse, high-energy pump beam. The pump and seed beams are arranged so that their difference in frequencies matches the frequency of electron plasma waves along the path. The plasma then mediates a resonant transfer of energy from the higher frequency pump laser to the lower frequency seed laser. So long as the electrons do not become highly relativistic in the wave fields, the hugely amplified seed beam can be focused to extremely high intensities at a point outside the plasma. Moreover, at the highest intensities the short-pulse seed beam becomes shorter duration as it grows, further increasing its power. To date, intensities of about 10^4 terawatts per square centimeter (TW/cm^2) have been achieved in the plasma at infrared wavelengths. For compressing 1000 TW of infrared power (roughly the state of the art), a single square centimeter plasma thus could replace a 1000-cm^2-area diffraction grating, which at that size is a very costly item; indeed, for compressing higher intensities, such gratings become impossible to build. According to the theory of Raman compression, the limiting intensity increases further for shorter

Plasma tolerance for high fields enables devices beyond material limits (Cont.)

wavelength lasers (where gratings are completely unable to withstand these intensities), and thus one can expect higher intensities in the optical and ultraviolet (UV) spectra.

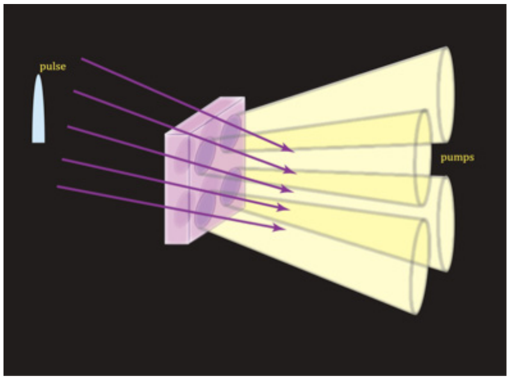


Figure 2. Relatively long pulses of laser light (yellow), not necessarily tightly focused, irradiate the plasma slab (purple) from the right. A counter-propagating short pulse of light (arrows) differing from the other by the frequency of the electron plasma waves can then capture the energy of the longer pulse and remain focused. (Image: N.J. Fisch and V.M. Malkin)

or not. Intellectually, the most exciting prospect may be that at extreme laser intensities we will be able to probe the interaction between light and the vacuum through which it usually propagates. In ordinary circumstances, photons do not interact with each other or with the vacuum in any observable way. However, the fundamental theory of interaction between light and matter, quantum electrodynamics, predicts that at extreme laser intensities such interactions should manifest themselves in the form of the creation of matter—electron-positron pairs—seemingly out of nothing (see sidebar, pages 73-74). It will be an exciting journey to see what surprises are in store for us as we try to reach such high intensities.

I. Status

The importance of collective excitations in plasmas was first noted with the observation of electron plasma waves in 1927 at relatively low temperatures and densities (Chapter 3). The development of powerful pulsed-power machines, lasers and accelerator facilities has allowed creation of plasmas of increasing total energy and energy density in the laboratory since the 1960s. In-depth scientific investigation of the HED regime with lasers capable of generating relativistic components in plasmas has been possible for about two decades, while precision intense particle beam accelerators capable of such studies are a more recent capability. New facilities will move cutting-edge HEDLP research toward the more extreme conditions observed in the universe—i.e., those in which the interactions generate plasma components with highly relativistic velocities, where fusion energy may be generated, where extremely energetic particle and photon beams are produced, and where our physics understanding is uncertain. At the same time, computer simulations, critical to understanding these collective and complex systems, are approaching the capability to model complete experiments. Theoretical understanding is

Fast ignition for inertial fusion energy

The world's most powerful lasers operate at peak powers exceeding a petawatt, a million billion watts, which is about 1000 times the electric power generating capacity of the entire US. The high power is achieved by accumulating energy over many seconds, then discharging it in an ultra-short and hence ultra-high-power pulse that lasts only a trillionth of a second, 1 picosecond. The laser light can be focused into a microscopic volume, creating a power density so great that matter at the focus is heated to temperatures of tens of millions of degrees or more, exceeding the temperature at the center of the Sun. It is possible that such a high-power laser can ignite thermonuclear fusion in dense deuterium-tritium (DT) fuel in a time much shorter than the time the fuel takes to fly apart.

The high focal intensity of petawatt lasers is the basis of the two-step "fast ignition" concept (figure 1): First, a shell of solid DT fuel is accelerated inward from all sides by a laser, ion-beam or Z-pinch (see figure 2-1. page 39). As it stagnates in the center, the fuel is compressed to a few hundred times the density of water, but it is not hot enough to initiate fusion reactions. Second, in the hundreds of picoseconds for which the relatively cool, dense fuel is inertially confined, a petawatt laser creates an intense beam of electrons that penetrate the fuel, depositing their energy in a microscopic volume and rapidly heating it to a temperature that initiates fusion reactions. This microscopic "spark plug" rapidly ignites the surrounding fuel. Computer simulations suggest that the ratio of fusion energy output over laser energy input can exceed one hundred—a necessary requirement for an inertial fusion energy system.

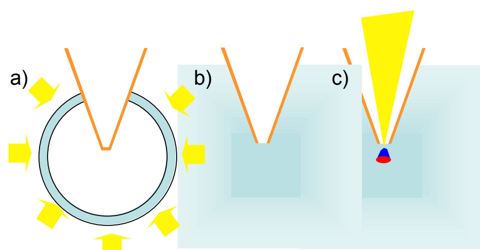
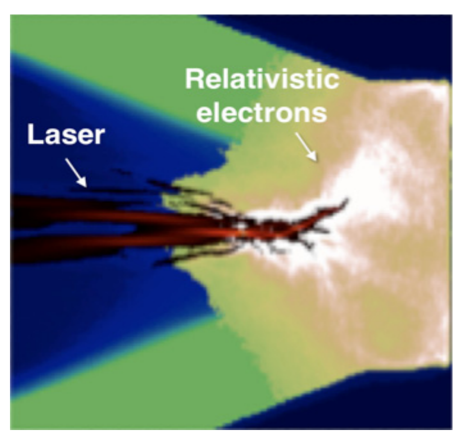


Figure 1. a) In a fast-ignition target, the outer shell (blue) is irradiated by a compression driver (yellow) to b) create a dense fuel core, which is then c) ignited by a picosecond laser (yellow) to create electrons (blue). The electrons propagate into the dense core and create an ignition spark (red).

Different variants of this concept address the fundamental challenge of delivering the ignition laser beam energy through the plasma generated by the compression beams to an ignition spot less than a tenth of a cubic millimeter in volume (see figure 2). Approaches would use a separate "hole-boring" laser or a metal cone inserted into the fuel capsule to provide a path for the petawatt laser. The latter can then convert its energy to energetic electrons, ions or a huge electric current to deliver the energy over the final stretch of highly compressed plasma. All these approaches are under investigation, with electron-driven, cone-based fast ignition being the front-runner.

Figure 2. A 2-D particle-in-cell simulation of an intense laser pulse that undergoes self-focusing and filamentation in the plasma one picosecond after the onset of the laser pulse at the cone tip, shown in blue. The interaction of the laser light with the plasma generates a spray of relativistic electrons. Control of this process is critical to the success of fast ignition.



Probing classical and quantum electromagnetic theory with intense lasers

When low-intensity light (for instance, a low-intensity laser beam) is incident on a group of atoms, the bound electrons re-radiate photons at the same wavelength as the incident light. These photons modify the propagation of the light through the medium, providing a refractive index, such as when light passes through a piece of glass. At low laser intensities, the refractive index is independent of intensity. As the intensity is increased, the refractive index becomes a nonlinear function of the intensity, which results in radiation at multiples of the laser frequency (harmonics), like overtones on a violin string. As the intensity is further increased, ionization of the atoms occurs and a plasma is formed. If the intensity is increased still further, many electrons from each atom are detached, eventually leading to formation of a dense plasma state with multiply ionized nuclei.

Similar effects can occur when the highest-intensity lasers available today interact with the vacuum. In the modern quantum mechanical view pioneered by Dirac, vacuum is not empty. Instead it contains “virtual” electron-positron pairs that interact with an applied electromagnetic field, not too differently from the way the above electrons do in atoms. As a result, at ultra-high laser intensities, the vacuum acts as a refractive medium. As the intensity is increased, the response becomes nonlinear, allowing production of harmonics of the laser frequencies. Further increasing the intensity to the point that the electric field exceeds a critical value known as the Schwinger field produces real electron-positron pairs. Exceeding this field by a large factor transforms much of the field energy into a multitude of electron-positron pairs, leading to the formation of a dense electron-positron plasma at temperatures of billions of degrees.

The Schwinger field is that required to accelerate an electron from rest to a kinetic energy equal to its rest energy within a distance equal to its own size, the so-called Compton wavelength of about 2.4 trillionths of a meter. Reaching the Schwinger field requires a laser intensity of about 4×10^{29} W/cm^2, an enormous number several orders of magnitude beyond present capabilities. Nevertheless, at intensities one hundred thousand to a million times below this, the vacuum begins to act like an optical medium, and some effects predicted by quantum electrodynamics (QED), as this field of study is known, have been observed.

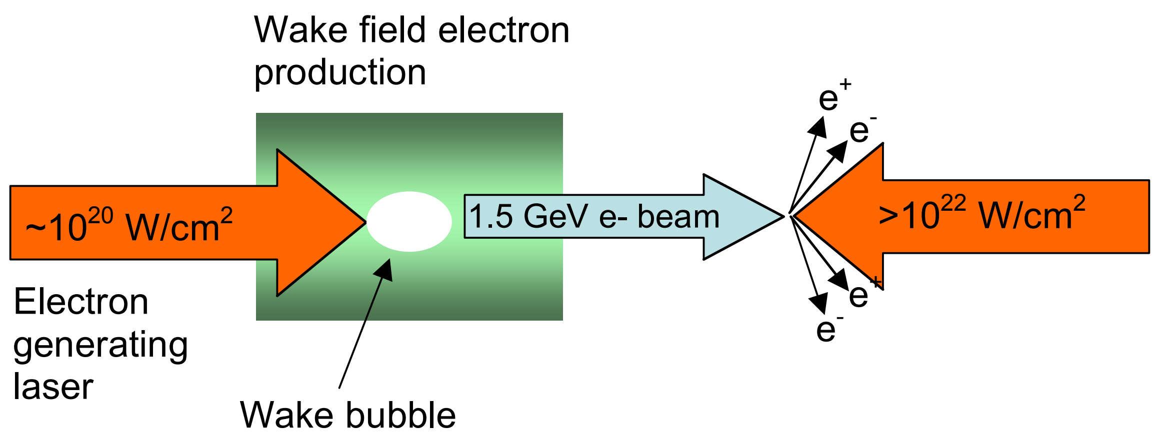
While QED is one of the most accurately verified of all physical theories, the nonlinear QED behavior arising in the presence of strong external fields remains mostly untested. However, an experiment carried out about 15 years ago at the Stanford Linear Accelerator Center (now the SLAC National Accelerator Center) did test one aspect of nonlinear QED. A laser system that produced intensities in excess of one-million trillion (10^{18}) W/cm^2 was counter-propagated with the 46.6-GeV SLAC electron beam. The effective intensity in the electrons’ reference frame was within a factor of ten of the Schwinger field, and interaction of the two beams did produce electron-positron pairs from the vacuum.

Present-day lasers produce intensities four or more orders of magnitude higher than in the SLAC experiment. It is now possible to conceive of experiments to explore nonlinear QED physics at and beyond the Schwinger critical field strength, providing an opportunity to reach beyond the known limit of classical electromagnetic interactions.

As shown in the sidebar figure (page 74), one high-intensity laser pulse produces a dense electron cloud moving at ultra-relativistic energy. The other laser pulse collides head-on with the electrons. If 1.5-GeV electrons can be generated by the first laser beam and they are reflected from a state-of-the-art (10^{22} W/cm^2) laser beam, the electrons will experience the critical acceleration of the Schwinger field.

Probing classical and quantum electromagnetic theory with intense lasers (Cont.)

An interesting challenge to carrying out this test of QED is that the experiment reaches unexplored physics domains; it is very possible that our attempted test will produce unanticipated results more interesting and exciting than we can presently imagine.



Conceptual diagram of an all-laser-based experiment to study nonlinear QED at and beyond the Schwinger field. It requires splitting an intense laser into two beams, one that produces the dense electron cloud (right-moving), and one that interacts with them (left-moving). Their collision produces acceleration of the electrons that break down the vacuum and create a multitude of pairs.

advancing in parallel. We have reached a point where three extremely important questions can be answered in the next decade:

- How can ultra-intense beams be used to ignite fusion reactions in hydrogen fuel?
- How can a plasma's tolerance for huge transient fields be used for energy transfer far beyond conventional material limits?
- What new collective behavior and fundamental physics will be found at the relativistic limits of high energy density physics?

Developing answers to these questions will contribute to our understanding of fundamental HED science and have important applications in other areas—compact accelerators, short-pulse lasers, intense light sources and, above all else, fusion energy. Progress in this area depends heavily on the effective use of existing and pending facilities, both experimental and computational. The collective nature of the plasma waves excited by intense lasers or particle beams determines the size of a useful experiment or numerical simulation. Though the detailed physics occurs on the femtosecond time and nanometer length scales, studying them requires dense plasmas with length scales of hundreds of micrometers and time scales of tens of nanoseconds. The opacity[11] of such plasmas and the rapid increase of emission intensity with energy density require state-of-

[11] For more on opacity, see Chapter 4, p. 60.

the-art instruments to detect relevant signals without being blinded. The complexity of the interactions (the plasma response to intense laser or particle beams is collective, relativistic, kinetic and nonlinear) requires detailed analysis. Progress in this field is tied to the development of diagnostics, simulation codes and ultra-fast computer capability as much as to experimental capabilities. As such, diagnostic and theoretical model development, computer simulations and access to adequate computing resources are all essential partners in exploring relativistic HED physics.

What's new? Each of the opportunities described below requires state-of-the-art experimental and computational facilities. The current generation of recently built, high-energy laser and pulsed-power facilities (the National Ignition Facility, the refurbished pulsed-power accelerator Z, and the University of Rochester's upgraded OMEGA facility) can provide relatively large volumes of dense, hot plasma. Each of these facilities has or will have lasers capable of generating relativistic interactions with plasmas (hundreds to thousands of joules in 1 to 10 picoseconds, focused on a spot tens of micrometers in diameter). The newest high-current particle accelerator (the Neutralized Drift Compression Experiment, or NDCX-II) can provide intense ion beams with precisely known properties, enabling high-quality investigation of ion beam-plasma interactions in the warm dense matter regime and of interest to the inertial fusion energy community. Smaller-scale but highly capable laser facilities at national laboratories and universities can also contribute to our achieving an understanding of relativistic HED physics. In parallel with the development of highly capable experimental facilities, computational capability and sophistication have grown to the point that integrated simulations of complete experiments with high fidelity physics models will be feasible very soon.

What's needed? Research needs for individual programs will be addressed below; however, rapid progress in all areas of relativistic HEDLP will depend on adequate access to even the largest of the national facilities and on the development of a vigorous and growing Joint HEDLP Program (see Executive Summary) that enables the effective use of facilities of all sizes as testbeds for many of the concepts to be discussed in this section. No less important is access to computational facilities at the national defense weapons laboratories and to HED plasma codes that are currently classified by directive of the NNSA (see Chapter 10 for more details).

We now turn to specific needs raised by each key question highlighted above.

II. Research Opportunities and Needs

(1) How can ultra-intense beams be used to ignite fusion reactions in hydrogen fuel?

Why is it important? The quest for fusion energy is one of the world's grand challenges. The expected ignition of inertially confined fusion fuel in the next few years, with 10-15 times as much fusion energy produced as laser energy delivered to the target ("gain of 10-15"), will be an exciting milestone on the way to developing inertial fusion energy. A gain greater than 100 is required for practical IFE, and a recent concept for achieving this gain is fast ignition (FI). The key to FI is the use of an ultra-intense picosecond laser pulse to accelerate particles that then deposit their energy in—and ignite—a small region within a larger mass of compressed deuterium-tritium fuel. Options for the ignition step include using laser-generated, ultra-intense electron beams to heat the compressed core directly or indirectly, the latter by having the electrons generate intense proton or other ion beams that in turn heat the compressed core. The electrons can be generated at the surface of the imploded fuel from inside a re-entrant cone or at the end of a channel created by a separate ”hole boring” laser (see sidebar, page 72), relativistic plasma physics is at the heart of the fast ignition concept.

The potential game-changing opportunity is to build up the existing FI program into a major national program to understand the relevant physics and develop a first FI “point design”[12] that could be utilized in an attempt to demonstrate fast ignition in the next 10 years as a practical means to realize inertial fusion energy. In the longer term, fuel compression for IFE may be most effectively driven by accelerator-based heavy ion beams. As such, an understanding of the underlying physics of collective ion beam-plasma interactions is an important objective of near-term research.

What’s new? The combined problems of increasing global demand on finite carbon-based energy resources, energy dependence and undesirable environmental impacts have made the quest for alternative, carbon-free energy sources—including fusion—very important. The expectation of ignition of an ICF target in the next few years has underscored the fact that IFE is a serious contender for practical fusion energy, with ignition expected more than a decade before the equivalent fusion energy gain is achieved at a magnetic fusion energy facility. The new generation of petawatt-class lasers in the US provides a vital resource enabling the required high energy density science research.

Conceptual IFE power plants have improved credibility due to recent advances in high-repetition-rate laser driver technology, including efficient diode pumping and new ceramic laser media. A key requirement for an IFE power plant is a net energy gain of about 10, which implies a gain of about 100 from the fuel-containing target itself. Central hot-spot ignition, the approach to ICF being pursued by the National Ignition Campaign (see Chapter 1 and page 72), is expected to be limited to a fuel capsule energy gain of about 15. Optimization may increase that and, with multi-megajoule driver energy, one could foresee meeting the IFE requirement. By contrast, computer simulations predict that the FI approach can give an energy gain of about 100 with the existing 1 megajoule of laser energy. The underlying reason for the higher gain is that the simulations predict that fast ignition requires lower fuel density relative to the central hot-spot ignition method, with a consequent reduction of energy invested in the compression. Compression to a lower density also leads to reduced growth of hydrodynamic instabilities. Furthermore, the extremely high compression required for hot-spot ignition necessitates exquisite symmetry in fuel capsule irradiation as well as symmetry of the capsule itself. Fast ignition is therefore potentially more robust than hot-spot ignition through reduced sensitivity to drive non-uniformity and target surface roughness. The lower ignition threshold energy for the IFE laser system in FI could also enable more compact inertial fusion energy plants than the hot-spot ignition approach.

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[12] “Point design” refers to a specific and complete ICF target design that is based upon a large number of fully integrated computer simulations.

What's needed? The fast ignition concept includes a number of alternative configurations, all based on challenging new science (see sidebar, page 72). Basic studies are needed to develop sufficient understanding of the ignition physics to select a baseline configuration. An IFE application-oriented campaign would build off this information to try to demonstrate FI as a concept. This research opportunity involves the ignition demonstration program and several basic science programs to understand details of the generation of energetic particles, both electrons and ions, and their propagation through dense plasmas.

(i) Demonstrating ignition using the fast ignition concept

Phase I will build on the fundamental science programs to develop 1) numerical models benchmarked with physics experiments at high intensity laser facilities, and 2) a high gain (greater than 100) ignition point design, which will be employed in Phase II. Access to supercomputers as well as to a variety of petawatt- (PW-) class lasers, ranging from university scale through the major national facilities, is required for benchmarking computer codes. The facility required to test the ignition point design, particularly the short-pulse ignition laser power and energy, will be defined by the point design. Laser research and development in Phase I is also needed to establish an engineering design for generating the 100-kilojoule short-pulse energy required for ignition in Phase II.

Phase II would utilize the point design in an ignition demonstration structured like the current National Ignition Campaign, which is working toward hot-spot ignition based upon indirect drive. Building on the National Ignition Campaign enables an accelerated national FI campaign to be carried out. The major investment required in Phase II is in the multi-PW-class laser(s) needed to provide 100-kilojoule short-pulse energy. The goals of Phase II should be no less than the demonstration of ignition and high gain, a conceptual design for an IFE power plant and an engineering design for a repetitive-pulse FI demonstration facility.

(ii) Controlling laser energy transfer into dense plasmas

Intense lasers couple their energy into a dense plasma via the electrons (except when the intensity exceeds approximately 10^{24} W cm^{-2}, see (iv) below). Petawatt laser power can be efficiently converted to intense energetic electron beams with the electron current at the giga-ampere (GA) level. A detailed understanding of that conversion process and the resulting parameters—conversion efficiency, spectrum and directionality—is critical to fast-ignition IFE. Measurements include detailed characterization of laser parameters such as focal intensity, pulse-shape and contrast, as well as experimental observables such as X-ray spectra, electron and ion energy spectra and plasma properties. Experimental data must be used to validate laser-plasma interaction simulation codes enabling improved predictive capability. Pursuit of this program requires availability of time on PW-class lasers, up to and including the existing and planned national laser facilities. Investment in innovative diagnostic capabilities to monitor laser parameters, laser-plasma interaction processes and target physics (both hohlraum and fuel capsule in indirect drive; Chapter 1) is essential. Modifications to existing facilities, such as improving focal spot quality or contrast, may be needed for these experiments.

(iii) Transport and coupling of intense electron beams to plasmas

Extreme fields, resulting in strong collective processes, affect the beam transport and coupling of the very large current densities generated by PW-class lasers. The dynamics of the coupled system is not well understood. A detailed understanding of the transport of billion-ampere currents in plasma densities and temperatures ranging from one to hundreds of grams per cubic centimeter and one to hundreds of electron volts, respectively, is critical to both fast-ignition IFE and use of electrons as an intermediary in ion-beam generation (see (iv), below). An initial two-year program that focused on thin metal foils and cones to generate the electrons would employ currently available intermediate-scale, short-pulse, high-power laser facilities and current modeling capability. A follow-on program utilizing the higher-temperature plasmas available from compression facilities would validate understanding in the lower-resistivity, higher-density plasmas typical of the compressed fuel. The development of the diagnostics needed to characterize the laser, to monitor particle beams and to determine plasma conditions will be challenging due to the required sub-micrometer spatial and sub-picosecond time resolution for detection of the signal in the face of extremely intense, high-energy emissions from the target. Benchmarking the computer codes that must be developed to understand these experiments will also be challenging. Realistic computer simulations will require sophisticated radiation hydrodynamics and atomic physics models, hybrid codes to properly include energetic particles, and considerable access to the largest-scale computational facilities.

(iv) Laser-generated energetic ion beams

Understanding the transfer of laser energy to protons and other ions is crucial to evaluating the potential of the ion-ignition version of fast ignition IFE. Ion-ignition physics varies with laser intensity, enabling several different ion-acceleration mechanisms as laser intensity increases: At today's state-of-the-art laser intensities, a broad spectrum of energetic electrons accelerated out of a plasma by the laser fields can create a strong electric field that accelerates ions; with laser intensities a few orders of magnitude higher, other mechanisms are predicted to take over that would produce controlled electron motion, enabling more efficient energy transfer from electrons to ions. At sufficiently high intensities ($\sim 10^{24}$ W/cm^2), laser-accelerated electrons would achieve a relativistic mass comparable to that of the proton rest mass, and a hydrogen plasma could be accelerated as a whole by the laser fields. The program must test novel acceleration schemes that can control the particle spectrum and improve conversion efficiency. Research in the first five years can be carried out on existing facilities. If results are promising, extension of these studies to demonstrate the higher energy and particle flux and precise parameter control for ion-driven FI will require development of facilities that can deliver high-intensity laser pulses carefully shaped in space and time. Developing numerical simulations to increase theoretical understanding requires including in Particle-in-Cell (PIC) codes high-field phenomena that are presently unaccounted for and for which there is no validated theoretical model. The recoil force on a charged particle when it emits electromagnetic radiation is a longstanding example. Access to the largest computers available today is required for the development of such codes.

(v) Transport and coupling of intense ion beams to plasmas

Heavy-ion-beam inertial fusion energy has the potential for much higher efficiency, high-repetition-rate drivers than are expected to be possible with lasers. The construction of an adequate heavy-ion driver for inertial fusion energy is beyond the time horizon of this report, but work is necessary to understand the dynamics of heavy-ion beam interaction with plasmas in (a) the focusing region, (b) the target corona and (c) the compressed fuel. With the completion of the NDCX-II facility at Lawrence Berkeley National Laboratory, this work can begin in 2012. Collective processes can play an important role in the first two of these regions, where several beam-plasma instabilities associated with the relative drift between the beam and plasma and the thermal anisotropy of the beam itself are expected. Through detailed analytical studies and advanced numerical simulations using PIC and Vlasov-Maxwell codes, and comparisons with present-day experiments, a very good understanding of these collective interaction processes, including the process of charge neutralization by background plasma, is being developed. Operating regimes to eliminate or minimize the deleterious effects of instabilities are being identified. As the beam density and current continue to increase in the next-generation experiments, the collective interaction processes will become correspondingly much more intense; it will be increasingly important to implement ever more accurate integrated modeling capabilities and experimental diagnostic techniques. Exciting research opportunities in beam physics to be investigated over the next ten years include (1) ion energy coupling into an ablating plasma using beams with ramped kinetic energy that could lead to direct-drive ion-beam fusion with possible higher gain than the baseline laser indirect-drive approach; (2) space-charge-dominated ion-beam dynamics; and (3) detailed physics investigations of collective beam-plasma interaction processes, intense ion beam focusing, and pulse compression in neutralizing background plasma.

(2) How can plasma's tolerance for huge transient fields be used for energy transfer far beyond conventional material limits?

Why is it important? Many plasma structures in the universe, such as gamma-ray bursts, accretion disks around massive black holes and the magnetospheres of radio pulsars, manifest magnetic fields that are one thousand times stronger than the limit yet demonstrated by any solid-state material. Moreover, the energy transfer mediated by the plasma in these phenomena takes place at intensities impossible with conventional materials. The physical mechanisms by which directed astrophysical plasma jets are created containing energy of as much as 10^{44} J and cosmic ray particles accelerated to 10^{20} eV or more are not understood. A detailed investigation of the complexities of fully nonlinear laser- and particle-beam-plasma interactions will yield understanding of how these ephemeral systems operate in nature, and how HED plasmas can be sculpted into structures that can serve as compact and versatile sources of charged particles and photons in the laboratory. The time scales of interest range from femtoseconds for the creation of the plasma structure to nanoseconds for the plasma generation.

We have an opportunity to create plasma-based accelerators that use field gradients orders of magnitude higher than conventional accelerators, accelerating charged particles to unprecedented energies in extremely compact devices. The charged particles can themselves radiate X-rays while being accelerated in the plasma structure or when wiggled in a magnetic field or the electromagnetic fields of a laser.

We also have the opportunity to compress light spatially and temporally using plasma-based optical elements, thereby reaching intensities orders of magnitude higher than would be possible through conventional material elements. The irradiated plasmas are also much more compact than amplifiers using conventional materials.

What's new? Accelerator experiments and intense beam radiation and particle sources have advanced significantly in the last few years. Relativistic wakefield structures driven by particle beams have achieved electric fields of greater than 10 GV/m, which have accelerated electrons to 84 GeV, have also been used to accelerate positrons. Mono-energetic electron beams in excess of 1 GeV have been produced in wakefields driven by lasers. Copious amounts of X-rays have been produced by betatron radiation in these wakefields, and these X-rays have been used to generate positrons. Raman compression, in which the energy from a relatively long laser pulse transfers energy via a plasma intermediary to a plasma-frequency down-shifted short-pulse laser beam, has been demonstrated with a pump laser of approximately one joule, which pumped a seed pulse into the nonlinear regime. The amplified pulse at the exit was of greater intensity and shorter duration than both the pump pulse and the input seed pulse. In another scheme of radiation generation, also utilizing nonlinear effects, high harmonics have been generated from bulk targets with photon energies up to 3 keV.

What's needed? Energy transfers mediated by plasmas can occur from photons to photons, photons to particles, and particles to photons and, in shocks, between components of the plasma. For clarity, this opportunity and details of applications and connections are divided into four programs by the type of energy transfer.

(i) Extending relativistic wakefields into highly nonlinear regimes (photons → particles)

An intense, short-pulse laser or electron beam propagating in a plasma creates a plasma wave wakefield with electric field gradients, enabling extremely compact electron accelerators. Next-generation lasers and electron beams will access a new regime where the plasma electrons from the wake flow ultra-relativistically and in highly nonlinear trajectories. Particles surfing these wakes could potentially develop into ultra-short, ultra-intense electron beams. Wakefields can also be used to manipulate and compress laser pulses. *Breakthroughs to new capability will occur with the ability to inject and accelerate particles in nonlinear wakes in small regions of six-dimensional phase space. With breakthroughs in laser technology, generation of wakefields adequate to directly accelerate ions to relativistic energies would become possible.* Initially, 100 terawatt (TW) or greater laser facilities could examine the dynamics of electrons in stable wakefields, as well as the basic physics of the propagation of laser pulses guided by self-generated nonlinearities. Such pulses remain tightly focused for distances far greater than the characteristic length over which the beam would normally spread out (the "Rayleigh length"). In the more distant future, acceleration of ions and higher energy and more intense electron beams could be studied at 10-100 PW facilities with intensities approaching and exceeding 10^{23} W cm^{-2} and/or laser energies approaching 10 kJ. This stage awaits a new generation of short-pulse (15-200 fs), energetic (10 J to 10 kJ) laser facilities. Analyzing such systems will require extensions of modeling capabilities to include new physics (see key question 3). As such, predictions as to what will happen in experiments at this high power density are to be taken with a grain of salt. The full experimental program will require upgrades to an existing short pulse laser facility, or the development of a new facility. Close coupling between experiment and simulation will be essential.

(ii) Creation of ultra-intense laser beams (photons → photons)

Laser intensities are limited by solid material properties. The development of chirped pulse amplification (CPA) lasers in the 1980s obviated the material limits in the gain medium. With current technology, they are limited by a solid grating damage threshold of a few joules per square centimeter at micrometer wavelengths. Through resonant Raman (temporal) compression in plasmas, fluxes of 1 kJ/cm^2 or more can be transferred from an energetic long pulse to a much shorter, nearly diffraction-limited seed pulse. For a given optical aperture in the plasma, one could potentially achieve three orders of magnitude higher light intensities. However, thus far Raman amplification has been demonstrated with spot sizes of less than 20 μm; it will be able to compete with present-day solid-state lasers only if the spot size is increased to the centimeter scale. If this can be demonstrated, then Raman amplification might be a strong candidate for a next-generation intense light source. Proceeding beyond the current concept demonstration studies at 1 μm requires dedicated experiments at intermediate scales to optimize the Raman-compressed beam intensity and increase the spot diameter. To extend this concept from IR to UV wavelengths requires new laser capabilities and new plasma sources. To extend this program to higher-power lasers would require a program at a higher level of effort at an NNSA facility with a higher-power laser. Extending this concept further, to the soft X-ray regime, needs theoretical development and exploratory experimental testing.

(iii) Ultra-bright VUV and X-ray sources beyond existing light sources (photons → high-energy photons)

There is broad recognition that ultra-bright X-ray sources, especially X-ray lasers, will be a transformational tool in many applications because of their ability to probe matter down to the atomic scale with unprecedented time resolution and brightness compared to synchrotron light sources. Unfortunately, both synchrotron and accelerator-driven X-ray free-electron laser (XFEL) sources are very few in number and fixed in location due to their kilometer-scale sizes, which prevents their use as mobile systems or as diagnostic tools in conjunction with other large-scale drivers. It is conceivable that lasers can provide game-changing alternatives in location, size and capability, by exploiting a number of different X-ray generation mechanisms that involve relativistic beams or plasmas: Laser-accelerated electrons propagating in a plasma channel can produce radiation at high harmonics of the laser frequency, as well as radiation from the electron undulation in the plasma channel; wakefield-accelerated electron beams can be passed through an undulator to produce radiation by the XFEL mechanism. More speculatively, laser light could be coherently Compton-backscattered off a mirror that had been accelerated to relativistic velocities by a second laser beam whose power profile was precisely controlled. The first of these mechanisms can be realized with a state-of-the-art titanium-sapphire laser system, potentially producing an X-ray beam that would be competitive with third-generation synchrotron light sources. Output from such a device could serve as a seed for the laser-driven XFEL, which would require a petawatt-class, ultra-short-pulse laser to control the production of a high-quality (less than 1% energy spread, 1mm-mr emittance), GeV electron beam. Photon energies from the highly speculative Compton scattering mechanism would be limited by the decreasing X-ray reflectivity of solid-density surfaces.

(iv) Energy flow in relativistic shocks (photons → shocks)

Laboratory experiments concerning relativistic shocks can proceed in two stages:

Mildly relativistic shocks can be investigated in the near term at existing and pending large-scale facilities through the collision of a single relativistic jet or beam generated by high-energy short-pulse lasers of energy 1 kJ or greater in a stationary background plasma. The 1 MJ of preheat energy now available would allow the creation of larger volumes of collisionless plasma to study the formation and propagation of collisionless shocks. With somewhat higher laser intensities (approximately 10^{21} W/cm^2), one can shock heat electrons to MeV temperatures in solid density hydrogen plasmas. Advances in this field might be achieved within 5 years.

Ultra-relativistic shock (shock speed very close to the speed of light) generation might someday be accomplished by the collisions of two or more relativistic dense electron-positron jets, which would require a facility with multiple short-pulse high-energy laser beams of energy at least 1 kJ. Additionally, pulsed magnets producing fields greater than 10 megagauss at the target would be needed to investigate magnetized shocks.

What's needed? Temperature, density, magnetic field, pair content, etc., need to be measured with high spatial resolution and with picosecond time resolution. The radiation and particle spectra from shocks must be quantified. The most critical computational need is a dedicated effort to smoothly and self-consistently link and merge a variety of multi-physics codes to perform end-to-end simulations of complete shock experiments.

Connections: The physics of relativistic shocks is still largely virgin territory in the laboratory, but relativistic shocks are thought to be responsible for many high-energy astrophysical phenomena. Collisions of supersonic flows are ubiquitous in astrophysics, and the resulting shock waves are thought to be responsible for the high-energy radiation of supernova remnants, gamma-ray bursts, pulsar winds and jets from active galactic nuclei and cosmic rays. The physics of shocks formed by ultra-intense lasers on high energy density plasmas is thought to be similar. *Observation, modeling and analysis of laboratory collisionless shock experiments will dramatically expand our understanding of many observations in the cosmos.* Such experiments will also be of great importance for fast ignition and the very practical development of intense, compact, energetic radiation and particle sources.

(3) What new collective behavior and fundamental physics must be accounted for at the relativistic limits of high energy density physics?

Why is it important? Plasma components and the interaction forces will change under the most extreme conditions. Plasmas composed of electrons and positrons occur widely in the universe; if and when we can produce them in the laboratory, we would expect novel dynamics and matter-antimatter elementary thermal processes. The extreme electromagnetic fields and particle energies now accessible approach the edge of understood physics, with the forces acting on electrons exceeding past experimental and even theoretical considerations, including gravity.

What's new? Facilities have recently demonstrated the laser power density necessary to attain ultra-relativistic conditions. Electron-positron jets with relativistic temperatures have been generated, with on the order of 10^{11} positrons at a density of order $10^{13}/cm^3$. Also, extrapolation of previous attempts to "boil the vacuum" using counter-propagating electron and laser beams (see sidebar, pages 73-74) indicate that existing facilities have the capability to cause interactions between electrons (in their rest frame) with photon intensities as high as 10^{29} W/cm^2, thus reaching deeply into a power-density regime where unanticipated phenomena may occur.

What's needed? The basic questions in the area of new relativistic collective phenomena are divided into two research directions: very high temperatures and extreme energy densities:

(i) Exploring the physics of relativistic electron-positron plasmas

There are two challenging steps that could lead to generation of high-density (~10^{18} cm^{-3}) electron-positron plasmas that would be many Debye lengths in spatial scale:

- Develop higher-energy petawatt (HEPW) beams, perhaps by converting 2-4 NIF quads to HEPW beam lines with intensity greater than 10^{20} W cm^{-2}.

- Trap the electron-positron jets to produce stationary relativistic electron-positron plasmas in order to study their properties. This will require the generation of a "mirror-type" magnetic configuration with multi-megagauss fields. Experiments described in Chapter 2 on magnetized HED plasma suggest paths towards this. New diagnostic techniques and target designs would be required to demonstrate that a relativistic electron-positron plasma was created.

Very interesting electron-positron plasmas might be achieved within a few years with existing laser facilities. However, the goal of 10^{18} cm^{-3} pair density is for the long term, as it is likely to require a facility with multiple HEPW beams.

(ii) Exploration of nonlinear QED (and beyond) and its relevance to fusion with ultra-intense fields

A major intellectual challenge is to test our fundamental understanding of matter and vacuum in the strong-field, low-energy, high-intensity regime of QED. Departures from the standard model may provide unexpected signatures. At extreme intensities, one expects to "short-circuit the vacuum" (see sidebar, pages 73-74) to create an ultra-relativistic plasma, where electrons, positrons and protons oscillate in the laser field with the same velocity, and to observe polarization and magnetization of the vacuum. While those effects might become observable at intensities beyond 10^{23-25} W/cm^2, en route one would almost certainly encounter new effects, possibly including completely unexpected phenomena. The development of theoretical and numerical methods to describe this new regime should lead to important advances in fundamental physics. These ultra-high intensities could also lead to as yet unknown mechanisms for particle acceleration and "hole-boring" for fast ignition (see sidebar, page 72). A series of topics of increasingly ambitious scale—ranging from challenges, which are just becoming accessible, to speculative topics emerging on the horizon—would be explored theoretically and experimentally over many years:

- Acceleration-radiation: The formulation of classical charged-particle motion assumes that the radiation emitted by accelerated charges is small. That assumption fails for relativistic electrons colliding with light pulses at laser intensities greater than 10^{22} W cm^{-2} that are realizable today. A major challenge here will be measuring the effect in the presence of an extremely high-intensity laser interacting with the electrons.

- Laser-vacuum interaction: Ultra-intense laser interaction with vacuum offers a unique opportunity to test the limits of high-intensity laser light propagating through the vacuum, thus testing the limits of existing understanding of QED (sidebar, pages 73-74). The necessary laser intensities are likely to be available during the next decade, and here again the diagnostic challenges of testing QED in the chaos of particles and photons anticipated in these experiments will be substantial.

- The inertial rest frame: By the equivalence principle, strong EM-field-induced acceleration is indistinguishable from strong gravity, providing an opportunity to study the connection of electromagnetism and gravity, and to probe QED vacuum structure as well as Mach's principle, which holds that acceleration refers to a universal inertial frame of reference, a challenge to the concept of a locally applied force. This example is indicative of the deep connections between HEDLP and other areas of fundamental physics.

The experimental strategy is to use lasers of increasing intensity to try to reach and study plasmas with relativistic effects playing a more and more prominent role. As we depart farther and farther from present-day experimental regimes, the outcome of experiments will become less and less predictable. Ultimately, it may be possible to reach laser intensities in which nonlinear QED effects are not only observable but should become major determinants of the interaction. A laser facility proposed to be built in Europe, ELI, which could reach such intensities as early as a decade from now, is on the drawing board.

Connections: The topic of new relativistic HED plasma phenomena directly connects to astrophysics. Electron-positron plasmas with relativistic particle energies are believed to be ubiquitous in the universe (for example, as the generation mechanism for gamma-ray bursters). Beyond that, progress in this area could improve and extend our basic understanding of quantum electrodynamics.

Chapter 6: Warm Dense Matter

What are the material and transport properties of warm dense matter?

Introduction

What science underlies the violent formation of planets or the creation of the Moon from the Earth 4.5 billion years ago? Why is Saturn so warm, and why does Jupiter have such a large magnetic field? Can we connect the birth of a star to fusion in the laboratory? What new chemistry emerges when high pressures and temperatures force electrons from inner orbits deep inside the atom into outer orbitals where they may interact with other atoms? What new phenomena emerge when ions, electrons and photons are found at high densities and with average energies comparable to those binding molecules or electrons to nuclei?

In common to all these questions is the study of warm dense matter (WDM), matter that is neither solid, gas, liquid nor plasma but shares properties of all four. Because WDM physics is defined by a departure from well-established disciplines, such as condensed matter or plasma physics, its boundaries are far from sharp. On the one hand, classical electric forces—the Coulomb force—that bind atoms to one another cannot be neglected, and this illustrates warm dense matter's kinship with condensed matter and liquids. On the other hand, depending on the materials involved, neither can one ignore purely quantum-mechanical phenomena—such as degeneracy pressure—that arise when electrons, neutrons and protons are compressed to high densities. Likewise, temperatures are high enough that electrons are thermally excited to higher energy levels, where they may transform insulators into metals; ultimately the electrons may be separated from their nuclei altogether, thus creating a plasma. Physical theories are most tractable when one force dominates over all the others; the smaller forces can then be ignored in modeling. In WDM, however, all the effects—classical and quantum—are of comparable magnitude, which presents a great difficulty to reliable modeling.

I. Status

Although WDM conditions exist in a wide variety of planetary and astrophysical objects throughout the universe, as well as in a plethora of rapidly heated or shock-compressed systems on Earth, their study is in its infancy, and we know very little about materials at WDM conditions. Basic properties, such as the equation of state (EOS, which relates the density, temperature and pressure of a material) of matter at WDM conditions, and the electronic or ionic structure of WDM, are not well known. Other properties, such as viscosity or the strength of materials at high densities, are essentially unknown. Optical properties, which are related to the dielectric function of the material, are also poorly constrained.

Warm dense matter and extreme chemistry

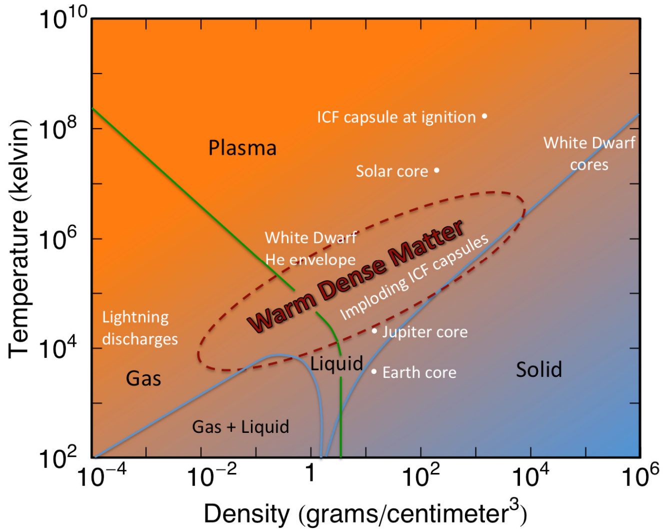


Figure 1. Warm dense matter lies at the confluence of plasma, gas, liquid and solid. The complicated interplay of the physical processes that it shares with its neighbors creates a "malfunction junction" for our theoretical descriptions of WDM, but it also creates unique and exciting challenges for experiment and diagnostics. This plot shows temperature versus density (water =1 g/cm^3) for various structures in the universe (compare figure 1-1, page 19). WDM lies approximately in the regime where the temperature is above 10,000 K and the pressure is between 100,000 and one billion atmospheres. The blue shaded region indicates the domain of strongly degenerate matter, where quantum-mechanical pressure due to the Pauli exclusion principle determines structure. The orange shaded region indicates the "classical" domain of non-degenerate matter, where quantum effects are not important. The high energy density region is found above and to the right of the green curve.

For WDM, the thermal energy of the electrons is comparable to the binding energy of the molecules themselves, and chemistry needs to be redefined and broadened. By extreme chemistry, we mean that chemical bonding by conventional outer-orbital (valence) electrons is superseded by core-electron interactions, which are very complex. How this extreme chemistry manifests itself in nature remains to be seen, but current predictions and experimental observations suggest numerous possibilities, including melting temperatures that are anomalously low; phase transitions to complex solid and liquid structures, or to new plasma states; and transitions between distinct liquid states. Defining, exploring, and evaluating this emerging extreme-chemistry paradigm represents a significant and challenging attraction to WDM.

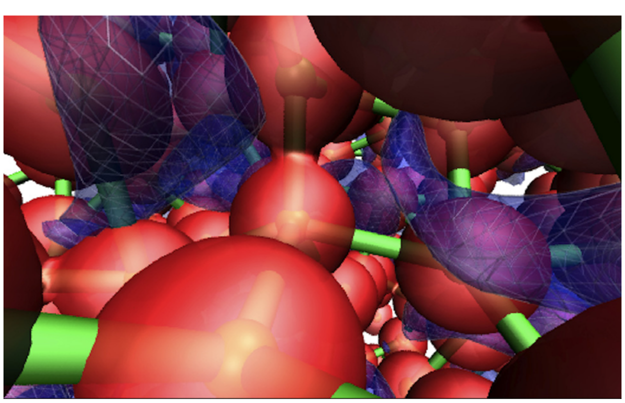


Figure 2. A modern quantum simulation of lithium at 3.5 million atmospheres and 1000 K. Surfaces of constant electron density indicate the location of the atom cores (red) and conduction electrons (blue). Normally core electrons are so localized that the electrons in different atoms don't interact, but at these high pressures the atoms are pushed close enough together that strong repulsion among core electrons can play a major role in determining structure. This simulation was made on the basis of "density functional theory." For more details, see pages 95-96. (Tamblyn, Raty, and Bonev, Phys. Rev. Lett. 101, 075703 (2008))

In addition to the theoretical difficulties that arise in addressing WDM physics, briefly described above, only a limited number of detailed experimental studies have been possible to date. Notable examples include electrical conductivity experiments on expanded hot metals and experiments documenting the pressure-density relationship for deuterium when subjected to shocks. These experiments have provided valuable data for improving theoretical understanding of matter.

New facilities are becoming available that can create well-controlled WDM conditions, yielding important new measurements over a broad range of WDM parameters. New diagnostic tools, such as X-ray free electron lasers, will enable highly precise measurements of temperature, density, ionization state and structural changes in WDM. Theoretical advances have also been made in recent years, such as in molecular dynamics simulations and Monte Carlo calculations. But it is only now, with the new ideas and advances in finite-temperature density functional theory, orbital-free methods and kinetic theories, coupled with tremendous advances in computing power, that we can begin a concerted research effort to address the difficult, many-body, multi-physics problem that is WDM.

II. Research Opportunities and Needs

As solids are heated and/or compressed to high pressures, there are many important physics questions for which we do not have answers. In spite of its being one of the fundamental phase transitions of condensed matter and playing a central role in the thermal and chemical evolution of planets, melting remains poorly understood as a physical phenomenon, and it is inadequately probed at high pressures by experiments to date. What other phase transitions, such as metal to insulator or even from one liquid to another (distinct liquid states of the same substance), occur at higher pressures and temperatures? As more electronic states are excited, how does the structure of atoms and packing of ions change? Another class of questions pertains to the mechanical properties of solids at high densities and high temperatures. What is the strength and elasticity of solid WDM? Additionally, the transition from electron orbitals and "normal" chemical bonding at Earth-surface conditions to the plasma regime at high densities and temperatures is poorly understood.

We also have only limited knowledge of transport properties, such as electrical and thermal conductivities, especially in the important region near where materials make a transition from metals to insulators. Understanding and controlling such properties will be crucial to enhancing nuclear fusion as a practical source of global energy.

An issue of wide-ranging importance, especially with regard to many planetary systems, is the description of the properties of WDM mixtures. All the above questions are equally valid when discussing materials that contain more than a single element. Of special concern for mixtures is the nature and strength of chemical bonding at very high pressures, where it may be possible to share more than the standard valence electrons.

Because the energies associated with temperatures and densities achieved in WDM can greatly exceed those associated with ionization or chemical bonding, it is necessary to consider states of disequilibrium between electrons and ions as well as external radiation fields. Electron–ion equilibration processes at low densities may be far less effective at high densities, especially as structural relaxation becomes the rate-limiting factor. Electron–ion processes also have important practical consequences for experiments, in that the driving fields may cause significant disequilibrium (e.g., "hot" electrons created by intense laser or X-ray fields); measurements may be difficult to interpret if diagnostics are recording data for only one component of a system that consists of several components that are out of equilibrium.

Why is it important?

Inertial fusion and stockpile stewardship: The quest for inertial confinement fusion in the laboratory hinges largely on our success in compressing the deuterium-tritium fuel, encapsulated in a shell of some ablator material, to high density while trying to keep all the matter in a near-degenerate state. The implosion is accomplished by compressing the fuel and capsule by a series of shocks, the first of which is sufficient to push the capsule material into the WDM regime. Knowledge of the high-pressure melt curve of the ablator shell is essential to ensuring that all the material has either melted or remained solid with the first shock, whichever is desired. If the outer layer were heterogeneous, a mixture of solid and liquid, it would surely introduce unwanted asymmetries into the implosion when the second shock arrives. The EOS of the DT fuel governs the speed and amplitude of the shocks launched there, as well as the ease with which the fuel can be compressed, and thus has direct consequences for the integrity of the implosion. As mentioned in Section I, the shock properties of deuterium in the WDM regime have been heavily studied over the last decade, with stockpile stewardship as the main driving force. However, experiments to date attain pressures that are far below those obtained in a fusion capsule. The transport properties, particularly the thermal conductivity, have direct bearing on the integrity of the interface between the fuel and capsule ablator material during the implosion. The thermal conductivity of these materials, particularly for mixtures of hydrogen isotopes with the surrounding materials, and near the transition from dense degenerate to non-degenerate matter, is poorly understood and no data are available. In lieu of definitive data, theory has played an important role in providing the best models possible. The urgent need has pushed the theoretical approaches into new regimes, where they have not yet been validated by experiments.

The interesting WDM physics found in ICF naturally has parallels in weapons science and stockpile stewardship. The extreme conditions, ranging from warm dense solids to hot, dense plasmas, coupled with the interplay of different phases of material, has provided many challenging problems in the field of warm dense matter.

Planetary science: A major opportunity for WDM research over the next decade is to address fundamental questions about the origin of planetary systems, the nature of giant planets, and the structure and evolution of planets in our own and other solar systems. Many unsolved problems, as well as improved accuracy in models and processes, depend critically on physical and chemical properties of WDM (e.g., EOS, phase, transport properties). Dramatic improvements in observational capabilities from Earth and space demand a new level of understanding of the complex, multiphase systems that exist under the extreme conditions found within planets.

Our solar system was born from a cloud of dust and gas 4.57 billion years ago. Unraveling the history of planets and understanding how the present solar system may retain a memory of that history is a key task of planetary science. The vast majority of planetary mass in our solar system is at very high pressures and temperatures—in other words, under WDM conditions. The most abundant constituents are hydrogen and helium. Other materials of importance include the simple molecular compounds such as water and methane (planetary "ices"), the oxides that make up the rocks and minerals of terrestrial planets, and iron alloys comprising the cores of planets.

Understanding the structure of planets from the surface to the core is fundamental to understanding their evolution and origins, and ultimately their potential for sustaining life. Below, we give several examples of key planetary questions that require new advances in understanding of WDM to answer.

What role did giant planetary impacts play in solar system history? It is now recognized that late-stage giant impacts between planet-sized bodies were a major factor in early solar system evolution and can explain such diverse phenomena as the origin of Earth's Moon, the slow rotation rate of Venus, the anomalously large core of Mercury and the marked contrast between the northern and southern hemispheres of Mars. Giant impacts produce transient states that lie in the WDM regime but are very poorly understood. Critical factors include general phase diagrams, melting and vaporization curves and chemistry under these extreme conditions, as well as the EOS under the impact of shocks (the Hugoniot). (See sidebar, page 90.)

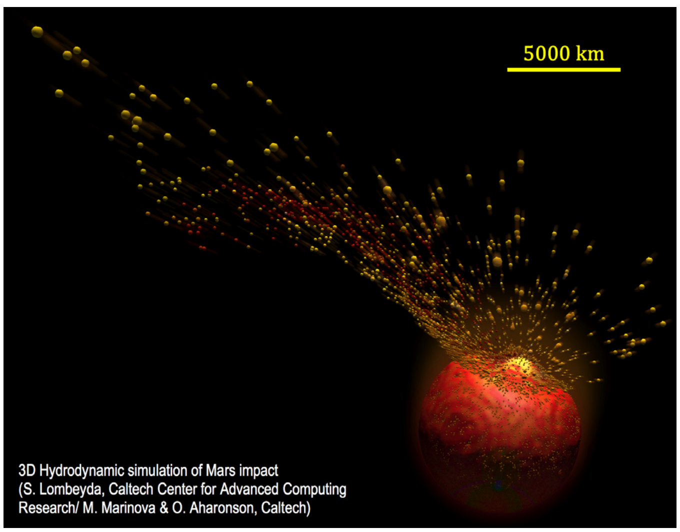
What is the nature of the Earth's iron core? The Earth's core contains one-third of our planet's mass and is predominantly composed of nickel-iron metal. While seismic studies provide increasingly detailed information on the structure of the core, there remain many unanswered questions that require new, advanced experimental and theoretical studies in the WDM regime. For example, the crystalline phase of the solid inner core remains unknown. The core is known to be less dense than pure nickel-iron, and constraints on the identity of the light element impurities are essential to understanding the bulk composition of the Earth, accretion processes, and the energy sources in the core that help sustain the magnetic field that protects life at Earth's surface. Other key questions include the origin of an unexplained seismic anisotropy of the inner core and possible chemical interactions between the core and mantle of the Earth.

How did Jupiter form? Jupiter is sufficiently massive to influence the dynamics and evolution of the entire solar system. It is thought that the formation of all the other planets was possible only because of Jupiter's rapid growth: we would not be here had the young Earth not been protected by Jupiter's early presence. One of the major unsolved problems in planetary science is to identify conclusively the mechanism by which Jupiter formed. In the first of two competing ideas, the core accretion model, Jupiter initially accretes a core of rock and ice that is roughly ten Earth masses in size. Once the core reaches this critical mass, its gravitational attraction is sufficient to collect the surrounding nebular gas of hydrogen and helium, rapidly transforming it into the gas-rich giant, Jupiter. Alternatively, in the disk-instability model, a gaseous nebular disk developed instabilities that caused a portion of it to collapse directly into a giant planet. These two models imply significantly different mechanisms and time scales for planetary formation, as well as interior structures for Jupiter, but our understanding of the properties of hydrogen under Jovian conditions is too crude to rule either of them out. Improvements in our knowledge of equations of state under planetary conditions are among the most urgent needs in WDM research on planets.

Giant planetary impacts

Collisions between protoplanets are a key process in the formation of the solar system. For example, the Moon is thought to have aggregated from material ejected out of the newly formed Earth by a titanic collision. Mars bears the scar of a huge impact that melted half its crust and left behind a depression covering most of its northern hemisphere.

Such planetary collisions, occurring at velocities of several kilometers per second, involve tremendous energies (10^{14} megatons of TNT in the simulation shown below, more than one trillion times the largest hydrogen bomb ever exploded). Rocky material is shocked to pressures and temperatures exceeding 50 million atmospheres and 100,000°C, respectively. The properties of the thick rocky plasma stew that is created—and from which the planet re-forms—are virtually unknown. The fate of water and other volatile constituents in the resulting extreme chemistry is also unknown. However, experimental facilities and theoretical capabilities now becoming available for WDM research can directly address these issues, reproducing the violent conditions experienced during planet formation.



3-D hydrodynamic simulation of Mars impact (S. Lombeyda, Caltech Center for Advanced Computing Research/M. Marinova and O. Aharonson, Caltech)

What is the origin of Saturn's anomalous luminosity? Another conundrum involving the giant planets is that Saturn is considerably hotter than expected based on its cooling history and the amount of radiation it receives from the Sun. One proposed explanation for this discrepancy is separation of helium from metallic hydrogen in the deep interior. Because it is heavier than hydrogen, helium sinks toward the center of the planet, releasing gravitational energy and providing the extra energy source needed to explain the excess radiation. The conditions inside Saturn may result in higher degrees of separation than in Jupiter, where this phenomenon is not required as an important energy source. This model is presently speculative and needs to be tested by accurate theoretical calculations and direct experiments on hydrogen and helium mixtures under the WDM conditions of planetary interiors. It is important to emphasize that theory and experiment play highly synergistic roles, as experiments provide stringent tests for theoretical models which, when satisfied, may allow confident extrapolations of theory to conditions outside the reach of direct experiment.

What is the reason for the unusual magnetic fields of the ice giants? Neptune and Uranus have unusual magnetic fields that—contrary to those of Earth, Jupiter and the Sun—are strongly tilted away from their rotation axes. Since their interiors consist to a large degree of water, methane and ammonia, a better understanding of the planetary dynamo that produces the magnetic field relies on knowing the electrical properties of these materials in the WDM regime. Besides the usual conduction of electricity in ionic liquids, exotic superionic phases may occur with electrical conduction due to almost-free proton diffusion through a lattice of oxygen, carbon or nitrogen at high pressures. Superionic phases may counteract the dynamo process.

What is the nature of exoplanet interiors? The discovery of hundreds of planets outside our solar system is one of the most exciting scientific developments of recent years. Most of these planets have characteristics that are quite different from those of our own solar system, making it clear that there is a wide diversity of planetary types, and challenging our current theories of planetary formation and evolution. It is presently unknown how unusual the formation of our own solar system may have been.

Observations of exoplanets are expected to improve dramatically in the coming years, revealing smaller, perhaps more Earth-like planets and placing stronger constraints on planetary origins. Studies of WDM are essential to place limits on the composition and structure of these bodies. Pressure and temperature in super-Jupiters may extend up to approximately one billion atmospheres and 100,000°C, respectively, conditions under which we have poor understanding of material thermodynamic properties, melting curves, and transport properties.

What's needed? WDM research in inertial fusion and planetary science requires access to facilities capable of extending the range of experimental investigations far beyond present limits, providing access to the full range of possible planetary pressure-temperature conditions. Developments of new experimental and theoretical capabilities for determining physical and chemical properties on complex systems to new levels of accuracy are required, which we now discuss in more detail. Both theoretical and experimental areas provide rich opportunities for major breakthroughs.

Experimental needs: WDM can be created in the laboratory in two fundamentally different ways: Energy can be added to the system by rapidly heating the material, in which case the electrons are excited and subsequently transfer the energy to the ions. Alternatively, the material can be rapidly compressed, in which case the ions are initially excited and then energy is transferred to the electrons. We are poised to take advantage of modern experimental facilities capable of rapidly delivering large amounts of energy to materials by both of these mechanisms in order to explore the WDM regime. While groundbreaking experiments have already begun over the past decade, and further improvements are expected in the experimental approaches used to create WDM in the laboratory, the most significant challenges and opportunities lie in diagnosing the WDM state. Due in large part to the fact that the highest energy states are achieved when compressing the material to the smallest size, and to the correspondingly short time scales of the experiments, specialized diagnostics are needed for many WDM experiments; in many cases, their exact nature remains to be determined. We now turn to discussion of needs in particular areas.

Equation of state: For decades, shock wave experiments, mainly in the condensed matter regime, have been designed to explore elevated pressure and density states. Methods exist to determine these quantities with reasonable precision and accuracy, in particular Doppler shift measurements using reflected laser light. However, as we push to new and significantly higher pressure regimes, using multiple shocks or shockless compression, it is expected that such techniques will begin to break down and that other methods will need to be pursued. Some progress has been made, for instance in using radiography to measure density; however, significant work is required for further development of alternative techniques.

Measurement of temperature has proven to be extremely difficult. Even in the condensed matter regime, at comparatively low temperatures and pressures, there has been only limited success with using optical pyrometry and Raman scattering to measure temperature in dynamic experiments. At higher temperatures, these techniques begin to break down. Conversely, X-ray Thomson scattering techniques developed by the plasma physics community to determine temperature and electron density break down on extension to lower temperatures. Thus, significant effort must go toward the measurement of temperatures in the heart of the WDM regime. Improved temperature diagnostics would help answer key questions about the behavior of materials under shockless compression (in addition to shock compression), including the effects of melting and other phase transitions.

Material structure: Measurements of ionic and electronic structure provide significant insight and are necessary to understand the phase of the material and its transport and mechanical properties. This type of information can be obtained using time-dependent diffraction and spectroscopy techniques. At ambient conditions, several variations of diffraction and spectroscopy are available, utilizing X-rays and optical photons, to provide information on electronic and ionic structure, density of states, etc. Applying these techniques to dynamic experiments is a challenge, and while work has begun in this area, it is in its infancy, as new facilities and capabilities are just now becoming available. Measurements of ionic and electronic structure will be crucial to validating our theoretical modeling.

Transport and mechanical properties: A critical need is to develop measurements of transport properties, such as electrical and thermal conductivity. Knowing transport properties accurately is crucial for modeling the implosion of inertial confinement fusion (ICF) capsules, as thermal conductivity has a significant effect on the growth of instabilities undermining the ignition process. Transport properties are also essential for planetary modeling. The transport models used in simulation codes are, however, poorly constrained by current experimental data.

Approach to equilibrium: As already mentioned, most techniques for generating WDM put energy into either the electrons or ions of the material, but not both. The energy must then be transferred between ions and electrons for the material to reach equilibrium. This relaxation timescale may be long compared to the experiment, however, which means that measurements of material properties could be unreliable. Definitive time-dependent information is lacking, and we anticipate that time resolution on the order of picoseconds will be required to address this issue. Successful collection of relevant data would represent a major breakthrough.

Heterogeneity and mixtures: It is important to recognize that the scientifically interesting states produced in WDM experiments could be both far from equilibrium and inhomogeneous. In particular, we are interested in mixtures of materials (as the discussion of Jupiter and Saturn indicates). A key question in this area is whether mixed materials can separate in phase, requiring that the measurements have sufficiently high spatial resolution, as well as the necessary time resolution, to elucidate the important physics. While it is not known *a priori* what the relevant spatial scales might be, resolution on the order of tens of nanometers to micrometers may be required.

Connections: Because warm dense matter is a "malfunction junction" that lies at the confluence of plasma, gas, liquid and solid, a common theme emerging from the evaluation of diagnostic needs for WDM experimental research is the need to consider multiple diagnostic methods. The vast range of pressure, density, and temperature conditions relevant to WDM—from the liquid-vapor critical point to the interior of giant planets—shows that there cannot be a "one-size-fits-all" diagnostic tool for measurement of the quantities of interest. At the same time, due to its position at the intersection of all the states of matter, solutions to the diagnostic problems will have an impact on studies of all of them.

Another important point that should be kept in mind as the WDM field begins to mature is that the role of experiments in new regions of parameter space is to discover new phenomena, not just to validate theory or simulation. As such, visionary experiments may produce important discoveries even if the experimental measurements exhibit large uncertainties. Scientific understanding under novel conditions requires synergy between experiments on the one hand and theory and simulation on the other, not just one or the other.

Theoretical needs: The problem of modeling optical excitation spectra and electrical conductivities of WDM presents a particularly formidable challenge to theory. In conventional cold metals, a powerful approximation is to treat *individual* electrons that are excited from occupied quantum states to unoccupied ones by optical photons. This picture of individually excited electrons, so-called "quasielectrons," is robust at low temperature because, through the Pauli exclusion principle, the unexcited electrons block the excited ones from interacting with each other in complicated ways. Thus, the optical properties of cold solids can now be accurately computed for most materials. In WDM, however, the profusion of thermally excited electrons invalidates this construct. An electron in WDM which is excited by a photon or by a time-varying electric field has many quantum states into which it can settle, and so the concept of an individual electron in a specific excited state is no longer valid.

Paradoxically, the high-temperature plasma limit can also be described adequately within the quasielectron concept. Current calculational approaches, however, are based entirely on perturbation theory which, among other problems, breaks down for the WDM regime. Hence, we urgently need an advanced, finite-temperature many-particle theory that yields the limiting cases of the zero-temperature (condensed matter) and high-temperature (fully to partially ionized plasmas) limits. Such an approach can be combined with molecular-dynamics simulations or integral equation methods to describe disorder and correlations in the WDM state properly.

Much of the success in the last ten years in calculating WDM properties has been a consequence of a powerful approach to solving the Schrödinger equation for many-body systems, known as density functional theory (DFT). In DFT, one replaces an intractable many-body problem of interacting electrons with the tractable problem of non-interacting electrons moving in an effective potential that includes the quantum contributions of exchange and correlation interactions. Though rigorously exact, in practice the exchange and correlation contributions require approximate representations. Standard DFT has been particularly successful in predicting shock- and shockless-compression states that agree well with experiments. While there has also been substantial progress in calculating transport properties, accuracy in the warm dense plasma limit is inherently limited by errors resulting from a varying degree of unphysical self-interaction for the electrons inherent in these approximate exchange and correlation terms.

DFT formulations can include the exchange energy “exactly” (EXX), and in recent years, zero-temperature EXX calculations for single atoms have produced much improved results for optical transitions. But EXX calculations are much more complex to implement, and they are one to two orders of magnitude more costly computationally. A major speedup in these calculations would add significantly to our ability to calculate accurate WDM optical, electrical and thermal conductivities, as well as improved thermodynamic properties. Finite-temperature approaches to this problem on the scale required for WDM studies are in their infancy and limited, but they have high potential payoff for accurate calculation of material properties in the WDM regime across a wide range of conditions.

The electron and ion dynamics in large-scale DFT molecular dynamics simulations are generally handled in the Born-Oppenheimer (BO) approximation, which assumes that the ions are completely stationary while the electrons relax completely to their thermal ground state. An extension of DFT uses *time-dependent* effective potentials (TD-DFT) to move away from today’s BO treatments. Going beyond the BO approximation is a major opportunity for two distinct reasons. Because of their low mass, the physics of hydrogen, deuterium, tritium and helium requires quantum dynamics. Second, electron-ion relaxation dynamics cannot be handled within the BO approximation. As a long-term theory, modeling, and simulation challenge, TD-DFT could have high payoff for electron-ion relaxation physics.

Connections: Density functional theory has been a major tool in condensed-matter physics and chemistry since the 1970s. Extending its realm of application would not only validate the theoretical tools, but also has the potential to illuminate our models of WDM in planetary interiors and inertial fusion.

Chapter 7: High-Z, Multiply Ionized HED Atomic Physics

How does the physics of heavy ions change under HED conditions?

Introduction

As its name implies, atomic physics is the fundamental science that concerns the physics of atoms as a whole; in particular, it concerns the behavior of the electrons orbiting the nucleus and their interactions with the nucleus itself. Bulk properties of materials are largely determined by atomic physics, as is the interaction of radiation with atoms. Atomic physics is so important that it may be regarded as the Rosetta stone of modern physics; indeed, historically it allowed scientists to decipher the inner workings of the atom. Atomic physics also links material properties on the atomic scale with the diverse world of plasma physics, and so it enables multiple aspects of high energy density science.

The theoretical framework for atomic physics is quantum mechanics. To be sure, the observed behavior of atoms served as the earliest tests of quantum mechanics. A great many of the most interesting HEDLP experiments are carried out at least in part with high-atomic-number, or “high-Z,” materials, “Z” being the standard abbreviation for atomic number. This is certainly the case for the intense radiation sources employed in the so-called “indirect-drive” inertial confinement fusion ignition campaign now under way at the National Ignition Facility, as described in the Executive Summary and in Chapter 1. The complicated nature of high-Z atoms at extreme densities makes their atomic physics and application to HEDLP a unique and complex sub-discipline. Achieving an understanding of high-Z atomic physics is essential to designing “well-posed” HEDLP experiments and diagnostic instruments, and to analyzing the data obtained from them. This is equally true of HED plasmas produced by lasers, pulsed-power machines and intense heavy-ion beams.

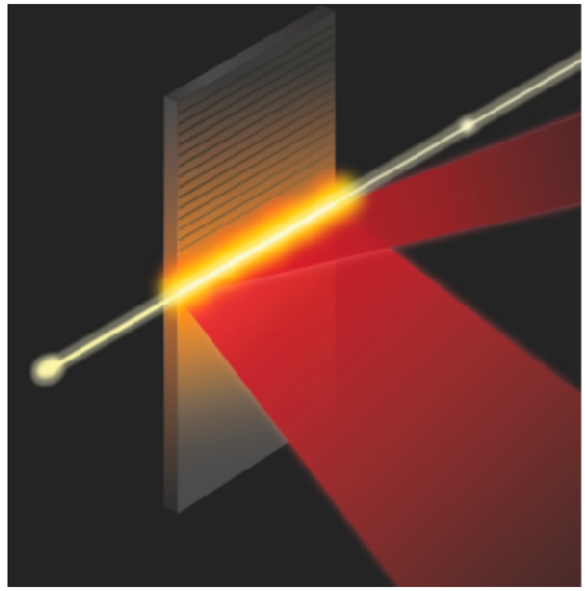
Applications of high-Z physics are not limited to diagnosing HED plasmas: biomedical, therapeutic and diagnostic applications of intense plasma X-ray sources can involve the use of high-Z nanoparticles; applications from plasma televisions to efficient lighting to extreme ultra-violet lithography are enabled by the high-Z atomic physics properties of plasmas. The atomic physics of highly charged ions in an HED plasma provides substantial challenges owing to the long-range interactions between neighboring ions and electrons. Addressing such challenges provides exciting opportunities for young research scientists in areas that push the frontiers of atomic physics, and it is also necessary in order to transform laboratory plasmas into an unlimited source of clean fusion energy.

I. Status

The initial work in atomic physics, and much of the effort that continues today, has concentrated on the properties of isolated atoms. Beginning in the 1970s, the laboratory production of HED environments changed this paradigm. New types of quantum states are now produced that

Tabletop X-ray lasers

An understanding of how electrons can excite high-atomic-number ("high-Z") atoms to higher energy levels, and how the electrons emit photons when dropping back to lower levels, enabled the first demonstration of X-ray lasers in the 1980s. This discovery, and the subsequent vast improvement in the brightness and photon energy, and reduction in physical size of X-ray lasers, represents a triumph, not only of experimental atomic physics applied in an HED environment, but in theoretical high-Z physics: Several theory groups predicted lasing at certain frequencies well in advance of the successful experiments. X-ray lasers can be engineered into compact, ultra-bright tabletop sources of coherent X-ray radiation for HEDP diagnostics, ultra-high resolution imaging and materials characterization.



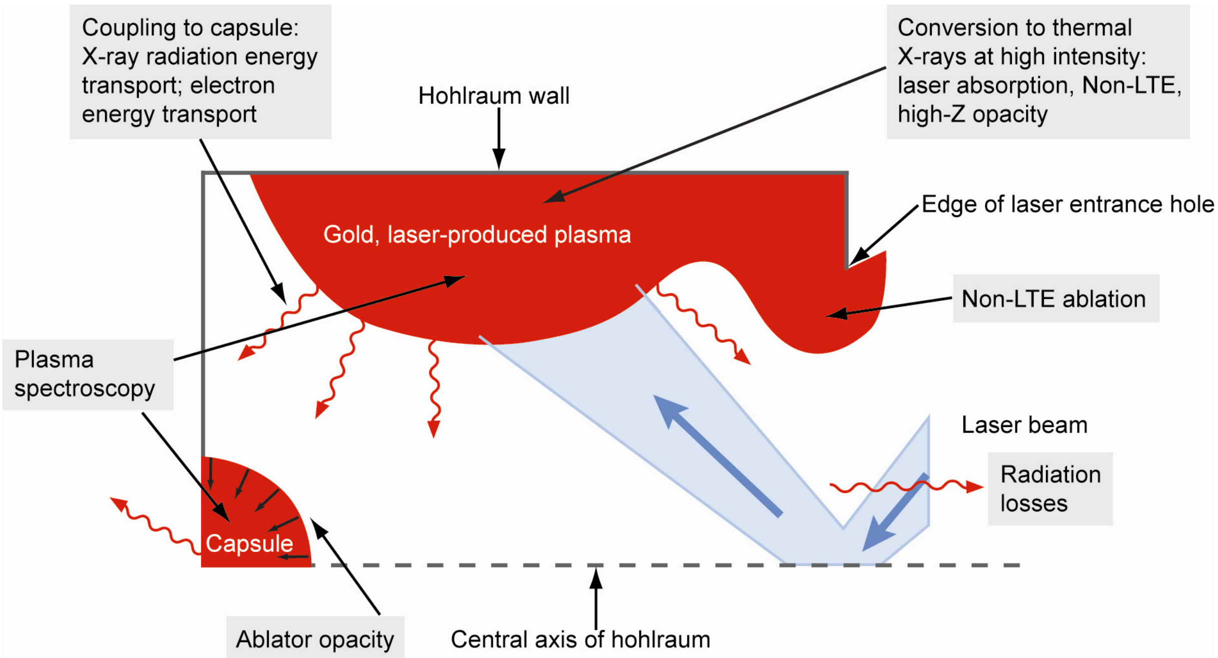
X-ray laser amplifier using an HED plasma medium.

involve multiple atoms in ultra-high electric and magnetic fields. High energy density scientists confront an enormous range of length and time scales in order to model, and ultimately control, laboratory plasmas; the atomic scale is one of the smallest of these. The atomic physics of high-Z ions, which can retain some of their electrons even in the extreme environments created by high-powered lasers and pulsed-power devices, will play a crucial role in the development of the nascent field of HEDLP in the coming years. If well stewarded, this field may, in turn, inform the development of fundamental atomic physics and emergent collective effects due to high electric and magnetic fields and strong interatomic interactions.

Apart from its fundamental scientific interest, an understanding of high-Z atoms in extreme environments is critical in other ways: atomic models contribute much of the basic physical data on which predictive radiation-hydrodynamics models rely, and spectroscopic measurement of line transitions between electronic states is one of the richest (and, for distant astrophysical objects, one of the only) sources of diagnostic information about plasma properties, energetics, and evolution. Unless the plasma is fully stripped[13]—and a high-Z HED plasma rarely is—spectroscopy enables monitoring of plasma temperatures, densities, ionization states, compositions, flows, and fields with both temporal and spatial resolution. And although the Dirac equation provides exact solutions for hydrogenic ions, there remain fundamental uncertainties about the structure and processes of complex multi-electron ions. For example, tungsten, which has produced record high X-ray radiation yields in Z-pinch experiments at the Z Facility, and which will be part of the wall facing the plasma in the international magnetic

[13] Meaning that all the electrons are removed from individual atoms, leaving a bare nucleus behind.

Anatomy and atomic physics of a typical HED plasma: gold-lined hohlraum



The sidebar in Chapter 1, page 17, shows a "hohlraum," the cylindrical vessel containing the fuel capsule in the indirect-drive approach to inertial confinement fusion (ICF). The figure here depicts one quadrant of a gold-lined hohlraum, illustrating the atomic physics involved as it is irradiated by ultra-high-powered lasers in the ICF process. One of many laser beams (blue arrow at right) passes through a hole in the hohlraum (large rectangle), strikes the inside wall of the vessel and produces a plasma containing gold ions. The time scales are so short that the entire process is mostly out of local thermodynamic equilibrium. To create an efficient implosion of the spherical fuel capsule (lower left, one quadrant shown), one must determine how effectively the gold converts the laser beams to X-rays, how well the X-rays compress the fuel capsule, and how to avoid the deleterious effects of energetic electrons and photons penetrating the capsule. One must also take into account the X-ray opacity, or absorption properties, of the gold and capsule material, the ablation properties of both and how much energy is lost to radiation. In an actual experiment, all of these properties are inferred from the data collected by advanced diagnostics, including spectroscopy, which measures the spectrum of radiation produced by the gold plasma and fuel capsule. Converting a spectrum into plasma properties requires extremely detailed atomic physics calculations of the radiative properties of each of the materials in the hohlraum and fuel.

confinement fusion development project, ITER, is not adequately described by current atomic kinetics models when not in local thermodynamic equilibrium (LTE). Neither is gold, which composes the radiation cavities for indirect-drive ICF.

Below, we describe some of the key questions and issues needing resolution in the atomic physics of multiply ionized media. We discuss their relevance to other HED research areas and suggest research areas that are ripe for development for the benefit of HED science. Key questions in the field include the following:

- How do we calculate and validate atomic properties, opacities and spectra of complex, high-Z, highly charged ions in the general case of non-equilibrium as a function of plasma temperature, density and radiation field?
- How does an HED-plasma environment change the atomic properties in strongly coupled plasmas, where the central potential approximation is no longer valid and multiple simultaneous interactions among plasma particles become significant?
- Can we establish the integrity of atomic physics and radiation transport in multidimensional fluid and particle-in-cell codes, and delineate regions of validity for these two contrasting approaches to modeling dynamic HED media?
- How do we calculate and validate the basic atomic physics of high-Z, highly charged ions in the nonlinear, strong-field regime?

Once we understand how to answer each of these questions, atomic physics can contribute to HED plasma diagnostics and, furthermore, feed back into the broader field of HED science. The complementary necessity is to identify, design and provide facilities to address the key questions listed above. The term “facilities” in this context refers to much more than experimental drivers to create HED media, though that aspect remains vital. It also means state-of-the-art instruments to diagnose the media, large-scale simulation codes that embody and unite the most modern descriptions of the fundamental processes, and up-to-date, ultra-fast computing facilities to run such software.

II. Research Opportunities and Needs

(1) What atomic properties are important and how are they modified in HED plasmas?

Why is it important? Although isolated atoms and ions have an infinite number of bound levels, this idealization breaks down upon the introduction of other particles. High-lying quantum states can extend over long distances and are thus easily disrupted by surrounding ions or electrons. Such perturbations affect the atomic structure and atomic state populations in a phenomenon known as “continuum lowering” or “pressure ionization.” The truncation of an infinite number of bound states to a finite number has significant effects: it makes ionization more likely by reducing the ionization potential, and it changes the relative binding energies of the orbitals, leading to spectral line shifts.

The presence of the oscillating electric and magnetic fields of an intense laser can also have a significant effect on the radiative properties of multiply ionized atoms (loosely called multi-charged ions) and even produce new spectral lines, which are termed "laser satellite transitions" and are clearly visible in X-ray spectra. The observation of such satellites presents a challenge because it requires high laser irradiance and diagnostics with very good spectral and time resolution. The modeling of such spectra will need not only the solution of atomic-level population kinetics in plasmas without laser interaction, but also inclusion of additional laser-assisted atomic processes. The laser-induced transitions might substantially alter decay rates and greatly decrease the lifetime of metastable levels in plasmas produced by a high-intensity laser. They may affect some X-ray laser collisional excitation schemes. In addition to such exotic transitions, line emission from "hollow atoms" (ions with multiple inner-shell vacancies, such as triply-excited Li-like ions) and previously unseen and unpredicted varieties of atomic radiation have been observed from media driven by intense, short-pulse ("ultra-fast") lasers.

In addition to atomic structure and its response to extreme environments, the processes that couple one electronic state to another are of critical importance to high-Z atomic physics in HED science—and challenges remain even for isolated ions. A particularly important process is dielectronic recombination, which is often the dominant recombination channel in HED plasmas composed mostly of highly charged, complex ions. This process consists of two steps: resonant electron capture, which creates an autoionizing state, followed by a stabilizing radiative transition. The difficulty of dielectronic recombination rate calculations increases with atomic number, especially for complex ions with half-open shells. Nonetheless, recombination cross sections and rate calculations based on the best available approximate theory are essential for improving our understanding of HED plasmas. This remains an acute challenge in the presence of high density and temperature effects.

Many fundamental questions on both atomic structure and processes remain to be addressed: Can any single model provide both highly accurate atomic physics (including, e.g., relativistic effects, fine structure and configuration interaction) and accurate plasma effects (e.g., continuum lowering and line broadening)? At present, the best models of each class form nonintersecting sets. There is also disagreement among the plasma models: Are orbitals destroyed gradually, as suggested by a model that is based upon statistical weights of the states, or sharply, as predicted by a model that treats ions as an ensemble of spheres? We can also ask what happens to the orbitals that are lost due to multiparticle interaction. Do they form measurable resonances in the continuum but retain their bound-state character in some way, or are they broadened into bands analogous to those in semiconductors, for which theory is well developed? How do the plasma effects in multi-element plasmas differ from those in single-element plasmas? Are continuum edges broadened in the same way as emission lines? A critical question that has received little attention is how the rates change under the influence of perturbing ions and electrons, a question that is especially important for plasmas that are not in local thermodynamic equilibrium (non-LTE plasmas). How do high electric and magnetic fields distort the electron wave functions?

What's new? In the last 20 years, several theoretical approaches to addressing atomic physics in high-Z plasmas have been explored, including self-consistent field models that treat free electrons as a uniform background and models that explicitly generate local microfields from plasma ions and electrons. In the last few years, new experimental facilities have come online capable of producing the above-solid density, high-Z plasmas with temperatures of 3-5 keV that are required to test existing theories and spur the development of new, more comprehensive theories. These facilities, however, will require advanced diagnostics to provide unambiguous, non-integrated measurements. University-scale lasers and pulsed-power sources, such as wire array Z-pinches, X-pinches and intense electron beams impinging upon high-Z targets, can all produce plasmas of mid- and high-Z multiply charged ions. Basic atomic radiative and dielectronic recombination rate measurements at the electron beam ion trap (EBIT) have been critical for benchmarking theory calculations under low density conditions.

What's needed? There are numerous basic-theory questions in this subject area, as just outlined, which are ripe for theoretical work that could start today if funding were available. Within five years, experiments could be devised and be well under way to measure recombination spectra of highly charged ions at conditions where the predicted continuum edges lie far from emission lines. This would offer a stringent test of continuum lowering theories. On a ten-year horizon, one can envision: a) developing rigorous, unified theories that yield self-consistent structure, rates, line shapes and equation-of-state (EOS) data for multi-electron ions in arbitrary HED environments; b) testing them by carefully designed and well-diagnosed experiments; and c) applying them as new means to determine plasma conditions and to provide basic data for integrated HED models. We note that in magnetized HED plasmas there are three broadening mechanisms that impact spectral line shapes: Stark effect (mainly dependent on density), Doppler broadening (dependent on ion temperature) and Zeeman effect (driven by the magnetic field). Doppler and Stark broadening have a direct impact on ICF physics: The gold (or high-Z alloy) lining a hohlraum (see Chapter 1 and sidebar, page 97) has sharp absorption lines in lower density plasmas and hence is transparent at most frequencies. As a hot, dense X-ray-emitting gold plasma is created in the hohlraum under the action of laser light, however, the line broadening mechanisms cause it to become much more broadly opaque to the X-rays, which are re-emitted at different frequencies. Thus, energy transport in the system is completely altered; such processes need to be understood for successful indirect-drive ICF.

Connections: The modification of atomic physics in an HED environment directly connects to diagnostic development (line intensities, shifts and broadening) and to HED hydrodynamics (opacity and EOS tables), and through these to fusion energy and astrophysics research. All plasma radiation sources, ranging from lighting to plasma televisions to extreme UV lithography to high- power X-ray production, are affected by the fundamental atomic processes within the plasma that generate photons. As just mentioned, line broadening has direct impact on ICF physics, and the atomic physics of strongly coupled plasmas is also connected to the science of warm dense matter and to condensed matter physics.

(2) What types of facilities and experiments are important to advance the atomic physics relevant to HED plasmas?

Why is it important? Fundamental theory and calculations of atomic properties and processes relevant to HED plasmas need to be verified with experiments performed under well-controlled conditions. It is rare that research solicitations call for proposals of such experiments. Since their goal would be to test and benchmark the atomic physics, plasma conditions must be diagnosed with methods that are independent of the atomic-physics properties being tested. These are important and challenging experiments, and very few examples exist to date. However, the need is always there and, as the demand for atomic physics relevant to HED plasmas increases, they will become even more important. A good example is plasma spectroscopy. On the one hand, spectroscopy has been widely used, and will continue to be used, to diagnose HED plasmas. On the other hand, very few experiments have been done with the goal of validating and quantifying the accuracy of a given spectroscopic method under HED plasma conditions.

What's new? The measurements of collisional excitation rates have been extended to highly ionized gold (Z = 79) using an EBIT machine. This is a recent and very valuable extension of previous experiments on simpler K- and L-shell ions, which have to date served as the standard for benchmarking atomic physics calculations and building confidence in plasma models that use them. The photon-energy-dependent opacity of an iron plasma at temperatures exceeding 150 eV has been recently measured and used to validate several atomic-physics models. In addition, this measurement is important for solar physics.

What's needed? Experiments will require the creation of well-controlled laboratory plasmas with steady and uniform conditions that can be determined by methods independent of the atomic property or process being tested. Steady-state and uniformity are tough requirements to meet in laboratory HED plasma experiments. New ideas for creating and controlling plasma conditions as close to this ideal as possible will be essential to developing and testing new HED plasma diagnostics.

Specific areas of focus should include, but not necessarily be limited to:

(i) measurements of fundamental atomic structure, cross sections, and spontaneous rates;

(ii) detailed Stark-broadened line shape and line shift measurements in emission and absorption;

(iii) measurements of photon-energy-dependent opacities of mid- and high-Z elements with open shells;

(iv) measurements of absorption and emission spectra from X-ray-driven, photoionized plasmas with well characterized radiation fluxes;

(v) X-ray and extreme UV spectral line intensity measurements at well characterized plasma conditions; and

(vi) creation of extreme field environments to develop new diagnostic signatures.

Any of these focus areas might deliver surprises because theory, if available, is largely untested. Consequently, all of these areas can provide exciting discoveries and challenges for the next generation of graduate students and for the advancement of HED science. In many cases, university-scale laser and pulsed-power drivers are sufficient for these applications, including accessing presently unexplored regions of HED plasma parameter space. However, the most extreme environments will require use of the largest facilities at the national laboratories, access to which will be important if the most interesting and exciting trails initiated at universities are to be followed.

Finally, future HEDLP solicitations will benefit the program by explicitly including atomic physics relevant for HED plasmas and by assuring that atomic physicists are represented in review and selection panels.

Connections: The need for plasma-condition measurements with suitable diagnostics that are independent of the atomic physics being benchmarked will require the development of alternative diagnostic methods based on imaging, scattering, lasers, particles, etc. Such benchmarking work will motivate new developments in HED plasma diagnostics and instrumentation. The study of the atomic physics and spectroscopy of multiply-charged ions is also important for magnetic confinement fusion plasmas and astrophysics. By understanding in great detail the atomic physics of individual atoms and ions, and how the properties of those atoms change in HED plasmas, we will also establish a connection between emission spectra from laboratory plasmas and the constituents and properties of distant galaxies.

(3) Can atomic and radiation physics be properly included in large-scale fluid and particle codes that simulate HED plasmas?

Why is it important? As increasingly high ionization states are produced by the more powerful plasma drivers of the future, there is increased likelihood that those plasmas will not be in local thermodynamic equilibrium (LTE). This results from the fact that higher radiative decay rates and lower collisional excitation and ionization cross sections are the general rule as the ionization state of an atom increases. Understanding these complex non-LTE media will require the solution of rate equations. Doing that will necessitate high-precision atomic databases of the fundamental processes listed above, as well as a sufficiently complete atomic structure in order to ensure that all important channels are included in the kinetics. Efficient and accurate algorithms for the self-consistent solution of the equations of radiative transfer, for non-equilibrium atomic-level populations and for (magneto) hydrodynamics, also will be needed. To solve the equation of radiative transfer requires high-precision opacities, which in turn also requires accurate atomic data. This closes the loop with the fundamental atomic data requirement in point (i) above. As is the case with all chains, it is only as strong as its weakest link. Therefore, all these links need to be given equal care and effort. *The payoff consists of accurate predictions of HED media properties, including the evolution of temperature, density, ionization state, radiative power losses, opacities and emissivities.*

Accurate atomic models that are valid in all HED regimes must be based on exhaustively complete models of atomic structure—especially in non-LTE situations, in which even states that have small populations can play an important role as ionization and recombination channels. Unfortunately, the number of states necessary for accurate modeling grows exponentially with the number of electrons, and the number of rates for the processes coupling those states grows even more rapidly with increasing ion complexity. Calculation of such atomic structure and rates by sophisticated codes will generate a volume of atomic data that may exceed the memory constraints of high-performance computing facilities—even before the computation of non-LTE populations has a chance to challenge their processing capacity. Nonetheless, the calculation of opacities and their experimental validation must be a vital component of any large-scale simulation effort. Several decades of effort worldwide have been devoted to the elaborate atomic calculations required to compute plasma opacities in laboratory and astrophysical sources.

However, high-accuracy opacities using state-of-the-art methods have been calculated for only a few specialized cases. Also, fundamental opacity-related atomic physics issues remain to be addressed. These include the role of inner-shell excitations, the related question of auto-ionization broadening, and the role of high-lying bound states close to the continuum.

What's new? As mentioned in the previous section, the photon-energy-dependent opacity of iron plasma under conditions relevant to astrophysical environments has recently been measured on Sandia's Z machine and successfully benchmarked against several diverse, detailed, line-by-line opacity calculations. Table look-up methods have been successfully extended from previously modeling only LTE plasmas to being able to support calculations of non-LTE HED plasmas. Detailed atomic models incorporated into several commonly used one-dimensional radiation-hydrodynamic codes, which had long been dominated by simple "average-atom models," have greatly increased the accuracy of non-LTE atomic physics calculations. Atomic and non-LTE kinetic models have been benchmarked on current experimental data from both high-power lasers and Z-pinches. Elaborate three-dimensional MHD calculations of imploding wire arrays have been carried out (although with relatively simple approximations to account for radiation energy loss), using hundreds of millions of computational zones. The one-million-level milestone has been exceeded in atomic models, demonstrating that, as yet, there appears to be no ceiling to computational complexity in this regard. A series of non-LTE code comparison workshops has helped to identify the essential components of reliable atomic models. Experiments are planned in which detailed non-LTE modeling will be used to guide quantitative X-ray photo-pumping of a multiply-charged ion utilizing the Linac Coherent Light Source (LCLS) Soft X-Ray Material (SXR) instrument.

What's needed? Rapidly advancing computer technology—CPU speed and storage—will make fulfilling the simulation challenges just described increasingly feasible. Computational tools attempting to deal with high-Z atomic systems should be developed to be scalable (i.e., designed to support calculations of increasingly complex ions) so that they take advantage of improvements in computer technology as they become available. Different applications require different levels of sophistication in terms of atomic models. For example, EOS codes, opacity codes, and single-cell spectral analysis codes are often used to study HED plasmas. Such codes compute plasma properties at a set of uniform temperature-density points, and therefore can utilize atomic models with a relatively high level of sophistication. Multi-zone spectral analysis codes are often employed to diagnose plasma properties from experimental measurements and to post-process output from radiation-hydrodynamics simulations. These codes can require significantly more CPU resources than single-cell codes because of non-local processes; that is, the radiation field seen at one location can be influenced by the plasma properties in other locations. Some radiation-hydrodynamics codes attempt to treat non-LTE processes in HED plasmas (as well as high-frequency-resolution grids), but they have difficulty dealing with atomic models that have a large number of energy levels and transitions. Because of the diverse needs of simulation codes used to analyze HED experiments, it is important to have atomic modeling tools that are flexible. Therefore, the future challenge is to develop atomic models that will be sufficiently detailed yet computationally manageable and that can accurately describe and diagnose laboratory or astrophysical HED plasmas. Successfully meeting this challenge will enable two-dimensional fluid and particle simulations with full non-LTE radiation transport to be feasible within 5 years. An analogous three-dimensional capability could be ready within 10 years.

Another fundamental goal should be to make the calculation and experimental validation of HED plasma opacities routine and standard, rather than the result of infrequent heroic efforts. This requires:

(i) Development of the necessary atomic physics for complex ions pertaining to inner-shell transitions, including a proper, complete consideration of resonance phenomena.

(ii) Large-scale, high-accuracy atomic calculations for heavy elements, including but going well beyond iron, to those relevant to DOE programs on laboratory fusion (e.g., up to tungsten and gold).

(iii) Improved calculations of photon-energy-dependent and mean plasma opacities that (a) constitute a standard database and (b) can be benchmarked against experiments on laboratory facilities.

Connections: Solutions of non-LTE kinetics using highly accurate data on important atomic processes that couple ionization physics, the radiation field and radiation hydrodynamics will greatly enhance understanding of the evolution of HED plasmas, which include those produced in all HEDLP facilities as well as in diverse astrophysical environments, such as supernovae. Additionally, non-LTE modeling is key to spectroscopic diagnostics of plasmas in the extreme regimes created in state-of-the-art experimental facilities and in cosmic sources. Effects of non-LTE kinetics are also fundamental in determining line formation in atmospheres that are intrinsically out of equilibrium due to the non-locality of abundances in stellar atmospheres and radiative transfer, as well as the change of opacity and emissivity with spatially varying plasma conditions. The revised predictions of stellar compositions using accurate non-LTE models may change our view of the early and expanding universe. Atoms first appeared during the "recombination epoch," at a redshift of roughly 5000, about 370,000 years after the Big Bang. Observations by the space observatory *Planck* could reveal signatures of the very first hydrogen and helium atoms. However, extremely precise non-LTE models are required to compute their observable effect on the measured cosmic microwave background.

(4) How does atomic physics impact the diagnoses of the properties of HED plasma?

Why is it important? Atomic physics enables the majority of the radiation-based diagnostics for HED plasmas. For the foreseeable future, emission and absorption spectroscopy will continue to be the most powerful tools to interrogate plasma over wide ranges of temperature and density conditions. In this connection, new developments are needed to extend its applicability to warm dense matter (see Chapter 6) and ICF implosion cores. However, other atomic processes, such as bound-electron contributions to the plasma index of refraction and Compton scattering, are increasingly relevant. Compton scattering radiography is a leading candidate to diagnose dense cryogenic imploding shells. Furthermore, Compton scattering profiles for mid- and high-Z elements will serve as an important diagnostic for HED plasmas created by free-electron lasers, such as those planned at LCLS and DESY (Deutsches Elektronen Synchrotron), as well as future fourth-generation X-ray laser facilities. The challenge here is to produce a substantial database, together with experimental benchmarks, of differential Compton scattering cross sections for as many elements as possible. An alternative would be to produce and benchmark a "simple to use" computer code that can provide the needed data.

What's new? The atomic physics of HED plasmas driven by high-intensity, ultra-short pulsed lasers now requires fully time-dependent atomic kinetics and non-Maxwellian electron distribution functions, including those of energetic electron beams and that take into account the interplay between atomic and electron kinetics. The connection must be made between the kinetics of magnetic sublevels and the directionality of the plasma, and its impact on line polarization measurements. Stark line broadening, including ion dynamics, of K- and L-shell transitions of highly-charged, high-Z ions at tens of keV and densities of over 10^{25} particles per cubic centimeter will be significant. For low-Z elements, the Compton profile is dominated by scattering from free electrons. The Compton scattering profile for low-Z elements is relatively simple, inasmuch as scattering from free electrons is independent of atomic structure details. However, for high-Z elements, X-ray scattering from bound electrons will interfere with and obscure the plasma wave peaks. To use the Compton scattering profile as a diagnostic tool will therefore require detailed calculations of X-ray scattering cross sections for many energies, scattering angles, and stages of ionization for all elements of interest. Although there are a few studies of Compton scattering of X-rays from neutral atoms, there are essentially none for the elements and ionization stages that are relevant for upcoming experiments at the LCLS facility.

What's needed? Relativistic atomic structure and scattering calculations that take into account both the relativistic effect on the atomic physics and the scattering of a relativistic electron are needed. These developments will provide the reference framework for future spectroscopic diagnostics involving HED plasmas with highly-charged high-Z ions. A new generation of accurate and fast relativistic scattering codes will be needed to supply the required fundamental atomic cross-section data. Line shape theory will be needed that takes into account strong electron correlations, quantum degeneracy, turbulence and relativistic effects. Polarization measurements are a unique tool for inferring directionality (e.g., presence of electron beams or macroscopic fields) in plasmas. New collisional-radiative atomic kinetic codes that take into account the processes and/or directionality that is imposed by external fields will become important for interpreting polarized line spectra data. A general-purpose Compton scattering code will be needed within the framework of relativistic quantum mechanics.

Connections: The atomic physics needs discussed in this section will motivate new instrumentation that will combine temporal, spatial and spectral resolutions. Relativistically correct atomic structure and scattering calculations will be required to interpret and model the measurements. Development of a universally available Compton scattering database or a Compton scattering computer code would be closely related to the development of databases for other atomic processes, such as photoionization, autoionization, or dielectronic recombination.

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Chapter 8: Research Infrastructure

Introduction

The high energy density laboratory physics community faces critical challenges to advance the field, energize researchers, attract and engage the brightest students and young scientists and engineers, and persuade the physics community that HEDLP is a discipline of great excitement and opportunity worthy of increased support by funding agencies. The many scientific opportunities that exist have been addressed in the earlier chapters of this report and in previous studies.

To fulfill the promise of providing great science in the Nation's broadest interest requires a healthy and vigorous research program, steady research support and world-class infrastructure. Researchers will be attracted by the excellence of the opportunities, by scientific and engineering grand challenges, by access to facilities needed to address the opportunities and grand challenges, and by the availability of funding for research on those facilities. The existing suite of experimental facilities is remarkable in its range (see Appendix B). It includes lasers with powers up to the petawatt range that are operated as user facilities and the highest-energy pulsed laser facility in the world, as well as the highest-power, -intensity and -brightness facilities in the world.[14] Pulsed-power facilities, including the highest such power facility in the world, provide extreme X-ray and magnetic-field environments to drive large targets. The most important issue here is user access to these facilities. Within the United States, the National Nuclear Security Administration is the primary funding source for HED research facilities. However, the NNSA provides very limited resources for academic involvement and facility access, an essential ingredient if HEDLP opportunities are to be addressed in the US by US-based scientists. Furthermore, we face a conspicuous absence of plans for next-generation HED facilities. Without those plans, the US will lose its primacy in HED science, despite its importance to national security and to our scientific community at large, because more advanced facilities are already on the drawing board in Europe.

Many scientific opportunities that could take further advantage of NNSA-sponsored facilities have already been discussed in Chapters 1-7. To do this, and in so doing, address the scientific challenges described in this report, the infrastructure needs of the HEDLP program are:

1. A diverse, world-class and world-leading suite of experimental facilities;

2. Open, routine, stable and coordinated access for US scientists to most intermediate- and large-scale NNSA-operated devices, with transparent peer review, selection and scheduling;

3. Stable and growing funding for the academic component, including for developing and maintaining university-scale facilities (a vital complement to both NNSA and DOE Office of Science [DOE/SC] facilities);

[14] The technical distinction between brightness and intensity is being made here: Brightness is power per solid angle and therefore independent of distance; intensity is power per unit area and varies with target distance.

4. Substantially increased target fabrication and metrology capabilities (required to take advantage of facility access);
5. Computational facilities for experimental design and analysis, as well as for theoretical modeling of new concepts to be tested in exploratory experiments;
6. Diagnostic capability, both for facility characterization and for HED parameter measurements; and
7. Strong and focused advocacy from within the DOE at the highest levels, from a government advisory committee, and from within the community itself.

In the remainder of this chapter, we address these needs in varying degrees of detail.

I. Experimental Facilities

Status

Most experimental HED research is performed on facilities funded by the NNSA. Most of the experimental time on the largest facilities supports the NNSA's programmatic mission, nuclear weapons stockpile stewardship, and only a small fraction of the time is made available for discovery-driven basic HED science. Smaller systems complement larger ones, and a larger fraction of the time on them is available for fundamental science experiments and exploratory research; the greater percentage of available time enables them to respond more quickly to unexpected discoveries. In some cases, the research performed on the smaller facilities leads to an end in itself, while in other cases an experimental platform or technique is developed to a level of sophistication and capability appropriate to moving the experiment from smaller to larger facilities. The current mix of capabilities enables strong scientific progress. However, insufficient resources, both in terms of funding and of facility access, are devoted to academic and private sector use of all of these facilities to enable their effective use for research not directly related to NNSA's mission. Recent and further projected funding decreases at the major experimental facilities have reduced experimental opportunities for basic science throughout the broad community.

What's needed?

Near term: A vigorous, scientifically effective HEDLP program will be possible only to the extent that NNSA operates its intermediate- and large-scale HED facilities either as national user facilities, in the manner developed for the DOE/SC synchrotron light sources[15], or as one of the NNSA-sponsored facilities that is operated partially as a user facility (to be discussed in Section II, below). Resources—both access to the facilities and funding to enable their use for science in the broadest national interest—need to increase to the greatest extent possible over the next 5 years for research outside the NNSA mission, consistent with the use of the facilities for NNSA's direct mission needs.

[15] http://www.er.doe.gov/bes/brochures/files/BES_Facilities.pdf.

Sufficient funds to operate university-scale facilities effectively are also needed, though not typically as national user facilities. The research carried out at university facilities is the "seed corn" from which the HEDLP field will grow, to the benefit of US science in general as well as to NNSA's mission-oriented science. The planning process should include the possibility that growth in the HEDLP community will lead to a need for additional university-scale facilities.

Outstanding HED capabilities and opportunities exist outside the US, which include unique experimental facilities, computational facilities, specialized diagnostic instruments and other expertise. Examples of experimental facilities are the petawatt laser user facilities at Rutherford-Appleton Laboratory in the UK and at the Laboratory of Laser Engineering in Osaka, Japan. International collaborations and exchanges are important to allow utilization of the full range of capabilities and thereby accelerate scientific advances, and they should be encouraged.

Long term: As has been discussed in Chapters 1-7, full utilization of current facilities will provide outstanding opportunities to undertake great science, and next-generation facilities will allow access to new physical regimes and thus open new frontiers of scientific discovery. HED opportunities have been identified that require innovative technologies, advanced diagnostics, and new or upgraded facilities. However, for the first time in a number of decades the US has no strategic roadmap or investment plan in place for building next-generation major HED facilities that would move the field significantly beyond its present capabilities. This stands in contrast to the European Union, Japan, and China, all of which have strategic plans in place to develop next-generation capabilities. The absence of such a strategic plan in the US is a distinct disincentive for building an HEDLP community in the US, and it places the US in a significantly disadvantaged position in a field that is seeing a significant upsurge in open science interests world-wide.

II. Access to Experimental Facilities

Status

The NNSA operates world-class HED research facilities in support of its national security mission. These represent a continuing investment of US resources that must be operated consistently to achieve and maintain technical excellence, thereby maximizing the benefit to the Nation. Some NNSA facilities provide necessary capability almost exclusively for a user community within the NNSA (and perhaps related organizations). The NNSA facilities that are of interest here we shall refer to as "Shared National Resources" (SNRs)—facilities like NIF, Z and OMEGA, which should be made accessible to users from academia, industry, national laboratories other than those operated by NNSA, etc. Of course, NNSA must effectively manage SNRs to ensure that its programmatic priorities are met, including development of the basic HED physics community as a source of the future scientific staff that is necessary to sustain NNSA's capability to carry out its core missions in the long term. The latter effectively requires that SNRs be available for use by the HED community outside of the NNSA laboratories.

Within NNSA, the only facilities formally operating as a "Designated User Facility" are the Lujan Neutron Scattering Center at LANSCE (Los Alamos Neutron Science Center) and the Center for Integrated Nanotechnology at the Los Alamos and Sandia National Laboratories. These facilities are subject to both NNSA and Office of Science oversight. However, other NNSA facilities, such as OMEGA, and intermediate-scale laser facilities at the national laboratories also operate as user facilities part of the time. For that aspect of their operation, facility access is based upon peer review by external committees of discovery-driven science proposals. The National Laser User Facility (NLUF) Program that began in 1979 allows user access to the OMEGA facility and provides incremental funding to support basic HED science for university and private industry investigators.

What's needed? Use of NNSA's shared national resources for science in the Nation's broadest interest can best be achieved by providing access to these facilities by the scientific community, consistent with NNSA's mission needs. Operating an SNR as a partial user facility requires funding well in excess of that required for minimum operation of the facility; funds for coordination, engineering and technical support, facility diagnostics, administrative support, etc. are also required.

Every SNR will benefit from having a Facility Management (or governance) Plan (FMP) that describes how the facility will meet its responsibilities to the NNSA and how it will optimize the overall experimental availability and effectiveness of operations, including the use of peer review of proposed experiments. The FMP should describe the processes by which users can have access to the facility and how access control is implemented. Measures of facility effectiveness and user productivity are needed, as are procedures for how the facility interacts with users, including the types of institutional agreements that are required. More details are provided in the postscript on facility governance and management at the end of this chapter. At a minimum, the facility governance for an SNR should encourage both NNSA researchers and the US technical and scientific community to make use of these facilities to maintain our Nation's technological and scientific leadership. It should encourage the development of partnerships with the DOE Office of Science and other government agencies (e.g., NSF, DoD, NASA, etc.) to establish joint programs that support long-term, broad national-interest research in physics and other core competencies important to NNSA missions.[16] Within this research need, it is important that NNSA continue to provide full operational funding for its facilities. As described in a recent NAS report,[17] shared facility operations funding by multiple agencies is a recipe for disaster.

There exist opportunities for cross-facility coordination and integration to optimize experimental effectiveness through the use of the appropriate facilities; to encourage validation and verification of critical experiments through multi-facility experiments; and to assist in staged experiments requiring moving, for example, from a small to a large facility. At present, there are few national mechanisms to utilize, coordinate, or integrate existing or planned user facilities,

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[16] All NNSA facilities operating as SNRs should apply for formal status as a DOE "Designated User Facility" under DOE Waiver No. W(C)2008-003 and DOE Waiver No. W(C)2008-005. This is consistent with DOE policy and congressional direction.

[17] National Research Council, *Cooperative Stewardship: Managing the Nation's Multidisciplinary User Facilities for Research* (National Academy of Sciences Press: Wash., D.C., 1999).

but this could be part of a plan to best employ available facilities. A clear success in this regard, and perhaps a model to follow, is the large number of diagnostics and concepts that have been developed and tested at OMEGA and then moved, in either conceptual or actual hardware form, to NIF. This process has been going on intensively for the last few years. Still, overlapping review- and proposal-committee membership across facilities is one approach to optimizing use of available facilities. Other coordination techniques should be explored, including high-level planning of strategic investments and capability enhancements.

Maintaining safety and security is essential in any research program. Currently, each facility requires its own safety and security training program and certification, without apparent regard to those of the others. This provides another opportunity for coordination among user facilities, which would certainly reduce the burden associated with redundant access requirements across different facilities for users who plan to move experiments from one facility to another, or simply to carry out experiments at multiple facilities.

It is important to provide an effective infrastructure, both technical and administrative, to support prospective facility users from the proposal solicitation phase through planning and execution of experiments to the dissemination of scientific results.

III. Other Infrastructure Needs

Targets

Successful HEDLP experiments depend crucially on well-designed, carefully fabricated and fully characterized targets for experiments involving lasers, heavy-ion beams, pulsed-power machines and the Linac Coherent Light Source. To that end, a robust infrastructure to support the development and fabrication of targets for the envisioned HEDLP science program is essential.

Target needs and the associated funding should be explicitly included in experimental proposals in response to HEDLP solicitations, and should be considered in the peer-review process, with input from target fabrication community liaisons and technical contacts as appropriate. In order to take advantage of common developmental elements and target similarity from one proposal to another, funding for target fabrication might, in certain circumstances, best be provided by NNSA/OFES directly to the target manufacturers, rather than through individual grants, in the same way that facility time for users and facility diagnostics are currently provided through NNSA funding to the facilities. This approach should also enable organizations that will fabricate targets to prepare the infrastructure they will need in a timely way for the funded experiment.

It should be stated, however, that the problem is a complex one. For example, target specification and design is a capability that resides largely only within the national labs, and it is not usually within the capabilities of university or private-industry investigators. In addition, the experimental target needs of university investigators are often not fully defined or fleshed out, nor can they be, in the proposal process. Given that target costing and fabrication frequently require long lead times (especially for non-standard targets, which are often the most interesting and important for advancing the science), this creates a dilemma that is difficult or sometimes impossible to resolve. Efforts should be made to address this state of affairs head-on, by developing and diligently maintaining a database or catalog of target types and capabilities that are available to the community. Certainly, a well-maintained database or catalog of target types and capabilities would be of great value to the wider community.

Computational capability

It will be essential for users on all major facilities to have access to theoretical and computational support for both experimental design and data interpretation. The necessary codes have been or will be discussed in Chapters 1-7 and in Chapter 10. Little more needs to be added here, except to point out that this user- (largely university-) focused support activity is in addition to the infrastructure needed for advanced code development. A user-focused support team, which might be common to all user facilities, would need access to large-scale, high-performance computational resources in order that they should be highly responsive to user needs. Their mandate could include development of advanced modeling capability specifically for the user community. The latter activity could be carried out in academia as part of the HEDLP program.

Facility diagnostics

As detailed in Chapter 9, facility diagnostics—as well as a standard set of HED diagnostics—are essential for all user facilities, and adequate funding for hardware, software and human resources should be incorporated into the facility budget.

The NNSA/OFES Joint HEDLP Program will benefit as a whole if solicitations for HEDLP research include funding for facility diagnostics, as well as for special-purpose and novel HED diagnostic development. Objectives of such solicitations could include obtaining greater university involvement in facility improvement and encouraging hands-on training for students.

Adequate assistance for users to qualify and implement user-developed diagnostics and to address any other system integration issues should be provided by user facilities. The value of diagnostic projects that involve coordinated design and development between a major national facility and one or more universities cannot be overstated. Joint development provides an effective mechanism for a student to obtain hands-on experience at his/her home university, which is a vital element of the education of an experimentalist. The large facility ultimately benefits from a new diagnostic that is engineered to be used there, and it may also benefit from hiring the students who developed it as they follow the diagnostic to assure its proper implementation. The facility must also provide technical liaison to assure that safety and security regulations are well understood.

Facility user groups

User groups, with the support of the facility management, have been effective at DOE's Office of Science user facilities and at NNSA's OMEGA laser facility. The HEDLP Joint Program will benefit from independent user groups at each facility. When there are user groups established at the various NNSA facilities, the leaders of each of the groups could easily develop a national coordination, as discussed above, to share "best practices," to promote the HEDLP field and to optimize the use of the whole suite of user facilities.

Postscript:

Management of NNSA Facilities (Shared National Resources) as User Facilities

The aim of this postscript is to illustrate how one might structure the management of NNSA facilities so as to realize their effective operation as user facilities for the wider academic research community. The key element is the Facility Management Plan (FMP), which must be consistent with the facility designation (in the case considered here, a Shared National Resource), size, and fraction of shared use, and detail the process for technical peer review of proposals for quality of science and engineering of the proposed work. The NNSA mission-directed work must be reviewed in a manner consistent with NNSA's missions, as well as for its scientific impact on the general field of HEDLP. We assume this will be carried out separately from the review process for the fundamental science proposals, which are of interest here.

In general, an FMP will:

- Define the organization structure and the roles and responsibilities of the key operational staff, including the facility director.
- Define the roles, responsibilities, membership type, selection procedure, terms of appointment, and frequency of meetings of all advisory or planning committee(s) that review and priority-rank proposals and/or make research needs relating to facility use and capabilities planning.
- Provide for an effective infrastructure, both technical and administrative, to support users, from the proposal solicitation phase through planning and execution of experiments to the dissemination (publication in the case of open results) of scientific results.
- Develop and publish a timeline associated with the process for facility scheduling, beginning with calls for proposals, through review, selection, and notification for scheduling of experiments.
- Provide and maintain an infrastructure that meets applicable NNSA and DOE safety and security requirements for users, including accommodating classified research if required, by means of facility security plans.
- Develop and communicate processes for:
  - **Proposal solicitation**. Proposals will be solicited for a given scheduling period in two major areas: NNSA national security (stockpile stewardship and non-proliferation) and science supporting broader national missions. The latter, of interest here, includes

fundamental HED science, inertial fusion energy, nuclear forensics, DOD-specific experiments and other activities. The facility director, when necessary, will consider proposals for facility-based improvements/capability enhancements.

- **Technical review** of proposals using well-defined evaluation criteria by a committee of peers is required and must ensure there are no conflicts of interest of committee members/facility staff that might bias the results.
- **Proposal selection, notification of principal investigators, and scheduling of experiments** in a timely manner.

- Provide guidance, in agreement with NNSA, for the allocation of facility time/resources resulting from the proposal review and evaluation process in terms of the categories (Direct Weapons Program and Basic Science Use), plus contingency, and assess the overall balance of the experimental program for the facility-scheduling period.
- Provide for user agreements that define roles and responsibilities, including financial obligations, of the facility and its personnel and facility users.
- Provide for grievance and appeals procedures.
- Provide for developing and cultivating relevant user communities to encourage NNSA researchers and researchers from the US technical and scientific community to make use of these facilities to maintain the Nation's technological and scientific leadership in the world.
- Develop a set of metrics appropriate for assessing the performance, overall experimental availability, and effectiveness of operation of the facility. Satisfaction of the user community should be considered an important metric.
- Track and report facilities/time resource allocation as part of the annual performance self-assessment.
- Define a change control process for making changes to facility governance, including any of the topics considered in this document.
- Describe review schedule and concurrence requirements for the Governance Plan, as well as how to communicate and distribute revisions.

Chapter 9: Diagnostics for High Energy Density Laboratory Physics (HEDLP)

Introduction

Controlled experiments are an essential tool used by scientists to test theories or simply explore new phenomena. New instrumentation and measurement techniques—collectively referred to as "diagnostics"— enable new experiments and insights. From the earliest spectrometers, which broke sunlight into its component parts, to the most advanced gamma-ray detectors, new diagnostic instruments have revealed a universe far beyond what human imagination had contemplated prior to their use, and this will very likely be true in the HEDLP field as well, as new measurements are conceived, developed and implemented. Indeed, diagnostics remain the heart and soul of scientific discovery.

Diagnostics are generally either active or passive. Passive techniques rely on capturing particles or photons emitted by the object of study and enlisting them to infer something about the object. For the most part, astronomers have had to rely on passive instruments—telescopes and spectrometers—to carry out their research. More advantageous when possible are active techniques, which use an external source of particles or photons to probe the object in some way; those particles, or the effects they create, can then be directly measured.

Until recently, the study of HED phenomena in the unclassified research community was largely restricted to the astrophysical domain; as a consequence, diagnostics were necessarily passive. With the advent of laboratory HED experiments, fortunately, diagnostics are moving from the passive to the active category. Researchers now have control over experimental conditions and are able to manipulate and probe nature in ways that astronomers and astrophysicists traditionally could not. Figuratively speaking, we can now hold a bit of star matter in our hands, poke it from different directions and prod it with as many kinds of instruments as we can devise. Many new instruments have in fact been invented in the last decade to study HED plasmas, but many more are needed because of the enormous range of densities and temperatures, as well as spatial and temporal scales, covered by high energy density physics.

In fact, the first of the two main challenges to HED diagnostics is that characteristic spatial scales in HED experiments can range from less than one micrometer to several centimeters; light emitted from HED plasmas can range from one one-hundredth of a nanometer in wavelength to one thousand nanometers; temperatures can range from ten thousand degrees to a hundred million degrees, while densities can range from several orders of magnitude below the densities of solids to several orders of magnitude above. No single instrument, diagnostic technique or detector technology will suffice. As a result, the largest facilities at the national laboratories need, and have developed, extensive suites of diagnostics for their HEDLP research. Progress in HED physics at the large facilities, however, has been limited because their diagnostic suites have often been determined primarily by the narrow needs of the weapons program, and some phenomena we believe to be important for understanding macroscopic behavior of HED plasmas have as yet escaped our grasp. In order to enable HEDLP physics to fulfill its potential, the development of new diagnostics needs active encouragement as part of the Joint HEDLP Program now established in the Office of Fusion Energy Sciences.

The second challenge facing HED diagnostics is that the extraordinary physical conditions encountered in the HED physics environment have caused a merging of the experiment and its necessary diagnostics. For instance, if one wishes to determine the properties of a plasma by its emitted X-ray spectrum, one must design the experiment so that the plasma will allow the X-rays of interest to escape. When the data are actually collected, one must determine whether the inferred conditions in the plasma are consistent with the assumptions made in the experimental design. If not, the conditions must be recalculated in an iterative process until the observed spectrum and the inferred plasma properties are self-consistent. In general, disentangling the computational design of the experiment, the physical experiment itself, and the measurement techniques, the interpretation of the data is the goal. By necessity, it is an iterative process.

- ***The challenge for HED diagnostics:*** *Can we benchmark computer simulations with the data from HEDLP diagnostic instruments when often we must use the very same computer simulation codes to analyze the experimental data? Can we measure plasma parameters by enough independent diagnostics, or analyze the results from diagnostic devices with enough independent analysis tools, to achieve credible validation of computer simulations and a comprehensive understanding of an HEDLP experiment?*

We turn to some key developments in "core" diagnostic areas that can have a large impact on multiple areas of high energy density physics. We have also attempted to capture some key diagnostic issues and needs in a few specific areas of HEDLP (in particular, those discussed in previous chapters of this report), because of their importance to the progress of the field.

I. Basic Imaging and Radiography Diagnostics

Status

Imaging diagnostics provide information about the spatial distribution of matter and electromagnetic fields. Passive imaging diagnostics capture emitted light (from optical through X-ray) or particles (e.g., neutrons). An optic captures the emission image; it can be as simple as a pinhole or it can be a more complex reflective optic (e.g., bent crystal, multi-layer mirror, zone plate, etc.), or anything in between. Time resolutions ranging from roughly 2 ps to 2 ns are typically achieved using time-gated CCD cameras, micro-channel plate cameras, or streak cameras. Active imaging uses an external photon or particle source as a probe. Familiar optical probing techniques in the visible, ultraviolet or infrared parts of the spectrum include schlieren imaging (to measure electron density gradients), interferometry (to measure electron density), and Faraday rotation (to measure magnetic fields). All of these are limited by diffraction, refraction, and/or absorption from dense plasmas. X-ray photons, by contrast, can pass through even relatively dense plasmas, and the absorption of the X-rays (radiography) can be used to measure the ion density under certain circumstances. The paths of charged particles provide information about the distribution of electric and magnetic fields by measuring how the particles are deflected. Time resolution in active diagnostics is provided either by gating the detector or by using a finite-duration source. The spatial resolution achievable in all these diagnostics varies over a wide range (few micrometers to hundreds of micrometers) and is governed by the magnification used, the resolution of the detector, diffraction and refraction limits, etc.

Research opportunities and needs

a) High-energy (100-1000 J) short-pulse (~1 ps) lasers have recently come online at several major facilities. Such lasers offer the possibility of high-energy (20-100 keV) radiography diagnostics during the next five years, which will enable measurements in denser/thicker plasmas, particularly those composed of high-atomic-number materials (e.g., Fe, Au). This would enable measurements of shocks in such plasmas, the flow of jets inside of a dense medium, the size of dense DT plasma in inertial confinement fusion capsules, etc. (See Chapters 1 and 4 in particular, on HED hydrodynamics and radiation-dominated hydrodynamics.)

b) The development of coherent, tabletop 10-100 eV photon sources during the past decade can be utilized over the next five to ten years to extend the applicability of measurement techniques that have traditionally been limited to the optical range (shadowgraphy, schlieren, interferometry, Faraday rotation). The higher-energy photons will allow quantitative measurements in the more dense plasmas that are typical of HED experiments, and the sources may be well suited to both smaller and larger research facilities.

c) New alternative sources of coherent radiation in the 0.1-100 keV range may be practical for diagnostic use within the next 15 years (e.g., linear accelerators and/or laser wakefield devices; see Chapter 5). Even relatively large and expensive sources may be viable for large research facilities (e.g., NIF, Z, OMEGA), given the importance of radiography diagnostics.

d) Energetic charged-particle sources have recently been developed on numerous facilities that can be used to map out the distribution of electric and magnetic fields. Such active diagnostics have the potential to unlock new local field measurements within the next 5-10 years as we learn to apply them to various HED configurations.

e) During the same timeframe, it will be necessary to develop new or extend present-day detector technologies to take advantage of extensions to the state of the art in photon energy, time resolution, and/or spatial resolution. Examples include extending time resolution to the sub-picosecond regime and extending time-gated detectors to the 20-100 keV regime.

II. Nuclear and Particle Diagnostics for ICF and HEDP

Status

As has been discussed in Chapter 1, NIF will extend our reach into the burning plasma regime and provide the conditions necessary to demonstrate fusion ignition and net energy gain in the laboratory. In this effort, nuclear and particle diagnostics must play an important role in guiding experiments towards ignition, because the effectiveness of X-ray-based techniques will be diminished due to optically thick implosions and neutron yields, which will blind them. Nuclear and particle diagnostics will also play an important role in basic HED science experiments that address several important questions regarding, for instance, possible non-thermal components in the neutron emission and alpha-particle physics in burning plasmas. Other experiments enabled by burning plasma conditions are expected to yield data on the fundamental cross sections and reactivities for reactions relevant to stellar nucleosynthesis. Figure 9-1 illustrates several of these reactions in the solar proton-proton (pp) chain and the carbon-nitrogen-oxygen (CNO) reaction cycle that dominates in slightly hotter, heavier stars.

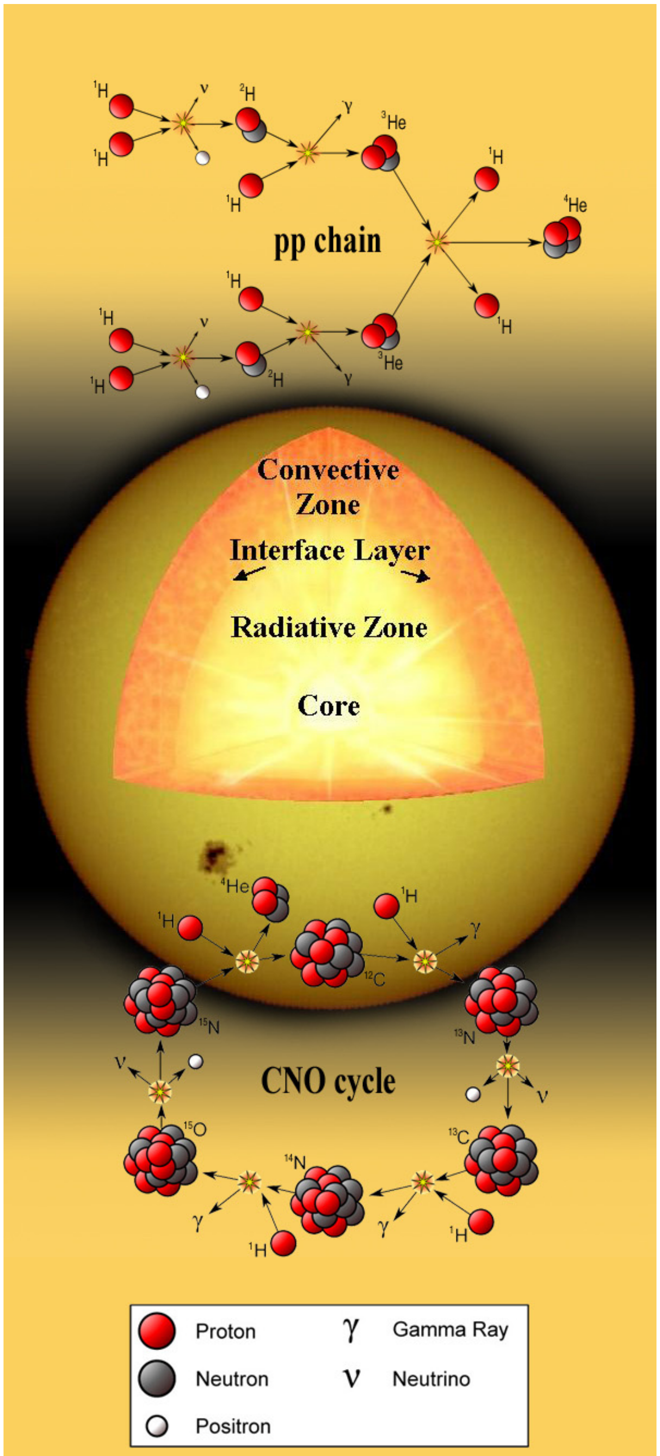

Figure 9-1. The National Ignition Facility and new diagnostics will let us recreate and measure several important nuclear reactions that take place in stars. In the core of the Sun, the pp chain transforms hydrogen nuclei into helium by slamming two protons (^{1}H) together with sufficient velocity to overcome their electrical repulsion. One proton emits a positron and a neutrino and is transformed into a neutron. The result is a deuterium nucleus (^{2}H), consisting of the neutron and proton. In the remainder of the chain, shown at top, deuterium is converted into helium-three (^{3}He) by addition of a proton, and then two ^{3}He nuclei are slammed together to get ordinary helium-four (^{4}He) plus two protons. The pp chain dominates in stars, like our Sun, in which the core temperature is less than 17 million Kelvins. For stars with higher core temperatures, the CNO cycle dominates. In this cycle, hydrogen is again converted into helium but requires carbon (^{12}C) as a catalyst. As shown in the bottom sequence, the cycle begins when ^{12}C is transmuted to ^{13}N by proton capture. The ^{13}N is unstable and decays by positron emission within a few minutes. Successive proton capture and positron decay result in a ^{4}He nucleus plus the original carbon.

Research opportunities and needs

New and improved nuclear and particle diagnostics that are needed to support the HED regimes and burning plasma conditions expected in the near term (3-5 years) include the magnetic recoil spectrometer (MRS), neutron time-of-flight (nTOF) measurements, neutron activation diagnostics (NAD), γ-ray reaction history (GRH) measurements and radiochemistry (RC). Another measurement that could prove very valuable for both laboratory-fusion and nuclear-astrophysics experiments is γ-ray spectroscopy.

It is not practical here to discuss all of these methods. A good example, however, is the MRS technique, in which there has been recent significant progress. Demonstrated recently on OMEGA, MRS provides measurements of the absolute neutron energy spectrum, from which fuel compression, ion heating and fusion yield in cryogenic deuterium-tritium implosions have been determined. In basic science experiments, MRS measurements have revealed features of the astrophysical S factor (a parameter formulated to describe reaction cross sections and reaction rates) in reactions between two tritium nuclei, an important mirror reaction to the reaction $^{3}He + {}^{3}He \rightarrow 2\,{}^{4}He + 2p$ that is part of the pp chain shown in figure 9-1. Adapting this high-precision diagnostic to NIF and exploring other extensions is a high priority.

The RC technique and γ-ray spectroscopy also have the potential to address very important questions about stellar s-processes (a series of slow neutron-capture reactions and beta decays that synthesize half the nuclei above iron), which involve capture reactions in excited nuclei. Thulium-171, which has an excited state at 5.025 keV above the ground state, is an example of such a nucleus. This excited state can be produced in an ignited fusion fuel capsule at NIF, and studied in the laboratory for the first time using γ-ray spectroscopy or the RC technique. Here is a case where we anticipate important new results from the alignment of science, new facilities, and new measurement capabilities.

III. X-Ray Spectral Tomography

Status

The conditions and environment of a plasma affect the ionization state, the bound electron energy states and the distribution of bound electrons. Passively probing the ionization and bound-state distribution by observing transitions of electrons between bound energy states (through the emission of X-rays) therefore provides information on plasma composition, electron and ion temperatures, electron density, ion velocity, and electric/magnetic field strengths. The information is decoded through comparisons to synthetic spectra computed under an assumed collection of plasma conditions. Accurate determination of the plasma conditions therefore depends on the accuracy of atomic theory, the theory of atoms in plasma and the coupling of these theories with radiation transport, subjects that are discussed in Chapters 4 and 7.

Research opportunities and needs

Traditional analysis of spectral data with limited spatial resolution requires an assumption about the symmetry and uniformity of the plasma, which can be alleviated by recording spectra from multiple space-resolved orthogonal views. This technique, termed spectral tomography, provides spectra from many lines of sight (LOS) through the plasma with intersecting views, thereby providing sensitivity to the multi-dimensional plasma conditions. Spectral tomography offers a tremendous opportunity for diagnosis of HED matter and has been demonstrated using multiple monochromatic images. This capability must be extended to highly resolved spectra:

a) Improvements in gated imaging detectors are required. Diagnosis of very hot or very dense plasmas will require high time- and space-resolution spectroscopy at photon energies greater than 10 keV. Future experiments will require detectors with higher spatial resolution and faster temporal response than can be provided by present-day microchannel plate (MCP) detectors. The exact requirements will depend sensitively on the application, but we expect that the need for new detectors will arise within 5-10 years.

b) Accurate spectral analysis requires detailed understanding of the spectrometer sensitivity. Significant progress must be made in the calibration of crystal reflectivity and detector sensitivity vs. photon energy over the next 3-5 years.

c) As discussed in Chapter 7 on high-Z physics, this area requires significant computational modeling, validated by dedicated experiments, to facilitate the desired scientific measurements. In brief:

    1. Spectral line profiles are sensitive to electron density (Stark effect), ion temperature (Doppler/Stark effect), magnetic field strength (Zeeman effect), and electric field strength (Stark shifting). The relevant theories are nearly untested in the HED regime and require experimental validation. Significant progress on benchmarking line broadening calculations can be made in the next 3-5 years, with resolution of most issues possible within 10 years.

    2. A collisional-radiative (CR) treatment of the plasma kinetics in HED plasmas is often required because collisions do not entirely determine the ionization or bound-state populations. Inclusion of radiative ionization and excitation often requires a detailed treatment of the radiative line transfer across the entire plasma volume. Progress in benchmarking CR computations can be made over 3-5 years, with resolution of most issues possible within 10 years.

    3. Decoding spectral tomography data requires computation of synthetic spectra under many different possible plasma conditions. The calculations must iterate until suitable agreement is found between computed and experimental spectra. It is impractical to test every possible permutation, necessitating the use of sophisticated search algorithms. The latter, together with faster CR calculations, have reduced convergence times to days. Extension to multiple dimensions, in order to move beyond assumptions of symmetry and uniformity, as needed for large, complex plasmas, will require more improvements in the next 3-5 years.

IV. Thomson Scattering – the Workhorse of Plasma Measurements

Status

Thomson scattering is an active diagnostic that provides direct access to fundamental plasma parameters (temperature, density) across all plasma regimes, including HED plasmas, through a quantitative view of the electron motion within the plasma. Photons from an external source scatter off of electrons in the plasma, with the scattered photons Doppler-shifted in frequency by an amount proportional to the velocity of the electron. An ensemble average over all the scattering electrons leads to a spectrum that is related to the plasma temperatures, density, and average ionization state. Thomson scattering requires high-power photon sources to overcome the inherently small scattering cross section of the electron. It also requires a photon frequency above the critical frequency of the plasma. Thus, visible light and even infrared lasers are ideal for probing the low-density plasmas of interest in magnetic confinement fusion studies, and so Thomson scattering has become a very common and extremely important diagnostic in that field.

As laser powers and detector efficiencies have improved, Thomson scattering has been used to measure the hydrodynamic properties and plasma instabilities in laser-produced plasmas at intermediate-scale facilities still using visible light or UV photons. Initial experiments have shown that Thomson scattering can be very effective in helping to understand the hydrodynamics and instabilities of HED plasmas at conditions relevant to ICF.

Research opportunities and needs

Optical Thomson scattering has demonstrated its importance in HED plasmas around the world and has matured as a diagnostic to the point where HED user facilities need to support it as a core diagnostic, as the MFE community has done for the last 25 years. This capability is vital to understanding the driver (laser, pulsed-power machine or intense particle beam) energy coupling and partition in HED plasmas as discussed throughout this report. The enabling technologies that will help realize the diagnostic opportunities with optical Thomson scattering are

1. Development of 0.25-μm probe lasers at the large-scale facilities, and

2. Development of efficient scattered light detection capability in the range of 180 nm to 210 nm.

The photon energy range between optical and X-ray light provides a rich arena for novel measurements but requires the development of a 30-nm ultraviolet probe beam with sufficient power to produce a detectable Thomson-scattered signal. This would allow the direct probing of the electron distribution function at densities where powerful optical lasers develop strong laser-plasma instabilities (10^{20} cm^{-3}) (e.g., inside a hohlraum in indirect-drive ICF research). Detailed measurements of the distribution function would lead directly to a fundamental understanding of kinetic instabilities that can prevent laser beams from depositing energy in the desired locations.

To expand Thomson scattering into the solid-density regime, powerful penetrating X-ray sources are required for probing. Initial experiments have employed laser-based X-ray sources that provide sufficient photon numbers in narrow bandwidth spectral lines to allow spectrally resolved X-ray scattering measurements from warm dense matter. The development of a 15-keV bright photon source would enable a direct measurement of the entropy within an ICF fuel capsule; this could be a game changer on the path to achieving high-gain and high-yield fusion.

Initial proof-of-principle Thomson X-ray scattering experiments to help determine the equation of state in warm dense matter have shown tremendous promise. However, this technique requires significant development before it can attain the reliability that optical Thomson scattering has achieved. Hardware, experimental technique, theory and modeling all require advances:

1. Bright, narrow-band X-ray source development is needed;

2. Detector development to increase quantum efficiency below 100 nm is necessary; and

3. Theoretical and modeling advances are needed to be able to calculate the scattered spectrum from WDM as a function of conditions.

In the long term, investment in the advancement of Thomson scattering will enable measurements of the electron and ion temperatures, densities, and particle distribution functions that will offer critical insight into the fundamental behavior of HED plasmas.

V. Diagnostics for Understanding HED States of Condensed Matter

Status

In general, extreme states are achieved by applying dynamic compression pulses to samples, either in the form of a single strong shock wave, by applying multiple shock waves, or by a gradually rising ramp wave. The sample container can play an important role—for example, by causing the compression pulse to reverberate in a sample that is confined between stiff anvils. Quantitative determination of the mechanical and thermodynamic parameters achieved in dynamic compression experiments relies heavily on velocity measurements, which are obtained by shining a probe laser onto the sample surface and measuring the Doppler shift due to surface motion in the reflected beam. The velocity measurements are then combined with the equations of motion and conservation laws to make accurate determinations of the pressure, density and internal energy of the sample, i.e., the equation of state (EOS). This information alone has produced important results for many materials. However, this technique provides only a starting point for investigating the properties of the high-pressure condensed states that are created.

Research opportunities and needs

There remains a great need to develop techniques that will augment the EOS information by probing the microscopic details of the compressed samples. For example, we would like to know the crystal structure (in crystalline solids) or the structure factor (in disordered materials), as well as the nature of the atomic bonding (in molecular solids and fluids) or the electronic band structure (in metals and dielectrics). To produce information at the atomic scale, adaptations of standard X-ray probing techniques will be required. For example, powder-diffraction methods can be adapted to determine crystalline structures. Near-edge X-ray absorption techniques, such as extended X-ray absorption fine structure (EXAFS), and the related X-ray absorption near-edge structure (XANES) techniques can be applied to reveal details of short-range order. While these techniques have been demonstrated on OMEGA, they require further development. With a very bright X-ray probe, it may be possible to determine structure factors. There is also a need to develop very bright broadband optical sources that can be used to do broadband probing of hot samples; this could be used, for example, to perform reflectivity measurements.

The probing techniques listed above must be integrated with target designs, and this may lead in many cases to a tightly coupled design involving simultaneous improvements in target design (new sample containers) and probing technique.

Finally, there is also a need to provide probing techniques that operate in domains where optical velocimetry techniques may be inapplicable. For example, progress in developing absolute multi-TPa shock Hugoniot measurements will require bright X-ray sources and high-resolution X-ray imaging capabilities in order to develop radiographic techniques for both density determination and velocity measurements.

VI. Warm Dense Matter Diagnostics

Status

Warm dense matter (WDM), the subject of Chapter 6, may be the least well-understood domain in HED physics. New facilities (including intense ion beams, free-electron lasers and short-pulse lasers) make WDM conditions much more accessible now, but theory and diagnostic techniques are still in their infancy. Even something as “simple” as particles slowing and stopping as they pass through WDM is not well understood. Techniques are needed to measure (and calculate) temperature relaxation in WDM. In the near term, instruments are needed for WDM studies at next-generation light sources.

Research opportunities and needs

Although some radiation-hydrodynamic codes have been reasonably well validated for certain HED plasma regimes, the hydrodynamic behavior of WDM is uncertain, in large measure because the equation of state and fundamental transport properties (e.g., viscosity and conductivity) are poorly known. Improved theoretical understanding is needed to guide experiments intended to determine electrical, thermal and optical properties in the WDM regime, but credible measurements from new diagnostics could be equally helpful in the opposite direction. Measurements of diffusion coefficients and viscosity are needed for hydrodynamic simulations. The challenge here is to develop diagnostics that can determine these properties hand-in-hand with developing the theoretical models required to understand the results in detail. As additional challenges for diagnosticians in this regime, we ask, “Can we observe a liquid-liquid phase transition in WDM?” and “Does the plasma phase transition exist?”

Significant new opportunities in X-ray free-electron-laser-based diagnostics and creation of HED matter are coming online in the near future with the recent commissioning of the Linac Coherent Light Source (LCLS) and the funding of a dedicated end station for HEDLP research. LCLS, a DOE Office of Science user facility located at the SLAC National Accelerator Center, is the world's brightest X-ray laser source, with a wavelength range of 0.15-1.5 nm. It will be especially valuable for WDM research, both to heat condensed matter isochorically (at constant volume) and to diagnose WDM heated by other means. New capabilities here include extending Thomson scattering measurements to higher plasma density regimes, efficiently probing polycrystalline matter, allowing phase contrast imaging of solid density matter with less than 70-fs temporal and 50-nm spatial resolution, probing hot dense matter and warm dense matter by selective pumping, and creating saturated bound-free continua for absorption measurement with 70-fs resolution.

In view of these issues and challenges, implementation of the following diagnostics are of great interest and importance. Some of these may require relatively modest extensions of the state-of-the-art before being ported to WDM facilities. Others will require use of new facilities, including the new end station at LCLS.

1. VISAR (Velocity Interferometer System for Any Reflector)—state of the art is a single wavelength; multiple wavelengths would allow probing to various critical densities.

2. Multi-wavelength optical pyrometry needs to be extended into the infrared and UV ranges.

3. Polarization pyrometry—using polarization of optical self-emission to improve determination of surface emissivity—should be developed.

4. Laser probes—transmission, reflection, and ellipsometry diagnostics are needed.

5. Electrical conductivity diagnostics are needed.

6. X-ray backlighting (e.g., with X-pinches) should be developed.

7. X-ray Thomson scattering for density and temperature measurements is needed. Here, there is a need for new X-ray sources with very narrow linewidth that can penetrate dense matter while having the capability to measure electron temperatures below 10 eV.

8. Proton radiography can measure density as well as electric and magnetic fields.

The facilities required to develop WDM diagnostics (and to address many interesting physics issues) are at the "university scale." The development and validation of both codes and models could be driven by experimental data obtained on university-scale devices.

VII. Magnetized High Energy Density Plasma Diagnostics

The Grand Challenge of diagnostics for magnetized HED plasmas, the subject of Chapter 2, is to invent and refine techniques to measure the magnetic fields within HED plasmas.

Status

Embedded fields in the megagauss to gigagauss range can be compressed or created inside HED plasmas or be used to compress them. As discussed in Chapter 2, magnetic fields can greatly modify plasma energy and particle transport, plasma-sheath-boundary interactions, shock behavior, electron and alpha-particle heat loss, etc. Since magnetic fields and plasma flow are typically correlated, magnetic measurements may provide a window on turbulent flows, eddies, and shear. A relatively unexplored inertial fusion energy option is Magneto-Inertial Fusion (MIF; see Chapter 2). Improved magnetic diagnostics are critical to our achieving an understanding of all of these properties, phenomena and concepts.

Research opportunities and needs

We note several active and passive magnetic field measurement techniques that warrant near-term investment:

1. Faraday rotation provides chord-averaged information about magnetic field direction and amplitude if the density is known from another diagnostic. Our ability to probe high-density plasmas requires operation at shorter wavelengths than are presently available. This possibility could be addressed in the next 5-10 years.

2. Zeeman splitting of emission lines in HED plasmas leads to broadening of spectral emission lines beyond the usual Stark (electric field) and Doppler (energy spread) mechanisms. Therefore, carefully chosen spectral lines can be analyzed to yield both quasi-steady and randomly fluctuating magnetic fields. The challenge is to extend this technique beyond the proof-of-principle experiments that have been carried out at the number-density level of less than $10^{18}cm^{-3}$. This work is in progress.

3. Local magnetic field and density could be measured by using pulsed polarimetry of backscattered laser light. Resolution to 20 ps and 1 cm are possible with visible laser light (next three years). The opportunity here is to take advantage of coherent short-wavelength, polarized radiation sources to probe higher densities.

4. Proton and other ion deflectometry, together with tomographic inversion methods to reconstruct the magnetic field, have been proven to work in laser-generated plasmas with strong magnetic fields. This method should be fielded on other experiments in the next five years.

VIII. Enabling Technology

A leveraged technology effort of great importance is the development of coherent, bright, and possibly polarized XUV to X-ray radiation sources to penetrate optically grey or thick plasmas. This would enable a much broader range of HED plasmas to be probed than the diagnostics in present use. A focused multi-institutional program including national labs and universities could lead to the development of useful semi-portable devices in five years, and convenient ones in 10 years.

IX. Theory and Computational Challenges for Diagnostics

Interpretation of diagnostic data requires theoretical understanding and reconciliation of the data with the physics models in computer simulations. Good magnetic measurements will benchmark, or prompt development of, theory and computational models to advance our understanding of magnetized HED plasmas. Comparison of data with simulations will require improvements to the theory and models in present 3-D MHD codes, and codes must also include accurate boundaries.

The power of modern computational platforms is enabling new ways of designing and analyzing HEDLP diagnostics. Advances in computer technologies make possible fine-scale simulations of HEDLP plasmas that should include detailed atomic physics, Monte Carlo, and radiative transport modules. Post-processing of these simulations (for example, to look at the transport of radiation, charged particles, and neutrons) provides a method to directly compare code simulations to diagnostic output. Explicit modeling of each diagnostic, using methods such as Monte Carlo, enable calculation of the relevant quantities. Modern computations allow the modeling of the facility noise background in which each diagnostic must operate. Finally, synthetic data post-processed from HEDLP physics codes can generate expected signals to exercise data analysis routines. The accumulation of all these calculations could provide a detailed understanding of each diagnostic before implementation.

Research opportunities and needs

To enable the accuracy demanded by HED experimental measurements, increased fidelity in both HED plasma modeling and diagnostic interaction is required. In a one-to-three-year time span, collisional-radiative and neutron transport physics should be included in radiation hydrodynamics and PIC codes, with linkage to state-of-the-art atomic physics and Monte Carlo packages. In addition, standardized linkages of experimental databases to diagnostic analysis tools can be developed.

Development of advanced algorithms to model the detailed kinetic effects in non-thermal, degenerate and strongly coupled plasmas inherent in ICF capsules, short-pulse laser-plasma interactions, ion-beam-produced warm dense matter, and magnetic Rayleigh Taylor unstable plasmas will require a time span of 5-10 years. This effort must include detailed physics modeling of basic nuclear and plasma processes and post processing of diagnostics. The resulting analysis tools will, for example, rapidly improve databases for equations of state for extreme

HEDLP conditions. Additionally, advanced multi-objective search and reconstruction algorithms, such as Pareto genetic algorithms, should be incorporated into codes in order to enable multiple diagnostic measurements to be tied together to build a self-consistent picture of the plasma under study.

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Chapter 10: Computer Infrastructure and Computing in the HEDLP Environment

Introduction

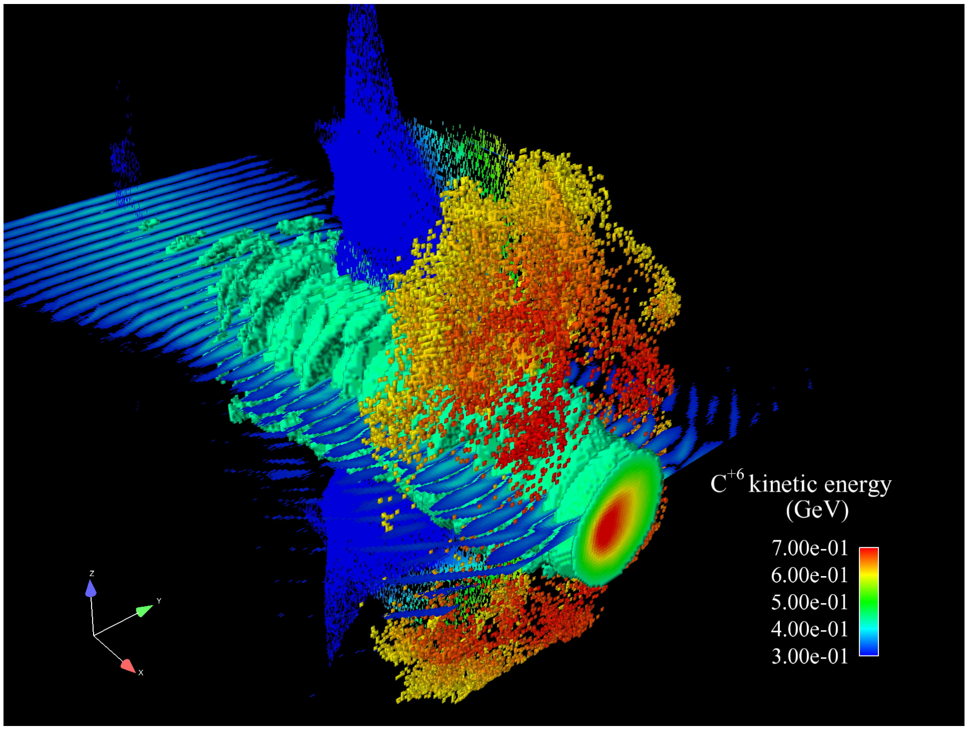
Computer modeling and simulations play a vital role in the study and exploration of high energy density plasma physics: they are crucial to the design, analysis, and interpretation of experiments and constitute an increasingly important tool for developing a predictive theory of HED physics. Computations have become a powerful symbiotic tool, complementing both theory and experiments; simulations provide roadmaps to the most informative experiments and those that would have the greatest impact on the field, while conversely experiments inform and direct the next round of simulations. Computer simulations can explore physical phenomena in regimes of matter and radiation that are difficult, and at times impossible, to access experimentally. By the same token, computer modeling also helps drive theory—it is frequently used to test new theories in situations as yet inaccessible to the laboratory. The increased importance and role of computing in HED plasma physics has been largely a result of the rapid growth in computing power and the parallel increase in the ability of computer codes to model and simulate complex, nonlinear phenomena. As such, computational tools have become an essential aspect of the HEDLP supporting infrastructure.

I. Status

Computer modeling and simulations of HED plasma physics experiments and phenomena currently span the range from kinetic modeling to continuum fluid modeling. In the kinetic approach, a plasma may be modeled either by directly solving for the motions of individual electrons and ions, as determined from self-consistent electromagnetic fields, or alternatively, by solving the evolution equations for the electron and ion particle distribution functions. In the continuum approach, by contrast, one solves the evolution equations for local plasma properties (such as velocity and energy density) by treating the plasma as a fluid in which the electrons and ions may be regarded as separate but interacting components. Which approach is adopted depends on the level of detail that is required in order to understand the local physics. Roughly speaking, if one is constrained by a given amount of computing power, calculations that require increasing levels of physical detail will become concomitantly limited in their temporal and spatial scope. Because HED plasma physics is typically multi-scale and multi-physics, spanning the broad range of both spatial and temporal scales encountered remains one of the outstanding challenges of this field. Additional challenges currently driving research in HEDLP modeling and simulations include the improved treatment of key physical processes and constitutive relations (mixing, equations of state and opacities, etc.) and improvements in the accuracy, speed and scalability of algorithms. These challenges, which are discussed in some of the previous disciplinary chapters, do not fundamentally distinguish HEDLP computational science from other physical sciences. The past decade has seen enormous advances in all of these areas,

Challenges for modeling and simulation

Understanding how an intense laser beam pushes into a dense plasma (see figure) and generates a giga-ampere of current in relativistic particles, and how this current moves through a plasma that ranges from the density of solids to one thousand times that density, is a challenge for modeling and simulation. Advances in physics models and algorithm development, with the ability to span vast space and time scales, are required to push the boundary of what is feasible with today's codes and supercomputers.



Recent 3-D particle-in-cell (PIC) simulations of an ultra-intense, short-pulse laser beam interacting with a nanometer-scale, diamond-like target have identified a new ion-acceleration mechanism. If the target is thin enough, the laser fields give its electrons so much energy that they become relativistic; that is, they travel essentially at the speed of light and become hundreds of times more massive than they would be at rest. Under such extreme conditions, the frequency of the laser light is greater than a critical frequency known as the plasma frequency, and the target abruptly becomes transparent to the laser beam (shown in green). As the laser beam "breaks out" of the target, it generates enormous electric fields—as high as tens of trillions of volts per meter—that accelerate the target ions to temperatures approaching a billion electron volts (equivalent to ten trillion degrees) over distances of mere micrometers, making this one of the most compact accelerators known. This ion-acceleration mechanism, known as the "Break-out Afterburner," generates ion beams (shown in red) in the form of a pair of lobes that propagate at a slight angle to the laser direction, a unique signature observed recently at the Los Alamos National Laboratory (LANL) Trident laser facility. The ion beams have a wide variety of applications, ranging from inertial fusion energy to tumor therapy. The simulation shown here employed 14 billion cells and 21 billion simulation particles and was run on the Roadrunner supercomputer at LANL. (Lin Yin, LANL) largely driven by HED research programs sponsored by DOE. These are primarily the National Nuclear Security Administration's ASC program;[18] the DOE Office of Science's INCITE program;[19] and the SciDAC program.[20] However, certain computational issues that must be addressed are uniquely associated with HEDLP; these are described in some detail in the following section.

II. Research Opportunities and Needs

(1) Creating a healthy and robust computing ecosystem

Why is it important? Computer modeling and simulations are crucial to the design, analysis and interpretation of HED plasma physics experiments. They are also essential to exploring phenomena and regimes of matter and radiation that are difficult or impossible to access experimentally, either because the phenomena are occurring in a distant part of the universe or because laboratory experiments cannot yet approach the regime of interest. A healthy and robust computing "ecosystem" is required in order for computer modeling and simulations to fulfill all of these roles.

Such a computing ecosystem does not currently exist. Algorithm and code development is often funded as an add-on to experiment, and there is no mechanism for setting priorities. The radically new architectures of the next generation of computing platforms will pose daunting challenges to the development of efficient algorithms and codes for HED plasma. Exacerbating the problem is a shortage of young scientists able to develop algorithms and software for these platforms, in part because access to such machines has been significantly restricted and the support for application code development (as opposed to the actual use of such codes) has been relatively sparse. The situation could be somewhat alleviated if computational scientists in the university community were encouraged to develop these tools within the HEDLP program, just as diagnosticians are encouraged to develop their tools (see preceding chapter).

Although a number of highly capable HED plasma physics codes exist at the defense program laboratories—Los Alamos National Laboratory, Lawrence Livermore National Laboratory and Sandia National Laboratories—most of those codes are classified, and the few that are not are export controlled. In the former case, the academic community members who happen to know about a particular code must ask people at the labs to run simulations for the design and analysis of their experiments; then, after some interval, data may be able to be provided to the academic who requested it. In the export control case, foreign nationals may be unable to get access to the source code and, consequently, only the binary executable code is available. In the case of commercial codes, the purchase cost may be prohibitive as well. These constraints mean investigators in the academic community are at a great disadvantage in designing and analyzing novel experiments in many important areas of HED plasma physics.

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[18] Advanced Simulation and Computing, previously known as the ASCI (Advanced Simulation and Computing Initiative) program. ASC supported the Academic Strategic Alliance Program (ASAP, 1997-2010), and currently supports the Predictive Science Academic Alliance Program (PSAAP, 2008-2013).

[19] Innovative and Novel Computational Impact on Theory and Experiment.

[20] Scientific Discovery through Advanced Computing.

What's needed? The constraints imposed by national security issues in the area of HED physics on already existing computational tools (largely located at the defense program laboratories) suggest the opportunity for developing a separate, open computing environment responsive to the needs of the academic and unclassified industrial science and technology communities. Efforts such as the DOE Office of Science SciDAC program have recently provided—and are continuing to provide—explicit funding for the development of algorithms and the creation of open codes for the academic plasma physics community. Such algorithm and code development is driven by physics and the modeling requirements demanded by experiments and phenomena. The approach is well matched to the current and anticipated needs of the HEDLP community.

However, the challenge is that, although the boundaries between what constitutes classified research and what is not in the simulation domain are very clearly articulated in the national laboratories, these boundaries are (intentionally) not defined in the unclassified world. This means that, as a practical matter, it will be very difficult to establish an unclassified HEDLP simulation program without the direct participation of scientists who do have sufficient security clearance that they know where these boundaries are located.[21] In other words, the DOE/NNSA will need to participate in any such code development program. If such a program is sustained, one or more such community codes can provide the academic HEDLP community with access to open simulation tools for use in the design, analysis and interpretation of HEDLP experiments, and can potentially also offer the opportunity to prototype and develop innovative new algorithms, thus allowing the community to guide the evolution of the codes required for its own research work. Such an approach also offers the opportunity to support the education and training of the applied mathematicians, computer scientists and computational scientists needed to develop algorithms and codes for HED plasma physics, and to make these algorithms and codes run at scale on the radically new architectures of the next generation of computing platforms.

In concert with access to simulation tools sufficiently capable to sensibly guide the design of HEDLP experiments and provide the capability to analyze the resulting data, the HEDLP community would also need open access to current and future large-scale computing platforms at the national laboratories. Without such access, the enormous computational resources needed for realistic modeling and simulation of HED plasma physics experiments and high-energy astrophysical phenomena are simply not possible.

There is also a critical need for a thoughtful revisiting of the classification and export control restrictions on HED plasma physics codes. This issue is, of course, closely related to the abovementioned classification problem facing the creation of open HEDLP simulation tools. As an example, any radiation-hydrodynamics code developed in the US has the potential to be declared export-controlled, regardless of where it is developed and by whom, and the vast majority of such codes have been so declared. The "export-controlled" designation can make it

[21] A positive development in this direction is the recent decision by DOE to make *Flash* a community code developed under the auspices of the DOE/NNSA; *Flash* is a modular and extensible compressible spatially adaptive hydrodynamics code, which incorporates capabilities for a broad range of physical processes, including nuclear reactions, complex equations of state, and radiation transport in the diffusion approximation, and performs well on a broad range of existing advanced computer architectures. Its built-in unit test framework provides verifiability; this and a rigorous software maintenance process allow the code to operate simultaneously in production and development modes.

illegal for foreign nationals to have access to the source code. In addition, current DOE regulations require that any radiation-hydrodynamics code having a "sufficiently accurate" radiation transport model be declared "UCNI" (unclassified controlled nuclear information). This makes the code entirely unavailable to foreign nationals. *These DOE regulations are not well understood within the community because the precise criteria used to decide these classification issues themselves are classified*.

As a result of the restrictions, foreign students may not be able to participate in research projects that require access to the source code of an export-controlled code, or to any code with an "accurate" radiation transport package. This eliminates some of the best students from participating in the projects and limits the educational options of foreign students relative to their US counterparts. Since roughly 50% of foreign students remain in the US upon completing their advanced degrees, we are negatively impacting our future scientific capability in HEDLP. Furthermore, the source code cannot be distributed to the international scientific community if it falls under the rules of export control and UCNI, thereby limiting the visibility and recognition of US scientists and their ability to collaborate with outstanding scientists abroad. The situation is exacerbated by the current and future availability, without restriction, of codes with similar capabilities that are developed in other countries, which puts US scientists working in the HED field at a severe disadvantage. All of these negatives should be viewed in the context of the strategic importance of this field to the US.

Recently, a National Academies study addressed the concern that our present export control rules are detrimental to American competitiveness and called for a thorough re-evaluation of those rules.[22] A key conclusion of that study is that only a narrow and limited set of simulation capabilities should be controlled. In light of this, three steps appear appropriate: (i) revisiting of classification and export control criteria, with the goal of expanding the range of capabilities that can be included in open codes, including the current and future availability, without restriction, of highly capable codes developed in other countries; (ii) clarification of rules regarding competitive development of open-source, multi-dimensional radiation-hydrodynamics codes with good open-source materials data; and (iii) provision of a set of unclassified, published experimental results in a common model format to enable quantitative validation of these codes. These steps would be best coordinated and carried out by DOE/NNSA—for the obvious reason that they have the responsibility of dealing with classification issues—but should also involve scientists from the HED community with considerable experience in the open academic science community who also have appropriate clearance levels.

[22] The study concludes: "As a nation, we cannot, and should not, abandon well-conceived efforts to keep dangerous technology and scientific know-how out of the hands of those who would use this knowledge to create weapons of mass destruction and other, equally dangerous military systems. However, such knowledge and technology represent a very narrow and limited set of goods, technology, and know-how." [See: "Beyond 'Fortress America': National Security Controls on Science and Technology in a Globalized World," Committee on Science, Security, and Prosperity; Committee on Scientific Communication and National Security; National Research Council (2009).]

(2) Improving our ability to trust the results of computer modeling and simulation of HED plasma physics experiments and phenomena

Why is it important? Modeling and simulations play a vital role in the design, analysis and interpretation of HED plasma physics experiments and, ultimately, in improving our understanding of the complex behavior of matter at high densities and temperatures. Verification of a code (i.e., demonstrating that the code is doing what it is supposed to do and replicates known analytic and numerical results) is critical to the ability of modeling and simulations to play this role. So, too, is validation of the simulation (i.e., knowing the uncertainties in the predictions made by the simulations, and establishing that those predictions agree with experiments within the uncertainties). The interplay between experiment and simulation builds confidence in the algorithms and physical models in the code and aids in understanding the limitations of the code, which in turn leads to implementation of additional physics in the code and improvements in the design of the experiment.

However, validation of HEDLP simulations is challenging. Most HED plasma physics experiments and phenomena are multi-scale and multi-physics, and involve tightly coupled nonlinear processes. Even if it is possible to validate simulations of individual, key physical processes through experiments, the behavior of the full system is likely to depend importantly on the nonlinear coupling of these processes. This makes global validation of the full system, as well as the key physical processes in it, essential.

Experiments able to truly validate simulations are often difficult to design and carry out because of the complex, nonlinear, multi-physics phenomena characteristic of HEDLP. Consequently, even very well-thought-out experiments can be affected unexpectedly by aspects of the experiment design or subtleties involving the physical processes, altering the outcome of the experiment in ways that reduce the power of the experiment to test the simulation. The ability to instrument experiments adequately, so that they provide data with sufficient signal-to-noise ratio and spatial and temporal resolution in order to truly validate the simulation, is difficult and often impossible.

With regard to laboratory astrophysics, the extremes of density, temperature and magnetic field strength encountered in astrophysical phenomena often cannot be reproduced in the laboratory. Consequently, the values of the physical parameters accessible to experiment may lie far from those in the astrophysical phenomenon of interest. A large extrapolation to the physical conditions in the phenomenon of interest is then necessary, but is often highly uncertain.

Finally, the computational cost of the highest-fidelity simulations is likely to be so high that only a few can be done, making it challenging to quantify the uncertainties in the predictions made by the simulation, and therefore to validate it.

What's needed? Verification using unit testing, automated test suites and regression analyses should become standard for simulation codes in the academic HEDLP community. Experiments are usually designed to explore new physical regimes or phenomena, but it is essential that experiments also be performed that are expressly designed to validate algorithms used to treat a key physical process or a specific physical model, or to provide global validation of a simulation.

A hierarchical approach to validation is essential. Such an approach employs experiments designed to validate the algorithms, then models designed to treat key physical processes, then models to treat the overall system. Approaches that utilize both a few high-fidelity simulations (to gain a better understanding of the physical processes involved and the nonlinear interactions among them), as well as a large number of moderate-fidelity simulations (to quantify the uncertainty in the predictions of the simulation) can help to meet these challenges.

Finally, methodologies need to be developed that make it possible to handle large amounts of data from the combination of a few large, high-fidelity, expensive simulations and large numbers of moderate-fidelity simulations. This will include both relatively sparse data sets (as is often the case for HEDLP experiments) and very large data sets (as is often the case with astrophysical phenomena). The challenge here will be to make optimal use of the information contained in these data sets in order to validate the simulation codes (that is, to combine data from different experiments and simulations and to conduct efficient sensitivity analyses). The development of formal validation methods (employing techniques such as systematic construction of adjoints, the use of automatic differentiation software, etc.) in such cases is still in its infancy, and therefore should be viewed as an opportunity for substantial research efforts.

(3) Developing new simulation capabilities

Why is it important? HEDLP shares a number of computational challenges with other physical science disciplines, challenges that make certain classes of computations currently infeasible. Perhaps the most obvious and well-known such challenge is related to the prevalence of multi-scale (in both space and time) phenomena that cannot be currently simulated at the smallest and largest physically important scales with a single code. In other instances, computational needs within HEDLP overlap with those of non-HED laboratory plasma physics. An important example is the need to describe dynamics in which both electron- and ion-dynamical time scales matter, so that one must then resort to one of various hybrid schemes that seek to capture both the kinetic and the fluid-dynamical aspects of a given problem. However, some regimes encountered in HEDLP are unique to this discipline, and therefore there is little likelihood of cross-fertilization with computational efforts in other physical disciplines. Examples of such unique simulation challenges include relativistic MHD, radiation-dominated hydrodynamics, and phenomena that bridge both MHD (fluid) behavior and vacuum electrodynamics. We are now seeing in all three of these HEDLP areas a real upswing in the kinds of vigorous iterative interaction between experiments and simulations that have led to great advances in simulation capabilities in other disciplines.

What's needed? The challenges posed by multi-scale phenomena will likely be met by the concerted efforts of computational scientists working in the range of scientific disciplines in which multi-scale phenomena are known to take place. Thus, it will be important for computational scientists working in the HEDLP arena to be well coupled to such efforts outside HEDLP. HEDLP must ensure that it becomes (and remains) enmeshed in the general physics community and does not become isolated; the past experience of the laboratory plasma physics community should serve as a reminder of how damaging such isolation can be.

The development of more sophisticated methods for treating kinetic and fluid behavior in unison will likely involve efforts in both the plasma and HEDLP communities. Therefore, coordinated support of hybrid- and Hall-MHD code development is to be encouraged. A promising area of research is model adaptivity—the use of generalized adaptive methods that match both grid and time resolution to localized conditions, and possibly adapt the very equations being solved to local conditions as well.[23] Substantial efforts should be made to explore this approach.

[23] For example, one might envision using a low-cost, low-Mach-number solver for domains in which the flow Mach number is much less than unity, while retaining a fully compressible solver in those domains in which compressible effects are known to be significant. The huge challenge here, of course, is how to implement such schemes, especially as this would mean that the order of the differential equations being solved (and the nature of the characteristics) might vary across the solution domain (which raises the challenging problem of how to match conditions across solution domain boundaries). Less drastic, but still potentially valuable, model adaptive schemes would include changes in the nature of the sub-grid modeling. These would take into account the differing requirements of solution fidelity in the different portions of the overall solution domain, e.g., retaining Large Eddy Simulation in favor of Reynolds Averaged Numerical Simulation modeling in regions where greater solution precision is needed.

Appendix A: ReNeW Report Charter and Panel Members

Department of Energy
Washington, DC 20585

July 9, 2009

Dear Colleague,

The Office of Fusion Energy Science (SC/OFES) and the National Nuclear Security Agency (NNSA/DP) plan to hold a Joint Research Needs Workshop on High Energy Density Laboratory Plasmas (HEDLP) from November 15-18, 2009 at Stanford University's Kavli Institute of Particle Astrophysics and Cosmology (KIPAC), co-located at the Stanford Linear Accelerator Center (SLAC), Menlo Park, California.

In January this year, the Fusion Energy Sciences Advisory Committee (FESAC) submitted its report to the U.S. Department of Energy on "Advancing the Science of High Energy Density Laboratory Plasmas," prepared by its Panel on High Energy Density Laboratory Plasma, chaired by Professor Riccardo Betti of the University of Rochester.

http://www.science.doe.gov/ofes/FESAC-HEDLP-REPORT%20(2).pdf

This report: (1) identified the compelling scientific opportunities for research in fundamental HEDLP and (2) identified the scientific issues of implosion and target design that need to be addressed to make the case for inertial fusion energy as a potential energy source.

As recommended by FESAC, we are jointly sponsoring a Workshop with the goal of examining these research opportunities in depth and deliberating on the research needs in order to pursue these opportunities. The workshop output will be a concise authoritative report suitable for wide distribution. The report of the Workshop will provide technical advice to be used as guidance in strategic planning for the joint program by OFES and NNSA.

The Workshop will be modeled after the Basic Research Needs Workshops conducted by the Office of Basic Energy Sciences (BES) as described in the BES report, The "Basic Research Needs" Workshop Series, http://www.sc.doe.gov/bes/reports/files/BRN_workshops.pdf. The OFES Technical Lead for the Workshop is Dr. Francis Thio, and the NNSA Technical Lead for the Workshop is Dr. Dillon McDaniel. Professor Robert Rosner of the University of Chicago and Professor David Hammer of Cornell University have agreed to Chair and Co-Chair the Workshop.

For both the energy-related HEDLP and the non-energy-related HEDLP, the FESAC HEDLP Panel identifies six scientific sub-disciplines:

- High Energy Density (HED) hydrodynamics,
- Nonlinear optics of plasmas
- Relativistic HED plasma and intense beam physics
- Magnetized HED plasma physics
- Radiation–dominated dynamics and material properties
- Warm dense matter

We envision the Workshop will address the opportunities and needs of these six sub-disciplines and cross-cutting issues using a panel structure. The OFES and NNSA Technical Leads will work together with the Workshop Co-Chairs to set up the Panel structure and to invite and appoint the Panel Leads and the Vice-Leads for the panels. The Chair and Co-Chair, the Panel Leads and Vice-Leads, and the Technical Leads of the OFES and NNSA/DP for the Workshop will form the Executive Committee for organizing the Workshop.

Members of the HEDLP research community will be invited to be panelists for each of the panels by the Workshop Co-chairs. While the Workshop itself will be by invitation only for participants, each panel will be responsible for gathering broad community input. We encourage and request your involvement in this process. A website for the Workshop is planned to keep the community posted on the progress and matters relating to the Workshop.

Sincerely,

Edmund Synakowski
Associate Director of the Office of Science
for Fusion Energy Sciences

Christopher Deeney
Director
Office of Inertial Confinement Fusion
and the National Ignition Facility Project

Workshop Leadership at DOE

Ed Synakowski (SC/OFES)
Christopher Deeney (NNSA)
Francis Thio (SC/OFES)
Dillon McDaniel (NNSA)
Kirk Levedahl (NNSA)

Chair and Co-Chair

Robert Rosner
David Hammer

HED Hydrodynamics (Top two names on each panel are panel leads**)**

Riccardo Betti
John Giuliani
Stefano Atzeni
Serge Bouquet
Guy Dimonte
John Perkins
Bruce Remington
Andrew Schmitt
John Sethian
Dov Shvarts
Max Tabak
Wolfgang Theobald

Magnetized HED Plasmas

Dmitri Ryutov
Jerry Chittenden
Bruno Bauer
Mike Cuneo
Ron Gilgenbach
Pierre Gourdain
Mark Herrmann
Scott Hsu
Jim Knauer
Sergey Lebedev
Marc Pound
Radu Presura
Dan Sinars
Glen Wurden

Nonlinear Optics

David Montgomery
Bill Kruer
Bedros Afeyan
Brian Albright
Mike Downer
Dustin Froula
Cameron Geddes
Ki-Yong Kim
Robert Kirkwood
Christophe Rousseaux
Vladimir Tikhonchuk
Ed Williams

Radiation-Dominated Dynamics and Material Properties

Jim Bailey
Steve Libby
Tina Back
Ehud Behar
Joyce Guzik
Carlos Iglesias
Steve Kahn
Michel Koenig
Carolyn Kuranz
Marc Pinsonneault
Sean Regan
Steve Rose
Don Winget

Relativistic HED Plasmas and Beams

Nat Fisch
Rich Stephens
Farhat Beg
Ron Davidson
Bjoern Hegelich
Tanaka Kazuo
Mike Key
Edison Liang
David Meyerhofer
Margaret Murnane
Pravesh Patel
Johann Rafelski
Markus Roth

Yasuhiko Sentoku
Igor Sokolov
Jonathan Wurtele

Warm Dense Matter

Mike Desjarlais
Raymond Jeanloz
Lorin Benedict
Tom Duffy
Jon Eggert
Yogi Gupta
Marcus Knudson
Dick Lee
Grant Logan
Dick More
Ronald Redmer
Sam Trickey

Hi-Z Multiply Ionized HED Atomic Physics

Roberto Mancini
John Apruzese
Peter Beiersdorfer
Arati Dasgupta
Stephanie Hansen
Walter Johnson
Joseph MacFarlane
Yitzhak Maron
Anil Pradhan
Jorge Rocca
Alla Safronova

Research infrastructure

Rich Petrasso
Alan Wootton
Roger Falcone
Nels Hoffman
Chris Keane
Joe Kindel
Karl Krushelnick
David Meyerhofer
Abbas Nikroo
Peter Norreys
John Porter

Ryan Rygg
Kurt Schoenberg
Mingsheng Wei

Diagnostics

Harry McLean
Ray Leeper
Frank Bieniosek
Peter Celliers
Johan Frenje
Siegfried Glenzer
John Greenly
Bob Heeter
Tom Intrator
John Kline
Jeff Koch
Greg Rochau
Dale Welch

Computing

Don Lamb
Melissa Douglas
David Arnett
John Cary
Luis Chacon
Phil Colella
Dongwook Lee
Jim Morel
Warren Mori
Charles Seyler
Fred Streitz
Lin Yin

Overall Cross-cutting

Paul Drake
Juan Fernandez
Cris Barnes
Sergei Bulanov
Patrick Colestock
Jill Dahlburg
Todd Ditmire
James Hammer
Chikang Li

Appendix B: US HEDLP Facilities

The United States boasts a large number of state-of-the-art facilities that are capable of creating and studying high energy density plasmas. The depth and breath of these facilities is sufficient to address many of the research opportunities discussed in this report. Some of these facilities are operated by various federal agencies at national laboratories to meet a wide range of mission needs, ranging from science-based stockpile stewardship, to fusion energy, to basic energy sciences. In principle, all of them could be made available for HEDLP studies for a portion of their time ranging from about 10% to more than 50%. Other HEDLP facilities are located at universities, and most of these are predominantly used for non-mission-oriented studies even now. The major exception to these "rules" is the OMEGA laser facility at the University of Rochester, which is largely used for inertial confinement fusion experiments in support of the National Ignition Campaign.

The table that follows lists some of the major U.S. facilities that are either in operation or will be so in the near future. They are characterized by type (e.g., laser, pulsed-power, ion-beam, X-ray), location, sponsor, and representative operating parameters. For lasers, performance is given at the quoted wavelength. Many of these can operate in different modes and trade energy for pulse width and/or wavelength. Note that some of these facilities can be coupled together to enhance capability. The OMEGA EP short-pulse laser can be coupled with the OMEGA laser to study the effect of short pulses on compressed plasmas. The Leopard laser can be coupled with the Zebra *Z*-pinch, the Z-Beamlet can be coupled with Z, and ARC will be a part of NIF.

We note that there are several major international facilities either now in operation or currently under construction, one of which, the Laser Mégajoule (LMJ) in France, is of a size comparable to NIF. Noteworthy facilities (because they are state-of-the-art facilities available for use by collaborations, including with scientists from the United States) are the petawatt-scale Vulcan laser at the Rutherford Appleton Laboratory in the United Kingdom and the petawatt-class lasers for fusion at the Institute for Laser Engineering in Osaka, Japan.

US HEDLP facilities (does not include all university-based facilities)

Name	Institution	Type	Key Parameters
Long-Pulse Lasers			
National Ignition Facility (NIF)	Lawrence Livermore National Laboratory	Nd:glass laser (351 nm)	1.5 MJ at 4 to 12 ns 1.8 MJ at 20 ns (shaped)
OMEGA	University of Rochester, LLE	Nd:glass laser (351 nm)	30 kJ at 4 ns
NIKE	Naval Research Laboratory	KrF laser (248 nm)	3 to 5 kJ at 4 to 12 ns
Janus	Lawrence Livermore National Laboratory	Nd:glass laser (1053 nm)	1 kJ at 3 ns 140 J at 250 ps
Short-Pulse Lasers			
Mercury Short Pulse	Lawrence Livermore National Laboratory	Yb:SFab > Ti:sapphire (527 nm)	500 J at 250 ps
OMEGA EP	University of Rochester, LLE	Nd:glass laser (1-µm short pulse, 352-nm long pulse)	2.6 kJ at 10 ps 1.0 kJ at 1 ps 26 kJ at 10 ns
Trident Laser	Los Alamos National Laboratory	Nd:glass laser (527 nm)	120 J at 500 fs 250 J at 5 ns
Titan	Lawrence Livermore National Laboratory	Nd:glass laser (1-µm short pulse, 1-µm or 0.5-µm long pulse)	200 J at 0.5 to 1 ps 350 J at 10 to 50 ps 1 kJ at 1 to 20 ns
Texas Petawatt Project	University of Texas at Austin	Nd:glass laser (1057 nm)	200 J at 150 fs
Leopard	University of Nevada at Reno	Nd:glass laser (1057 nm)	15 J at 350 fs 25 J at 1 ns
Z-Beamlet/Petawatt	Sandia National Laboratories	Nd:glass laser (351 nm)	500 J at 250 ps
Hercules	University of Michigan	Ti:Sapphire	1 J at 30 fs up to 10^{22} W/cm^2
ARC (under development)	Lawrence Livermore National Laboratory	Nd:glass laser (1 µm)	13 kJ at <1 ps
Comet	Lawrence Livermore National Laboratory	Ti:Sapphire	7.5 J at 0.5 ps
Callisto	Lawrence Livermore National Laboratory	Ti:Sapphire	10 J at 150 fs
Europa	Lawrence Livermore National Laboratory	Ti:Sapphire	1 J at 800 nm 0.25 J at 400 nm, 0.1 J at 10 Hz
LOASIS	Lawrence Berkeley National Laboratory	Ti:Sapphire	0.2 J at 40 fs up to 10 Hz

US HEDLP facilities (does not include all university-based facilities) (Cont.)			
Name	Institution	Type	Key Parameters
Heavy Ion			
NDCX-I	Lawrence Berkeley National Laboratory	Heavy ion	10 mJ at 10 μs 1 mJ at 2 ns
Pulsed Power			
COBRA	Cornell University	Pulsed power (*Z*-pinch)	1.2 MA at 100 ns 0.9 MA at 200 ns
Gamble II	Naval Research Laboratory	Pulsed power (e-beams and *Z*-pinch)	1 MA at 100 ns
MAIZE	University of Michigan/Ann Arbor	Pulsed power	16 kJ at 200 ns 1 MA
Saturn	Sandia National Laboratories	Pulsed power (*Z*-pinch)	6 MA at 140 ns
Shiva Star	Air Force Research Laboratory	Pulsed power (MIF - linar implosions)	12 MA, 5 MJ at 10 μs
XP Pulser	Cornell University	Pulsed power (*X*-pinch)	0.5 MA at 50 ns
ZEBRA	University of Nevada	Pulsed power (*Z*-pinch)	1 MA at 100 ns 0.6 MA at 200 ns
Z	Sandia National Laboratories	Pulsed power (*Z*-pinch)	25 MA at 100 ns
ATLAS	Nevada Test Site (dormant)	Capacitor bank Materials, shocks, 20 Mbar in a few cm^3	36 MJ, 4-5 μs rise 30-50 MA
PLX	Los Alamos (initial operation in 2011)	Capacitor banks power plasma guns	0.3-1.5 MJ at 5 μs
X-Ray Lasers			
Linac Coherent Light Source	SLAC National Accelerator Center	X-ray free-electron laser 120-Hz repetition rate	2 mJ at 200 fs, tunable (0.8 to 8 keV)
Electron and Positron Beams			
Stanford Linear Accelerator	SLAC National Accelerator Center	Short-bunch electron and positron beams	25 GeV at 50 fs ~1 nC
Integrated Facilities			
NIF	Lawrence Livermore National Laboratory	Effect of short pulses on compressed plasma	NIF and ARC
OMEGA	University of Rochester, LLE	Effect of short pulses on compressed plasma	OMEGA EP and OMEGA
Z	Sandia National Laboratories	Z-pinch plasma diagnostics Fast-ignition fusion research	Z-Beamlet and Z
Nevada Terawatt Facility	University of Nevada, Reno	Z-pinch plasma diagnostics Magnetized laser–plasma interactions	Leopard and Zebra

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Publishing support services provided by Argonne National Laboratory