FUSION ENERGY SCIENCE ADVISORY COMMITTEE

Panel on High Energy Density Laboratory Plasmas

ADVANCING THE SCIENCE OF HIGH ENERGY DENSITY LABORATORY PLASMAS

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EXECUTIVE SUMMARY

I. High Energy Density Laboratory Plasma Science

The high energy density laboratory plasmas (HEDLP) that can be produced with state-of-the-art facilities are among the most scientifically interesting states of matter. Their densities and pressures can exceed those of the solar core, and their temperatures and flows can be high enough that relativistic effects become important. Understanding such states of matter will greatly expand the current knowledge in plasma physics and related areas. Particle acceleration by nonlinear waves, radiation-dominated plasmas, large self-generated magnetic fields, degenerate states of matter, strongly coupled plasmas, relativistic flows, and the interaction of intense particle and laser beams with matter are only some of the many fascinating and exciting physical phenomena that can be studied with present or soon to be completed high energy density facilities. High energy density plasmas have many important practical applications. Understanding the behavior of these plasmas is key to the development of inertial fusion energy, verification and validation experiments for national security science, compact particle accelerators, bright coherent x-ray sources, and intense particle beam sources for medical applications. It is critical that the Department of Energy (DOE) play the central role in the stewardship of this exciting field in order to ensure future scientific advances commensurate with its high degree of promise.

The DOE Office of Fusion Energy Sciences (OFES) and the National Nuclear Security Administration (NNSA) are commended for establishing the Joint Program for HEDLP science to steward HEDLP science and to nurture new approaches to inertial fusion energy. Effective stewardship is essential to foster growth in this exciting field of science. This report is in response to the charge from the Department of Energy to the Fusion Energy Science Advisory Committee (FESAC) to "work with the HEDLP community to provide information" to develop "a scientific roadmap for the joint HEDLP program in the next decade."

High energy density laboratory plasma research can greatly benefit other fields of science in addition to being an exciting science on its own merits. Research in high energy density plasma physics has the potential to address fundamental science issues relevant to astrophysics, planetary physics, nuclear physics, condensed matter physics, material science, particle beam physics, and atomic and molecular physics.

A wide variety of high energy density (HED) states of matter, spanning many orders-of-magnitude in density and temperature, can be produced in the laboratory. The physics of HED plasmas varies greatly within this wide parameter space, which includes solid-density matter at ~1 eV; matter well above solid density at temperatures up to 100 keV and dense plasmas with relativistic temperatures. Areas of HEDLP physics that are ripe for near-term discoveries are:

- **High energy density hydrodynamics.** Overarching question: *How do the distinct properties of high energy density systems alter hydrodynamic behavior?*
- **Radiation-dominated dynamics and material properties.** Overarching question: *What are the unique properties of radiation-dominated HED plasmas?*

- **Magnetized high energy density plasma physics.** Overarching question: *How do magnetic fields form, evolve, and affect the properties of high energy density plasmas?*
- **Nonlinear optics of plasmas.** Overarching question: *How does high-intensity coherent radiation alter the behavior of high energy density plasmas?*
- **Relativistic high energy density plasma physics.** Overarching question: *How do plasmas with relativistic temperatures or relativistic flows behave?*
- **Warm dense matter physics.** Overarching question: *What are the state, transport, and dynamic properties of warm dense matter?*

Recommendation on fundamental HEDLP science: *It is now an opportune time for the Joint Program to assume the stewardship of the fundamental science of high energy density laboratory plasmas. By taking advantage of the new generation of domestic experimental and computational facilities capable of detailed exploration of high energy density plasmas, the Joint Program can and should foster the rapid growth and development of this new and exciting field of science.*

Among the most important applications of HEDLP science is inertial fusion energy (IFE). High energy density plasma physics provides the basis for inertial fusion energy sciences. The imploding core of an IFE target is in an ultrahigh energy density plasma state. The fusion energy produced in an IFE target can be up to two hundred times larger than the energy required to implode it. Inertial fusion energy offers the prospects for an economically viable, carbon free, and abundant energy source.

In the near future, the National Ignition Facility (NIF) is expected to achieve thermonuclear ignition and moderate energy gains, through the indirect-drive approach. It is anticipated that many aspects of high energy density burning-plasma physics relevant to inertial fusion energy will be studied on the NIF. The next step in target physics after ignition is the demonstration of high gains. High gains are essential to the viability of inertial fusion energy as an economically attractive energy source. Alternative IFE concepts funded through OFES and NNSA have the potential to generate the gains needed for IFE. Similarly to the innovative confinement concepts in magnetic fusion energy, the alternative concepts in IFE will play a crucial role in the development of inertial fusion energy, since high gains and high driver efficiencies are required features of an economically viable IFE power plant.

The major alternative IFE concepts currently pursued in the U.S. are:

- high gain direct drive
- *z*-pinch IFE
- fast ignition
- shock ignition
- heavy ion fusion
- magneto-inertial fusion

The high energy density plasmas studied in the context of alternative IFE concepts feature a wealth of new and exciting physical phenomena that must be investigated to advance these concepts. Especially important phenomena include the relativistic interaction of intense laser light with solids and plasmas, the generation of ultrahigh magnetic fields, the transport of intense particle beams in plasmas, and the propagation of ultrastrong convergent shocks.

Recommendation on alternative IFE concepts: *It is recommended that the Joint Program expand the development of alternative inertial fusion energy concepts. The Joint Program should take advantage of the available NNSA facilities to test the most promising alternative concepts at the proof-of-principle level. The current alternative concept effort should be extended by promoting wider university involvement.*

The United States has a large number of state-of-the art facilities that are capable of creating and studying high energy density plasmas. The present and next generation of high energy density facilities offers unique prospects of both accessing extreme high energy density states of matter and exploring high energy density phenomena never before observed in the laboratory.

Recommendation on facilities: *The current excitement surrounding HEDLP is based upon existing and near term large- and intermediate- scale experimental facilities in the U.S. that are capable of generating high energy density conditions. Taking full advantage of the opportunities described in this report over the next decade requires continuing and assured access for the broader scientific community to these facilities. Formal or informal user programs should be expanded, and new ones should be developed to increase access to HEDLP facilities. Modest facility upgrades will enable even more exciting and challenging experiments of high intellectual value.*

Efficient use of the experimental facilities requires precise measurements in well diagnosed experiments. The short temporal and small spatial scales of high energy density phenomena make measurements exceptionally difficult and diagnostic development extremely challenging.

Recommendation on diagnostics: *The Joint Program in HEDLP should include, within its scope, funding for the development of novel diagnostic methods that are essential to fully characterize HEDLP systems. This area has historically been underemphasized, to the disadvantage of the field.*

In addition to well-diagnosed experiments, true understanding of high energy density plasmas both for inertial fusion energy and basic science requires theory and advanced numerical simulations. The continued rapid development of high-performance computing will allow unprecedented time and length scales to be resolved using micro-, meso-, and multi-scale models. Significant code capabilities exist inside and outside of the NNSA laboratories. Most of the world's largest super-computer capabilities exist within NNSA and the Office of Science.

Recommendation on computing: *The Joint Program in high energy density laboratory plasmas should include significant components of theory and advanced simulation both for basic research and for supporting the experimental elements of the program. The program should encourage access to the Office of Science and NNSA computing facilities, and unclassified codes for outside users. It should also support innovation in developing new algorithms and theories. It is also recommended that funds be provided for community code-development projects under the DOE program called Scientific Discovery through Advanced Computing.*

II. The Charge to FESAC, the Panel Process, and the Stewardship of the Joint HEDLP Program

The Fusion Energy Science Advisory Committee, in consultation with the DOE Office of Fusion Energy Science and the National Nuclear Security Administration, appointed a panel of 17 scientists from universities and national laboratories. This panel was tasked with addressing the charge issued by the DOE Under Secretary for Science and Under Secretary for Nuclear Security. ***The first part*** *of the charge is to identify: (a) the compelling scientific opportunities in fundamental HEDLP science, and (b) the HED target-physics issues relevant to inertial fusion energy.* ***The second part*** *of the charge is "meant to provide background for a scientific plan for energy-related HEDLP studies."*

To acquire all the necessary input from the HEDLP community, the committee organized a three-day workshop on August 25-27, 2008, in Washington D.C. The workshop was open to the HEDLP community at large, policy makers and other government officials.

When identifying the scientific opportunities in HEDLP research (first part of the charge), the panel found the need for separate approaches for addressing energy-related and fundamental HEDLP physics, reflecting the differences between science that is mission oriented and science that is discovery driven.

Recommendation on stewardship: *The Joint Program should independently steward fundamental and energy-related high energy density laboratory plasma science, managing solicitations and develop review criteria to respect the important need for both discovery-driven and mission-oriented science.*

Recommendation on planning: *To facilitate the growth of HEDLP research, the agencies should hold a research needs workshop at an earliest possible date. It should be focused on fundamental and energy-related HEDLP science. The workshop should take into account the need for both discovery-driven and mission-oriented science and the differences between them.*

III. Issues and Opportunities in HEDLP Science: Assessment and Prioritization

To address the first part of the charge, the panel developed two lists of the most compelling scientific issues in HEDLP science and two sets of ranking criteria. The first list is concerned with the HEDLP science issues relevant to the development of inertial fusion energy (IFE). The second list includes compelling issues for research in fundamental high energy density science. The panel developed two distinct sets of criteria—one for energy-related HEDLP and the other for fundamental HEDLP science.

The prioritization of the energy-related issues was developed using a set of ranking criteria emphasizing: (1) their importance to the development of inertial fusion energy; (2) the distinctiveness with respect to the NNSA-funded inertial confinement fusion (ICF) program; (3) the ability to answer the science questions using existing facilities; (4) the applicability of the underlying science to multiple IFE approaches; and (5) the estimated resources required to address the issues.

A different approach was used in addressing fundamental HEDLP science. The panel recognized that fundamental science is not suitable for the same kind of prioritization as mission-oriented science. An assessment of the HEDLP areas, rather than a prioritization of each scientific issue, was the preferred option for fundamental HEDLP science.

The assessment of the HELDP areas was carried out using a set of criteria emphasizing: (1) the importance to the fundamental understanding of high energy density physics; (2) the potential for important practical applications (excluding energy applications); (3) the potential for resolving major issues in other fields of science; and (4) the readiness for progress and the ability to address the issues with existing facilities.

III.A Scientific opportunities in energy-related HEDLP science

The scientific opportunities for research in energy-related HEDLP were examined through the ranking process described above and a prioritized list was developed. For the sake of conciseness, only the highest priority issues and opportunities are mentioned in this summary. A detailed description of all the issues and opportunities can be found in Sec. 9 of the report.

Recommendation on priorities for energy-related HEDLP science: *HEDLP scientific issues that are essential to the achievement of high gains and improved inertial fusion energy concepts should be given a high priority within the Joint HEDLP Program. All of these high-priority issues are either not addressed or are only partially addressed by the NNSA-ICF program. Out of fourteen, six high-priority scientific issues* * *are identified that can be addressed by the Joint Program with existing facilities:*

- **Intense particle-beam generation by ultra-intense lasers.** Science question: *What are the essential features of the energetic particles generated by intense lasers interacting with plasmas, and how does intense light affect the plasma dynamics?*
- **Transport and energy coupling of intense particle beams in high energy density plasmas.** Science question: *How are intense charged-particle beams transported in and how does their energy couple to HED plasmas?*
- **Influence of magnetic fields on high energy density fusion plasmas.** Science question: *How do magnetic fields, either spontaneous or induced, affect the behavior of HED fusion plasmas, and how can they be utilized to improve the prospects for inertial fusion energy?*
- **Laser-plasma instabilities and hot-electron generation.** Science question: *How do laser-plasma instabilities reflect light, how do they generate energetic electrons, and how can they be controlled?*
- **Implosion hydrodynamics for high gains**. Science question: *How can HED plasmas be assembled to the densities and pressures required for maximizing the fusion-energy output?*
- **Integrated target physics for inertial fusion energy.** Science question: *What are the optimal target designs to achieve high gains with good stability and efficient driver coupling?*

*Note that the order of the above issues does not represent a ranking.

This is a subset of those fundamental HEDLP science issues, considered by the HEDLP panel, that have a high potential to advance the knowledge of HELDP physics as well as inertial fusion energy science. The exploration of the science issues above provides a wealth of exciting opportunities for HEDLP research within the Joint Program. Descriptions of the issues and details of the possible approaches to address them on existing facilities are provided in Sec. 9 of the report.

III.B Scientific opportunities in fundamental HEDLP science

All six areas of HEDLP science offer a wide array of exciting scientific issues and opportunities for research on existing and near-term facilities. Turbulent mixing, new instabilities, and plastic flows of solid materials are some of the intriguing aspects of **HED hydrodynamics**. Radiative shocks, radiative instabilities, and radiative cooling are some of the unique features of the **radiation-dominated dynamics** of HED plasmas. Understanding how the basic properties of HED plasmas are influenced by strong magnetic fields and how such fields reconnect in HED conditions are challenging questions of **magnetized HED plasma physics**. Using coherent radiation to drive nonlinear self-organized states in plasmas and exploiting quantum phenomena in HED environments are examples of how the **nonlinear optics of plasmas** can be used to control laser interaction with matter. The acceleration of electrons to relativistic velocities, the creation of electron–positron plasmas, and the generation of collisionless shocks by intense lasers are some of the most exotic phenomena of **relativistic HED plasma physics**. When the electrostatic interactions overcome the particle thermal motion, new state and transport properties emerge that characterize the **warm dense matter regime** of HED physics.

All six areas are essential to the advancement of the field and all should be funded within the Joint Program. An assessment of the HEDLP areas, rather than a prioritization of the scientific issues, was performed by the panel to identify the scientific opportunities in fundamental HEDLP science. The HEDLP areas are ranked with respect to four evaluation criteria on a three level scale: *high, medium, and marginal*. A summary of the assessment levels for the six areas is provided below. Details of the assessment are given in Sec. 10 of the report.

Table I: Assessment of the HEDLP science areas with respect to four ranking criteria.

Area/Criterion	(1)*	(2)**	(3)***	(4)****
HED hydrodynamics	High	Marginal	Medium	High
Radiation-dominated dynamics and material properties	High	Medium	High	Medium
Magnetized HED plasma physics	High	Medium	High	High
Nonlinear optics of plasmas	High	Medium	Medium	High
Relativistic HED plasma and intense beam physics	High	High	Medium	High
Warm dense matter physics	Medium	Marginal	High	High
*Criterion (1): Importance to the fundamental understanding and development of high energy density science				
**Criterion (2): Potential for important practical applications				
***Criterion (3): Potential for resolving major issues in other fields of science				
****Criterion (4): Readiness for progress in the next five/ten years				

Recommendation on priorities for fundamental HEDLP science: *The Joint Program should support all six areas of fundamental HEDLP science. Priority should be given to discovery-driven research efforts of high intellectual value that are expected to advance the field, explore its practical and scientific potentials, stimulate the interest of graduate students, and attract scientists from other disciplines.*

IV. A Scientific Roadmap for Energy-Related HEDLP Studies

The second part of the charge to FESAC is to provide "background for a scientific plan for energy-related HEDLP studies." There are many attractive aspects of inertial fusion energy. Among them are the separable components, the modular nature of the driver, and the ability to test the target physics on a single shot basis.

To address the second part of the charge, the panel chair appointed a subcommittee of experts in inertial fusion science to develop a scientific plan for energy-related HEDLP studies. The charge letter specifically requests the panel to develop a prioritized list of "gaps in knowledge and opportunities for research in energy related HEDLP" During this process, FESAC should consider "sequential phases of activity focusing" on

1. Exploiting available facilities to explore energy-related HEDLP science
2. Exploiting the National Ignition Facility (NIF) capabilities to address ignition science issues related to inertial fusion energy
3. Resolving scientific issues to promote a transition from a burning plasma experiment to a fusion-energy-science development program.

IV.A Exploiting available facilities to explore energy-related HEDLP science

A national research effort will rely on non-ignition experimental facilities to develop a viable approach to inertial fusion energy. These facilities provide the avenue for university users to participate in this area of extreme national interest. The NIF is likely to be oversubscribed during the next decade and exploration of some of the IFE concepts would require significant modifications of the NIF, with associated costs of the new hardware and a loss of shot time while modifications are being performed. These concepts should be developed on existing HEDLP facilities, with the most promising transferred to the NIF for further research. A close collaboration with international groups and access to HEDLP facilities abroad can significantly improve the effectiveness of this approach. For example, experiments on integrated laser facilities (implosion facility with short pulse capability) such as FIREX-I (Fast Ignition Realization Experiment) in Japan can provide access to regions of the fast-ignition parameter space otherwise inaccessible on OMEGA EP. More opportunities for international collaborations will become available as additional facilities such as PETAL (Petawatt Aquitaine Laser) and LMJ (Laser Megajoule) in France will start operation in the next decade.

Recommendation on energy-related HEDLP studies on existing facilities: *The Joint Program should take advantage of the available non-ignition facilities to develop the tools and concepts that will lead to a viable IFE system. The Joint Program should support research activities on existing facilities for:*

a. *Studying specific IFE-science issues:* Specific IFE-science issues can be investigated through experiments designed to identify the features of a specific phenomenon in isolation to facilitate the measurements and the interpretation of the results. A prioritized list is provided in Sec. 11.1.1.

b. *Fielding integrated implosion experiments with surrogate targets:* Some aspects of implosion physics can be studied with room temperature (warm) surrogate targets that can be easily manufactured and fielded at a relatively high rate. Warm targets are a practical surrogate for the cryogenic capsules required for IFE. A prioritized list of warm-target-implosion experiments is provided in Sec. 11.1.2.

c. *Fielding ignition-scalable integrated implosion experiments.* Fast ignition and direct-drive cryogenic implosion experiments at existing facilities can be designed to scale in target size and driver energy to ignition conditions on the National Ignition Facility (Sec. 11.1.3)

IV.B Exploiting the National Ignition Facility to study energy-related ignition science

Several IFE concepts are based on the same ignition method: central hot-spot ignition. The National Ignition Facility (NIF) is expected to demonstrate central hot-spot ignition and achieve moderate energy gains in the near future through the indirect drive approach. The fundamental physics of central hot-spot ignition that the NIF will study is relevant to indirect drive and direct drive, *z*-pinch, shock ignition, and heavy-ion inertial fusion.

The NIF will also be able to study the fuel assembly of ignition-relevant fast-ignition targets. To trigger ignition with an intense laser, NIF will require a high-energy short-pulse petawatt laser system. According to the most recent results, achieving ignition through the fast-ignition scheme will require a ~100-kJ-scale, short-pulse high-power laser system. Advances in fast-ignition physics may reduce the short-pulse-laser-energy requirements. Advances in short-pulse-laser technologies may reduce the construction costs and technical challenges for building such a large system.

While achieving ignition with the fast-ignition scheme will require a new laser system or the adaptation of several existing beamlines for short-pulse operation, important advances in fast-ignition research can be made with the current NIF configuration and the short-pulse capability (ARC) currently planned.

Recommendation on fast-ignition studies on the NIF: *The NIF-ARC system should be made available for integrated experiments of compression and fast-electron heating in ignition-scale targets. Results from fast-ignition experiments on the NIF-ARC and OMEGA EP lasers will provide the scientific basis for future developments of fast-ignition research, including a major upgrade of the NIF's short-pulse-laser system to ignition-relevant energies.*

Demonstrating direct-drive ignition on the NIF is of fundamental importance to the development of inertial fusion energy and should be an important goal for the NNSA-ICF and

Joint HEDLP Programs. However, converting the NIF into a fully spherically-symmetric laser facility ideal for direct-drive ICF will likely cost several hundred million dollars. An interim, far more economical step might be to attempt a demonstration of direct-drive ignition through the "polar drive" scheme. Polar drive is a variant of the conventional spherically-symmetric direct-drive scheme. In polar drive, the current two-sided "polar" beam configuration of the NIF is used to directly drive a spherical capsule.

Initial polar-drive-implosion experiments can be fielded on the NIF using the currently planned laser-beam-smoothing techniques. These experiments can be used to study fuel assembly and target compression. However, as currently configured, the NIF will not be capable of providing the level of single-beam illumination uniformity believed to be required for direct drive ignition. The cost of the laser upgrades required to improve the beam uniformity will likely be in the range of tens of millions of dollars.

Recommendation on direct-drive ignition: *The funding agencies should develop a plan to facilitate the demonstration of ignition with the direct-drive approach on the National Ignition Facility. This will require upgrades of the laser system to improve the laser-beam uniformity as needed for polar drive ignition.*

IV.C Transition to an energy science and technology development program: remaining science and technology issues

Even after a successful demonstration of ignition on the National Ignition Facility (NIF), difficult technological, engineering, and scientific challenges remain on the path to an attractive inertial fusion energy (IFE) power plant. The engineering and technological aspects of IFE are not discussed in this report since the charge to FESAC is restricted to the HEDLP science of inertial fusion.

All inertial-confinement-fusion concepts require high target gains to be viable for energy applications. The target gains required for a viable power plant vary for different concepts depending on the driver efficiency. The product of the driver efficiency and target gain must exceed ~10 to reduce the recirculating power and minimize the capital cost of an IFE power plant. While the underlying burning plasma physics exhibits only minor differences between moderate (~10) and high (~100) gains, accessing higher gains is important for a direct validation of the predictive capabilities in the IFE-relevant regimes. This will permit an accurate evaluation of the target and driver requirements for a power plant. In the current configuration, the NIF may not be able to create the proper conditions required for many fusion-energy target designs. Substantial upgrades of the laser system or another type of laser or driver will probably be required for achieving gains greater than ~50. Even without a direct demonstration of high gains on the NIF, a credible validation of some IFE target designs can take place with a combination of experiments in relevant physics regimes and multidimensional, high-resolution simulations using codes that have been benchmarked with experiments.

Recommendation on high energy gains and target-design validation: *After a demonstration of ignition, an assessment should be made of the upgrades required for the achievement of high gains on the NIF. Possible paths to high gains on the NIF include alternative concepts such as direct-drive, fast, and shock ignition. In addition, a strategy should be developed to achieve a* *credible validation of other plausible IFE-relevant target designs through a combination of experiments in relevant physics regimes with existing and/or new facilities, and multi dimensional, high resolution simulations using codes that have been benchmarked with experiments.*

In addition to the HEDLP science of ignition and high-gains, other critical issues remain to be addressed concerning driver technology, target fabrication and injection, and chamber materials. Those are described in detail in Sec. 11.3.2. For some IFE concepts, there has been considerable progress in addressing the pressing science and technology issues, as well as in identifying the steps to resolve them. A formal DOE program to resolve these issues should be coordinated with the progress in target physics expected on the National Ignition Facility or elsewhere.

Recommendation on the establishment of an energy science and technology development program: *A formal program to resolve the remaining key science and technology issues of the integrated IFE system should be coordinated with the progress in target physics. The establishment of this program should follow from a careful assessment of the potential benefits of inertial fusion energy, and of the pros and cons of the different IFE concepts.*

A program in inertial fusion energy sciences should make it possible for sufficient resources to take the most mature/promising concepts to the next stage of development. This will establish the technical basis to determine which (if any) warrant advancing to a major initiative, such as an Integrated Research Experiment, or another facility that demonstrates long-term production of meaningful fusion power. The program must be oriented along integrated concept lines to develop the science and technology for all of the components, including the driver, the chamber, target fabrication, and target injection/engagement systems.

Recommendation on the structure of an energy science and technology development program: *A program in inertial fusion energy science and technology should have sufficient resources to take the most mature/promising concepts to the next stage of development. This program should be oriented along integrated concept lines and make room for the pursuit of advanced ideas that are outside the main approaches. Achieving the balance between fostering new ideas and developing complete integrated concepts will be challenging, but achievable.*

1 HIGH ENERGY DENSITY LABORATORY PLASMA SCIENCE

Matter at high energy density is found throughout the universe. Recent technical advances, substantially extending the energy and power of lasers, particle beams, and *Z*-pinch devices, make it possible to create matter with extremely high energy density in the laboratory. The collective interaction of this matter with itself, intense particle and laser beams, and radiation fields constitute a rich, expanding field of physics, termed *high energy density* (HED) physics.[1–5] This field is characterized by extreme states of matter previously unattainable in laboratory experiments. It is a field rich in new physics phenomena and characterized by compelling applications, such as inertial fusion energy, stockpile stewardship, and high-gradient particle accelerators, to mention a few. In this report, we refer to energy densities exceeding 10^{10} to 10^{11} J/m^3, or equivalently, pressures exceeding 0.1 to 1 Mbar, as a working definition of *high energy density*. For example, solid-density matter at 10,000 K (1 eV) has an energy density of about 10^{10} J/m^3 (0.1 Mbar), while the energy density of a hydrogen molecule and the bulk moduli of solid materials have an energy density of about 10^{11} J/m^3 (Fig. 1). Warm dense matter (WDM) is an intermediate state between condensed matter (solids and liquids), gases, and ideal plasmas. It exists in the lower-temperature portion of the HED regime, under conditions where the assumptions of both condensed-matter theory and ideal-plasma theory break down, and where quantum mechanics, particle correlations, and electric forces are all important.

Finding: *High energy density plasmas that can be produced within state-of-the-art laboratory facilities are among the most scientifically interesting states of matter. Their densities and pressures can exceed those of the solar core, and their temperatures and flows can be high enough that relativistic effects become important. Particle acceleration by nonlinear waves, radiation-dominated plasmas, large self-generated magnetic fields, degenerate states of matter, strongly coupled plasmas, relativistic flows, and the interaction of intense particle and laser beams with matter are only some of the many fascinating and exciting physical phenomena that can be studied with present, or soon to be completed, high energy density facilities. Understanding such states of matter will greatly extend the limits of knowledge in plasma physics and related areas.*

As documented in several recent national studies,[1–5] high energy density laboratory experiments connect areas of physics, including plasma physics, material science and condensed-matter physics, atomic and molecular physics, fluid dynamics and magnetohydrodynamics, and astrophysics.

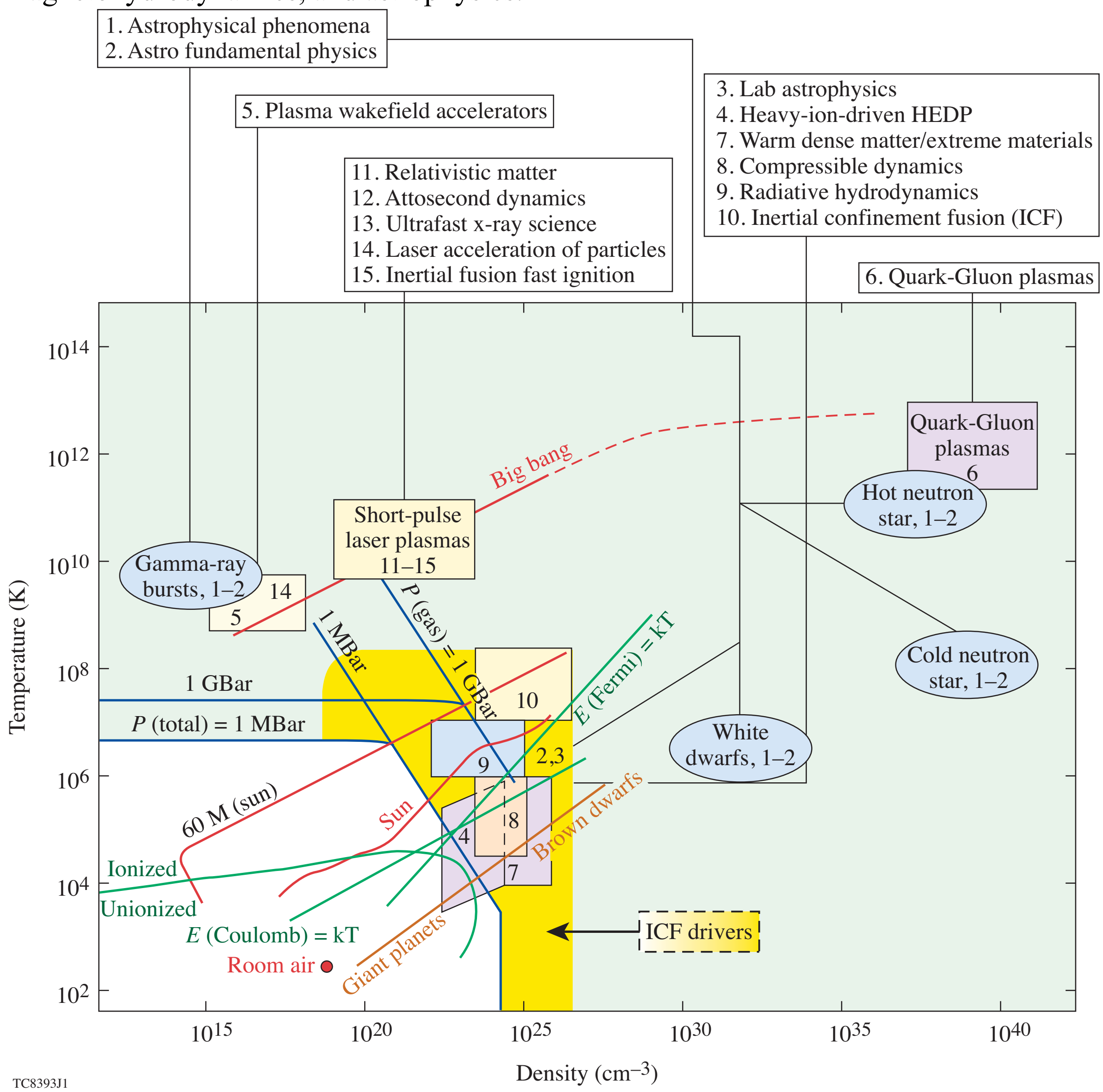

Figure 1. Map of the high energy density (HED) universe in temperature–density space illustrating the wide range of physical processes and parameter space accessible in the HED regime in naturally occurring and laboratory plasmas.[2–5]

While a number of scientific areas are represented in high energy density physics, many of the techniques have grown out of ongoing research in plasma science, fusion energy science, astrophysics, beam physics, inertial confinement fusion, and nuclear weapons research. The intellectual challenge of high energy density physics lies in the complexity and nonlinearity of the collective interaction processes.

It is evident from these studies[1–5] that it is a highly opportune time to develop an understanding of the fundamental properties of high energy density plasmas. Present space-based instruments for measuring astrophysical processes under extreme conditions provide unprecedented accuracy and detail, revealing a universe of tempestuous change. A new generation of sophisticated laboratory systems (drivers) that create high energy density matter exist or are nearing completion permitting the detailed exploration of physics phenomena under conditions similar to those in astrophysical systems.

We briefly consider some examples of the systems (drivers) that deliver the energy in high energy density laboratory experiments. State-of-the-art short-pulse lasers and particle beams can be focused to deliver more than 10^{22} W/cm^2 on target. The present generation of lasers employed for inertial confinement fusion delivers 1 to 40 kJ to a few cubic millimeters volume in a few nanoseconds. The *Z*-pinch facility at Sandia National Laboratories delivers 1.8 MJ of soft x rays to a few cubic centimeters volume in about 15 ns. With the completion of the National Ignition Facility (NIF), the parameter range of high energy density physics phenomena that can be explored will expand significantly (see Fig. 1).

In response to the reports by the National Academies and the Office of Science and Technology Policy,[1–3] an Interagency Working Group was formed to examine the national stewardship of high energy density physics.[6] The Interagency Working Group identified four research categories within high energy density physics. They concluded that three of these were already well stewarded; specifically, high energy density systems in astrophysics, in nuclear physics (specifically quark-gluon plasmas), and in ultrafast, ultra-intense laser science. With regard to the fourth area—high energy density laboratory plasmas—the Working Group concluded that "advancing research in High Energy Density Laboratory Plasmas (HEDLP) requires federal organization and mechanisms for planning, management, and merit-based, science-driven stewardship." This led to the formation of the Joint Program in HEDLP between the Office of Fusion Energy Sciences (OFES) and the National Nuclear Security Administration (NNSA), which is seeking advice regarding its activities, and provides the context for the present report.

> **Finding**: *The Office of Fusion Energy Sciences and the National Nuclear Security Administration are commended for establishing the Joint Program to steward HEDLP science and to nurture new approaches to inertial fusion energy. Effective stewardship is essential to foster growth in this exciting field of science.*

An integrated approach to investigate the scientific issues in related subfields will enable significant advances in understanding the physics of high energy density plasmas. This will lead to new applications and benefit other areas of science. Learning to control and manipulate high energy density plasmas in the laboratory will benefit national programs, such as inertial confinement fusion, inertial fusion energy science, and the stockpile stewardship programs, through the development of new ideas and the training of a new generation of scientists and engineers. It will enable a wide range of practical applications to be advanced, ranging from particle beams for oncology to compact x-ray sources for materials science, to be advanced.

In summary, elucidating the physics of high energy density plasmas through experiment, theory, and numerical simulation is of considerable national importance to understand (a) physical phenomena in laboratory-generated high energy density plasmas, with applications ranging from inertial fusion energy to particle accelerators, and (b) astrophysical phenomena that are observed with increasing detail and accuracy with new space-based and ground-based observational tools. This field is developing rapidly, so that a vigorous research program is warranted. This report explores the compelling research opportunities in high energy density physics and synergies among related subfields and provides recommendations for the optimization and growth of the research programs.

> **Finding**: *High energy density plasmas have many important practical applications. Understanding the behavior of plasmas is key to the development of inertial fusion energy, verification and validation experiments for national security science, compact particle accelerators, bright coherent x-ray sources, and intense particle-beam sources for medical applications.*

2 The Charge to FESAC

The Department of Energy Under Secretary for Science Dr. R. L. Orbach and the Under Secretary for Nuclear Security Mr. T. P. D'Agostino issued a charge to the Fusion Energy Science Advisory Committee (FESAC) to "work with the HEDLP community to provide information to develop a scientific roadmap for the Joint HEDLP Program in the next decade."

The first part of the charge is concerned with the stewardship of the new joint OFES-NNSA HEDLP program. The charge letter (Appendix A) requires that FESAC identify: (1) "the compelling scientific opportunities for research in fundamental HEDLP that could be investigated using existing and planned facilities in support of the OFES and NNSA/DP missions"; (2) "the scientific issues of implosion and target design that must be addressed to make the case for inertial fusion energy as a potential future energy source." The letter tasks FESAC with developing a prioritized list of compelling HEDLP science "issues and opportunities that can be pursued over the next decade or so" through the Joint HEDLP Program.

The second part of the charge is "meant to provide background for a scientific plan for energy-related HEDLP studies." FESAC is tasked with developing a set of scientific questions "to support the case for energy applications for inertial fusion energy (IFE) sciences." More specifically, the charge to FESAC is to develop a prioritized list of "gaps in knowledge and opportunities for research in energy-related HEDLP research." During this process, FESAC should consider "sequential phases of activity" focusing on: (1) exploiting available facilities to explore IFE-related HEDLP science in anticipation of future studies on the National Ignition Facility (NIF); (2) exploiting the NIF capabilities to address ignition-science issues related to IFE, and (3) resolving scientific issues to promote a transition from a burning plasma experiment to a fusion-energy-science development program.

The engineering and technological aspects of inertial fusion energy are not discussed in this report since the charge to FESAC is restricted to the HEDLP science of inertial fusion. A detailed description of the IFE technology can be found in an earlier FESAC report "A review of the inertial fusion energy program," (Report No. DOE-SC-0087, March 29, 2004, text available at: http://www.ofes.fusion.doe.gov/More_HTML/FESAC_Charges_Reports.html).

Most recent developments in IFE technology can be found on the HAPL (High Average Power Lasers) website (http://aries.ucsd.edu/HAPL/). HAPL is an NNSA-funded effort to develop the science and technology of laser direct-drive inertial fusion energy.

3 THE PANEL PROCESS

The Fusion Energy Science Advisory Committee, in consultation with the Department of Energy Office of Fusion Energy Science and the National Nuclear Security Administration appointed a panel of 17 scientists from Universities and National Laboratories. This panel was tasked with addressing the charge (Sec. 2) issued by the DOE Under Secretary for Science and the Under Secretary for Nuclear Security. The charge to FESAC is divided in two parts. The first part is to "identify the compelling scientific opportunities" in the area of high energy density plasma science and their application to inertial fusion energy. The second part is to "provide background for a scientific plan for energy-related HEDLP studies."

The HEDLP panel was formed in June 2008. Eleven panel members are from U.S. universities and six from national laboratories. The panel members (see Appendix B) bring expertise in all the areas of high energy density physics including: laser–plasma interaction, hydrodynamics, shock physics, warm dense matter physics, radiation transport, high-intensity lasers, pulsed-power, inertial fusion energy, fast ignition, magnetized target fusion, and heavy-ion fusion.

To acquire input from the HEDLP community, the panel organized a three-day workshop on August 25-27, 2008, in Washington, DC. The list of invited and contributed presentations is provided in Appendix C. The workshop was open to the HEDLP community at large, policy makers, and other government officials. About 90 attendees participated at the workshop and provided input to the committee. Among the participants were scientists from national laboratories, universities, small businesses, and representatives from government agencies. On the first day, Dr. G. Nardella and Dr. M. Donovan described the perspectives of the Office of Fusion Energy Science and the National Nuclear Security Administration in their opening presentations. Six invited speakers gave overview talks in the area of high energy density science applications to inertial fusion energy (IFE) including: high-gain target physics and advanced concepts, heavy-ion fusion, magneto-inertial fusion, fast ignition, laser direct drive, and *Z*-pinch IFE. The invited talks on IFE were followed by thirteen contributed talks on the same theme. The second day of the workshop was devoted to fundamental high energy density science. Six invited speakers reviewed the scientific opportunities in fundamental HEDLP science including: hydrodynamics, laboratory astrophysics, radiation and magnetohydrodynamics, material properties at high pressures, nonlinear optics of plasmas, and high-intensity laser–plasma interaction. The invited presentations were followed by twelve contributed talks on fundamental HEDLP science. A summary of the scientific issues and opportunities in HEDLP science was provided by two panel members on the morning of the third day. Both invited and contributed presentations are available on the panel web site http://fsc.lle.rochester.edu/hedlp/hedlp.php.

The panel has interacted through weekly conference calls, e-mails, and two face-to-face meetings. The first meeting took place on August 27, 2008 following the HEDLP workshop in Washington, DC. The second meeting took place in Los Angeles on September 18-19, 2008.

To address the first part of the charge, the committee developed two lists of the most compelling scientific issues in HEDLP science and two sets of ranking criteria. The first list is concerned with the HEDLP science issues relevant to the development of inertial fusion energy. The second list includes compelling issues for research in fundamental high energy density science. The issue lists are described in Secs. 9 and 10. The panel developed two distinct sets of criteria—one for energy-related HEDLP and the other for fundamental HEDLP science. The prioritization of the energy-related issues was carried out using a set of criteria to evaluate their importance to the development of inertial fusion energy, the ability to answer the science questions using existing facilities, distinctiveness with respect to the research effort within the NNSA-funded inertial confinement fusion program, the applicability of the underlying science to multiple IFE approaches, and the estimated resources required to address the issues. The five criteria used in the prioritization of the energy-related HEDLP science issues are:

- IMPORTANCE: to the advancement of fusion-energy sciences
- DISTINCTIVENESS: the degree to which the issue is NOT addressed in the NNSA-funded conventional ICF ignition program
- READINESS: progress expected in the next five/ten years
- GENERALITY: the degree to which the solution of the issue impacts multiple IFE concepts
- COST: level of resources required to address the issue

A somewhat different approach was used to address fundamental HEDLP science. The panel recognized that fundamental science is not suitable for the same kind of prioritization as mission-oriented science, such as IFE science. An assessment of the HEDLP areas, rather than a prioritization of each scientific issue, was performed for fundamental HEDLP science. This assessment was carried out using a set of criteria that emphasize the importance to the fundamental understanding of high energy density physics (excluding inertial fusion energy sciences), the ability to address the issues with existing facilities, the impact to other fields of science, and the prospects for practical applications. The criteria used to assess the fundamental HEDLP science areas are:

- IMPORTANCE: to the fundamental understanding and development of high energy density science
- POTENTIAL: for important practical applications
- POTENTIAL: for resolving major issues in other fields of science
- READINESS: for progress in the next five/ten years

After carrying out a preliminary assessment via e-mail, the panel discussed and analyzed the issue lists for energy-related and fundamental HEDLP science created during the face-to-face Los Angeles meeting and following weekly conference calls. The panel developed the assessment of the fundamental HEDLP science areas and the prioritization of the energy-related HEDLP issues. The energy-related issues were clustered within three priority levels: (1) The highest priority level includes the HEDLP science issues to be addressed by the Joint Program in the short term (~5 to 10 years) using existing facilities to allow immediate progress in the field; (2) The medium priority level includes those issues that can be addressed on a longer time scale (>10 years) without severely impeding short-term progress in the IFE sciences and important issues that are partially addressed within the NNSA-funded inertial confinement fusion (ICF) program. (3) The lower priority level includes important scientific issues that are adequately addressed within the NNSA–ICF program. The prioritized lists of compelling scientific opportunities for research in the field of HEDLP science are discussed in detail in Secs. 9 and 10.

To address the second part of the charge, the panel chair appointed a subcommittee of experts (Appendix D) in inertial fusion energy science to develop a scientific plan for energy-related HEDLP studies. This subcommittee interacted though several conference calls and developed a plan (Sec. 11) for energy-related HEDLP studies to be implemented on available facilities including the National Ignition Facility. The plan also includes important recommendations regarding the need for a science and technology development program coordinated with the expected advances in target physics.

4 Stewardship of the Joint Program

When identifying the scientific opportunities in HEDLP research (first part of the charge), the panel found the need for separate approaches for addressing energy-related and fundamental HEDLP physics, reflecting the differences between science that is mission oriented and science that is discovery driven.

> **Recommendation:** *The Joint Program should independently steward fundamental and energy-related high energy density laboratory plasma science, managing solicitations and develop review criteria to respect the important need for both discovery-driven and mission-oriented science.*

A research needs workshop (ReNeW) should be organized at an earliest possible date to plan for an efficient stewardship of the field. The workshop should be organized to reflect the different strategies required for advancing discovery-driven and mission-oriented science.

> **Recommendation:** *To facilitate the growth of HEDLP research, the agencies should hold a research needs workshop at an earliest possible date. It should be focused on fundamental and energy-related HEDLP science. The workshop should be organized by taking into account the need for and the differences between mission-oriented and discovery-driven science.*

The United States has a large number of state-of the-art facilities that are capable of creating and studying high energy density plasmas. The present and next-generation of high energy density facilities offers unique prospects of accessing extreme high energy density states of matter and exploring high energy density phenomena never before observed in the laboratory.

> **Recommendation:** *The current excitement surrounding HEDLP is based upon existing and near term large- and intermediate- scale experimental facilities in the U.S. that are capable of generating high energy density conditions. Taking full advantage of the opportunities described in this report over the next decade requires continuing and assured access for the broader scientific community to these facilities. Formal or informal user programs should be expanded, and new ones should be developed to increase access to HEDLP facilities. Modest facility upgrades will enable even more exciting and challenging experiments of high intellectual value.*

An efficient use of the experimental facilities requires precise measurements in well diagnosed experiments. The short time and spatial scales of high energy density (HED) phenomena makes measurements exceptionally difficult and diagnostic development extremely challenging.

> **Recommendation:** *The Joint Program in HEDLP should include, within its scope, funding for the development of novel diagnostic methods that are essential to fully characterize HEDLP systems. This area has historically been underemphasized, to the disadvantage of the field.*

In addition to well-diagnosed experiments, true understanding of high energy density plasmas both for inertial fusion energy and basic science requires theory and advanced numerical simulations. The advent of petascale and exascale, and high-performance desktop computing will allow unprecedented time and length scales to be resolved using micro-, meso-, and multi-scale models. Significant code capabilities exist inside and outside of the NNSA laboratories. Most of the world's largest super-computer capabilities exist within NNSA and the Office of Science.

> **Recommendation:** *The Joint Program in high energy density laboratory plasmas should include significant components of theory and advanced simulation both for basic research and for supporting the experimental elements of the program. The program should encourage access to the Office of Science and NNSA computing facilities, and unclassified codes for outside users. It should also support innovation in developing new algorithms and theories. It is recommended that funds be provided for community code development projects under the Department of Energy program called Scientific Discovery through Advanced Computing.*

5 Overview of the HEDLP Science Areas

The panel organized the scientific issues and opportunities within HEDLP science into several sub areas, both to place these opportunities in a sensible context and to communicate our belief that the federal research program in HEDLP must span the field to be productive over time. We chose these areas both to span the field and to highlight the research opportunities we see to be, at present, most compelling. The reader will recognize that there is overlap among the areas and that some research may impact more than one area. We emphasize that it would be a mistake to decline to fund an outstanding research proposal solely because it does not fit neatly into the division of the intellectual turf presented here. With this caveat, the development of the science areas follows.

The matter found in high energy density (HED) systems is inherently in an extreme state. The differences between HED matter and ordinary matter drive many of the scientific opportunities detailed below. One can illustrate these differences by contrasting HED matter to an ideal plasma. Boyle's Law describes the pressure of an ideal plasma as a function of temperature and density, but often does not describe HED matter, in which either the interactions of the charged particles (Coulomb interactions) or relativistic and/or radiation effects can be too strong. Ideal plasmas are nearly always treated as having fixed ionization, but much HED matter is actively ionizing so that changes in ionization state, and sometimes the specific ionization history, have a large impact on its behavior. At high enough temperatures, above $\sim 10^{10}$ K, HED matter becomes relativistic. At temperatures above $\sim 10^5$ K, HED matter radiates copiously and this radiation alters the properties and dynamics. At high enough density, HED matter becomes Fermi degenerate as are typical solids, increasing the energy required to compress it. There are real challenges and opportunities associated with all the above aspects, some of which are detailed further below.

From the standpoint of material properties, bigger challenges than those just mentioned arise at high enough density and low enough temperature that the energy of the Coulomb interactions exceeds the energy of thermal motion. This is the regime of *warm dense matter*, where the matter is, in some sense, in an intermediate regime between solid, liquid, gas, and plasma. Quantum effects are often essential, but Coulomb interactions cannot be ignored. The ions are strongly correlated, but the assumptions of condensed-matter theory break down. Free electrons are abundant and plasma effects are present, but the plasma is far from ideal. Warm dense matter is important in many scientific areas including laser, pulsed-power, and high-pressure-gas-gun experiments, inertial confinement fusion, formation and evolution of giant planets, and formation and evolution of white dwarfs. It can be significant in material-processing methods that involve high enough pressures or temperatures. With an increased focus on producing and diagnosing warm dense matter, substantial and important advances in knowledge are likely in the near future.

New challenges arise when HED matter begins to move, leading to *HED hydrodynamics*. The hydrodynamic behavior of HED systems has aspects that differ in significant ways from those of traditional fluids. HED systems are strongly compressible, dynamically ionizing, potentially supersonic, and involve complex material evolution, such as chunk formation and dissolution. New instabilities arise under these conditions. Bizarre regimes exist such as that of flowing, yet solid, material. The mixing of materials in the HED regime is not well understood. Basic properties that affect the material flows, such as mass diffusivity and viscosity, arise from complex mechanisms and are difficult to calculate but may be determined from well-designed hydrodynamic experiments. The limits of scaling from these systems to other hydrodynamic systems and the challenge of accurately simulating HED hydrodynamic behavior are not understood. HED hydrodynamics has applications to a wide range of issues in astrophysics and planetary physics, where ionizing and compressible conditions are common. Current and anticipated facilities are well suited to making progress in this area, and progress would be facilitated by an increased focus on improved diagnostics.

When moving HED matter becomes hot enough (above $\sim 10^5$ K), radiation begins to alter its behavior and one enters the regime of *radiation-dominated HED plasmas*, also known as radiation hydrodynamics. Radiation hydrodynamics emerges and exists primarily under HED conditions in the laboratory and in astrophysics, with only a few astrophysical analogues existing outside the HED regime. Particle interactions (such as ion–ion collisions) control the behavior of ordinary plasmas, while in radiation-dominated plasmas, radiation may control heating, cooling, ionization, or pressure. This leads to novel phenomena such as radiative shocks, radiation waves, radiation pressure, and photon-controlled ionization. These laboratory phenomena are connected to frontier research areas in astrophysics, including black holes, gamma-ray bursts, star formation, supernovae, molecular cloud destruction, and radiatively collapsed astrophysical shocks. To fully understand plasma dynamics under intense radiation, a detailed knowledge of *material properties* in these extreme environments (such as opacities and equations of state) is required. Although radiation hydrodynamics is difficult to study experimentally and numerically, substantial progress has been made in both these areas and we are on the threshold of a period when very substantial advances are possible.

Because HED matter is ionized, its free electrons can carry substantial currents that can produce enormous magnetic fields. This creates *magnetized HED matter*, with its own unique features. It has become clear in laser and pulsed-power experiments that such conditions can exist. In these systems, the particle collision length is the smallest relevant physical scale, in sharp contrast to other magnetized systems. We do not understand how the field dynamics, the electron transport, or other properties change under such conditions. Experiments are possible in which the magnetic pressure is comparable to the particle pressure, enabling the study of dynamo processes that occur in the sun and in galactic accretion disks and galactic jets. In the strongest laboratory magnetic fields—

exceeding one billion times that of the earth—the behavior of atoms, ions plasmas, and shock waves is significantly changed. This is relevant to phenomena near the surface of neutron stars and the event horizon—the point of no return—around black holes. A wide range of experimental facilities, from small ultrafast lasers, to the largest high-energy lasers, to pulsed-power systems, can produce and study magnetized HED systems, creating substantial opportunities for ground-breaking research.

HED matter is not purchased from a supply company; it must be created and manipulated before it can be studied. This often involves the use of coherent radiation such as lasers, which in turn produce complex interactions of great potential practical importance, designated here as the *nonlinear optics of HED plasmas*. The dynamics that develop goes far beyond the behavior of the light waves and the internal waves that represent the natural, decoupled oscillations of the plasma. It has become clear that self-organized nonlinear states develop that can exchange energy with the light at multiple places and times. It appears that these states can be controlled by driving other waves in the plasma, leading to the possibility of producing the controlled release of energy as beams or jets of particles. The understanding and control of these nonlinear states may impact fields such as 2-D Euler turbulence, vortex dynamics in fluids, and stellar and galactic evolution, and may be of use in accelerators, in light sources, and in understanding astrophysical and solar observations. As the coherent radiation becomes more intense and of shorter duration, it becomes possible to manipulate electrons on the attosecond time scales characteristic of their inherent quantum transitions. This will make it possible for scientists to create bright coherent beams of hard x rays on a desktop. These and other new tools will enable us to view and manipulate the nanoworld. A wide range of lasers exist that can explore the behavior of coherent radiation in HED plasmas.

When the temperature becomes high enough, or the lasers or particles used to create HED conditions become intense enough, one reaches the *relativistic HED* regime. Just as a boat drives a wake in the water, one can drive relativistic wakes behind disturbances in plasmas. These, in turn, can accelerate relativistic beams of electrons, positrons, or, potentially, ions. Important applications follow from the propagation of such particle beams or of laser beams through extended plasmas or into solids. Current facilities can produce relativistic shocks, and may be able to produce electron–positron plasmas and plasmas with relativistic thermal temperatures. Achieving a deep understanding of these phenomena will improve our understanding of physical conditions relevant to gamma-ray bursts, accretion disks around massive black holes, and the magnetospheres of radio pulsars. This understanding will have a practical impact on generating ion beams for oncology and spallation neutron sources, in producing compact photon sources, and in advanced IFE concepts. This is an area where advances in facilities are enabling and will allow progressively more demanding and sophisticated research. Much is possible now—much more will be possible in the very near future.

Finding: *A wide variety of HED states of matter, spanning many orders-of-magnitude in density and temperature, can be produced in the laboratory. The physics of HED plasmas varies greatly within this wide parameter space, such as solid-density matter at ~1 eV, matter well above solid density at temperatures up to 100 keV and dense plasmas with relativistic temperatures. Areas of HEDLP physics that are ripe for near-term discoveries are*

- *high energy density hydrodynamics*
- *radiation-dominated dynamics and material properties*
- *magnetized high energy density plasma physics*
- *nonlinear optics of plasmas*
- *relativistic high energy density plasma physics*
- *warm dense matter physics*

Recommendation: *It is now an opportune time for the Joint Program to assume the stewardship of the fundamental science of high energy density laboratory plasmas. By taking advantage of the new generation of domestic experimental and computational facilities capable of detailed exploration of high energy density plasmas, the Joint Program can and should foster the rapid growth and development of this new and exciting field of science.*

6 U.S. 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. These facilities are operated by various federal agencies 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.

> **Finding:** *The present and next generation of high energy density facilities offers unique prospects of accessing extreme high energy density states of matter and exploring high energy density phenomena never before observed in the laboratory.*

The table below lists some of the major U.S. facilities that are either in operation, or will be within the next few years. They are characterized by type of power source (e.g., laser, pulsed-power, ion beam, x ray), location, sponsor, and key parameters. Parameters are representative. 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, Z-Beamlet can be coupled with ZR, and ARC can be coupled with NIF.

A close collaboration with international groups and access to HEDLP facilities abroad can significantly improve the effectiveness of the Joint HEDLP Program. For example, experiments on integrated laser facilities (implosion facility with short pulse capability) such as FIREX-I (Fast Ignition Realization Experiment) in Japan can provide access to regions of the fast ignition parameter space otherwise inaccessible on OMEGA EP. FIREX-I features a 10kJ petawatt laser integrated with the ~10kJ GEKKO implosion facility that uses 12 beams of 532 nm light. More opportunities for international collaborations will become available as additional facilities such as PETAL (Petawatt Aquitaine Laser, a short-pulse laser designed to deliver 3.6kJ of 1053 nm light in 0.5-5ps pulses) and LMJ (Laser Megajoule, a 240 beam indirect drive ignition facility designed to deliver 2MJ of 351nm light in 9 ns) in France will start operation during the next decade.

Table 6.I: U.S. HEDLP facilities (does not include all university-based facilities).

Name	Institution	Type	Key Parameters
Long-Pulse Lasers			
National Ignition Facility (NIF) (operational in 2009)	Lawrence Livermore National Laboratory	Nd:glass laser (351 nm)	1.5 MJ at 4 to 12 ns 1.8MJ at 20ns (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
ARC (under development)	Lawrence Livermore National Laboratory	Nd:glass Laser (1 µm)	13 kJ at <1 ps
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
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
Heavy Ion			
NDCX-I	Lawrence Berkeley National Laboratory	Heavy ion	10 mJ at 10 µs 1 mJ at 2 ns
Pulsed-Power Facilities			
COBRA	Cornell University	*Z*-pinch	1.2 MA at 100 ns 0.9MA at 200ns
Gamble II	Naval Research Laboratory	*Z*-pinch	1 MA at 100 ns
Saturn	Sandia National Laboratories	*Z*-pinch	6 MA at 140 ns
Shiva Star	Air Force Research Laboratory	MIF - liner implosions	12 MA, 5 MJ at 10 µs
XP Pulser	Cornell University	*X*-pinch	0.5 MA at 50 ns
ZEBRA	University of Nevada	*Z*-pinch	1 MA at 100 ns 0.6 MA at 200 ns
ZR	Sandia National Laboratories	*Z*-pinch	25 MA at 100 ns
X-Ray Lasers			
Linac Coherent Light Source	Stanford Linear 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	Stanford Linear Accelerator Center	Short-bunch electron and positron beams	25 GeV at 50 fs ~1 nC

Integrated Facilities			
NIF (under construction)	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
ZR	Sandia National Laboratories	Z-pinch plasma diagnostics Fast-Ignitor fusion research	Z-Beamlet and ZR
Nevada Terawatt Facility	University of Nevada, Reno	Z-pinch plasma diagnostics Magnetized laser–plasma interactions	Leopard and Zebra

7 HEDLP Science Applications to Inertial Fusion Energy

The half-century quest for a laboratory demonstration of controlled thermonuclear fusion energy is expected to reach a major milestone with the demonstration of ignition on the NIF. This will be a major scientific achievement as well. The ignition campaign is scheduled to start in 2010. Thermonuclear ignition is a thermal instability, a self-heating process in the thermal energy of the thermonuclear fuel [typically a 50:50 mixture of deuterium (D) and tritium (T)]. In an ignited DT plasma, the fraction of the energy associated with the α-particles (3.5 MeV) from the fusion reactions D + T $\rightarrow \alpha$ + n + 17.6 MeV is deposited in the plasma, increasing its temperature and, in turn, the fusion reaction rate. The hotter the plasma, the greater the number of fusion reactions that heat it. This self-heating process ceases when either disassembly of the fuel, or the saturation of the fusion rates, prevents further growth of the temperature. The amplification of the fusion reaction rate resulting from the plasma self-heating process can lead to a fusion energy output many times larger than the input energy required to bring the plasma to ignition conditions. The energy gain is the ratio of the energy output to the energy input.

Demonstrating thermonuclear ignition and energy gain in the laboratory has been a goal of fusion-energy research for decades. One needs to recognize, however, that ignition in the laboratory does not imply that economically attractive fusion energy is just around the corner. Daunting scientific and engineering challenges remain after the demonstration of ignition. The development of a viable fusion-power plant requires large scientific and financial investments.

In inertial confinement fusion (ICF), the hot plasma is confined for only a very short time (hundreds of picoseconds) by its own inertia, and the thermonuclear instability (i.e., ignition) develops in the center of a tiny capsule of DT plasma (~1 mg) compressed to ultrahigh densities (>100 g/cc) and pressures (>10^{11} atm) by an external driver, typically a laser, particle beams, or some other source of intense radiation. The ignition process in inertial fusion is analogous to that in an automotive engine. The spark in the center of the compressed plasma ignites the neighboring DT nuclei, launching a burn wave that propagates through the entire mass of thermonuclear fuel. In keeping with the internal combustion analogy, the spark can be created by pure compression (diesel engine) as in conventional "hot-spot" ignition or by an external source (gasoline engine) as in fast ignition. The hot blob of DT plasma keeps burning until it cools down due to its hydrodynamic expansion.

An ignited ICF capsule is one of the most extreme states of HED matter that can be produced in the laboratory. The pressure or energy density of an ignited capsule can reach several terabar (1 Tbar = 10^{11} J/cc $\approx 10^{12}$ atm). Just before ignition occurs, the compressed core reaches densities of several hundred g/cc. After the fusion burn has propagated throughout the entire compressed core, the temperature reaches several hundred million degrees K before the core finally expands at velocities exceeding

1000 km/s. To increase the energy gain requires more fuel mass, a larger driver, and/or greater compression. In terms of burning plasma physics, there are only minor qualitative differences between a gain of 10 and 100 in inertial fusion. In terms of demonstrating the viability of inertial fusion energy, achieving gains in excess of 100 is of fundamental importance.

The National Ignition Facility (NIF), a formidable laser (500 TW, 1.8 MJ of ultraviolet light on target), at Lawrence Livermore National Laboratory, will be completed in 2009. The predicted energy gain of ~20 to 30 is large enough to fully test the physics principles of thermonuclear ignition via inertial confinement. Achieving higher gains is a possibility under favorable circumstances. The NIF will first test the indirect-drive approach to inertial confinement fusion. In indirect drive (Fig. 2), a cryogenic spherical capsule containing a solid-DT layer is imploded by the x rays emitted from a cylindrical enclosure irradiated with the NIF laser. According to complex numerical simulations, the NIF capsule volume shrinks by about 40,000×, the DT density reaches ~1000 g/cc, and the central plasma is heated to a temperature of about 100 million K before the onset of ignition. Achieving such an extreme state of matter can be accomplished only if the compression is uniform. This requires a large number of laser beams (192 for the NIF), careful control of the illumination pattern, and a target with very smooth surfaces.

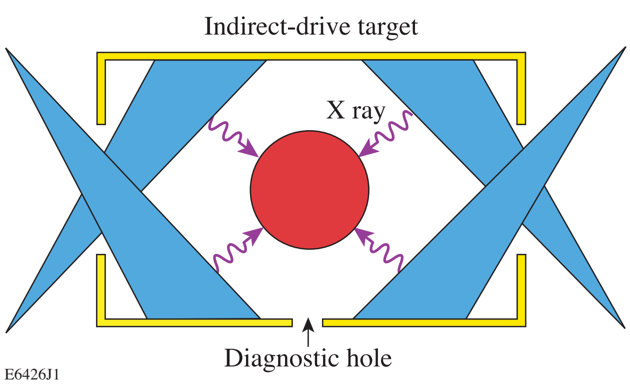

Figure 2. Schematic of the indirect-drive approach to inertial fusion. The x rays from the laser heating of a cylindrical enclosure (hohlraum) drive the target implosion.

Another approach, known as “direct-drive” can also be tested on the NIF. In direct drive (Fig. 3), the laser beams are directed onto the target surface and used to accelerate the cryogenic-DT shell to implosion velocities up to 400 km/s. Imploding shells are unstable to hydrodynamic instabilities that amplify the initial nonuniformities which are either imprinted by the laser on target surfaces or caused by imperfections in target manufacturing. An excessive growth of such instabilities can lead to target breakup and failure to reach the ignition condition. While numerical simulations indicate that hydrodynamic instabilities can be controlled to acceptable levels, uncertainties remain with regard to the achievement of ignition and energy gains on the NIF.

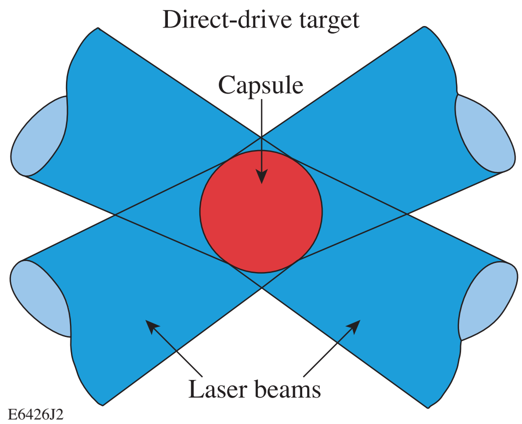

Figure 3. Schematic of the direct-drive approach to inertial fusion. Multiple laser beams directly illuminate the target surface to drive the implosion.

The National Nuclear Security Administration funds the National Ignition Campaign (NIC), a collaborative effort among national laboratories and other institutions to develop the physics and technological basis for a successful demonstration of ignition on the NIF through the conventional central-ignition approach. The participants in the NIC are Livermore National Laboratory, Los Alamos National Laboratory, Sandia National Laboratories, the University of Rochester, and General Atomics. NNSA also supports construction and operation of major facilities besides NIF such as OMEGA, Z, and NIKE.

Within the next five years, initial data on the performance of indirect-drive-ignition targets will provide essential information on the prospects for thermonuclear ignition and viability of inertial fusion energy.

> **Finding:** *The National Ignition Facility (NIF) is expected to achieve thermonuclear ignition and moderate energy gains in the near future through the indirect-drive approach. Many aspects of high energy density burning-plasma physics relevant to inertial fusion energy will be studied on the NIF.*

7.1 ALTERNATIVE CONCEPTS FOR IFE AND THE PATH TO HIGH ENERGY GAINS

The next step in target physics after ignition is the demonstration of high gains. High gains are essential to the viability of inertial fusion energy since the wall-plug driver efficiency is typically rather low, ~10%–20% or less. To satisfy the power-plant requirements, the product of driver efficiency and target gain must exceed ~10. Target gains in excess of ~50 to ~100 are, therefore, required for a viable IFE reactor, depending on the driver efficiency.

To achieve high gains (~100), several options have been proposed that differ from the conventional approach that will first be tested on the NIF. In this report, we refer to these concepts as “alternatives.” Some of the alternative concepts are aimed to improve the driver efficiency, others to increase the target gain, some to relax the driver power requirements, and others to combine several such features to maximize the efficiency-gain product. Research activities in alternative IFE concepts are currently funded by the Office of Fusion Energy Science, the High Average Power Laser project within the NNSA, and by internal laboratory funds. In most cases, this work leverages existing NNSA facilities and research.

The underlying goal of all the alternative IFE concepts is to improve the economic viability of inertial fusion energy. High-gain laser direct drive, pursued over the past 40 years, is the most advanced among the alternative concepts. While high-energy lasers have been the drivers of choice for a great deal of the research effort to date, *Z*-pinch and heavy-ion drivers, mostly for indirect drive, have also been regarded as viable IFE drivers in light of their considerably higher wall-plug efficiency. *Z*-pinch and heavy-ion fusion are distinct from the laser IFE approach only in the driver concept rather than in the target physics. Work to date with all these drivers has focused primarily on central ignition, involving the compression of a cryogenic DT shell and ignition from a central hot spot heated by the piston action of the imploding shell.

Other alternative concepts make use of innovative ways to bring the DT fuel to the ignition conditions. While all IFE concepts rely on the compression of DT targets by a high-energy driver, they can differ on the heating mechanisms. The alternative approaches to ignition use external means to increase the temperature of DT fuel and trigger ignition. These can be energetic particle beams (fast ignition), spherically convergent shocks (shock ignition), high-velocity impactors (impact ignition), or externally applied magnetic fields (magneto-inertial fusion).

Finding: *Alternative inertial fusion energy (IFE) concepts are required for a viable path to high energy gains and economically attractive fusion energy systems. Alternative IFE concepts funded by OFES and NNSA have the potential to generate the gains needed for inertial fusion energy.*

The major alternative IFE concepts under investigation in the U.S. are

- *high-gain laser direct-drive*
- *Z-pinch IFE*
- *fast ignition*
- *shock ignition*
- *heavy-ion fusion*
- *magneto-inertial fusion*

Alternative concept research is multidisciplinary and involves extreme states of matter never before achieved. For instance, fast ignition of DT fuel at ~300 g/cc requires the transport of a 20-µm-radius electron beam with a current of ~1 GA through a plasma having a density that varies over three orders of magnitude. Shock ignition of an IFE capsule requires the generation of a spherically convergent shock with a pressure in the gigabar range. Impact ignition, pursued at Osaka University in Japan, requires the acceleration of the impactor target to velocities exceeding 1000 km/s, followed by a collision with the dense core to generate an ~10^8 K hot spot. Magnetizing the core of an imploding capsule requires the generation of ultrahigh magnetic fields (ranging from a few to tens of megagauss) inside a plasma with a temperature of about hundred million degrees. Such a large field might be induced by the magnetic-flux compression of a magnetized plasma target as in magneto-inertial fusion.

Magnetized HED plasmas are interesting and novel states of matter that can be used to improve the conditions for thermonuclear ignition. A magnetized plasma exhibits better heat retention (i.e., lower heat conduction) making it possible to achieve ignition-relevant temperatures with less driver power. While the magneto-inertial-fusion concept relies on the amplification of an externally applied seed magnetic field, large fields (1 to 10 megagauss) can also be self-generated. In IFE implosions, as in fast ignition, self-generated fields are induced by hydrodynamic instabilities, thermal instabilities, or return currents. The magnetic fields induced by the cold return current in resistive plasmas can effectively collimate the fast electrons in fast ignition and significantly reduce the energy required for ignition. Large magnetic fields have been measured in the lower-density ablated plasmas surrounding a laser-driven imploding shell. In this case, the magnetic field can be detrimental to the implosion, because it can inhibit the transport of the laser energy from the critical surface to the ablation front.

> **Finding**: *The high energy density plasmas studied in the context of innovative IFE concepts feature a wealth of new and exciting physical phenomena that must be investigated to advance these concepts. Especially important phenomena include the relativistic interaction of intense laser light with solids and plasmas, the generation of ultrahigh magnetic fields, the transport of intense particle beams in plasmas, and the propagation of ultrastrong convergent shocks.*

Some of the IFE alternatives listed above, such as high-gain direct drive, fast ignition, and shock ignition, can be tested at the proof-of-principle level on the NIF. Key aspects can be tested on other facilities such as OMEGA and NIKE. All the IFE alternative concepts require the generation of extreme states of matter never before accessed. The scientific interest in such high energy density regimes combined with their role in the development of inertial fusion energy make research in IFE alternatives an exciting and promising endeavor.

> **Recommendation:** *It is recommended that the Joint Program expands the development of alternative IFE concepts. The Joint Program should take advantage of the existing NNSA facilities to test the most promising*

alternative concepts at the proof-of-principle level. The current IFE alternative concept effort should be extended by promoting wider university involvement.

Another potentially important application of inertial fusion energy is in the area of fission–fusion, hybrid-energy systems. Both Lawrence Livermore National Laboratory (LLNL) and Sandia National Laboratories are exploring the use of a fission blanket to amplify the energy yield of an IFE device. For example, in the Livermore laser inertial fusion–fission energy (LIFE) concept, the IFE device is based on the laser indirect-drive approach whereas the Sandia Inzinerator concept is based on a *Z*-pinch. This committee acknowledges that hybrid concepts have some potential benefits and should be given careful consideration as they achieve higher levels of maturity.

Finding: *A fusion–fission combination would considerably reduce the IFE target-gain requirements and may prove to be a viable course to an attractive power plant. While the latest work on fusion–fission hybrids (e.g., the LLNL LIFE or Sandia Inzinerator concept) is too recent to be included in this report, the committee recognizes the need for a careful evaluation of the opportunities afforded by these as they mature.*

7.1.1 High-gain direct drive

High-gain direct-drive is the most advanced alternative concept developed in the U.S. A spherical pellet, ~5 mm across, is uniformly illuminated with laser pulses. The outer layer is ablated producing multi-megabar pressures and, in reaction, the inner layer accelerated inward to velocities of several hundred km/s. Upon implosion, the inner shell consisting of deuterium–tritium fuel is compressed to sufficiently high densities (1000× solid). A central "hot spot" is heated to 100 million K, sufficient to undergo fusion ignition. Like the conventional indirect-drive approach, direct drive is based on the central hot-spot-ignition concept where the central spark ignites the surrounding fuel. In a power plant the target is injected about five to ten times per second into a reaction chamber, and the collected energy is converted to electricity or hydrogen.

Extensive experimental and theoretical research carried out over the past 40 years enhances confidence that direct-drive ICF represents a viable path to high gains for inertial fusion energy. A number of target designs show sufficient gain for energy in integrated, multidimensional simulations. The underlying codes have been benchmarked with experiments, and the relevant physics has been developed in the NNSA-funded ICF program. From an energy perspective, the targets are spherical shells that are readily mass-produced with no debris to recycle. The design has been tailored to meet the multifaceted requirements for energy (for example, thermal protection during injection into the chamber).

The generally accepted criterion is that the driver efficiency, η, multiplied by gain G, should be >10. (The driver-target coupling is included in G.) This $\eta G > 10$ constraint brings the recirculating power to a tractable level and warrants the inherent complexities of a power plant. With realistic laser efficiencies of 7%–10%, the *minimum* gain should be in the range of 100 to 140.

Maximizing the target gain requires maximizing both the coupling of the driver(s) to the target and the areal density (ρR) at the point of ignition while minimizing the laser energy. The main issues are overall symmetry of the implosion, hydrodynamic stability, and control of laser–plasma instabilities. The implosion hydrodynamics has been largely addressed through modeling and experiments. The physics of the laser–plasma interactions is more of a challenge. While experiments show it may be less of an issue with the shorter wavelength lasers, detailed predictive capability is still being developed. This is a fertile area for HEDLP research.

Current high-gain target designs feature an ablator layer of DT-filled low-density foam and a fuel layer of solid DT. The foam enhances laser coupling, while use of DT enhances stability (by raising the ablation velocity). Conventional direct-drive designs have gains of up to 140 with laser energies of 1.3 to 3 MJ (depending on the laser and design details). Numerous high-resolution 2-D simulations at the Naval Research Laboratory (NRL),[1,2] as well as 2-D single-mode simulations at LLNL,[3] show these designs can be robust against hydrodynamic instabilities seeded by laser and target nonuniformities (Fig. 4).

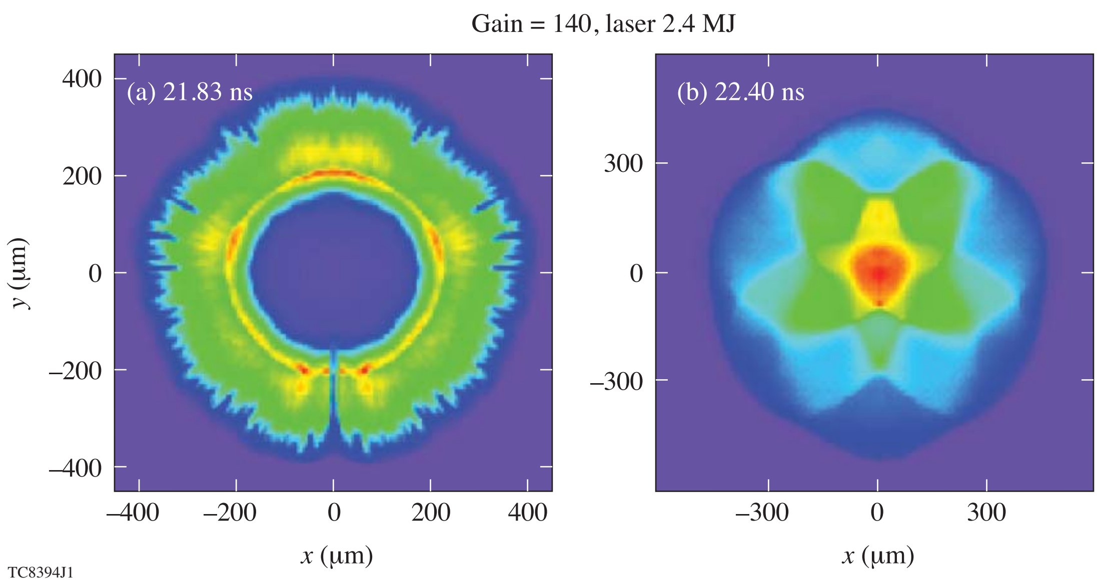

Figure 4. Snapshots of an IFE target implosion (isodensity contours) from a two-dimensional simulation (courtesy, A. J. Schmitt, NRL).[2] Hydrodynamic instabilities cause density nonuniformities in the dense shell during the implosion (at 21.83 ns) and the burn phase (at 22.40 ns).

These designs have a similar level of maturity as indirect-drive designs. An example of a high-gain implosion simulation is shown in Fig. 4. Some designs have been carried out past burn to generate an emission spectrum to develop chamber and optics materials.

Recent work has explored the advantages of going to shorter wavelengths, such as would be available with a krypton-fluoride (KrF) laser (wavelength of 248 nm) versus the more common tripled neodymium glass laser (351 nm). Deeper ultraviolet (UV) light allows higher intensities before exceeding the threshold for laser–plasma instabilities, allowing higher ablation pressures and a concomitant reduction in acceleration distance. This reduces the susceptibility to hydrodynamic disruptions. Recent designs show gains of 60 with KrF lasers as low as 500 kJ (Ref. 4), and fusion-class gains of 140 with KrF lasers with energy as low as 1.1 MJ (Ref. 5). This wavelength advantage is partially offset by the potential for greater anticipated wall-plug efficiency with diode-pumped solid-state lasers (~10% versus ~7% with KrF).

Further gain increases may be possible with *shock ignition.*[6] The laser applies a short (few hundred picoseconds), high-intensity (~10^{16} W/cm^2) pulse near peak compression. This pulse launches a shock to ignite the target. Shock ignition requires laser configurations and targets that are very similar to conventional direct drive. The same advantages with the deeper UV light from a KrF laser may apply as well. Some shock-ignition designs predict gains of 140 with laser energies of only 500 kJ (with a KrF driver).[5] The practical (economic) advantages for IFE are significant. Shock ignition is described in greater detail in Sec. 7.2.3.

7.1.2 Fast ignition

In fast ignition (FI) the target is compressed to high density with a low implosion velocity and then ignited by a short, high-energy pulse of electrons or ions. This is the gasoline engine analogy described in the introduction to Sec. 7. Fast ignition has two potential advantages over conventional hot-spot ignition: higher gain, because the target does not need to be compressed as much (~300 versus ~ 600 g/cc), and relaxed symmetry requirements because ignition does not depend on uniform compression to very high densities. The fast-ignition concept for inertial confinement fusion was proposed[1] with the emergence of ultrahigh-intensity, ultrashort pulse lasers using the chirped-pulse–amplification (CPA) technique.[2] The target compression can be done by a traditional ICF driver (direct-drive by lasers or ion beams, or indirect drive from x rays using a hohlraum driven by nanosecond lasers, ion beams, or a *Z*-pinch). The ignition is initiated by a fast laser pulse (the so-called "ignitor pulse"), which produces a high-energy electron or ion beam when it interacts with the target. In a conventional "hot-spot" ignition design, approximately 50% of the driver energy is used to form the hot spot.[3] The gain can be higher for fast ignition if the total energy of the compressor and ignitor drivers is less than that required for compression of a conventional target, as is suggested by numerical simulations.

A number of different schemes for coupling a high-energy, short-pulse laser to a compressed core have been proposed. The "hole-boring" scheme[1] assumed that there would be two short-pulse laser beams, one having an ~100-ps duration to create a channel in the coronal plasma through which the high-intensity laser pulse that generates energetic electrons would propagate (Fig. 5). More recently, hole boring by the intense laser beam itself was proposed.[4]

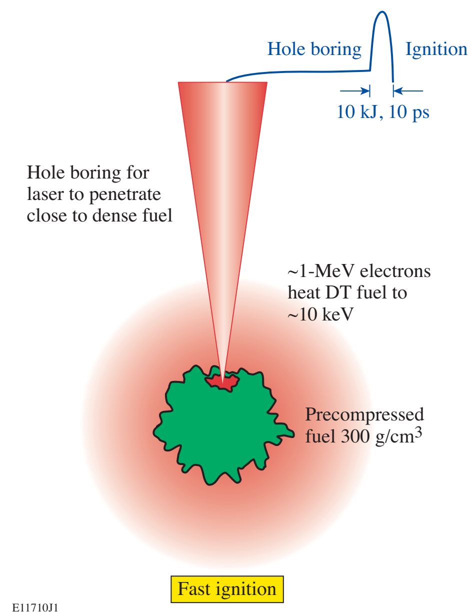

Figure 5. Schematic of the channeling and hole-boring concept first proposed for fast ignition.

An alternative design using a hollow Au cone inserted in the spherical shell[5] is illustrated in Fig. 6(a). The fuel implosion produces dense plasma at the tip of the cone, while the hollow cone makes it possible for the short-pulse-ignition laser to be transported inside the cone without having to propagate through the coronal plasma, and enables the generation of hot electrons at its tip, very close to the dense plasma. A variant cone concept [illustrated in Fig. 6(b)] uses a thin foil to generate a proton plasma jet with multi-MeV proton energies.[6] The protons deliver the energy to the ignition hot spot—with the loss of efficiency in the conversion of hot electrons into energetic protons balanced by the ability to focus the protons to a small spot.

The minimum areal density for ignition at the core (ρR ~ 0.3 g/cm^2 at 10 keV) is set by the 3.5-MeV α-particle range in D-T and the hot-spot disassembly time. This must be matched by the electron-energy deposition range. This occurs for electron energy in the ~1- to 3-MeV range. The minimum ignition energy E_{ig} is independent of target size and scales only with the density of the target as $E_{ig} \sim \rho^{-1.85}$ (Ref. 7).

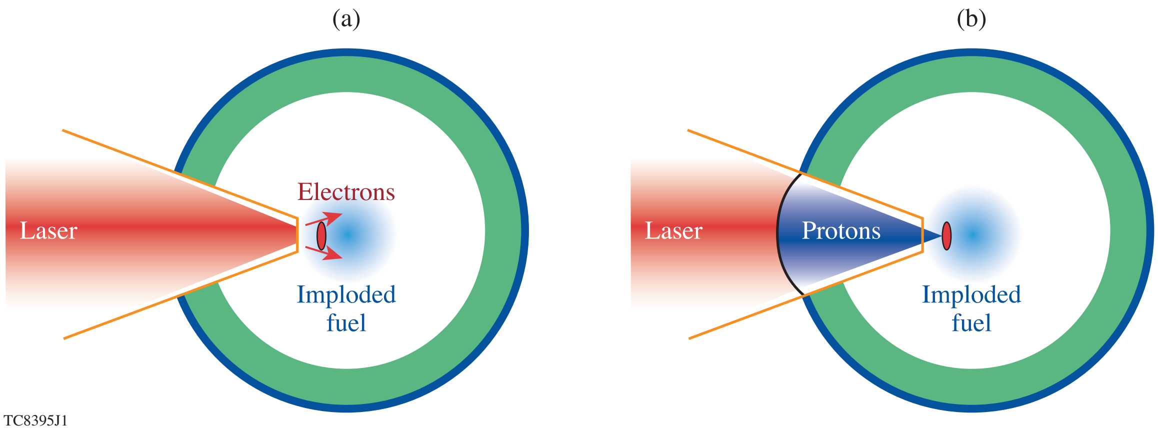

Figure 6. The cone-guided implosion concepts in which (a) electrons or (b) protons ignite the compressed fuel.

The optimum compressed-fuel configuration for fast ignition is an approximately uniform-density spherical assembly of high-density DT fuel without a central hot spot. Small hot spots and high densities can be achieved by imploding thick cryogenic-DT shells with a low-implosion velocity and low entropy.[6] Such massive cold shells produce a large and dense DT fuel assembly, leading to high gains and large burn-up fractions.

Experimental investigations of the fast-ignition concept are challenging. The fast-ignition concept involves extremely high energy density physics: ultra-intense laser (intensities $>10^{19}$ W cm^{-2}) produces a >100-Mbar pressure, a magnetic field in excess of 100 MG, and electric fields $>10^{12}$ V/m. These laser fields generate massive currents (~GA in tens of microns diameter) at the critical surface. These currents can propagate through a variety of plasma conditions, from cold, nearly solid systems to hot (~keV), dense (~g/cc) plasmas. The sheer scale of the problem, e.g., the generation of a large current pulse of tens of picoseconds time duration that traverses ~100 µm requires the investigation of this concept and inherently requires high-energy and high-power laser facilities that are now becoming available (e.g., OMEGA EP, NIF-ARC, etc).

7.1.3 Shock ignition

As in fast ignition, shock ignition[1] separates the compression of the thermonuclear fuel from the ignition trigger. The ignition process is initiated by a spherically convergent strong shock (the *ignitor* shock) launched at the end of the compression pulse (Fig. 7). This late shock collides with the return shock driven by the rising pressure inside the central hot spot and enhances the hot-spot pressure. Since the ignitor shock is launched when the imploding shell is still cold, the shock propagation occurs through a strongly-coupled dense plasma. Understanding the generation and propagation of strong shocks in high energy density, strongly coupled plasmas is important to the success of shock ignition.

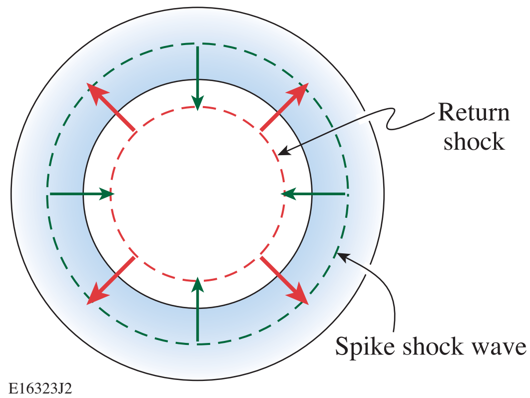

Figure 7. Schematic of the shock-ignition concept. A spherically convergence shock is launched at the end of the laser pulse and collides with the return shock, raising the hot-spot pressure and triggering the ignition process.

If timed correctly, the shock-induced pressure enhancement triggers the ignition of the central hot spot. In laser direct-drive shock ignition, the capsule is a thick wetted-foam shell [Fig. 8(a)] with a low (~2 to 3) initial aspect ratio driven at a relatively low-implosion velocity of ~250 km/s. The compression pulse consists of a shaped laser pulse designed to implode the capsule with a low entropy to achieve high densities and areal densities.

Massive shells compressed at a low entropy are optimal for high gains. The large mass of thermonuclear fuel leads to high fusion-energy yields and the low entropy leads to high areal densities and large burn-up fractions. Because of their low velocities, the central hot spot of such massive shells is too cold to reach the ignition condition with the conventional ICF approach. An external mechanism is required to heat up a small fraction of the DT fuel to ignition-relevant temperatures. In shock ignition, such an external trigger is a spherically convergent shock launched after the compression pulse. The ignitor shock can be launched by a spike [Fig. 8(b)] in the laser intensity on target or by particle beams incident on the target surface.

Recent theoretical work[1] and two-dimensional hydrodynamic simulations[2] have suggested that ~250 kJ of UV 351-nm-wavelength laser light could be enough to implode a DT wetted-foam capsule to achieve high densities (~600 g/cc) and high areal densities of ~1.2 g/cm^2. An ignitor shock launched by a 150-kJ spike in the laser power at the end of the compression pulse is predicted to ignite the central hot spot and trigger a propagating burn wave. The amount of laser energy used to drive the shock (150 kJ) is three times larger than the minimum energy required for 1-D marginal ignition (~50 kJ). The resulting energy gain is about 60. Shock ignition can be more efficiently implemented using krypton-fluoride (KrF) lasers. The KrF laser architecture makes it easy to change the focal-spot size during the implosion and to focus[3] the laser light onto the target during the late spike in the laser power. This leads to a better coupling of the laser energy to the capsule and a stronger shock wave. The deep blue light of KrF lasers (248 nm wavelength) increases the laser-light absorption and the hydrodynamic efficiency of the implosion. Gains over 100 are predicted for 351-nm light and a driver energy of 1 MJ, or 248-nm light and a driver energy of about 500 kJ. Figure 8(a) shows a typical wetted-foam target design for shock-ignition experiments on the NIF. The UV laser pulse shape shown in Fig. 8(b) is designed to achieve 1-D marginal ignition with 250 kJ in the compression pulse and 50 kJ in the shock-launching power spike.

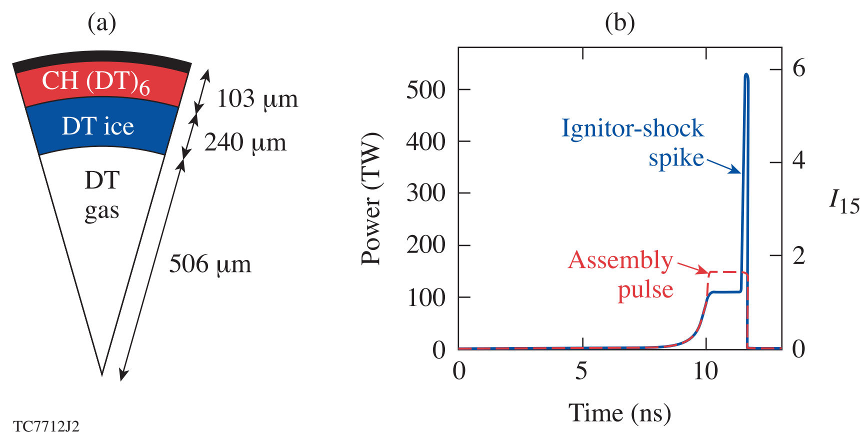

Figure 8. (a) Wetted-foam target and (b) 1-D marginal ignition 300-kJ UV laser pulse with (solid curve) and without (dashed) the shock-driving power spike. [From Ref. 1]

Recent experiments[4] carried out on the OMEGA laser have tested the shock-ignition concept using surrogate plastic shells filled with D_2 gas. The capsules were imploded with the 60 UV beams of the OMEGA laser using pulse shapes with and without the final power spike designed to drive a late shock. The total energy in the laser pulses was kept constant. These experiments showed that fusion yield and target compression are significantly enhanced by the late shock. The measured neutron yield increased about fourfold, while the areal density rose by up to 50% when the late shock was applied.

A possible detrimental effect in shock ignition is the preheat of the target caused by the hot electrons produced by laser–plasma instabilities during the high-intensity spike. Similar to conventional direct-drive ICF, a preheated target would lead to a lower areal density and to the inhibition of the ignition process. However, the shock-ignition scheme is more resistant to hot-electron preheat since the areal density at the time of the high-intensity spike is already large enough to stop hot electrons with moderate energies (<150 keV) within a relatively thin outer layer of the target. This would prevent preheat of the inner portion of the shell and significantly reduce the areal-density degradation. By depositing their energy within a thin-outer-shell layer, hot electrons may enhance the ignitor shock strength. Experimental data is unavailable on hot-electron production in long-scale-length plasmas at shock-ignition-relevant intensities (~10^{16} W/cm^2). Whether hot electrons are beneficial or detrimental to shock ignition depends on their energy distribution, directionality, and laser-to-electron conversion efficiency. This is an opportunity for research in shock ignition.

Shock ignition has the potential to achieve high gains exceeding 100, with relatively low driver energies below 1 MJ. The potential to use smaller drivers could improve the economic viability of inertial fusion energy. It should be noted that in all IFE power plant studies based on conventional direct drive, the laser represents one third to one half of the capital cost.[5]

7.1.4 Heavy-ion fusion

Heavy-ion beams have a number of potential advantages as drivers of targets for inertial fusion energy. Fast heavy ions can have a range exceeding the mean-free-path of thermal x rays, so that they are able to penetrate and deposit most of their energy deep inside the targets. This implies that no “entrance hole” is needed for indirect-drive targets, and that efficient volumetric deposition is possible for directly driven targets. Heavy-ion beams lose energy in dense target plasmas primarily by slowing down in collisions with plasma electrons traveling slower than the beam ions. When the beam ion-kinetic energy far exceeds the target electron temperature and the target plasma is many orders of magnitude more dense than the beam ion density, the stopping of heavy ions is virtually classical (negligible effects of weak collective instabilities) and virtually 100% efficient (small scattering loss compared to the energy loss on plasma electrons). As such, intense heavy-ion beams can efficiently heat indirect-drive fusion hohlraum targets (for conversion to x rays)[1] or the ablators of direct-drive fusion capsules.[2] Recent advances in generating, compressing, and focusing intense ion beams in the presence of a neutralizing background plasma[3,4] enable heavy-ion beams of modest energy and cost to produce uniform volumetric heating for nanosecond time scales of the order of hydrodynamic response time, enabling cost-effective accelerators to study the target physics for heavy-ion fusion.

Heavy-ion fusion, similar to other IFE approaches based on central hot-spot ignition driven by either particle or laser beams, requires

- beams focused to spot sizes of a few millimeter radius from a distance of several meters—to protect the final optics,
- a total driver energy of about 1 MJ provided by about 100 beams—for target illumination symmetry,
- beam power strongly increasing in time over about a 10-ns pulse time for efficient fuel compression,
- beams accurately aimed (with some active steering) toward targets injected at several hertz pulse rates for fusion yields of the order of 100 MJ, and

- a product of driver efficiency and target gain of about ten for good plant power balance.

Particular motivation for using heavy-ion accelerators for inertial fusion energy (IFE) has been documented in many national reviews:[5]

1. Worldwide experience with high-energy accelerators supports the prospect that a heavy-ion driver for inertial fusion energy can achieve the necessary efficiency, pulse-rate, and durability;
2. Focusing magnets are expected to survive target radiation and debris;
3. Ion-target coupling is expected to be very efficient and predictable; and
4. Heavy-ion beams can propagate in the vapor pressure of thick-liquid-protected chambers to increase the lifetime of the fusion chamber structural materials.

The heavy-ion-beam pulse length for efficient induction acceleration (~200 ns) must be temporally compressed by more than 10× by ramping up the beam velocity going from the front of the beam to the rear of the beam. Ramping the beam velocity during the drive pulse increases the ion range in the target, which could lead to much higher hydrodynamic coupling efficiencies in direct drive (>18% of the beam input energy ends up in the target kinetic energy).[2] Figure 9 illustrates why strongly increasing the ion range during the drive pulse enables the high-coupling efficiency.

Analytic models suggest that heavy-on hydrocoupling efficiencies up to 25% may be possible, which is sufficient to compress DD-fuel layers with enough areal density to convert neutron energy into plasma energy for direct conversion.[6]

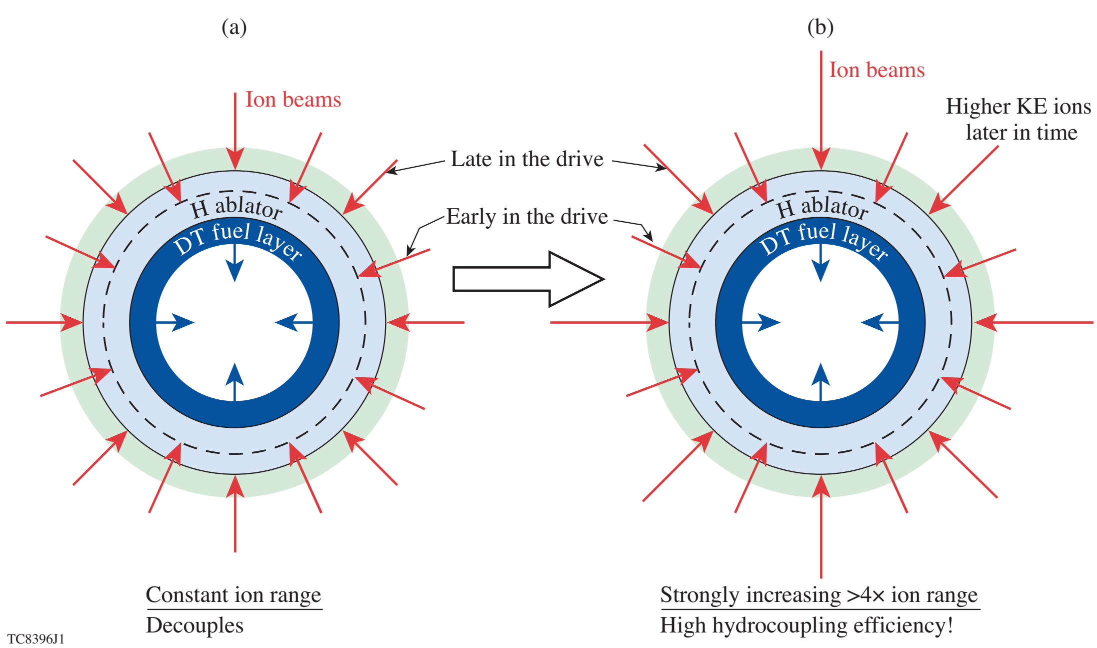

Figure 9. Increasing ion range during ablative direct drive increases hydrocoupling efficiency.

The prospects for heavy-ion-fusion depend on many research areas that can be investigated on existing or near-term upgraded facilities. For brevity, we mention only a few here: 2-D Rayleigh–Taylor stability using oblique-ray illumination with rotating ion-beam spots using radio-frequency wobblers; beam neutralization with plasma in strong magnetic fields;[7] collective stability properties of intense ion beams;[8] and ionization and stripping cross sections.[9]

7.1.5 *Z*-pinch IFE

In the mid-1990s, pulsed-power-driven, wire-array *Z*-pinch experiments generated nearly 2 MJ total x-ray yield and up to 240 TW of peak power from 11 MJ of stored electrical energy. The possibility that a suitable scaled-up pulsed-power machine might be used to achieve indirect-drive inertial confinement fusion breakeven and even high yield was an obvious implication of those results.[1] Recent work[2] has indicated the possibility of coupling stored electrical energy into a fusion-fuel implosion directly by means of the $J \times B$ ("pinch") force produced by the current near the outer surface of the imploding structure. The energy transfer efficiency from the primary storage into the fusion fuel can be substantially higher[2] than by using the indirect-drive approach. The fuel can be magnetized before the main phase of the implosion,[3] somewhat similar to what is being studied in the magnetized target approach (see Sec. 7.1.6), reducing heat losses from the fuel and confining fusion alpha particles.

Recent designs of a high-yield facility are based upon "linear transformer driver" (LTD) technology.[4] LTD's can be operated at a high repetition rate and have been shown to be more reliable and twice as efficient as the Marx Generator technology used, at present, in most pulsed-power machines. This, plus their inherent low cost, make the *Z*-pinch approach to inertial fusion energy, as well as other concepts based on pulsed power, more attractive.

Studies have been carried out to identify a path from *Z*-pinch physics experiments currently conducted on the *Z* machine to an economically attractive IFE power plant. Although not exhaustive, these studies point to a power plant with a low repetition rate (less than one pulse per second) and multigigajoule yield per pulse using a concept that uses a transmission line made of recyclable material.[5,6] Issues that must be addressed for this approach to IFE are related to *Z*-pinch physics, to the coupling of energy from the energy-storage capacitors to the *Z*-pinch, to the development of highly reliable components in the LTD modules, and to the protection of the IFE chamber from high-yield fusion explosions.

Z-pinch physics is being studied predominantly with wire-array *Z* pinches.[1] Figure 10(a) shows how the $J \times B$ force drives a wire-array *Z*-pinch. Since the mid-1990s, substantial progress has been made in understanding the dynamics and radiative properties of these plasmas at up to ~20 MA on the *Z* machine and at the 1-MA level in university experiments. There has also been considerable progress on ICF capsule and hohlraum designs that would meet the radiation symmetry needed for indirect-drive inertial fusion [Fig. 10(b)]. However, predictive capability is not yet established through the validation of theoretical models in computer simulations. Based on present experiments on *Z* and other machines, it is not yet possible to determine the current and pulse length in a pulsed-power machine needed to achieve high yield. At the higher current and power of the next-generation *Z*-pinch machines, it will be possible for thin foils[7] or gas puffs[8] to replace wire arrays as the optimized initial state for ICF experiments and, eventually, for IFE.

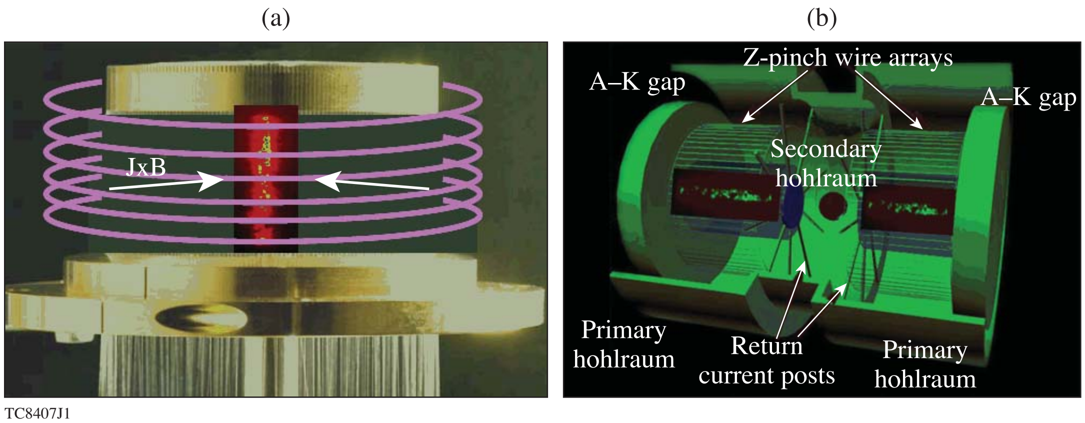

Figure 10. (a) A cylindrical wire-array Z-pinch with ~300 wires carrying current in parallel is illustrated (lower part). The $J \times B$ force (J is the axial current density, B is the azimuthal magnetic field) acts to implode and heat the wire-generated plasma (upper part). (b) Double ended hohlraum target. The x rays from two wire-array *Z*-pinch implosions are used to drive an ICF target.

The success of Z-pinch IFE will require control of MHD instabilities[3] at high energy density in the *Z*-pinch–implosion process regardless of whether the plasma is initiated from a wire array or a foil. It will require an understanding of radiation emission and transport in high-*Z* HED plasmas that undergo rapid ionization upon convergence onto the axis. The formation of fast-particle beams at different stages of the implosion and their effect on the behavior of the fusion target may be quite important in some *Z*-pinch fusion systems. At the currents and pulse lengths expected to be required to make high fusion yields possible, the opacity of the x-ray source may limit the conversion efficiency of magnetic energy into x-rays. This work (except for the studies of fast-particle beams) is presently supported by NNSA.

The development of highly efficient LTD drivers is important to the economic viability of *Z*-pinch–based IFE, as is the optimization of coupling electrical energy from the capacitors in the LTD driver to the *Z*-pinch loads. As part of the latter, the physics, performance, and optimization of rep-rated power delivered through magnetically insulated transmission lines, made from relevant recyclable materials followed by impedance-matching structures, must be studied. Efficient LTD driver development and coupling to the load would be within the scope of the research carried out within an IFE driver-development program. Target chamber issues for high-yield fusion are of interest in the IFE portion of the HEDLP program, since they will have to be faced by every IFE system and involve HED plasmas (at the very least at the "warm dense matter" limit). Ablative shocks will be delivered to the liquid surfaces that will make up the bulk of the surfaces facing the fusion explosions, as well as to any wetted-wall solid surfaces that may directly view the explosions. Shock-mitigation schemes, such as entrained voids in flowing liquids and using metallic foam solids, should be investigated because they will benefit all IFE approaches. These can be studied in the near future using existing facilities.

7.1.6 Magneto-Inertial Fusion

All fusion systems must maintain a high temperature for long enough to allow the fuel to ignite and burn. Magnetic fields can reduce the thermal conductivity perpendicular to the field. This is the fundamental basis for any concept in the magnetic-fusion-energy program. Theoretically, magnetic fields in an inertial fusion approach would allow significant advantages, such as reduced implosion velocity and operating with lower energy density.[1–5]

The potential reduction of the required energy density and total required energy assuming a magnetic field embedded in the fuel is shown in Fig. 11. Assuming a temperature of 10 keV, then fuel density (or pressure) determines the characteristic scale length needed to achieve breakeven in the presence of diffusive energy loss. The scale length, assuming a spherical or quasi-spherical geometry, then implies a minimum volume, or mass given the density, or thermal energy given the 10-keV temperature, which leads to the plot in Fig. 11 (mass on the left, and energy on the right).[6] It is shown that working with density considerably higher than in typical magnetic systems leads to much reduced system size and energy, but requires working at pressures that exceed normal material strength, which implies the use of a pulsed system.

Magneto-inertial fusion (MIF) systems allow ignition-relevant fusion parameters to be achieved with reduced power input, or implosion velocity.[3] For some parts of this parameter space the requirement for "high gain" might be relaxed if more electrically efficient drivers than lasers were used for compressing and heating the fuel.[7,8] In some versions of MIF an additional benefit comes from the better confinement of alpha particles in the burning fusion plasma.

Magnetic fields for inertial fusion have, to date, received relatively little attention. Preliminary analyses have shown that HEDP-magnetized plasmas will still be susceptible to a variety of small-scale instabilities leading to enhanced transport.[9] However, because of much shorter confinement times (compared to MFE systems), the margin on the acceptable transport enhancement is much wider. As research progresses from basic scientific studies to practical and economic considerations, the potential improvements made possible by magnetic fields are likely to attract interest.

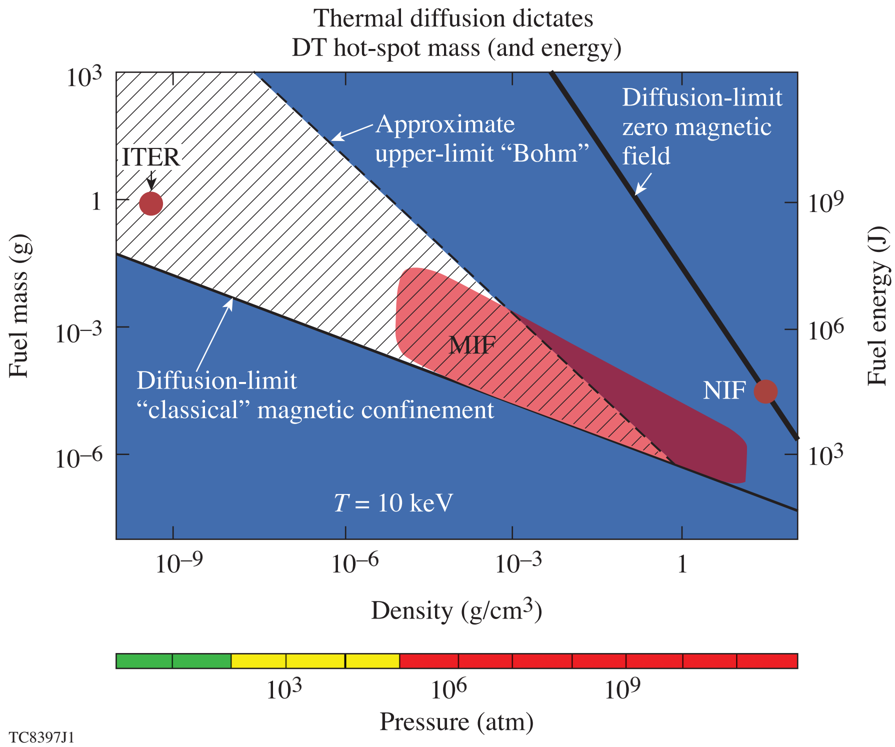

Figure 11. Required mass for fusion gain of unity (or required energy assuming kT = 10 keV) as function of fuel density (or pressure).

One way magnetic fields are presently used is by imploding and shocking material into high energy density conditions. High-power *Z*-pinches, like the ones developed at Sandia National Laboratories (described in the previous section), allow efficient conversion of pulsed electricity into several MJ of x-ray energy for the purpose of imploding various inertial fusion targets. Direct *Z*-pinch implosions of DT fibers, gas puffs, or various other target designs may also lead to net fusion gain.[10,11] A lower-voltage type of implosion system, such as the Shiva Star facility at the Air Force Research Laboratory (AFRL) in Albuquerque, uses liners (conducting metal shells) in cylindrical or quasi-spherical geometries to achieve slower but highly precise implosions to Mbar conditions of compressed magnetic flux, compressed plasma, or a combination of the two.[12] An advanced type of implosion, based upon focused jets of plasma,[13] is also being studied for example at the HyperV company. The purpose is to accomplish both target formation and pusher acceleration with hardware that is well separated from the pulsed burst of fusion energy generated at the focus of the implosion.

Exploratory experiments at the AFRL and Los Alamos National Laboratory, working in collaboration with the University of Nevada at Reno, the University of New Mexico, and the University of Washington,[14] are planned in the next few years to study liner-compression of preheated plasmas. The goal is to use an imploding metal liner to compress magnetic fields and plasma.

The plasma target will be a field-reversed magnetic configuration with an initial temperature of 100 to 300 eV, injected into a 10-cm-diameter aluminum liner (Fig. 12). Peak compression magnetic fields of about 5 MG and peak temperatures of several keV are projected with plasma beta close to unity.

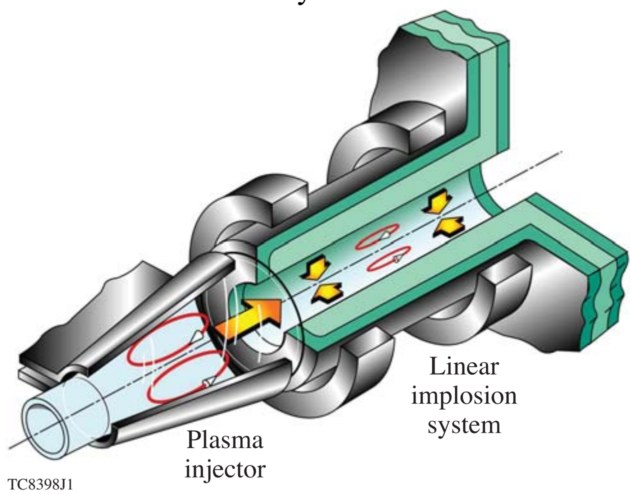

Figure 12. Schematic of the injection and implosion of a magnetized target plasma.

Cylindrical implosions driven with laser ablation have recently been used at the University of Rochester to study compression of magnetic flux trapped by a shock-heated deuterium plasma.[15] Compressed magnetic fields of several megagauss (MG) have been inferred for implosions with ~0.1 MG initial (seed) field. The goal is to quantify the effect of the compressed field on the hot-spot energetics, including possible thermal insulation for improved nuclear yield designs.

If generating fusion-relevant temperatures and significant neutrons is successful, this work would point the way toward exciting opportunities for further study.

7.2 SIMILARITIES WITH THE MFE PROGRAM

Although funded by multiple agencies with different missions, the U.S. IFE research effort has a structure that exhibits many similarities with the OFES-funded Magnetic Fusion Energy (MFE) program. The U.S. MFE program structure is based on a leading concept—the tokamak—accompanied by a substantial effort on alternative approaches to MFE, the so-called Innovative Confinement Concepts (ICC’s) or Alternates. Based on the performance of past and current experiments, the tokamak appears to be the most promising approach to achieve burning-plasma conditions in the next 15 years. The International Thermonuclear Experimental Reactor (ITER) is the result of an intense international collaboration to build a burning-plasma experiment based on the tokamak concept. While the tokamak has been selected as the premiere burning-plasma experiment, a strong ICC program is justified by the fact that alternative magnetic configurations present some major engineering advantages, with respect to the tokamak, when extrapolated to a reactor size.

The inertial confinement approach to fusion has followed a similar path. After decades of research, the conventional direct- and indirect-drive approaches to inertial fusion had reached a level of maturity ripe for a burning-plasma experiment. Like ITER, the National Ignition Facility (NIF) in the U.S. and the Laser Megajoule Facility in France, are the two largest ICF facilities designed to achieve thermonuclear ignition and moderate energy gains (~10 to 20). Both laser systems are based on the rather inefficient flash-lamp–pumped neodymium glass amplifier technology. Economically attractive IFE reactors require energy gains in excess of 100 and more efficient drivers. The product of wall-plug efficiency and target gain should reach values of ~10 or higher. Like the ICC's in MFE, alternative IFE concepts offer prospects for improved fusion-energy systems. Some IFE alternatives, such as fast ignition and shock ignition, are expected to achieve high gains at modest driver energies by using a two-step approach to ignition. High-gain direct-drive promises higher driver efficiencies by employing krypton-fluoride or diode-pumped lasers, and larger fusion gains by using wetted-foam cryogenic targets. Magneto-inertial fusion uses embedded magnetic fields to improve the plasma-energy confinement, thus reducing the requirements on the target-implosion velocity and driver input power. Heavy-ion and Z-pinch fusion take advantage of the high wall-plug efficiency and of the use of liquid walls.

Similar to the innovative confinement concepts in MFE, the IFE alternative concepts play a crucial role in developing inertial fusion energy, since high gains and high driver efficiencies are required features of any economically viable IFE power plant.

8 HEDLP SCIENCE APPLICATIONS TO OTHER FIELDS

This chapter provides a sampling of the vast array of new science and potential future applications of HEDLP science. The ability to produce electric fields that are orders of magnitude larger than those produced in any other medium enables applications in particle acceleration, ranging from next-generation accelerators for high energy physics, to proton sources for radiation oncology. The ability to produce strong shock waves, to ionize matter at very high pressures, and to generate significant radiative energy fluxes and enormous magnetic fields enables applications in astrophysics and planetary physics. The prospect of large neutron fluxes from fusion ignition opens the door to potential applications in nuclear physics. The precise ability to control, at the quantum level, the interaction of light waves with plasmas and with ions enables unique radiation sources with applications from clinical medicine to biological research to fundamental condensed-matter science. These advances will not only lead to advances in fundamental understanding of the universe, but will also lead to new technologies that have the potential to benefit society in many ways, from healthcare to defense to commerce. We consider here the origins of these capabilities and underpinning technologies before turning, in the remainder of this section, to discuss some examples.

HEDLP science emerged during the 20th century from other fields of research. The first scientists to consider ionized, highly compressed matter in which radiative energy transport was important were Eddington and others who strove to understand the structure of stars. The scientists who developed nuclear weapons made further advances in these areas and were among the first to face the challenges of warm dense matter. With the invention of the laser came the potential for research toward achieving inertial confinement fusion. This work launched the development of facilities throughout the 1970s that could produce HED conditions in the laboratory.

The 1980s saw the emergence of laboratory HED physics through the development of versatile facilities with improved diagnostics, the growth of the first user facility program (at OMEGA), the demonstration of solid-density plasmas that could emit short bursts of x rays, and the initiation of research into laser-based particle accelerators. In addition, the invention of chirped pulse amplification in this same era enabled the compression of laser energy in time as well as space, leading by now to the production of laser pulses a few femtoseconds (10^{-15} s) in duration, laser intensities of 10^{22} W/cm^2, and laser-based harmonic pulses lasting only tens of attoseconds (1 as = 10^{-18} s). Present-day facilities can produce HED conditions on time scales of attoseconds to microseconds and with energies ranging from a fraction of a joule to megajoules. These capabilities have in turn led to the production of pressures of hundreds of megabars, shock waves moving hundreds of km/s, radiation sources producing temperatures of millions of degrees or yielding megajoules of x rays, large-scale and table-top sources of coherent laser-like x-ray beams, laser-based accelerators producing GeV electron beams and HED particle-beam-based accelerators producing electron beams of tens of GeV. These capabilities and accomplishments in turn feed the very broad range of existing and potential future applications of HED science and technology.

The following sections provide brief overviews of the applications of HEDLP science to other fields such as astrophysics, planetary physics, nuclear physics, accelerator physics, medicine, condensed-matter physics, and material science.

> **Finding**. *HEDLP experiments can greatly benefit other fields of science. Research in high energy density plasma physics has the potential to address fundamental science issues relevant to astrophysics, planetary physics, nuclear physics, condensed-matter physics, material science, particle-beam physics, and atomic and molecular physics.*

8.1 APPLICATIONS TO ASTROPHYSICS

Today's HED experimental facilities, such as high-power lasers and magnetic pinches, can place millimeter-scale quantities of matter in extreme states of density, temperature, or velocity. This has created the field of HED laboratory astrophysics, which studies the properties of matter and the processes that occur under astrophysical conditions. Figure 13 illustrates just a small subset of possible areas of research: Eagle nebula dynamics and stellar birth [Fig. 13(a)]; stellar dynamics, as demonstrated by Eta Carinae [Fig. 13(b)]; and stellar death via violent supernova explosions, as illustrated by Cassiopeia-A [Fig. 13(c)]. Additional fertile areas of study include x-ray absorption

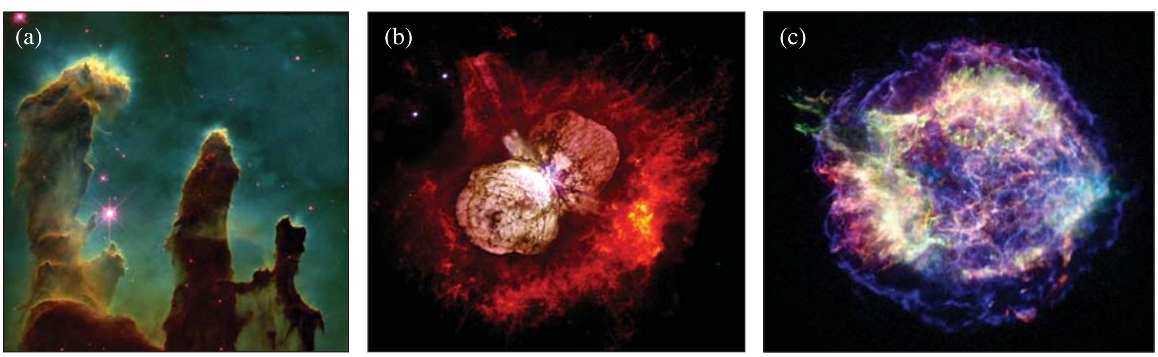

Figure 13. (a) Hubble Space Telescope optical image of the "Pillars of Creation" from the Eagle Nebula, also known as Messier Object 16 (M16) or NGC 6611. The Eagle Nebula is located in a region of active star formation at a distance of ~2 kiloparsec. (b) Hubble Space Telescope optical image of Eta Carinae, one of the most massive stars in the universe, with probably more than 100 solar masses, located at a distance of 3 kiloparsecs in our galaxy. (c) Chandra Observatory x-ray image of Cassiopeia A, the remnant from a core collapse supernova that exploded 300 years ago in our galaxy at a distance of 3 kiloparsecs.

relevant to stellar interiors, strong-shock-driven nonlinear hydrodynamics and radiative dynamics relevant to supernova explosions and supernova remnants, protostellar jets and high-Mach-number flows, radiatively driven molecular clouds and photoevaporation fronts, and photoionized plasmas relevant to accretion disks around black holes and neutron stars. A number of review articles have been written on HED laboratory astrophysics.[1–6] The topics discussed below are described in detail in these review articles, and in the extensive references therein.

Shock waves are ubiquitous in the universe, arising generally where an energy release or a collision creates a supersonic interaction. The astrophysical matter is very often ionized and at high temperature. Because HED facilities can readily create very strong shocks in ionized matter, they have the potential to generate conditions relevant to a variety of systems involving astrophysical shocks. One specific, well-developed application is the destruction of localized clumps of material by shock waves. Experiments were conducted on the Nova laser and the OMEGA laser in which a shock wave impacted a spherical clump of material and the subsequent evolution was observed by radiography. Such experiments are well-scaled to some astrophysical systems, including the Puppis A supernova remnant. Early experiments[7] have been used directly[8] to interpret the evolutionary stage of an observed structure in Puppis A by direct comparison with the experimental data (Fig. 14).

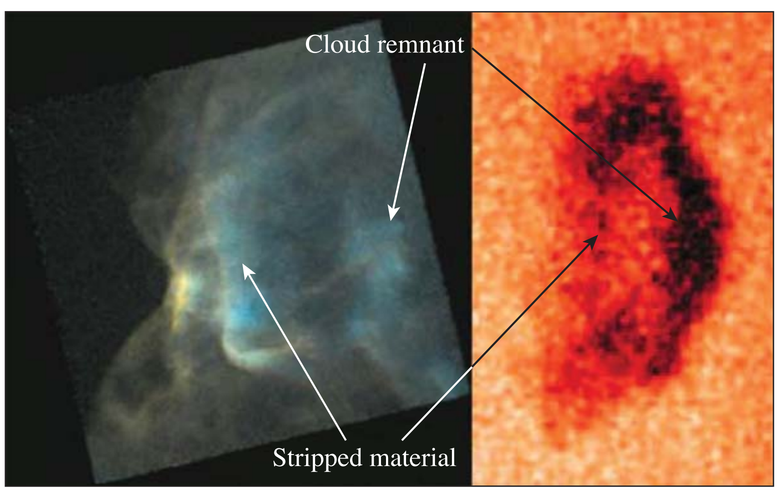

Figure. 14. Astrophysical (Chandra Space Telescope, left) and laboratory (Nova laser, right) data showing the destruction of a clump of material by a shock wave. The laboratory data[7] were used to interpret the astrophysical image.[8]

Shock waves play an important role in core-collapse supernovae (SNe), one of nature's most spectacular explosions, which release ~10^{53} ergs of energy in a few seconds due to the gravitational collapse of the core of a massive star. The details of how this collapse occurs, and how it triggers the spectacular explosions seen around the universe are very active areas of research. Fundamental uncertainties remain about how matter from the stellar interior is ejected so early in time and at such high velocities. Laboratory experiments on OMEGA are addressing the hydrodynamically unstable flow evolution during the explosion of the material outside the collapsed core. They do so by creating a shock-driven system whose shape and evolution are well-scaled to those of the supernova.[9] Other OMEGA experiments are producing radiative shock waves whose key dimensionless parameters are in the regime corresponding to the emergence of shocks from supernovae.[10] Meanwhile, ultrafast laser experiments using atomic clusters are exploring radiative cooling instabilities relevant to shock waves in the interstellar medium.[11]

There are many other possible applications of HED facilities to shock waves in astrophysics. Examples include shock waves generated in star formation, mergers of neutron stars, stellar winds sweeping past planets, protostellar jets interacting with the interstellar medium, and in supernova remnants, whose aftereffects ripple and reverberate through the galaxy for thousands of years.

Jets in astrophysics are also ubiquitous, from the bipolar protostellar jets launched during star formation to spectacular, highly collimated galactic jets launched across megaparsecs of intergalactic space from active galactic nuclei. Yet our understanding of these impressive objects is far from complete. The production and propagation of jets has been an extremely active area of work in HED experiments, which have use a range of laser and pulsed-power facilities. Jets have been produced by ejecting laser-driven material through a collimator[12] or by generating colliding flows of plasma,[13] as well as by magnetic launching.[14] An active multinational European collaboration of laboratory scientists and astrophysicists (the JetSet) is funded to pursue connections between the two.

Understanding stellar evolution is one of the longest-standing goals of astronomy and astrophysics, yet major questions and discrepancies remain. With regard to our own sun, there is a significant discrepancy between the predicted location of the boundary where the heat-flow changes from radiative heat conduction to convection, and that measured by helioseismology. The Z facility has produced plasmas having the densities and temperatures that are present in the solar convection zones. Irradiating these plasmas with a measured source of x rays has enabled direct measurement of the x-ray absorption rate of iron, testing the calculations in the solar models.[15] Future HED facilities will be able to produce and use plasmas corresponding to increasing depth in the sun. Another application has been the use of similar techniques for detailed validation of the computational models of x-ray absorption, also in Fe. These models were central to understanding the observed brightness oscillations of stars known as Cepheid variables, which are used as “standard candles” distance indicators in cosmology.

HED experiments may also contribute to the understanding of many other astrophysical systems. Accreting black holes or neutron stars are some of the most interesting objects in the universe. As black holes accrete material, incoming matter is gravitationally pulled into orbit around the black hole, becoming its spiraling "accretion disk," and only some material eventually slips through the "event horizon" into the black hole. In the case of an accreting neutron star, the matter swept inward through the accretion disk crashes into the neutron star surface. Both scenarios yield prodigious sources of continuum x rays, since the matter gets viscously heated as it gets "squeezed" inward toward the central compact object. These x rays then photoionize the nearby plasma environment, which, in turn, fluoresces, giving tell-tale hints about what is going on very near to these exotic objects. Interpreting these hints requires simulations of the accretion-disk dynamics, using an experimentally validated model of plasma photoionization in the relevant regimes. Photoionization experiments have been developed and researchers are now working to increase their relevance. Fascinating questions such as these can be actively pursued in laboratories of current and future facilities.

Dense molecular clouds are often referred to as stellar nurseries. Clumping in molecular clouds, possibly enhanced by shocks, can create the localized high-density regions that are necessary for star formation. Once a star begins to burn, the emitted, intense, UV radiation ablatively sweeps away regions of the surrounding molecular cloud. The dynamics of this interaction lead to the formation of columns or pillars, such as those of the famous Eagle Nebula, in which several protostars have been observed. It is not clear how these columns are formed. One model suggests they are formed by a Rayleigh–Taylor instability. Another posits they are formed when pre-existing dense clumps shadow the regions behind them. Well-scaled experiments of such systems are now possible, and could provide discriminating tests of these different models of pillar formation.

Dust in the center of molecular clouds is the dominant radiator, controlling the thermodynamic balance of the cloud, and thereby (indirectly) controlling when molecular clouds become dense and cool enough to start the gravitational collapse to form a star. A key uncertainty is the dust size distribution in molecular clouds and in interstellar space. To address this uncertainty, the recent NASA Stardust mission collected dust from a cometary tail, catching the dust in aerogel foam catchers, and returned this dust to earth to be examined for clues about the conditions in the early galaxy. A number of questions have emerged from initial analysis of these dust grains returned to earth. Scaled experiments can be developed to improve our understanding of hypervelocity dust-impact and shock processing dynamics. This area is largely untouched experimentally, yet holds enormous potential for fascinating research on current HED facilities, small and large.

The frontiers of astrophysics are often defined by the most energetic phenomena of the universe, which constitute the field of high energy astrophysics (HEA). Classic HEA objects include black holes, neutron stars and magnetars, pulsars and their wind nebula, active galactic nuclei and their jets, and gamma-ray bursts. In many HEA phenomena, magnetic fields and electron–positron pairs are believed to play important roles, even though their presence can be inferred only indirectly and is model-dependent. Existing and future facilities can perform scaled experiments in relevant parameter regimes to help answer some of the fundamental problems in HEA. Experiments on the Titan laser have already demonstrated the generation of relativistic positron densities of $\sim 10^{16}$ positrons/cm^3, the highest ever created in the laboratory;[16] and experiments relevant to γ-ray bursts and ultrarelativistic particle outflows from pulsar winds are being designed for OMEGA EP. A wealth of exciting research opportunities for experiments on both small- and large-scale facilities exist in this area.

8.2 APPLICATIONS TO PLANETARY PHYSICS

From early observations, by ancient astronomers, of wandering lights among the starry skies, to present-day catalogs of over ~300 planetary worlds outside our solar system, the existence of these exoplanets, and their unknown conditions, have fueled our imagination and curiosity. While much has been learned in the last few decades, surprisingly little is known with certainty about the formation and evolution of planets even in our own solar system. Their composition, internal structure, and dynamics remain a mystery.[1] The evidence for hundreds of planets orbiting neighboring stars,[2] with the possibility of yet undiscovered Earth-like planets, is of central importance to the search for life beyond Earth, and has invigorated further research in planetary science.

Lacking the ability to directly probe the deep internal structure of planets, knowledge of planetary interiors relies on theoretical models that are often beset by large uncertainties.[1] Planetary interiors are known to exist in moderately extreme states of pressure, density, and temperature, where standard theoretical treatments for cold, condensed matter, or hot, ionized plasma are not well suited. In addition, such internal pressures often exceed those attainable with conventional laboratory methods, such as diamond-anvil cells or gas guns, making reliance on theoretical models a seeming inevitability. This is starting to change with the advent of high energy density facilities, such as intense lasers and pulsed-power machines. These facilities can recreate the conditions found in planetary interiors, and can be used to experimentally test theoretical models to improve our understanding of the formation, evolution, and structure of planets.

As an example, an outstanding question is the identification of the processes that drive the internal energy of giant gas planets such as Jupiter (Fig. 15) and Saturn. It is well known that these planets radiate nearly twice as much energy as they receive from the sun.[1] It is predicted that helium separates and condenses from mixtures with hydrogen in the dense outer layers of gas giants, and "rains" downward toward the core, converting gravitational potential energy into internal heat.[3] Whether such a phase separation occurs in dense, partially ionized mixtures of helium and hydrogen at very high pressures, and how the surrounding materials affect this process, can be addressed with next-generation experiments using existing and soon to be completed, high energy density facilities.

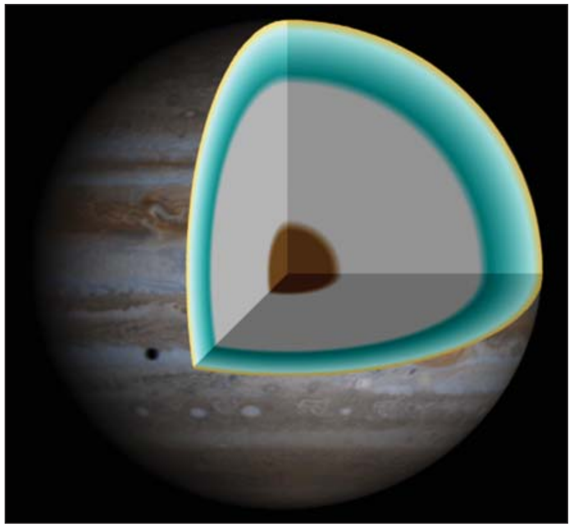

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Figure 15. Rendering of Jupiter interior. HEDLP experiments can answer questions about the interior of giant planets

As a further example of the application of high energy density experiments to understand planetary interiors, hydrogen forms a metallic, conducting state at extreme densities and pressures. This allows electric currents to flow and is believed to control the formation of magnetic fields in giant gas planets.[1] Initial experiments have confirmed the metallic phase of hydrogen,[4] but the full range of parameter space, where hydrogen transitions from an insulator to a conductor, has yet to be explored. Finally, an intriguing possibility exists in dense, metallic hydrogen and deuterium, where a nuclear-fusion reaction occurs at a much lower temperature due to electron screening of the Coulomb repulsion between nuclei—so-called pycnonuclear reactions.[5] These reactions are predicted to occur in supergiant gas planets and brown dwarfs, where temperatures are much too low to create thermonuclear reactions. Such exotic nuclear reactions might be accessible in experiments on future high energy density facilities.

8.3 APPLICATIONS TO NUCLEAR PHYSICS

With the availability of large HED experimental facilities, such as OMEGA and *ZR*, and with the next-generation HED facilities, such as the NIF and LMJ, a new capability emerges; namely, the ability to study nuclear physics in a dense, hot-plasma environment. With the added capability of ignition expected to be achieved on the NIF in the near future, the parameter space available for nuclear-physics studies broadens significantly. We will list a few areas of nuclear-plasma physics that look promising for the coming decade.

A very dense plasma environment can affect nuclear-reaction levels via screening, enhancing nuclear-reaction rates at low energies, as expressed by the electron-shielding factor. Dense, hot plasma can also excite low-lying nuclear states from which subsequent nuclear reactions occur, leading to significant differences in reaction rates, as expressed by the stellar enhancement factor. Astrophysical nuclear reactions relevant to, for example, burning in main sequence stars—the *s*-process, *r*-process, and *p*-process (including the *rp*-process and γ-process) of nucleosynthesis—may also be accessible. Each of these areas will be briefly discussed below.

Thermonuclear reaction rates in a dense plasma are different than rates assuming bare nuclei due to screening. The continuum electrons in a dense plasma tend to clump around the embedded nuclei, which has the effect of screening some of the nuclear charge, therefore, lowering the effective Coulomb potential. These screening effects occur in dense, burning plasmas both in the laboratory and in astrophysics (stellar interiors, supernovae, accreting compact objects, etc). There is the potential with ICF implosions, compared to accelerators, to access much higher densities and lower temperatures, so potentially stronger screening effects might be accessible. Results could be relevant to burning in stars, accreting white dwarfs (novae), accreting neutron stars (x-ray bursters), and supernovae.[1]

In a hot dense plasma, nuclei in an isomeric state can have a decay rate that is modified by the plasma environment. For example, the internal-conversion (IC) decay rate can be modified by the lower number of available electrons in the partially ionized atom. Various excitation processes can also take place, such as photon absorption; nuclear excitation by electron capture (NEEC), whereby a free electron is captured in an empty state of an atomic shell; inelastic and super-elastic electron scattering; and nuclear excitation by electron transition (NEET). The field of nuclear physics in hot dense plasmas, where decay rates can be modified and plasma modes of excitation can become significant, is poised to become an exciting new area of research in current and future HED experimental facilities.[2–4]

An example of nuclear reactions in dense hot plasma relevant to burning plasma in main sequence stars is the ^{3}He(^{4}He,γ)^{7}Be reaction, which is relevant to the *p*–*p* chain and neutrino production in the sun. Accurate measurements of this nuclear-reaction rate in a thermal plasma would provide better constraints on stellar models. The difficulty of obtaining relevant nuclear cross-section measurements using conventional accelerators is twofold. First, to achieve sufficient reaction rates in the ^{3}He(^{4}He,γ)^{7}Be reaction, measurements are made at He beam-kinetic energies of ~400 keV, whereas thermal energies relevant to stellar interiors are ~10× lower. Second, the presence of a hot dense plasma can result in electron screening and a population of nuclear excited states, both of which will affect the reaction cross sections. These effects cannot be duplicated in accelerator experiments. Thus, the potential impact of performing burn experiments in implosions will be the ability to provide conditions of greater relevance to reactions in stellar interiors and supernova explosions.

Another example is the $^{14}N(p, \gamma)^{15}O$ reaction, which is the slowest reaction in the main hydrogen burning cycle that occurs in massive stars. It is the reaction that determines how long such stars burn hydrogen in their cores. This has interesting implications to the globular clusters—clusters of millions of stars that all appear to have been created at the same time early in the history of our galaxy. Use of a stellar-evolution code then can determine the ages of those stars and, therefore, provide a lower limit on the age of the universe. The $^{14}N(p,\gamma)^{15}O$ reaction is crucial to that determination. A recent measurement of this reaction found that its rate was only 60% of the rate that had been accepted for many years. There are some difficult corrections that must be made to obtain the reaction rate that goes into the stellar-evolution codes from the measured data. Because of the importance of this rate to both cosmology and our understanding of stellar evolution, it is important that a remeasurement of this rate be made using an independent technique. The NIF and LMJ will provide a unique opportunity in this regard.[1,5–7]

The heavy nuclides are produced largely by neutron-capture processes. The *s*-process corresponds to a "slow" sequence of neutron captures, compared with the typical β-decay time and is thought to occur during helium burning, in asymptotic giant branch (AGB) stars. It proceeds via a series of (n,γ) reactions and β-decays until an unstable isotope is synthesized, and has a long enough lifetime (typically greater than one year) that the (n,γ) rate competes with β-decay. This produces a "branch point," and these branch-point nuclei provide information about the conditions, temperature, and neutron density in the *s*-process environment. The conditions in an imploded, non-ignition NIF target ($k_B T \sim 1$ to 10 keV and $\rho \sim$ several hundred g/cm^3) are very similar to those found in an AGB stellar interior. Thus, a (n,γ) cross-section measurement relevant to the *s*-process could be performed by adding branch-point nuclei to a NIF target. These, together with their (n,γ) reaction-product nuclei, could be collected following the NIF shot, their ratio used to determine the cross section, and, potentially, be a good case for *s*-process relevant studies in NIF experiments.

This proposed experimental activity relevant to *r*-process nucleosynthesis of the neutron-rich elements is to study the formation of heavy elements in explosive nucleosynthesis settings, such as supernovae and the accretion disks around massive objects (black holes, neutron stars, etc.). In these settings large, extremely high neutron densities (>10^{22} n/s/cm^2) and temperatures ($k_B T >$ ~50 keV) form unique environments, where multiple rapid-neutron-capture reactions, referred to as the *r*-process, can lead to the formation of extremely heavy nuclei far from the nuclear β-stability valley. At these densities, rapid-neutron capture occurs until equilibrium between (n,γ) and (γ,n) photodissociation is reached. These nuclei must wait for a neutron to β-decay to a proton prior to the process continuing. The location of these "waiting points" is determined, in large part, by the neutron binding energy in these extremely neutron-rich nuclei. Once the conditions that initiate the *r*-process are met, the resulting neutron-rich products decay via β-decay until a stable nucleus is formed. The *r*-process is thought to occur in supernovae and other explosive environments that create the necessary conditions of high temperature and neutron density. Relevant conditions might be accessed by high-gain implosions on the NIF laser.[8]

Recent evidence of the existence of ^{60}Fe (half-life = 1.5 My) in the galaxy[9] has brought to light the significance of measuring cross sections for the reactions that synthesize and destroy ^{60}Fe in core-collapse supernovae. These involve successive (n,γ) neutron-capture reactions of thermal neutrons, beginning with ^{58}Fe. Accurate determination of these reaction rates, plus the amount of ^{60}Fe in the galaxy, then places a strong constraint on models of supernovae, even at the level of the sites within the supernovae (specifically, locations undergoing carbon burning) in which the ^{60}Fe is produced.[9] By producing ^{59}Fe from a separate accelerator bombardment and then doping the NIF target with the resulting ^{59}Fe, neutrons from a NIF shot should produce sufficient ^{60}Fe for it to be measured off-line to determine the reaction yield from neutrons produced. Preliminary calculations suggest that it would be possible to infer the cross section for the ^{59}Fe(n,γ)^{60}Fe reaction from the ^{60}Fe/^{59}Fe ratio in the debris of an appropriately designed NIF shot.

8.4 APPLICATIONS TO ACCELERATOR PHYSICS

Accelerators strongly impact a number of areas in the pure and applied sciences. This includes accelerators as drivers for the next generation of coherent x-ray lasers (e.g., the Linac Coherent Light Source at SLAC) for ultrafast science, laser-electron beam backscatter sources of directed gamma-rays for homeland security, and large-scale colliders for high energy physics. Conventional accelerators are based on radio-frequency (RF) technology.

For the past 80 years, the tool of choice in experimental high energy physics has been particle accelerators. The Large Hadron Collider (LHC) at CERN will soon become fully operational. The construction cost alone for the LHC machine was nearly ten billion dollars and it is clear that, if the same technology is used, the world's next "atom smasher" will cost at least several times that in today's dollars. However, that need not be the case; the cost of the next-generation accelerator could be several times less (an order of magnitude or more) by using relativistically moving plasma waves as the accelerating structure.[1,2] The wakefield is excited by the space charge forces of a charged particle beam (called Plasma Wakefield Acceleration: PWFA) or the radiation pressure of a laser (called Laser Wakefield Acceleration: LWFA) pushing plasma electrons forward and to the side as they propagate forward. The electrons are then pulled back by the unshielded ions, thereby exciting a wake moving at the speed of the laser or particle beam, i.e., nearly the speed of light.

The interaction of intense lasers and particle beams with plasmas is a core subject in high energy density science. This subject combines relativistic, nonlinear, and ultrafast plasma physics. The acceleration gradients and focusing forces in plasma wakefields can be more than three orders of magnitude higher than conventional accelerators. Besides having the potential for being the basis for the next linear collider, they could also be used to build compact and robust accelerators for use in photon sources, medicine, and industry.

The past several years have seen incredible progress in experiment, theory, and simulation in laser- and beam-driven wakefield acceleration.[3,4] Advances in laser technology has progressed to the point to where pure LWFA can finally be studied experimentally; the electron and positron beams at SLAC have been shortened such that the beam's own fields can be used to field-ionize a uniform plasma. Current laser and particle beams are now short enough to form a wake by expelling all the plasma electrons. This is called the blowout or bubble regime.[5–7] This regime (Fig. 16) is ideal for accelerating electrons since it provides linear focusing forces and uniform (in *r*) accelerating fields. In LWFA, self-injected monoenergetic beams of energies up to GeV have been observed in a channel-guided experiment[8] [results are shown in Fig. 16(a)], while in PWFA experiments the energy of a fraction of the 42-GeV electron beam at SLAC has been doubled in an 85-cm-long self-ionized plasma.[9] Additionally, the theoretical understanding of weak and strong nonlinear wakes and the capability of fully nonlinear and kinetic simulations, have improved dramatically.

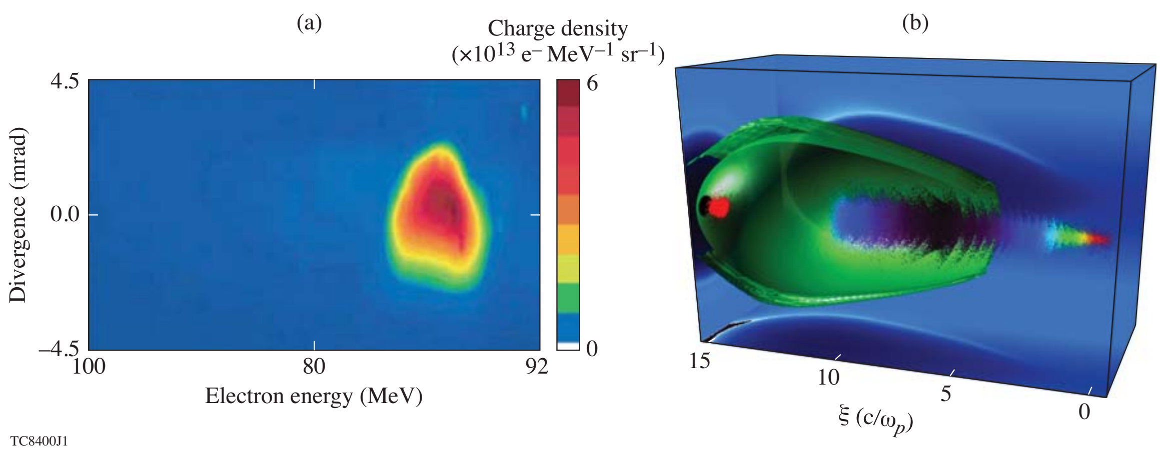

Figure 16. (a) Electron energy spectra measured from laser–plasma accelerator experiments at LBNL.[8] 1-GeV monoenergetic electron beams were produced in a centimeter-scale plasma. (b) A simulation of a high transformer ratio plasma wakefield accelerator for generating an electron beam for a next generation light source. The image shows a drive beam (mostly blue) and a trailing beam (red) moving from left to right. The green bubble is an isosurface plot of the plasma density of the wake.

In Fig. 16(b) is an image generated from a quasi-static particle-in-cell simulation of a PWFA stage which produces a high-quality electron beam that might be of use in a future-generation light source. In the simulations, a high-current, low-energy beam (a few GeV) is converted into a low-current, high-energy beam (~20 GeV) that could be used in a next-generation light source.

This field is ripe for new discoveries and opportunities. For example, electron energies approaching 10 GeV in wakes driven by lasers and monoenergetic beams could be achieved in the next decade. Furthermore, high efficiencies in wakes driven by particle beams, high-gradient positron acceleration, and table-top accelerators for use in light sources could all be demonstrated. It is likely that over the next decade, laser intensities will be high enough to excite wakes that can even trap and accelerate ions.

8.5 Applications in Condensed Matter Physics and Material Science

Emerging capabilities are enabling a new generation of materials research under high energy density conditions. This includes high-density matter at 10- to 100-fold compression, warm-dense matter at temperatures associated with energies on scale with the energy bands of solids, and dense hot plasmas at energy density conditions associated with highly ionized matter. The initial study of materials at these conditions has revealed several discoveries, including polymeric Si-O at 10 Mbar and 30,000 K; core electrons affect bonding in ultradense Li; the melt temperature of carbon near 10 Mbar decreases with increasing pressure; and transport for warm or hot dense materials depend on subtle details of the atomic wavefunctions of the anybody fluid. Exploring these new material states will, for example, provide a rigorous test for planet evolution models, determine potential new materials for energy and defense applications, and provide a predictive capability for potential fusion- and/or fission-target performance.

Matter at extreme densities is predicted to have truly exotic properties, including high-temperature superconductivity, superfluidity, and Wigner crystallization to name a few. Such high-pressure environments distort valence electron bands at levels associated with strong chemical shifts and Fermi energies. They also provide a unique resource to explore processes and conditions that control intrinsic materials behavior and that might lead to the development of enhanced performance materials. Until recently, however, these extreme states of matter existed only in the deepest interiors of large planets, brown dwarfs, and low-mass stars, so there are no data to test such material predictions.

Exploring dense matter at higher temperatures is equally fertile and important for science and technology. A detailed understanding of both warm and hot dense matter are required for building a predictive capabilities extending from regimes associated with failure of materials under high particle and light fluxes (eV's per unit cell), to inertial confinement fusion (ICF) implosions and understanding the structure and formation of stars. For example, the hydrogen fuel in a typical ICF implosion design spans temperatures ranging from 10 to 10^8 K, pressures from 1 to 10^6 Mbar, and densities from

0.2 to 1000 g/cc. At several stages of such an implosion, models for the opacity, equation of state, transport properties, and equilibration rates for multiple materials are important for accurate numerical predictions. However, theories used to construct these material models are untested over most of this density-temperature range.

Using driver technologies such as intense lasers, together with probe-measurement techniques such as x-ray pulses from point plasmas and free-electron lasers, we can produce and characterize the inherently transient pressure and temperature conditions associated with novel atomic structures and bonding, and electronic and structural properties in condensed matter at high energy density. Over the next several years, a new generation of HED-materials experiments will begin to explore these new HED states, providing a rigorous benchmark for theory and simulation and push for a new age of materials discoveries.

8.6 Applications in Medicine and Biology

When a high-intensity, short-pulse laser (subterawatt to petawatt level) interacts with matter it produces copious amount of radiation and particles. The emission is for an extremely short duration and from a small volume. These qualities make laser-produced radiation and particle sources extremely attractive to a number of applications in medical science, including proton (Fig. 17) and carbon ion oncology, Positron Emission Tomography (PET) scanning, microscopy, precision radiographic imaging, and spinal surgery, among others.

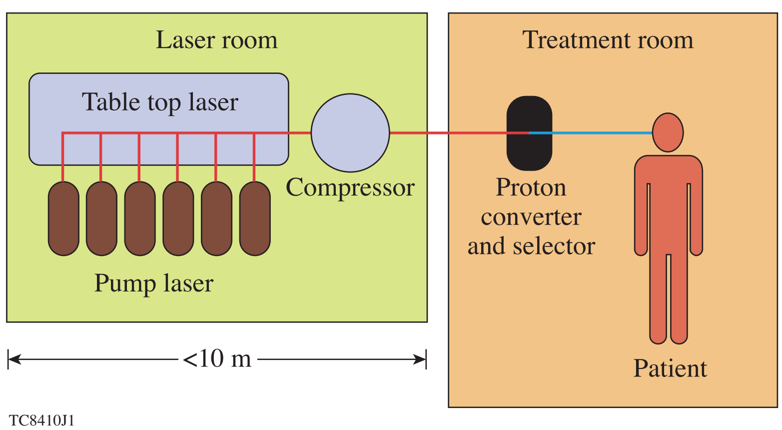

Figure 17. Schematic of a short-pulse laser device used as a proton source for proton therapy.

Particularly, production of protons and ions in these interactions is of significant importance because of applications in PET and radiation oncology. The short-lived isotopes ^{11}C or ^{18}F are used in PET scanning and these isotopes are produced using proton beams from cyclotrons or accelerators. This capability is available to only limited medical facilities because of large costs involved. However, laser-produced protons offer a low-cost solution to the problem, and it has been recently successfully demonstrated that the current short-pulse lasers can indeed produce short-lived isotopes.[1] The activity is still lower than the required value, in excess of a gigabecquerel. However, with increases in laser intensity and repetition rate, it will become feasible in the near future that the protons will be used not only to produce short-lived radioisotopes, but also to destroy cancer tumors. The use of light ions, such as protons or carbon, is advantageous in human cancer therapy because of accurate, spatial-dose distribution compared to photons and electrons, which reduces damage to surrounding healthy tissue. Presently, cyclotron- and synchrotron[2]-based facilities are used to accelerate protons. The cost of these facilities, including gantries, is in excess of 100 million dollars, and their large size, often hundreds of tons, limit proton and ion therapy to a small number of hospitals across the country. With compact, intense short-pulse lasers, laser-produced proton or ion beams can reduce this cost by bringing the source closer to the treatment room, and requiring a much smaller capital investment in equipment. This may facilitate availability of proton and ion therapy to a much larger number of hospitals.

The ion energies required to treat prostate cancer, brain tumors, etc., are in excess of 200 MeV. Recent simulations show[3] that it may be possible to accelerate proton and carbon ions with more than 200-MeV energies at laser intensities of 10^{21} to 10^{22} Wcm^{-2}. In these simulations, with a 30-fs pulse length and target thicknesses ranging from 1.6 to 3.3 μm, protons were accelerated to energies in excess of 200 MeV. Recent results[4] also indicate that magnets could be used to select proton and ion energies to make a monoenergetic beam. These developments are extremely encouraging for laser-produced proton/ion beams in cancer therapy. Lasers with these intensities will be available in the near future, and it will be possible to have the above-mentioned intensities with high-repetition-rate systems.

Another important medical application of short-pulse, high-intensity lasers is the generation of bright coherent x rays with femtosecond or even attosecond duration. Recently, it has been demonstrated[5,6] that high-order harmonics with wavelengths <4 nm can be produced using femtosecond lasers. These advances open up the possibility of x-ray microscopy and tomography in the “water window” region of the spectrum using compact sources that will have sufficient flux for applications, particularly when coupled with the development of very high-repetition rate short-pulse lasers (<30 fs). Such compact, bright, high-repetition rate x-ray sources will find a wide variety of applications in biology, biochemistry, and medicine.

Finally, medical imaging will benefit from laser-produced x-ray sources. Such x-ray sources are extremely bright, and their small spot size enables high-resolution radiography techniques such as x-ray phase-contrast imaging. This technique relies on gradients in the object density, rather than absorption, to produce an image, and promises the ability for high-resolution imaging of tissue, as well as lower patient doses compared to conventional x-ray absorption-based radiography. Laser-produced x-ray sources also produce short-duration x-ray pulses, eliminating any blurring of the image caused by movement and providing high contrast in intense ambient radiation or light environments. While such bright, coherent x-ray sources are currently produced at synchrotron facilities, laser-produced x-ray sources promise much more compact, portable, and lower-cost alternatives with greater patient accessibility than those at large synchrotron facilities.

8.7 APPLICATIONS IN ATOMIC-MOLECULAR-OPTICAL (AMO) SCIENCE

Research that combines high energy density science with atomic and molecular physics is an exciting new "interface" area of study. The development of intense, ultrafast x-ray free-electron lasers promises to reveal coupled nonlinear optical and plasma phenomena in a new parameter regime that was simply not accessible in the past. Moreover, technological advancements that make it possible to "sculpt" the electric-field shape of an intense femtosecond laser pulse, on a cycle-by-cycle basis, allows us, for the first time, to study and manipulate quantum phenomena in high energy density environments. This research combines high energy density plasma science with AMO science to address questions that have not been explored either experimentally or theoretically. This is exciting because historically, many important advances have occurred at the interface between disciplines, and because many important applications are possible as an outgrowth of this work.[1]

When an intense ultrafast x-ray pulse from a free-electron laser illuminates a molecule or protein, the resulting nanoplasma must necessarily explode on a rapid, femtosecond timescale.[2] However, exactly what will happen? This regime of light–molecule interaction is far beyond any experimental regime probed to date—on earth or perhaps even in the universe. Moreover, few theories have been developed and none have been tested to date. Rapid multiple ionization of the most deeply bound electrons in atoms and molecules will lead to the creation of super-excited "hollow atoms," i.e., atoms or molecules with two or more electrons missing from the highly bound region at the very center, next to the atomic nucleus. Even the highest power visible-wavelength lasers cannot produce such hollow atoms, because their fields, although enormous, oscillate too slowly to affect the most deeply bound electron orbits. Multiple electrons in an atom or molecule will be excited, and in some cases a single electron may absorb multiple x rays. New and unanticipated science, where electron and nuclear motions are intricately coupled, has already been uncovered when a fast burst of soft x rays irradiate molecules, as shown in Fig. 18. In the future, we need to understand the dynamics of these super-excited, complex, nanoplasmas both to understand the fundamental interaction of intense beams with matter, and also to lay the groundwork needed if the goal of single-molecule imaging is ever to be achieved. As shown in Fig. 19 with a sufficiently short burst of intense, coherent, x rays, the image of a protein molecule can be captured before the resulting nanoplasma explodes. This is an important goal because many protein molecules cannot be crystallized and, therefore, their structure is not known.

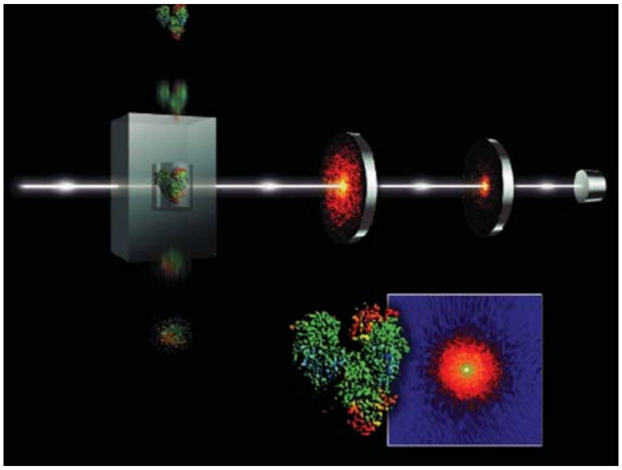

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Figure 18. Single-molecule diffraction by an x-ray laser. Individual biological molecules fall through the x-ray beam, one at a time, and are imaged by x-ray diffraction before the superexcited nanoplasma explodes. (from http://www.ssrl.slac.stanford.edu/lcls/downloads/lcls_brochure_screen.pdf).

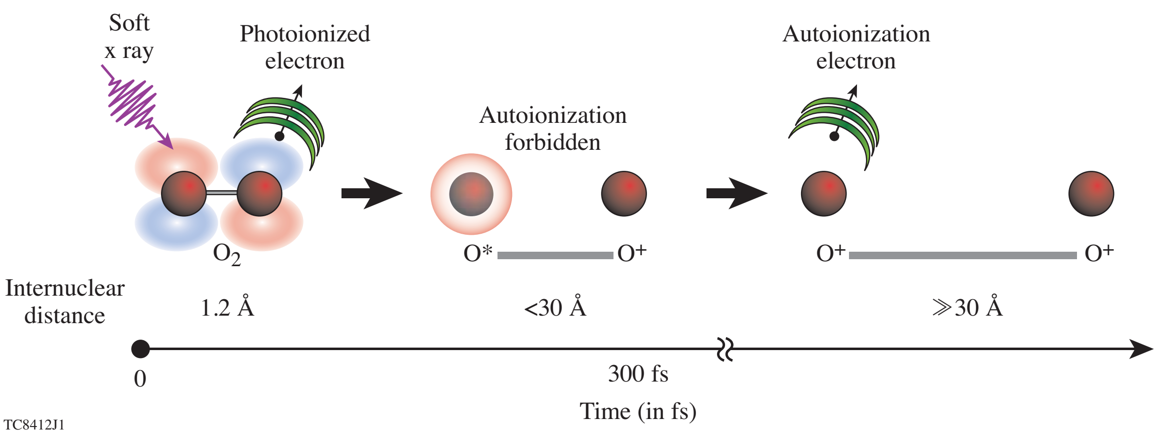

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Figure 19. Example of complex, multistep, x-ray–induced ionization processes in the soft x-ray region that is currently experimentally accessible. Surprisingly, after creating super-excited O_2^+ by irradiating an oxygen molecule with an x ray, the second electron can take a long time to be ejected—up to 300 fs—because it feels an attraction to each of the O^+ fragments. Even more complex phenomena will be accessible using the advanced laser facilities coming on line in the near future. From Ref. [5].

Many other exotic phenomena may follow the development of intense x-ray lasers. High-flux, short-wavelength radiation will have dramatic affects on materials, which might even lead to new kinds of x-ray lasing mechanics in highly excited, high-density solids.

Another very interesting new frontier to be explored is the regime where both quantum effects and high energy density plasma effects are important.[3,4] High-order harmonic generation, for example, results from the extreme distortion of an electron-wave function as an atom or molecule is ionized by an intense femtosecond laser. Using a simple analogy, an atom or molecule driven by a strong laser field behaves like an antenna. An electron is first ripped from the atom or molecule by a strong laser field. Next, the free electron is accelerated away from the ion, and then back toward it, before recombining with the parent ion approximately half of an optical cycle following ionization. Any excess electron-kinetic energy is then emitted as a short-wavelength photon. However, to date, the conversion efficiency of laser light to shorter wavelengths has been limited. Since the generation of very high harmonics is accompanied by rapid ionization of the medium, the resulting free-electron plasma causes a phase mismatch, allowing the laser light to outrun the generated light. This phase mismatch limits the useful flux at the highest keV photon energies. Thus, developing new schemes to counteract this phase slip is a grand challenge.

Fortunately, there is a way to overcome this grand challenge. They key idea is that the quantum phase of a radiating electron can be manipulated by a second beam of light. While the ionizing electron is free from the ion, its quantum (deBroglie) phase evolves over many cycles, particularly for a high-energy (keV) electron. By shining a second, weak, laser beam on this free electron, the value of this quantum phase can be adjusted slightly, so that the driving laser light and generated x rays stay in phase as they travel through the medium, therefore greatly enhancing the efficiency of the frequency-conversion process. To avoid very large plasma ionization and defocusing losses in the driving laser field, the medium ideally would consist of a tailored, multiple-ionized, discharge-plasma channel that guides the driving laser. Extending these studies to high laser intensities and multiple-ionized plasmas will make it possible to explore and control new regimes of quantum physics and intense laser-beam interactions with plasmas in high energy density environments. The ultimate goal of this work is to generate bright, coherent, keV, high-harmonic beams for applications in biomaterials, nanomaterials, materials imaging, and medicine.

9 ENERGY-RELATED HEDLP SCIENCE: ISSUES AND OPPORTUNITIES

Targets for inertial fusion energy (IFE) are compressed to extreme densities and pressures by a high-energy driver such as a laser, ion accelerator, or a pulsed-power device. The compression occurs by accelerating relatively thin millimeter-scale fuel shells at high velocities and then converting their kinetic energy into internal energy as they decelerate and stagnate. In most designs, the thermonuclear fuel is a cryogenic layer of solid deuterium and tritium (DT) within a shell of plastic, beryllium, or other ablators. The driver is either a set of laser or ion beams directly incident on target (direct-drive IFE) or an x-ray flash from a hot, dense plasma produced by either a laser illuminating a high-*Z* enclosure or a *z*-pinch compressing a high-*Z* plasma (indirect drive). In the magnetized target-fusion concept, the target consists of a centimeter-scale preformed plasma confined by a magnetic field and compressed by a magnetically driven metal liner or other means.

The compressed targets are ultrahigh energy density states of matter with pressures of hundreds of gigabars that are studied with the tools of HEDLP physics. If the temperature and density of the compressed core of an IFE target are large enough, a thermonuclear burn starts, leading to a rapid amplification of the plasma temperature and propagation of a burn wave through the compressed fuel. The heated fuel burns until it disassembles, generating high fusion-energy yields that can greatly exceed the energy required for the compression.

There are many scientific issues involved in the production of a dense and hot core that achieves the conditions for thermonuclear ignition and high energy gains. Many important issues must be addressed including:

- the coupling of the driver energy to the target;
- the properties of the target material under high pressures and temperatures;
- the dynamics and the stability of imploding HED plasmas;
- the absorption and emission of radiation;
- the effects of magnetic fields on the plasma energy confinement

Addressing many of those issues is essential for the success of the ignition campaign on the National Ignition Facility (NIF). Many of them are adequately addressed by the NNSA-funded ICF program. Others, in particular those issues affecting alternative IFE concepts, are either not considered or are only marginally dealt with within the NNSA ICF program. For the FESAC charge, we carefully reviewed the current ICF science campaigns and analyzed the science issues relevant to alternative IFE concepts to identify the scientific opportunities for the Joint HEDLP Program. In the next section, the major issues of HEDLP physics related to the achievement of ignition and high gains are described and the scientific opportunities for the Joint HEDLP Program are identified in Sec. 9.2.

> **Finding.** *High energy density plasma physics provides the basis for inertial fusion energy sciences. The imploding core of an IFE target is in an ultrahigh energy density plasma state. The fusion energy produced in an IFE target can, in principle, be hundreds of times larger than the energy required to implode it. Inertial fusion energy offers prospects for an economically viable, carbon free, and unlimited energy source.*

9.1 HEDLP Science Issues for Inertial Fusion Energy

In this section, energy-related HEDLP science issues are described in the context of the six areas of fundamental HEDLP physics:

- HED hydrodynamics
- nonlinear optics of plasmas
- relativistic HED plasma and intense beam physics
- magnetized HED plasma physics
- radiation-dominated HED plasma physics and material properties
- warm dense matter physics

A seventh area—integrated HEDLP physics—is introduced to accommodate those issues linked to the integrated nature of IFE systems. Most of the issues described here are fundamental HEDLP issues of IFE target physics crucial for the advancement of inertial fusion energy sciences.

During the next five years, significant progress is likely to be made in understanding indirect-drive ICF because this is the baseline concept to achieve ignition on the NIF. While much of the discussion below emphasizes alternatives to indirect-drive ICF, some of the issues are currently being addressed within NNSA's ICF program, primarily through the National Ignition Campaign (NIC). The NIC has the immediate goal of performing an ignition attempt on the NIF in 2010. In this report, *issues that are adequately addressed within the NNSA-ICF program are ranked as lower priority for the Joint HEDLP Program*.

The six areas of fundamental HEDLP science are described in Sec. 5. The science issues are accompanied by a "relevant question" to highlight what must be addressed through further research and followed by a detailed description. Three priority levels are used to convey the degree of urgency to which the issues must be addressed within the Joint HEDLP Program: (1) high, (2) medium, and (3) low. The priority ranking is based on the set of criteria described in Sec. 3 and further examined in Sec. 9.2.

9.1.1 Area: High Energy Density Hydrodynamics

Issue: Implosion hydrodynamics for high energy gains
Question: *How can HED plasmas be assembled to the densities and pressures required for maximizing the fusion-energy output?*
Priority level: (1) High
Description: Every IFE scheme requires optimized implosions to achieve the level of compression (density, temperature, and pressure) required for ignition. Implosions of a spherical shell with a cryogenic-DT layer are used to generate the high densities and pressures required for high gain-inertial fusion. The DT layer must be kept cold (nearly Fermi-degenerate) during the implosion to achieve the highest densities and areal densities for a given driver energy. In conventional hot-spot ignition, the shell must be accelerated to velocities exceeding 3×10^7 cm/s to heat and compress the central hot spot to a temperature of several keV and pressure of hundreds of gigabars. To achieve such extreme states of matter, the driving pressure pulse must be precisely tuned to correctly time the launching of shocks and compression waves during the implosion. This requires the development of an accurate and experimentally validated predictive capability to simulate the dynamics of the imploding target. Recent work within NNSA's National Ignition Campaign has made significant progress in these areas.

In high-gain, direct-drive implosions, an initial shock decays in the shell to shape the adiabat (i.e., entropy) profile and keep the inner portion of the fuel cold while heating the ablation front (adiabat shaping). Adiabat shaping improves the implosion stability by raising the ablation velocity without affecting the final compression. The initial decaying shock must be precisely timed with subsequent shock or compression waves to prevent shock preheating of the cold fuel.

In shock ignition, a strong shock (>300 Mbar) is launched at the end of the fuel assembly pulse to heat and compress the hot spot to ignition conditions. The launching time of the ignitor shock must be precisely synchronized with the propagation of the return shock from the target center. The shock strength depends on the absorbed laser energy, the laser-target coupling at the time of the shock launching, the fraction of laser energy transferred to laser–plasma instabilities and hot electrons, and the hot-electron energy. To date, virtually no experimental data on ultrastrong-shock (>300 Mbar) generation and propagation in HED plasmas is available. With the large laser facilities now available (OMEGA EP and the NIF), ultrastrong shocks can be produced in the laboratory using planar targets (OMEGA EP) and in spherical implosions (NIF). Experiments at these facilities are crucial to assess the potential of shock ignition as a viable IFE concept.

In cone-guided fast ignition, the dense fuel must be assembled without a large central hot spot and positioned in the proximity of the cone tip. The integrity of the cone tip must be preserved until the time of interaction with the intense laser pulse. All these aspects of the fast-ignition fuel assembly are largely unexplored. Significant progress will be made using existing and future integrated facilities (OMEGA and NIF) in the next five to ten years.

In magneto-inertial fusion, an imploding shell is used to compress a plasma with an embedded magnetic field. The field must remain frozen in the plasma and amplified to reach a magnitude of several megagauss to magnetically insulate the plasma from thermal-energy losses. Experimental demonstrations of magnetized target compression are now possible using existing facilities.

Issue: Hydrodynamic Instabilities and Turbulent Mix

Question: *How do hydrodynamic instabilities and turbulence develop, how do they affect the compression of HED plasmas, and how can they be controlled?*

Priority level: (2) Medium

Description. Hydrodynamic instabilities are ubiquitous in imploding capsules and severely degrade the performance of any IFE scheme. Several hydrodynamic instabilities develop and grow during the four phases of a capsule implosion:

1. shock propagation
2. acceleration
3. coasting phase
4. deceleration

The Richtmyer–Meshkov instability develops during phase (1) and provides the seed for the Rayleigh–Taylor instability that grows during phase (2). Nonunifomities are amplified further during phase (3) by the Bell–Plesset instability and feed through from the outer- to the inner-shell surface, where they are enhanced by the Rayleigh–Taylor instability during phase (4). The resulting surface and mass perturbations can either break up the imploding shell while in-flight or can mix the cold shell with the hot-spot material (during the deceleration phase) quenching the ignition process. Techniques to mitigate the growth of hydrodynamic instabilities in laser-driven implosions (adiabat shaping and double-ablation fronts) have been recently proposed but require experimental validations. Uncertainties persist about the effects of mass ablation and radiation transport on the nonlinear stage of the instabilities. Neither the transition from the linear to the nonlinear phase and, subsequently, turbulent stage nor the dependence of the size and topology of the mixing region on the initial perturbation spectrum is well understood. High-Z layers have been proposed to reduce the seeds of the instabilities, but only a few experiments have been carried out to confirm their effectiveness. Convergent shocks transfer nonuniformities from the outer to the inner-shell surfaces in conventional and shock-ignition inertial fusion. These transfer mechanisms are theoretically understood but they have not been experimentally investigated. In magnetically driven implosions, hydrodynamic instabilities profoundly affect the path of the electric current, an effect that is still poorly understood. In metal–liner implosions, hydrodynamic instabilities cause the liner material to mix with the hot, low-density, magnetized-target plasma—an issue explored neither theoretically nor experimentally.

9.1.2 Area: Nonlinear Optics of Plasmas and Laser–Plasma Interactions

Issue: Laser–Plasma Instabilities and Hot-Electron Generation
Question: *How do laser-plasma instabilities reflect light, how do they generate energetic electrons, and how can they be controlled?*
Priority level: (1) High
Description: Laser–plasma instabilities result when an intense laser propagates through a high energy density, long-scale-length plasma. One branch of laser–plasma instabilities involves the resonant decay of the laser wave into a scattered light wave and a plasma wave. For stimulated Brillouin scattering (SBS), this involves the resonant scattering of the laser from a low-frequency ion-acoustic wave. This instability can occur for densities at or below the critical density n_{cr}, where the critical density n_{cr} is defined as the density at which the laser frequency equals the electron-plasma frequency. Stimulated Raman scattering (SRS) involves the resonant decay of the intense laser into a scattered-light wave and a high-frequency, high-phase-velocity electron plasma wave, and occurs at plasma densities below 0.25 n_{cr}. A second branch of instabilities involves the resonant decay of the intense laser wave into two plasma waves. Important among these is the two-plasmon-decay instability, which involves the resonant decay of the laser wave into two electron-plasma waves, and occurs only at plasma densities near 0.25 n_{cr}. Finally, the laser can couple directly with zero-frequency density fluctuations that cause the laser beam to self-focus or form intense filaments of light.

For conventional hot-spot ignition, laser–plasma instabilities often occur near the peak of the laser power, and can limit the peak laser intensity used to drive the implosion (in both direct or indirect drive). Scattering instabilities can substantially reduce the fraction of laser energy coupled to the target. For indirect-drive ignition, scattering instabilities can degrade implosion symmetry, especially via crossed-beam energy transfer, whereby two laser beams crossing in a plasma can transfer energy from one beam to another via a mediating plasma wave, degrading implosion symmetry. Laser filamentation and self-focusing, if not controlled, can potentially increase the growth of SRS, SBS, and two-plasmon decay, and further reduce coupling efficiency. For direct drive, filamentation and self-focusing can imprint density modulations at the critical-density surface of the capsule, which act as seeds for hydrodynamic instabilities of the imploding capsule. Plasma waves driven by laser–plasma instabilities can drive secondary instabilities or develop strong nonlinear behavior, dissipating energy via multiple wave–wave or wave–particle interactions and accelerating electrons to high energies. In this inherently multiscale problem with many degrees of freedom, understanding and predicting the laser absorption or fraction of energy into hot electrons is a challenge. If hot electrons are generated early in the pulse of a conventional ICF implosion, the cold-fuel layer is preheated by the deposition of the electron energy. If the preheat energy exceeds 0.1% of the laser energy, the implosion is predicted to fail. While progress has been made in observing these instabilities and the associated nonlinear behavior through controlled idealized experiments, modeling and experiments addressing laser–plasma instabilities in realistic structured laser-beam, and long-scale-length plasma conditions is a frontier research area. The theory of nonlinear plasma waves is far from complete. Understanding how spectrums of multidimensional nonlinear and driven plasma waves produce non-Maxwellian electron-distribution functions is also a frontier research area in this field. Laser–plasma instabilities can often be controlled by decreasing their linear growth rates, but this typically places stringent limits on the laser intensity, driving the laser-intensity down and degrading the target performance.

For the shock-ignition concept, in which a high laser-intensity pulse is used to drive a very strong shock late in the implosion phase—heating the fuel to fusion conditions—initial calculations suggest that hot electrons from laser–plasma instabilities may augment the strength of the late-time heating shock and may be beneficial to this approach.

Controlling laser–plasma instabilities by collective, nonlinear means is a frontier research area that is relatively unexplored. Many experiments and simulations indicate that one instability can create either favorable or unfavorable conditions for growth of other instabilities and might be used to control, for example, instabilities that create hot electrons.

The grand challenge is to understand the behavior of HEDLP plasmas when multiple overlapping laser beams are involved, and collective or single-beam instability thresholds are surpassed and mutual interactions are dominant. Finding islands of stability in this regime will further the optimization of target designs for laser IFE.

Issue: Nonlocal Transport of Energy

Question: *What is the correct model of electron thermal transport from the energy deposition region to the ablation surface?*

Priority level: (3) Low (adequately addressed within the NNSA ICF program)

Description: The energy deposited by a laser or x rays near the critical surface is transported by the electrons to the ablation surface. The energy transport determines the driver-to-target coupling in all laser-driven implosions (laser-driven IFE, shock ignition, and fast ignition). Current theoretical models implemented in most hydrocodes treat the energy transport as diffusive with the heat flux proportional to the temperature gradient. The diffusive model (Spitzer heat conduction) is valid as long as the electron mean free path is much smaller than the temperature-gradient scale length. This is not the case for laser-produced plasmas where the high plasma temperature and the steep temperature gradients cause the electron mean free path to be comparable to or exceed the temperature-gradient scale length (nonlocal heat transport). This limitation of the diffusive model is heuristically accounted for by using a flux limiter that artificially reduces the heat flux when the temperature profile becomes too steep. To correctly model the heat transport in laser-produced plasmas, a Fokker–Planck kinetic description must be adopted. The computational cost associated with solving the Fokker–Plank and Maxwell's equations coupled with the radiation hydrodynamics in multidimensions is a major difficulty that cannot be overcome with the current generation of parallel computers. Attempts have been made in the past to develop simplified models to capture the essential physics of nonlocal heat transport in such a way that can be easily implemented into current hydrocodes. Such models have shortcomings since the approximations used are quite crude and they have not been tested against kinetic simulations and experimental observations. Self-generated magnetic fields can complicate the energy transport even further by trapping electrons in small gyro orbits. A full kinetic solution of the electron-energy-transport problem including magnetic fields and multi-dimensionality is required to achieve a reliable predictive capability of the energy transport in laser-produced plasmas.

9.1.3 Area: Relativistic HED Plasma and Intense Beam Physics

Issue: Intense Particle-Beam Acceleration by Ultra-Intense Lasers
Question: *What are the essential features of the energetic particles generated by intense lasers interacting with plasmas, and how does intense light affect the plasma dynamics?*
Priority level: (1) High
Description. Energetically charged particles are generated in high-intensity laser–matter interactions via a number of physical mechanisms such as resonance absorption, vacuum heating, and ponderomotive ($J \times B$) accelerations, etc. Protons and ions in short-pulse, high-intensity laser–matter interactions are accelerated via the Target Normal Sheath Acceleration (TNSA) mechanism. The general idea is that the when the laser irradiates a target, its energy is transferred efficiently to the hot electrons, which consequently, because of TNSA, accelerate protons/ions. Understanding the mechanisms causing the acceleration of energetically charged particles is important to fast ignition. In full-scale, fast-ignition experiments, there may be inherent laser prepulse (with an energy contrast ~10^{-5}) caused by amplified spontaneous emission (ASE) in the range of 0.5 to 1.0 J. There are ongoing efforts to reduce the prepulse level. This ASE prepulse can significantly affect the mechanisms accelerating the charged particles (electrons, protons, or ions) by modifying the hot-electron distribution and temperature. The hot-electron spectrum and conversion efficiency are crucial to the success of fast ignition. A hot-electron temperature of 1 to 2 MeV is required for an efficient electron energy coupling to the compressed core. The temperature prediction from some of the above-mentioned mechanisms (e.g., ponderomotive scaling) is significantly higher than the required values

at the intensities of 10^{20} Wcm^{-2}. Recent analytical models and simulations suggest that lower hot-electron temperature could be achieved with density steepening by ponderomotive pressure. Furthermore, simulations indicate that most of the inward-directed heat flux is carried by less energetic electrons. These effects were not yet tested because of the lack of facilities for full-scale, fast-ignition experiments. It is becoming possible to perform such experiments on OMEGA EP and on the NIF ARC in a couple of years. Direct measurements of the electron source at the point of generation are not physically possible; indirect methods (K_α emission, bremsstrahlung radiation, and escaping electrons) are routinely used. The conversion-efficiency measurements assume Monte Carlo transport for the electrons and photon production. Complex transport issues such as electric and magnetic fields within the target have typically been ignored. The inclusion of complex physics could affect the conversion efficiency, angular spread, and hot-electron temperature.

The evolution of proton/ion fast ignition will be driven by two key factors: (1) conversion efficiency of laser into protons/ions and (2) ballistic focusing of the laser-driven proton beam by proper shaping of the target. There has been extensive effort both numerically and experimentally to increase the conversion efficiency and develop a better understanding of focusing. Furthermore, integrated hydro and hybrid simulations are required for proton/ion fast ignition studies.

One of the key issues in fast ignition is to move the ignition pulse energy-delivery point as close to the core as possible without significant energy loss. There are two approaches to achieve this: the channeling/hole-boring scheme and the cone-in-shell target scheme. In the channeling/hole-boring scheme, a channeling pulse, which could be the prepulse of the ignition pulse or a separate pulse, produces a low-density channel to reduce the nonlinear interactions of the ignition pulse in the underdense region. Once the channel has been formed, a short ignition pulse propagates in the channel. At the end of the channel, the ignition pulse may continue to push forward into the overdense plasma through its ponderomotive pressure ("hole-boring") and relativistic transparency. In the cone-in-shell target scheme, a hollow cone is attached to the side of a fuel target shell to provide a protected path for the ignition pulse.

Most of previous channeling experiments and simulations were performed with 100-μm-scale plasmas. The residual plasma in the channel can continue to interact with the latter part of the channeling pulse and the ignition pulse. Therefore, channeling in 1000-μm-scale plasmas can introduce phenomena that are not present in the shorter-scale plasmas. Key issues are how the channeling speed and the required energy scale with the channeling pulse intensity, whether the channel is straight, what the density of the residual plasma remaining in the channel is, and how the ignition pulse interacts with the residual plasma. These issues have been recently studied in a series of 2-D particle-in-cell simulations with millimeter-scale plasmas. However, important 3-D effects must be considered. Full-scale 3-D simulations require a 4000-fold increase in computational speed over the 2-D simulations and are not feasible even on the largest computers currently available. Near term 3-D simulations will be confined to a reduced scale and the results will be compared with those from experiments and simplified theory.

After the channel is formed, the ignition pulse can propagate to the end and start interacting with the overdense plasma through the ponderomotive pressure. This can potentially cause density ripples at the laser–plasma interface that can increase laser absorption. Emerging collisionless shocks and related magnetic fields can further change the local density profiles, which, in turn, will change laser absorption and the hot-electron spectrum. Channeling can be studied on the OMEGA EP Laser System, with long-pulse beams creating a preformed plasma, a ~100-ps, high-energy pulse creating a channel, and a second high-energy, short-pulse beam propagating in it.

Ponderomotive pressure effects are also important in the cone-in-shell scheme. Even though the coronal plasma can be kept from entering the cone, it can still be filled by a low-density plasma formed by the prepulse of the ignition pulse. The ignitor laser can sweep away this plasma and reduce the density-gradient scale length of the plasma. Particle-in-Cell (PIC) simulations found that a shorter density-gradient scale length can lower the energy of the hot electrons illustrating the dynamic nature of the laser propagation and absorption in fast ignition. The ponderomotive pressure of the high-intensity laser can change the density profile, affecting the laser propagation, the laser-to-hot-electron conversion efficiency, and the hot-electron spectrum.

The new generation of high-energy, short-pulse laser systems, coupled with long-pulse drivers are poised to significantly increase the understanding of the generation of intense particle beams for fast ignition.

Issue: Transport and Energy Coupling of Intense Charged-Particle Beams in HED Plasmas

Question: *How are intense charged-particle beams transported in and how does their energy couple to HED plasmas?*

Priority level: (1) High

Description: The underlying physics of transporting intense charge-particle beams in plasmas is of great interest for fast-ignition and heavy-ion-fusion research. In electron fast ignition (FI), heating the dense fuel is induced by a beam of energetic electrons (electron FI) or ions (ion FI), accelerated by an intense laser pulse. To date, electron fast-ignition research has focused on two concepts: the channeling scheme and the cone-in-shell target scheme. Ion FI requires a solid target to generate the fast ions. Such a target can be inserted into a cone-in-shell target.

Most of the electron-FI-related experiments to date have been performed with cold targets, where the resistivities are far higher than those expected for full-scale fast ignition. Spitzer resistivity has been used in modeling such experiments. It is also unclear what effect the shock wave that is generated during the target compression will have on the re-entrant cone. This suggests that experiments with well-defined plasma conditions having simple geometries are crucial to understanding the key issues in fast ignition and particularly for benchmarking PIC/hybrid codes. The gigaAmpere current of ~1-MeV electrons must traverse the cone wall into a lower density hot (of the order of 0.1 to 1 keV) plasma, and proceed through increasing density from 1 to 2 g/cc to the compressed core at 300 g/cc. The propagation of such large currents challenges the present understanding of charged-particle-beam transport in plasmas. This requires developing accurate integrated modeling and well-diagnosed experiments.

There has been experimental evidence that the electron beam is produced with a finite divergence that would prevent localized heating of the dense fuel. However, in fast ignition targets, there is substantial plasma between the electron sources and the core. Recent full and hybrid PIC simulations indicate that self-generated magnetic fields can suppress radial transport and even collimate the beam at highly compressed densities. Such a field has not been observed experimentally in solid-target experiments, but it could be present when the beam propagates in the plasma of realistic fast-ignition targets. The issue of beam collimation is crucially important to the success of electron fast ignition because it has a significant effect on the minimum electron-beam energy required to ignite the target.

The general idea of proton/ion fast ignition is that a petawatt laser pulse irradiates a target, which is distinct from the fuel capsule. The laser power is efficiently converted to the hot-electron population. Subsequently, the hot-electron energy is extracted by the ions under various acceleration mechanisms, namely Target Normal Sheath Acceleration (TNSA), Break-Out After Burner (BOA), and Radiation Pressure Acceleration (RPA). The resulting ion beam is the directed into the fuel to ignite it. The challenge is to efficiently transfer the laser energy to the ions. Recent progress includes the demonstration of ballistic focusing of the laser-driven proton beam by shaping (hemisphere) the target, and the production of quasi-monoenergetic carbon ions using layered or micro-structured targets. Simulations indicate that laser-driven, quasi-monoenergetic C-ion beams (energy spread $\delta E/E \sim 10\%$) can be generated with energies approaching 1 GeV.

The quasi-monoenergetic nature of the beam enables controlled energy deposition in the compressed core. The high ion energy facilitates the beam to deposit its energy in the desired areal density ($\rho R \sim 1.5$ to 3 g/cm^2) range in the core. This sets the required energy for a given ion species. To heat the hot spot to the required temperature ~5 to 10 keV faster than the heat-conduction loss rate, a sufficiently high-power density must be deposited by the ignitor particle beam. To produce a hot spot that initiates a propagating fusion burn ~10 kJ/20 ps/(25 to 50 μm)^3 ~10^{22} W/cm^3 with a required fuel density of $\rho \sim 300$ to 500 g/cm^3 is needed.

An optimized ion fast-ignition design requires a particle-beam energy of ~10 kJ that sets the required laser driver energy directly through the laser ion-beam-conversion efficiency, which is one of the key parameters for proton/ion fast ignition. Another key factor is the ion energy for a given species, set by the required range of the particle in the fuel ρR. This value is ~10 MeV for protons and ~450 MeV for C (35 to 40 MeV/nucleon). However, the detailed density and temperature profiles of the compressed fuel can significantly affect the ion-energy requirement.

Proton/ion fast ignition can take advantage of the significant progress made on the hydro design of electron fast-ignition targets. The conversion efficiency from laser to protons must be increased, in part, because the electron-proton conversion efficiency is typically 30%. This can be overcome, in part, by focusing from larger distances using larger source areas to generate the proton/ion beam. In summary, important issues—(1) conversion efficiency and (2) focusing—must be addressed numerically and experimentally for integrated proton/ion fast-ignition experiments.

The physics of ion collisions slowing down in dense plasma is of great importance to heavy-ion fusion. Because target densities are greater than 10^{22} cm^{-3}, whereas incident-focused, heavy-ion driver-beam densities are less than 10^{13} cm^{-3}, the ion density per beam incident on target is more than nine orders of magnitude smaller than the target density. Therefore, beam-plasma instabilities are not theoretically predicted in ion beams that slow down in short 0.1-cm density-scale-length targets. For beam ions traveling faster than the target electron-thermal velocity, the dominant energy-loss mechanism is slowing down (dE/dx) on target electrons; this has been confirmed by comparing detailed energy loss of multi-GeV heavy ions in dense gas, plasma, and solid-foil targets at GSI to the few-percent level in dE/dx. While details must still be investigated regarding the equilibrium and nonequilibrium beam ion-charge states when ions slow down in direct- and indirect-drive targets, the most important frontier research issue for heavy-ion beam-target coupling is the effect of increasing the beam velocity in time (velocity ramping up from the head to the tail of the drive pulse), either to keep the ion range constant while the target heats up (for indirect drive), or to increase the ion range several times in direct drive to sufficiently keep ion-energy deposition close to the imploding ablation front. The latter effect can greatly increase the hydrocoupling efficiency (and target gain) in direct drive, but can also steepen the pressure gradients behind the ablation front, increasing the growth rates of hydrodynamic instabilities. Resolution of this issue requires detailed 2-D hydrocode calculations and experiments.

At the beam currents and densities envisioned for electron fast ignition and heavy-ion fusion, collective processes and beam–plasma interactions affect beam transport and focusing. In fast ignition, the collisionless Weibel and the resistive filamentation instabilities can break up the ignitor electron beam into filaments. The Weibel instability can also drive large localized magnetic fields that can turn the electron back and stop their forward motion. A large transverse electron temperature can suppress the Weibel instability but it can also lead to an excessive beam divergence. In the channeling concept, the electron beam, generated after the hole boring of the intense laser pulse, travels through a low-density plasma before reaching the dense core. PIC simulations have shown that the collisionless Weibel instability breaks up the beam into divergent filaments of the size of the plasma skin depth. Most of the transport physics in the channeling concept are relatively unexplored and little experimental data is available on fast-electron transport in plasmas.

In heavy-ion fusion, collective processes can play an important role in (a) the acceleration and transport regions of the one-component driver beam, (b) the compression region where neutralizing background plasma is introduced to help focus the intense ion beam longitudinally and transversely onto the target, and (c) to a lesser extent in the target region, where classical beam–plasma interaction processes are expected to dominate. Depending on the region of beam propagation, these collective processes can include the electrostatic Harris instability driven by thermal-energy anisotropy of the beam ions, electrostatic two-stream instabilities associated with beam–plasma interactions, the resistive hose instability, and the multispecies electromagnetic Weibel (filamentation) instability associated with beam–plasma interactions. Through detailed analytical studies and advanced numerical simulations using particle-in-cell (PIC) and nonlinear δf 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 collective 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 develop and implement ever-more-accurate integrated modeling capabilities and experimental diagnostic techniques.

The new generation of high-energy, short-pulse laser systems coupled with long-pulse drivers are poised to significantly increase the understanding of the transport of intense particle beams for fast ignition.

9.1.4 Area: Magnetized High Energy Density Plasma Physics

Issue: Influence of Magnetic Field on HED Fusion Plasmas

Question: *How do magnetic fields, either spontaneous or induced, affect the behavior of HED fusion plasmas, and how can they be utilized to improve the prospects for inertial fusion energy?*

Priority level: (1) High

Description: The possibility of thermal insulation with a magnetic field forms the basis for magnetic fusion energy (MFE), but relatively little has been done to explore the possible benefits of a magnetic field for inertial fusion energy. Many possible magnetic configurations for a target are possible, with subtle but important differences in the properties of equilibrium, stability, and energy transport. In the HEDLP regime, the plasma pressure is typically much larger than the magnetic pressure (plasma beta $\beta > 1$), and the role of collisions is much stronger than in MFE. The theoretical advantage of magnetic insulation is that less energy and power must be deposited in a lower-density hot spot to achieve fusion gain. Magnetic fields can be introduced in a target by conventional coils before compression, and then large fields can be generated by flux compression in the electrically conducting plasma. This is the principle of magneto-inertial fusion (see Sec. 7.1.6). The flux compression can be driven by an imploding metal liner, converging plasma jets, an imploding ICF target, or other means. Less explored possibilities to avoid the requirement of coil fabrication would be laser- or particle-beam-driven currents delivered by a remote source. Magnetic fields are generated spontaneously by spatial inhomogeneities in hot spots, whose effects have been studied very little. Another subject of importance is how magnetic fields influence the possibilities for fusion gain. The additional energy required to compress the magnetic pressure as well as fuel pressure will be small for high-β systems. Even in low-β systems, it will not be important for highly efficient drivers, such as metal liners. While the magnetic fields suppress thermal conduction losses perpendicular to B in HEDLP conditions, they also influence alpha-particle heating. This happens because the deuterium–tritium alpha-particle range in nearby unheated fuel is considerably reduced as the alpha particles spiral and can be confined by the magnetic fields. The importance of heating additional fuel is not obvious. There are numerous effects to consider, such as energy transfer from the hot spot to surroundings by radiation, or by the class of alpha particles moving along field lines that intercept surrounding fuel outside the hot spot. As in some regimes, the gyro-periods of plasma particles and alpha particles are shorter than scattering and slowing-down times and microinstabilities may develop and may induce Bohm-like transport. More studies are needed with improved numerical-modeling methods and well-diagnosed experiments to evaluate the possibilities for fusion applications using magnetic fields in HEDLP systems.

Self-generated magnetic fields can play an important role in conventional inertial confinement fusion and in fast ignition. Large self-generated magnetic fields have been measured in the coronal plasmas of conventional ICF and cone-in-shell fast-ignition implosions. Such fields can inhibit the heat transfer from the critical surface to the ablation front. Heat-flux inhibition would reduce the laser-energy coupling to the target and degrade the target performance with respect to the final compression.

In fast ignition, PIC/hybrid simulations have shown that large self-generated magnetic fields develop around the fast-electron beam propagating from the cone tip to the dense core. The simulations show that these fields keep the beam collimated. Without such fields, the intrinsic divergence of the fast electrons would prevent the localized heating of the dense fuel, therefore raising the value of the beam energy required for ignition.

Issue: Magnetically Driven Implosions

Question: *What are the limits for achieving high energy conditions using magnetically driven implosions?*

Priority level: (2) Medium

Description: Modern high-power *Z*-pinches create IFE-relevant HEDLP conditions using magnetically driven implosions. Fairly efficient conversion of electrical energy to intense x rays has been observed and used to implode ICF capsules. A plasma is accelerated after it is ablated from an array of thin wires. Turbulence resulting from the magnetic Rayleigh–Taylor instability, and *z*-pinch MHD modes, leads to a three-dimensional structure of the magnetic field (and current flow) and a spatially nonuniform imploded plasma. A quantitative predictive description requires three-dimensional radiation-magnetohydrodynamic numerical models that need much more development. Examples where development is needed consist of the theory of turbulence, including the effects of magnetic field, and a better understanding of the resistivity and equation-of-state for warm dense matter that occurs when generating HEDLP conditions.

Besides wire-array *z*-pinches, implosions with magnetically driven cylindrical solid-metal liners (magnetized target fusion) or quasi-spherical meshes (quasi-spherical magnetically-driven direct-drive) might deliver pressure pulses relevant to an inertial fusion system. Quasi-spherical, *z*-pinch, direct-drive implosions could improve the energy coupling to the fusion fuel. In magnetized target fusion, the maximum pressure possible in converging flows and the interaction of pushers with internal megagauss magnetic fields need to be studied through improved numerical-modeling methods and well-diagnosed experiments in order to evaluate the limits to high energy conditions achievable. Resolving these issues is essential for a successful compression of magnetized targets. The latter are used to generate high energy density magnetized plasmas for improving the ignition conditions through magnetic thermal insulation.

9.1.5 Area: Radiation-Dominated Plasma Dynamics and Material Properties

Issue: Laser/Particle-Beam X-Ray Conversion

Question: *How do the details of x-ray conversion affect the implosion symmetry?*

Priority level: (3) Low (adequately addressed within the NNSA ICF program)

Description. In indirect-drive IFE target designs, one of the most important determinants of target performance is the symmetry of the x-ray irradiation and that of the resulting target implosion. While indirect-drive ICF is currently the mainline ICF concept for the NIF, uncertainties remain. The capsule must be symmetrically driven to achieve ignition conditions. While x-ray conversion from planar-solid targets is well-understood, the dynamics in a hohlraum are much more complex. Any deviation of the driver direction, such as caused by laser–plasma instabilities, can change the symmetry of the drive. Heating the hohlraum can affect the x-ray re-emission properties of the wall. A finite density scale length at the hohlraum wall can affect both the x-ray absorption and re-emission. These very complex physics, coupled with uncertainties in the HED opacities of the wall material, can significantly affect the symmetry of indirect-drive target designs.

Issue: Radiation Hydrodynamics

Question: *How does radiation transport affect hydrodynamics in HED plasmas?*

Priority Level: (3) Low (adequately addressed within the NNSA ICF program)

Description. Understanding the hydrodynamics and magnetohydrodynamics (MHD) of radiation-dominated HED plasmas is key to achieving ignition in ICF by all approaches. This includes the ability to measure the properties of radiation-dominated ICF implosions, especially at the moment that ignition should be taking place. Since the success of ICF/IFE requires high Mach number, high convergence-ratio implosions, it is important to gain control of hydrodynamic and magnetohydrodynamic instabilities in an environment in which radiation flow is a major energy-transport mechanism. Radiation transport can substantially change the character of shock waves in a radiation-dominated HED plasma. Radiation affects the temperature and, therefore, the density profile both upstream and downstream in ways that depend on opacity and the equation of state; the density profile, in turn, affects the growth rates and nonlinear evolution of the Rayleigh–Taylor (RT) and magneto-Rayleigh–Taylor (MRT) instabilities. Those instabilities influence the implosion symmetry, the effective convergence ratio, and the capsule gain. The coupled physics issues require integrated computer simulations with physically correct models of radiation transport to understand and predict radiation-dominated HED plasmas. Validated radiation-hydrodynamics and radiation-magnetohydrodynamics codes are indispensable tools for achieving success in ICF. Three-dimensional versions of such codes are challenging to develop and in their nascent state. Many different extremely well-diagnosed HED experiments that can be compared quantitatively with computer simulations will be required to validate those codes. Rapid progress will be greatly aided by broad availability of such validated codes.

For *z*-pinches a 25-MA current flowing in a ~1-cm-radius plasma implies a magnetic field at the plasma surface of 500 T, which is equivalent to 1 Mbar of pressure. MHD issues of importance to *z*-pinch–based ICF include a full understanding of (a) where the current flows as the imploding plasma undergoes MHD instabilities, (b) how to properly model the regions with very-low-plasma density, (c) what limits the current that can be delivered to an imploding plasma, and (d) how to control the MRT instability

Issue: Equation of State and Opacities of HED Plasmas and Materials at High Pressures

Question: *What are the equations of state and opacities of HED plasmas and materials at high pressures?*

Priority: (3) Low (adequately addressed within the NNSA-ICF program)

Description. All schemes for high-gain inertial fusion energy depend on the coupling of driver energy to a target. Energy coupling and flow through the target depends on the equation of state and opacity of the compressed target. While HED material properties have been studied for many years, new target designs often include material/plasma conditions that have not been previously studied. The equation of state (EOS) of compressed deuterium provides a clear example of this. The EOS of deuterium has been studied for many years, but many different results have been reported. Understanding the equation of state of hydrogenic isotopes is essential for achieving ignition on the NIF. Most ignition target designs involve the compression of cryogenic deuterium–tritium targets. "Hot-spot" ignition target designs depend on the accurate timing of the hydrodynamic waves (shock and compression) necessary to create the ignition conditions in the compressed core and to assemble the surrounding fuel shell. The shock and compression waves must be timed to ~1% of the pulse duration. This requires that the equation of state of hydrogenic isotopes be known to high precision. Experiments measuring compression of deuterium at pressures relevant to ignition target designs have shown a wide variety of values. A recent summary has resolved many of the discrepancies. Some experiments remain unexplained. A complete understanding of the equation of state of hydrogenic materials is required to design ignition targets.

While a consensus of the EOS of deuterium is converging, it shows that even the simplest material can have unknowns that must be resolved. These issues can provide significant uncertainties in the performance of IFE targets. In the various IFE schemes, the material properties of the targets and their plasma state determine the performance. One possibility for a direct-drive IFE target design is to coat the target with a high-*Z* layer that both reduces the thermal perturbation of the target during injection into an IFE reactor and laser imprinting and preheat caused by fast electrons by increasing the threshold for the two-plasmon-decay instability. In high-energy ion-driven fusion, the direct-drive compression scheme volumetrically heats the outer layers of the target. The EOS/Opacity of this material determines the details of the ignition target design.

The EOS/Opacity of the gold cone in fast-ignition designs determines whether it remains intact during the high-intensity-beam interaction. All high-gain IFE target designs rely on a detailed understanding of the EOS/opacity of the materials under HED conditions. The study of these properties is important to the success of IFE.

9.1.6 Area: Warm Dense Matter Physics

Issue: Transport Properties of Strongly Coupled HED Plasmas
Question: *What are the transport coefficients of strongly coupled and degenerate HED plasmas?*
Priority level: (2) Medium
Description: Transport coefficients of matter include thermal conductivity, viscosity, electrical conductivity and, for materials of varying composition, mutual diffusivity. Knowledge of the transport coefficients is required to analyze and predict the behavior of the dynamical ICF systems at small scales; in particular, to find the cutoff wavelength for the Rayleigh–Taylor (RT) instability (the wavelength at which transport coefficients stabilize the RT instability for all shorter wavelengths). Thermal conductivity may destabilize the RT instability in situations where the composition of the matter varies in space. The very intriguing question about magnetic-field enhancement and/or self-generation in the dense, strongly coupled plasmas requires the knowledge of electrical conductivity. Hydrocodes used in target design studies, use transport coefficients calculated in the weakly coupled regime with *ad hoc* corrections to include strongly coupled plasma effects. Such transport coefficients depend on the Coulomb logarithm. In the strongly coupled regime of high-gain IFE targets, the value of the Coulomb logarithm can fall below unity, rendering the expansion used to derive the transport coefficients invalid. To overcome this problem, most hydrocodes artificially set a lower limit of about two for the Coulomb logarithm without any physical justification. First-principle calculations of the transport coefficients for the strongly coupled, sometimes degenerate plasmas characteristic of ICF research, are much more difficult than first-principle calculations of equations of state. Molecular–Dynamics-type simulations are still in the early state of development. Significant progress is needed to develop the corresponding computer capabilities. It is desirable to find ways for experimental measurements of the transport coefficients in the relevant parameter domain. This will require developing novel, inventive approaches to probe the matter in the HED state. The results would be of great value not only for ICF, but also for planetary physics and astrophysics.

9.1.7 Area: Integrated HEDLP Physics

Issue: Integrated Physics of High-Gain Targets
Question: *What are the optimal target designs to achieve high gains with good stability and efficient driver coupling?*
Priority level: (1) High
Description: Achieving a target design suitable for fusion energy production is a challenging and complex task. It requires an integrated self-consistent design that produces sufficient gain for the energy application with adequate stability. This requires balancing the constraints imposed by the physics areas cited above. It will open exciting

scientific opportunities. Producing a self-consistent target with sufficient gain for fusion energy stresses our understanding and control of the underlying HEDLP physics.

The gain required for the energy application is determined by both the driver efficiency and the economics of providing a competitive energy source. The generally accepted criterion is that the driver efficiency η multiplied by the gain G should be greater than ten. Maximizing gain requires maximizing coupling the driver(s) to the target and maximizing the ignition areal density (ρR). Understanding the relevant physics is the key to achieving these simultaneously. The more important issues are listed below along with their relevance to various target designs and their underlying questions.

Our knowledge in many of these areas has advanced to the point that integrated target designs have been generated. In some cases, the designs are quite mature and look very attractive for energy, pending resolution of some key physics and technology issues. Priority should be given to addressing these. And in general, research emphasis in these areas should be in the context of an integrated target design.

Maximizing Driver Coupling

There are a number of issues that must be understood and addressed to optimize the coupling of the driver energy to an IFE target.

1. Laser–Plasma Instabilities (LPI): ***Laser IFE, Shock Ignition***

(a). How much LPI can be tolerated in an IFE target? How does the laser wavelength affect the target performance? Can predictive LPI models be developed and can experiments be performed in the relevant regimes?

(b). Are LPI-generated hot electrons necessarily deleterious? Under what conditions should LPI be suppressed, encouraged, or controlled? In some target designs (shock ignition) hot electrons may be beneficial: if their energy is relatively low and/or the plasma is dense, they can be stopped in a short distance and enhance the coupling. In other target designs, LPI may be deleterious, if the electron energy is high enough to induce preheat and compromise the implosion, or if the electrons cannot be directed to where they are needed or they change the symmetry of the energy coupling.

2. Radiation Transport: *All IFE Concepts*

(a). How accurately must the transport of radiation (including generation and absorption) be predicted to confidently design an IFE target? How accurately *can* we predict the transport? How important, and accurate, is non-LTE modeling? And how do these affect the prediction of the target performance? Radiation plays a major role in many high-gain target designs. Several examples include: the high-*Z* layer used in direct-drive targets to improve stability, the transport of *z*-pinch-generated x rays into the imploding plasma, and the use of radiative layers to control the target adiabat. In fast ignition, an inserted high-*Z* cone significantly complicates the radiation hydrodynamics. Radiation transport determines the performance of all indirect-drive ICF schemes. Prediction requires precise understanding and control of radiation transport in plasmas under conditions of extreme density and pressure, steep gradients, and possibly turbulence.

3. Nonlocal Electron Transport: *All IFE Schemes*

(a). What are the effects and importance of nonlocal heat transport on the target performance; in particular, on driver-energy absorption, preheat and, in some cases, on LPI? [Nonlocal transport refers both to transport of thermal electrons through steep (non-Spitzer) temperature gradients, as well as the transport of hot, or suprathermal, electrons generated by the wave–particle interactions from LPI.] This problem is indigenous to all laser IFE approaches. A combination of experiments in relevant regimes and modeling to develop a predictive capability will be required.

4. Lasers/Particle-Beam to X-Ray Conversion Efficiency: *Indirect Drive*

(a). How can the x-ray conversion efficiencies in IFE targets be maximized? From the point of view of fusion energy, one of the fundamental physics impediments to the conventional indirect-drive approach with lasers is the coupling efficiency of the x rays to the target due to the energy losses to the wall and out of the laser entrance hole. (This is less of an issue with heavy ions because there is not entrance hole.) Both of these would benefit from research in this area.

5. Coupling: Magnetic Fields to Plasmas: *Z-Pinch, Magneto-Inertial Fusion*

(a). Can sufficient energy be coupled from a magnetic field drive to the plasma to realize a high-gain target? How much control of hydrodynamic instabilities, turbulent mixing, current profiles, and/or anomalously resistive sheaths is needed to achieve high gains?

6. Coupling: Heavy Ions to Plasmas: *Heavy-Ion Fusion*

(a). How can heavy-ion deposition be controlled to maximize target performance? It is essential to understand the stopping of the low-density, energetic heavy-ion beam in a high-density plasma. One important issue is to understand how to temporally control the ion-beam parameters (energy and/or velocity) to achieve an optimal ion-energy-deposition profile. The optimal profile is different for indirect and direct drive.

7. Coupling: Fast Ignition: *Fast Ignition*

(a). What conversion efficiency and coupling efficiency between lasers to particle beams is needed to make fast ignition an attractive approach? One of the potentially attractive facets of fast ignition for IFE is that it provides extremely high gains with an acceptable increase in complexity. This is a key issue for fast ignition, and experiments and modeling in the relevant regimes are required.

(b). How does the transport and energy deposition of particle beams affect the target gain? In the case of fast ignition, charged particle beams must propagate through a plasma to a dense core. The beams carry gigaAmpere-scale currents, and are subject to several instabilities. The linear theory of these instabilities is well developed, but their nonlinear stage is still poorly understood. Determining the effects of these instabilities on transport and controlling them, if need be, is one of the key issues to making Fast Ignition a viable approach to IFE.

Achieving Maximum Compression

8. Hydrodynamic Instabilities: *All IFE Concepts*

(a). How can stability be maximized without compromising the target gain? The fundamental physics of stability is fairly well understood, but applying it to these complex systems is not. Adjusting the drive pulse shape, target materials, and the target topology, to control the adiabat, shock timing, radiation transport, and implosion velocity profile, are techniques that have been exploited to achieve high-performance targets. Research will continue to determine if other opportunities exist with a potentially higher payoff.

(b). How much turbulent mix is allowed in a high-gain target, can it be predicted, and how can it be controlled? Turbulent mix is the mixing of the pusher with the fuel. The pusher can be a high-density plasma or an imploding liner. The less mix, the purer the fuel, and the higher the performance. This issue can affect power plant economics since the level of mix determines the required thickness of the DT-fuel layer. A thinner layer offers the potential for a significantly reduced tritium inventory.

9. Implosion Dynamics: *All IFE Concepts*

(a). What level of compression and symmetry is required for the various target concepts and how can this be achieved? How much less strenuous are the implosion-symmetry requirements for fast ignition compared to conventional hot-spot ignition? How much can the direct- and indirect-drive symmetry be reduced while maintaining ignition conditions? For shock ignition, how uniform must the ignitor shock be to prevent quenching of the ignition process?

10. Equation of State of Compressed Hydrogenic Isotopes: *All IFE Concepts*

(a). How accurately must the equation of state (EOS) of hydrogenic isotopes under fusion conditions be predicted to confidently design an IFE target? How accurately *can* it be predicted? And how does the accuracy of the predictions affect those of target performance? Because of its importance, hydrogen EOS has been investigated by many researchers, using a wide range of drivers and a wide range of diagnostics.

11. Effect of Magnetic Fields: *Fast Ignition, Lasers, Heavy Ions, Magnetically Driven Targets, MIF*

(a). Can realistic IFE targets be designed to take advantage of the beneficial effects of applied magnetic fields? How can such fields be effectively applied?

(b). If a self-generated magnetic field in the corona of laser-IFE capsules leads to a severe inhibition of the thermal transport, how can this be taken into account in the hydrodynamic codes used in the IFE target design? What is the optimal fast-ignition target design that enhances the collimating effects of the self-generated resistive magnetic fields?

(c). How does the presence of magnetic fields modify the nonlinear stage of the Rayleigh–Taylor instability, mix, and time duration of the final pulse of x rays in *z*-pinch implosions? Can rapid changes of the shape of the imploding shell lead to large voltage spikes (caused by changes in inductance) and the generation of particle beams? If the liner compresses a premagnetized plasma, what configurational (e.g., ballooning) instabilities can develop in this plasma? How is the answer modified if the pusher is made of merged plasma jets?

Issue: Target-System Integration

Question: *How can the target physics be optimally matched to an integrated IFE system?*

Priority level: (2) Medium

Description: A target suitable for the energy application requires more than achieving sufficiently high gain with adequate stability. The target design must be compatible with the other components in an IFE system. The target design must

- match the driver capabilities
- be compatible with low-cost mass production
- be suited for accurate, repetitive injection/placement
- produce an emission spectra that can be tolerated by the chamber/first wall.

This is a complex, multifaceted undertaking that requires a thorough understanding of a number of disciplines including, of course, HEDLP. The only path to success is an integrated "give and take" approach that considers all of the constraints as a coherent system. Producing an integrated target design for fusion energy is the ultimate test of our understanding and control of the underlying HEDLP physics. Some specific areas for consideration are:

1. How can the target be designed to be compatible with realistic driver capabilities? Efficiency, which is discussed in the section on gain, is only one of several constraints applied by the driver. Others to be considered are: repetition rate, pulse-shaping capabilities, rise-time limitations, drive uniformity, and energy spectrum (e.g., laser wavelength, ion energy, field strength). These can affect coupling, stability, implosion dynamics, radiation transport, etc.

2. How can the target be designed to produce high gain within the constraints of low-cost, mass-production target fabrication? All IFE approaches have a target of some type. All of these have a set of specifications for uniformity, composition, density, surface finish, areal mass uniformity, dimensions, nonconcentricity, etc., that are required by target physics. The key is to ensure these specifications are within the credible capabilities of the target fabricators.

3. How can the target be designed to produce high gain within the constraints of target placement/injection and tracking? All IFE approaches must repetitively place the target at a precise point in a chamber. The same methodology, as described above, must be applied here as well. An example of the interplay between HEDLP physics and target injection is the use of high-*Z* layers on the outside of a laser direct-drive target. Researchers working on target injection wanted a reflective layer on the surface to reflect

infrared radiation to thermally protect the cryogenic target from the hot walls of the chamber. HEDLP studies soon established that not only does this layer not compromise the target physics, it enhances it by producing an initial flux of soft x rays that tend to smooth out any drive nonuniformities. Some concepts on the other hand, do not have problems of this type: for example, the low (1HZ) frequency z-pinch implosions driven by recyclable transmission lines.

4. How can the permanent energy source be protected from the fusion blasts in higher repetition-rate electromagnetically driven systems? Can the standoff problem be solved by disposable solid or liquid electrodes, plasma electrodes, plasma jets, or a combination thereof?

5. Can the emission spectra from a target be accurately predicted and can it be tuned to be compatible with the chamber first wall? The energy from an IFE target exits as pulses of neutrons (roughly 70%), x rays, ions, and, to a much smaller degree, gammas. The chamber first wall must be able to repeatedly withstand this "threat" spectrum. The challenge for HEDLP is twofold: the first is to confidently predict this spectra, the second is to tune it. Prediction is a daunting HEDLP task, because the expanding fusion's by-products pass through the dense "unburnt" corona. The physics in this region is not well known. The coupling takes place in a transition regime between pure hydro- and single-particle formalisms. Numerous streaming instabilities are possible. Tuning is required because the relative balance between ions and x rays totally dictates the chamber configuration. Indirect-drive targets produce primarily x rays. These have very high instantaneous power deposition, which would cause any solid to melt and vaporize. Therefore, indirect-drive approaches must use liquid walls. Direct-drive targets produce primarily ions. The thermal loading on the wall is reduced to tractable levels because the ion-energy pulse is about 20× longer than the x-ray pulse. But the ion spectra is dominated by helium ions caused by interactions with expanding fusion by-products interacting with the dense corona. These helium ions embed themselves in the wall, leading to exfoliation. As a final example, encasing a magnetized targets with a relatively massive shell may allow direct electrical conversion, which could significantly enhance the attractiveness of some approaches. The conclusion is that the ability to tune these spectra to meet the needs of the chamber is a fertile field and would be a notable accomplishment for HEDLP physics.

9.2 Scientific Opportunities for Research within the Joint HEDLP Program–Priorities

The scientific opportunities for research in energy-related HEDLP described in Sec. 9.1 are prioritized in this section. While all the research opportunities are important for IFE, a priority ranking is provided to help the agencies determine those issues whose funding by the Joint Program will provide the highest impact in the next five to ten years. The priority ranking is based on the set of criteria described in Sec. 3:

- IMPORTANCE: to the advancement of fusion energy sciences
- DISTINCTIVENESS: degree to which the issue is <u>NOT</u> addressed in the NNSA-funded conventional ICF ignition program
- READINESS: progress expected in the next five/ten years
- GENERALITY: degree to which the solution of the issue impacts multiple IFE concepts
- COST: level of resources required to address the issue

The "distinctiveness" criterion is used to reduce the overlap between the HEDLP research that is supported by the Joint HEDLP Program and the NNSA-funded ICF program. Issues that are *adequately* addressed within the NNSA-ICF program are given lower priority as scientific opportunities within the Joint HEDLP Program. If a science issue is deemed as *partially* addressed within the NNSA-ICF program, the scientific opportunities that do not overlap with current research in the NNSA-ICF program are identified. From the list in Sec. 9.1, the science issues can be divided according to the degree to which they are addressed by the NNSA-ICF program.

- **HEDLP issues *not* addressed within the NNSA-ICF program**
  - Intense particle-beam generation by intense lasers
  - Transport and energy coupling of intense particle beams in HED plasmas
  - Influence of magnetic fields on HED fusion plasmas
  - Target-system integration

- **HEDLP issues *partially* addressed within the NNSA-ICF program**
  - Magnetically driven implosions
  - Hydrodynamic instabilities and turbulent mix
  - Laser–plasma instabilities and hot-electron generation
  - Implosion hydrodynamics for high energy gains
  - Integrated target physics for inertial fusion energy

- **HEDLP issues *adequately* addressed within the NNSA-ICF program**
  - Nonlocal transport of energy
  - Laser/particle beam x-ray conversion
  - Radiation hydrodynamics
  - Equation of state and opacities of HED plasmas and materials at high pressure

Using the ranking criteria above, the energy-related HEDLP science issues are placed into three tiers characterized by Priority Levels 1–3. Important issues that are *adequately* addressed with the NNSA-ICF program are included within Tier-3. Note that the order of the issues listed within each tier does not represent a ranking. The different issues within each tier have similar priorities.

Tier 1 (highest priority) includes the most important scientific issues to be addressed in the short term (~5 years) using existing or planned facilities to answer questions of crucial importance to inertial fusion energy science development. Those issues are either not addressed or partially addressed by the NNSA ICF program. They offer the most significant opportunities for research within the Joint HEDLP Program in the short term.

Tier 2 (medium priority) includes science issues that are either partially (but not fully) addressed within the NNSA ICF program or issues that can be explored over a longer time frame (~10 years). They offer important opportunities for research within the Joint HEDLP Program.

Tier 3 (low priority) includes important science issues that are adequately addressed by the NNSA-ICF program.

A prioritized list of the issues described in Sec. 9.1 is given below

Tier 1 (Highest Priority)

- Intense particle-beam generation by ultra-intense lasers
- Transport and energy coupling of intense particle beams in HED plasmas
- Influence of magnetic fields on HED fusion plasmas
- Laser–plasma instabilities and hot-electron generation
- Implosion hydrodynamics for high energy gains
- Integrated target physics for inertial fusion energy

Tier 2 (Medium Priority)

- Magnetically driven implosions
- Hydrodynamic instabilities and turbulent mix
- Transport properties of strongly coupled plasmas
- Target system integration

Tier 3 (Low Priority)—adequately addressed within the NNSA-ICF program

- Nonlocal energy transport
- Laser/particle beam x-ray conversion and symmetry
- Radiation hydrodynamics
- Equation of state and opacities of HED plasmas and materials at high pressures

Recommendation on priorities for energy-related HEDLP science: *HEDLP scientific issues that are essential to the achievement of high gains and improved inertial fusion energy concepts should be given a high priority within the Joint HEDLP Program. All of these high-priority issues are either not addressed or are only partially addressed by the NNSA-ICF program. Out of fourteen, six high-priority scientific issues*are identified that can be addressed by the Joint Program with existing facilities:*

- **Intense particle-beam generation by ultra-intense lasers.** Science question: *What are the essential features of the energetic particles generated by intense lasers interacting with plasmas, and how does intense light affect the plasma dynamics?*
- **Transport and energy coupling of intense particle beams in high energy density plasmas.** Science question: *How are intense charged-particle beams transported in and how does their energy couple to HED plasmas?*
- **Influence of magnetic fields on high energy density fusion plasmas.** Science question: *How do magnetic fields, either spontaneous or induced, affect the behavior of HED fusion plasmas, and how can they be utilized to improve the prospects for inertial fusion energy?*
- **Laser-plasma instabilities and hot-electron generation.** Science question: *How do laser-plasma instabilities reflect light, how do they generate energetic electrons, and how can they be controlled?*
- **Implosion hydrodynamics for high gains**. Science question: *How can HED plasmas be assembled to the densities and pressures required for maximizing the fusion-energy output?*
- **Integrated target physics for inertial fusion energy.** Science question: *What are the optimal target designs to achieve high gains with good stability and efficient driver coupling?*

*Note that the order of the above issues does not represent a ranking.

The scientific opportunities for research within the Joint HEDLP Program are identified and assessed within the context of the ranking criteria.

Tier 1: Scientific Opportunities for Research within the Joint HEDLP Program

Intense Particle-Beam Generation by Ultra-Intense Lasers

Well-diagnosed experiments and PIC simulations are needed to determine the laser-to-particle-conversion efficiencies, the energy spectrum, and the angular spread of the energetic particles accelerated by intense lasers. This is essential for understanding the viability of the fast-ignition concept. It is important to determine whether the conversion efficiencies measured with picosecond and subpicosecond laser pulses remain the same as the laser-pulse duration is lengthened to the 10 ~ 20-ps durations that are required for fast-ignition IFE. The next generation of high-energy short-pulse laser systems (OMEGA EP and NIF-ARC) will allow this to be explored. The next generation of computational capability will allow more realistic simulations. Well-designed, simple experiments should be developed and used to benchmark the simulations and simple analytical models.

Innovative approaches for enhancing the conversion efficiencies (such as the use of foams, microstuctured targets, or microspheres) should be explored. The effects of pre-plasmas (generated by the laser prepulse) on the electron spectrum should be thoroughly investigated and ways to control the hot-electron temperature should be developed. The goal of this research should be to maximize the laser-particle conversion efficiency while maintaining a particle energy and angular distribution that can be optimally transported to the compressed target.

The feasibility of the channeling and fast-ignition schemes should be assessed using facilities such as OMEGA EP and NIF-ARC and 3-D PIC simulations. The energy and power requirements to successfully form a plasma-free channel in the underdense region and bore a hole inside the critical surface must be understood. While less work has been devoted to these areas, recent PIC simulations have been encouraging.

Transport and Energy Coupling of Intense Particle Beams in HED Plasmas

In *fast ignition*, the coupling of laser-produced energetic particles with the dense core of the imploded target must be assessed. While a significant amount of work has been carried out, almost all of it has been under conditions that are far different than expected in an ignition-scale fast-ignition experiment. The highest priority should be to understand the transport and coupling under ignition-relevant conditions. Recent simulations have suggested that in the relevant conditions, a self-generated resistive magnetic field is produced that collimates the electron beam. The collimating effect of this field must be assessed through experiments capable of measuring the self-generated field and the electron-beam radial size and evolution. Electron filaments induced by the resistive-filamentation instability must be characterized and the different transport regimes through regions of sharply increasing density must be investigated with dedicated experiments using preformed plasmas having varying densities. The transport of electrons through the cone tip must be studied with dedicated cone-target experiments and hybrid-PIC simulations. The possibility of using externally induced magnetic fields must be explored to reduce the fast-electron angular spread and improve the electron coupling to the dense core. Implosion experiments with cryogenic cone-in-shell targets must be performed to study the fast-electron-energy coupling to and the transport in hydrogenic plasmas. Integrated hole-boring experiments should be performed to determine the energy-coupling efficiency of the fast electron to the dense core.

All forms of ICF rely on a detailed knowledge of electron- and ion-stopping rates in warm and hot dense plasmas. There have been numerous theoretical models that disagree among themselves about these rates. Novel, high-precision experiments should be developed to measure these rates under ignition-relevant plasma conditions.

Heavy ion fusion would benefit from both longitudinal beam compression as well as transverse focusing of intense ion beams within background plasma to reduce beam space charge forces which would otherwise resist the compression to target requirements. In order to achieve the best transverse focusing and emittance-limited longitudinal compression, the background plasma density must exceed the local beam density by several fold, and depending on the beam and plasma densities, collective instabilities may limit the focused beam intensity. Advanced theory and simulation is needed, as well as more data from intense beam experiments such as NDCX-II (a near-term upgrade of NDCX-I) with longer scale lengths for to study beam plasma interaction, to improve understanding and optimizing the nonlinear beam dynamics, collective interaction processes, and beam compression and focusing.

The research opportunities include experimental, analytical and numerical investigations of nonlinear beam dynamics, collective beam-plasma interaction processes, and intense beam compression and focusing. To achieve the high focal spot intensities necessary for high energy density physics and heavy ion fusion applications, the ion beam pulse must be compressed longitudinally by about a factor of one hundred, and transversely by a factor of ten or more before it is focused onto the target. To achieve maximum compression, the space charge of the ion beam is neutralized by propagation of the beam pulse through a dense neutralizing background plasma. If the space charge is fully neutralized by the plasma, the final compression is limited only by the initial temperature of the beam ions and possible collective processes which may prevent full neutralization of the beam space charge. In one scenario, transverse compression of the beam ions is facilitated by using high field solenoidal focusing magnets. NDCX-II will provide a near term versatile test bed to pursue these research opportunities.

Influence of the Magnetic Field on HED Fusion Plasmas

Integrated implosion experiments must be carried out to compress magnetized plasma targets to high energy density regimes. Integrated experiments with target plasmas in a field-reverse-configuration compressed by imploding cylindrical liners can be carried out using existing facilities. These experiments should be diagnosed to measure the compressed magnetic field, plasma temperature and density, and the effects of the liner-plasma mix on the implosion performance. Integrated experiments can also be carried out using ICF capsules embedded in a seed magnetic field to achieve ultrahigh magnetic field and to magnetize the hot spot in ICF implosions. Such experiments can be carried out on existing implosion facilities and should explore different capsule geometries and seed-field strengths. In both of these conditions, the effects on the alpha-particle transport and subsequent energy deposition should be assessed.

The effects of self-generated magnetic fields in the coronal plasma, in the conduction zone of laser-driven implosions, in the interior of hohlraums, and in fast-ignition cone implosions must be assessed. The mechanism at the origin of the field generation must be identified through controlled experiments and hydro and kinetic simulations. Possible thermal-transport inhibition induced by the magnetic field must be studied and its effects on the implosion performance must be determined.

Laser–Plasma Instabilities and Hot-Electron Generation

Theory and experiments are required to determine the characteristics of the hot electrons generated by laser–plasma instabilities in IFE-relevant plasmas. The latest generation of three-dimensional particle-in-cell (PIC) codes can be used to study the onset of laser–plasma instabilities and study the hot-electron-energy spectrum and directionality. Experiments can be carried out at existing facilities to measure the hot-electron production over a wide range of laser intensities and plasma scale lengths. Most-relevant instabilities with respect to hot-electron production are the two-plasmon-decay (TPD) and the Raman instabilities. Both instabilities are relevant to conventional indirect drive, high-gain direct drive, and shock ignition. In indirect and direct drive, hot electrons are highly detrimental to the implosion performance. Laser–plasma instabilities that produce hot electrons must be controlled. There is some evidence that high-Z elements can suppress the TPD instability but additional work is needed in this area. In shock ignition, hot electrons can be beneficial if their energy is sufficiently low (<150 keV). In this case, a control mechanism must be developed to enhance the production of Raman electrons that are considerably colder than TPD electrons. Colder electrons deposit their energy in a thin outer layer of the imploding shell, augmenting the strength of the ignition shock without uniformly preheating the target material.

Laser–plasma instabilities can affect the implosion symmetry either through scattering of laser light or by causing energy transfer among overlapping laser beams. The complex geometries and plasma conditions make it challenging to model these effects.

Implosion Hydrodynamics for High Energy Gains

Experimental and theoretical investigations, as well as novel approaches, are required to optimize fuel assembly resulting from the capsule implosion. Improving the target design and the implosion dynamics to achieve the highest compression is a common goal of all IFE concepts.

In *fast ignition*, cone-in-shell target implosions must be optimized by bringing the dense core closer to the cone tip while minimizing the mixing of shell and cone material. The pressure in the imploding shell must be tailored to preserve the integrity of the cone tip until the core achieves areal densities high enough for ignition and high gains. This requires many implosion experiments and simulations with hydrocodes capable of simulating cone-in-shell target implosions. A community effort to develop hydrodynamic codes capable of simulating HEDLP experiments (including cone-in-shell target implosions) should be held as a high priority. Fast-ignition integrated experiments using cryogenic cone-in-shell targets can be carried out on OMEGA and, later, on the National Ignition Facility. Such experiments can be designed to validate the fast-ignition concept at the proof-of-principle level. Continued optimization of low-velocity implosions that maximize the target density and minimize the energy in the hot spot is required for the channeling/hole-boring concept.

In *shock ignition*, the ignitor shock strength and dynamics must be investigated for realistic intensities in the range 5×10^{15} to 10^{16} W/cm^2 in long-scale-length plasmas. The role of hot electrons in driving the ignitor shock must be determined and their contribution to the hydrodynamic evolution must be studied. Since shock ignition achieves high gains through the shock-induced compression of the hot spot, the effect of the nonuniformities transferred from the ignitor shock to the central hot spot must be investigated through experiments and multidimensional simulations. Shock-ignition experiments should be designed for the National Ignition Facility using the polar-drive configuration.

In *high-gain direct-drive*, multidimensional simulations are needed to identify the robustness of the high-gain target designs developed for IFE. The present optimal ablator for laser IFE is a wetted plastic-foam shell (CH+DT). According to hydrodynamic simulations, wetted foams offer the best performance with respect to the laser-energy absorption and hydrodynamic stability. However, results from implosion experiments on OMEGA have indicated that pure hydrogenic ablators perform poorly with respect to the final compression. Alternative high-gain designs using different ablators should be developed and their stability properties assessed through experiments and hydrodynamic simulations.

In *heavy-ion direct drive*, NDCX-II (a near-term upgrade of NDCX-I) offers opportunities for planar hydrodynamics experiments involving ion deposition, ablation, acceleration, and stability at energy densities well above the cohesive energies of cryogenic hydrogen, and high enough for optical measurements of hydromotion with dopant lines, at energy densities low enough to neglect radiation transport. Unlike lasers, ion beams do not, in general, have "speckles," i.e., intensity variations with high spatial frequency and high amplitude. However, low-spatial-frequency variations (on the scale of the beam radius or somewhat smaller) do exist and the effect of these variations on the ablation and acceleration of a planar target can be explored. These low-mode-number variations can be mitigated by "wobbling" the beam with controlled amplitude radio-frequency (RF) perturbations impressed on the beam between the accelerator and the target. Furthermore, the deposition of ion-beam energy is volumetric and, therefore, ablation effects (that stabilize Rayleigh–Taylor growth in laser–plasma interactions) may be quite different, simply because the temperature and pressure variation of the ablation layer will be quite different than that arising from the near-surface deposition of lasers. Therefore, experiments that examine acceleration of planar target layers would be of great scientific interest. Experiments with imprinted density variations will make it possible to study the Rayleigh–Taylor instability under a variety of experimental situations.

In *magneto-inertial fusion*, multidimensional simulations are required to optimize the compression of the target plasma and minimize the mixing of the liner material with the hot plasma. Integrated experiments of an imploding metal liner compressing a target plasma must be carried out to demonstrate the compression, heating, and magnetic-thermal insulation of the plasma. Innovative approaches such as plasma jets should also be evaluated through multidimensional simulations. Embedding seed magnetic fields directly into an ICF target may offer significant advantages in terms of energy gains. The conservation of the magnetic flux can lead to extreme fields and magnetic-thermal insulation in an ICF target's hot spot. Higher temperatures can be achieved with lower-implosion velocities, therefore leading to higher energy gains. ICF-implosion experiments using an embedded magnetic field must be designed and simulated with magnetohydrodynamic codes, with the aim of optimizing the magnetic-field compression and inhibiting thermal losses. Using available magnetic-field generators, implosion experiments can be carried out by embedding a seed field within an ICF target and imploding it using existing facilities.

Integrated Target Physics for Inertial Fusion Energy

Integrated studies should be carried out to optimize the target design for short-term implosion experiments and for longer term inertial fusion energy applications. Optimization studies are required to identify the point design for proof-of-principle fast-ignition experiments with cryogenic cone-in-shell targets on OMEGA, magneto-inertial-fusion integrated experiments with imploding metal liners on Shiva-Star, heavy-ion direct-drive IFE targets, laser-driven IFE targets, *z*-pinch IFE targets, fast-ignition IFE targets, and shock-ignited IFE targets. Of great importance are integrated design studies for fast ignition, shock ignition, and direct-drive-ignition demonstration experiments at the National Ignition Facility in the next five to ten years. High-gain, laser indirect-drive designs should also be pursued. Indirect drive is expected to provide the first demonstration of ICF ignition on the NIF in the next few years. Once a robust ignition platform with modest gain has been demonstrated, it should be exploited to further develop the indirect-drive ICF concept to increase the target gain. This may involve adjustments in the x-ray coupling to the target, for example, by changing the case-to-capsule ratio or by using the second harmonic (green) to increase the laser energy available, making it possible to implode larger capsules with more fuel. Other possibilities include indirect-drive fast or shock ignition. The latter could involve a direct–indirect-drive hybrid scheme. Since increasing the gain will involve design tradeoffs that will have to be balanced to optimize the target gain, these efforts will have the distinct advantage of starting from an igniting platform. The other schemes described above will likely demonstrate ignition after it is demonstrated with indirect drive.

Tier 2: Scientific Opportunities for Research within the Joint HEDLP Program
Hydrodynamic Instabilities and Turbulent Mix

Understanding the properties of fully turbulent flows driven by hydrodynamic instabilities in imploding capsules requires highly resolved, three-dimensional simulations and dedicated experiments. An outstanding issue concerning the turbulent stage of hydrodynamic instabilities is the dependence of the turbulent spectrum on the initial conditions. Well-diagnosed controlled experiments on regular fluids (liquids and gases) in non-HED conditions can study the transition to turbulence and the dependence on the initial conditions. There remains an outstanding uncertainty as to whether the properties of materials at HED conditions modify the understanding developed from non-HED experiments.

It is thought that turbulent mix during the deceleration phase of an ICF implosion is a primary cause of reduced neutron yields relative to 1-D simulations. A major limitation to understanding the effects of turbulent mix in ICF implosions is the scarcity of well-developed diagnostic techniques. New concepts are needed and their development should be encouraged.

The effects of distorted shock fronts on the hot-spot formation in shock ignition can be studied through 2-D and 3-D hydrodynamic simulations and implosion experiments on OMEGA and the NIF. The rate of mixing at the liner–fuel interface in magnetized-target-fusion implosion can be studied through integrated implosion experiments on Shiva-Star, provided a plasma target is successfully injected. Studies in wire-array *z*-pinch implosions should be carried out on existing facilities to identify how hydrodynamic instabilities alter the current flow.

Magnetically Driven Implosions

Three-dimensional radiation-hydrodynamic codes are becoming available to study magnetically driven implosions. The concept of quasi-spherical direct drive should be explored through 3-D simulations to determine the energy coupling to the fuel and the role of the magneto-Rayleigh–Taylor instability. Magnetically driven implosions of cylindrical liners can be optimized through experiments on Shiva Star and integrated with the plasma target injected with a field-reverse configuration. Further development of magnetically driven implosions with pulse-power devices should be explored.

Transport Properties of Strongly Coupled Plasmas

Molecular dynamic simulations can be carried out to study the transport coefficients of plasmas in the strongly coupled regimes relevant to inertial fusion. These transport coefficients depend on the Coulomb logarithm that can fall below unity in high-gain IFE targets. Hydrodynamic models used in current hydrocodes, artificially set a floor of about two for the Coulomb logarithm to maintain the mathematical validity of the hydrodynamic model. Because of the strong electrostatic interactions, particle-based or molecular-dynamic numerical simulations are required to study the dynamics of strongly coupled plasmas. Such complicated and time-consuming simulations are not suitable for target-design studies and can be used only for specialized physics studies. The question is whether a hydrodynamic model can be developed to correctly simulate the dynamics of strongly coupled plasmas. It is important to assess the validity of the hydrodynamic model to treat such complicated plasmas. Benchmarking simulations need to be carried out to compare how the hydrodynamic models predict the dynamics of strongly coupled plasmas with respect to more accurate PIC-based or molecular-dynamic simulations. New experimental techniques must be developed to determine the transport properties of strongly coupled plasmas. This will require a creative approach.

Target-System Integration

Integrated studies must be carried out to develop IFE target designs compatible with the requirements of an IFE power plant. These integrated target studies must consider the thermal and structural requirements for target injections, the target compatibility with the driver capabilities, the target cost and mass-production requirements for the economic viability of IFE and the compatibility of the target-emission spectra with the chamber first wall.

Tier 3: Scientific Opportunities for Research within the Joint HEDLP Program

Nonlocal Energy Transport

The transport of energy from the region where the driver energy is deposited to where it drives the target ablation is an essential part of ICF and IFE target designs. While this opportunity appears to be most important for direct-drive target designs, nonlocal effects must be considered for all concepts. In all cases, the acceleration phase of an ICF implosion involves very steep gradients in temperature and density where nonlocal effects become important. This important ICF issue is currently studied within NNSA’s ICF program, but its application to more advanced IFE approaches must be considered.

Laser/Particle-Beam X-Ray Conversion and Symmetry

In the laser-drive indirect-drive ICF scheme, the conversion of laser energy to the x rays that drive the implosion is an essential part of the target-design process. The subsequent radiation transport affects the symmetry of the target implosion. This opportunity is a major component of NNSA’s ICF mission.

X-ray conversion efficiency and radiation transport are important aspects for other ICF concepts. Any concept that involves high-*Z* materials requires an understanding of the performance of these materials. For example, some direct-drive concepts use a high-Z layer on the outside of the capsule to reduce the effects of hydrodynamic instabilities or laser–plasma instabilities. Optimizing this layer requires an understanding of conversion efficiency. Fast-ignition concepts using a cone-in-shell target require an understanding of how x-ray radiation interacts with high-Z materials.

Radiation Hydrodynamics

As mentioned in the previous subsection, any ICF concept that uses high-Z materials depends on the details of the radiation hydrodynamics. In the baseline indirect-drive concept, radiation hydrodynamics is essential to target performance. This is another major area of NNSA-funded research. This research has been devoted to those issues relevant to indirect-drive ignition. Radiation hydrodynamics is likely to be important to other concepts, so a broader study of this area is justified.

Equation of State and Opacities of HED Plasmas and Materials at High Pressures

A major effort has been devoted within NNSA's ICF program to understand the equation of state and opacities of the primary indirect-drive target materials, hydrogenic isotopes, beryllium, plastic, and diamond. To the extent that these materials are used for advanced IFE concepts, the current results provide guidance. If new materials, such as wetted foams, are used in advanced designs, their equation of state and opacity properties must be understood. Opportunities exist to develop an understanding of materials that can be useful for advanced IFE schemes.

10 Fundamental HEDLP Science: Areas, Issues, and Opportunities

Earlier sections of this report showed that HED matter exists across a vast range of density and temperature, that understanding its properties and dynamics is a challenge, and that such understanding enables both practical and scientific applications. The potential practical applications range from particle sources for medicine to novel materials-processing techniques to light sources for diagnosing structure in industry or homeland security. The scientific applications range from astrophysics to biophysics. Each of these elements—unexplored territory, practical applications, and scientific applications—motivates the discovery-driven exploration of the properties and dynamics of HED matter, which is the quest of fundamental HEDLP research.

Recent years have seen progress in the laboratory study of HED systems on many fronts. Lasers have improved their range in all directions, reaching higher energies (to above 1 MJ), higher intensities (to ~10^{22} W/cm^2), and shorter pulses (to <10 fs). Pulsed-power devices have reached x-ray output powers approaching 300 TW, and HED particle-beam facilities have produced the unprecedented short bunches needed for particle acceleration in plasmas. In addition to facilities at these forefronts, other existing research facilities have the potential to serve a growing community working in fundamental HEDLP research. Of equal importance, most such facilities provide multiple sources of energy and numerous diagnostics, both of which are essential for sophisticated experiments that seek to produce HED conditions, alter them in some way to reveal behavior of interest, and diagnose the results.

This combination of motive and opportunity has led to an explosion of research activity and a plethora of opportunity on many fronts. In preparing this report, the committee sought to organize fundamental HEDLP science into a manageable number of areas (six), focused in directions that have evident current research potential. All six areas are essential to the advancement of the field and should be considered for funding within the Joint Program. As detailed in Sec. 10.2, all areas offer significant opportunities for scientific discovery. We emphasize that novel and creative research proposals may overlap between these categories or not fit cleanly into them, and that the funding process should not downgrade them for this.

In Sec. 10.1, the six areas are assessed according to their importance, prospects for rapid progress, and their potential for practical applications. An assessment of the six areas, rather than a prioritization of the scientific issues, is the method followed for this category of fundamental, discovery-driven science. While prioritizing the scientific issues is appropriate for mission-oriented science (such as inertial fusion energy science), fundamental science is better characterized through an assessment of its different areas with respect to their potential and prospects for growth.

The six areas of fundamental HEDLP science assessed in this section are

- high energy density hydrodynamics

- radiation-dominated dynamics and material properties
- magnetized high energy density plasma physics
- nonlinear optics of plasmas and laser–matter interactions
- relativistic high energy density plasma physics
- warm dense matter physics

Recommendation: *The Joint Program should support all six areas of fundamental HEDLP. Priority should be given to discovery-driven research efforts that are expected to advance the field, explore its practical and scientific potentials, stimulate the interest of graduate students, and attract scientists from other disciplines.*

Each HEDLP science area is characterized by several fundamental issues. Each issue offers numerous opportunities for scientific research. Those identified by the panel are described in Sec. 10.2. Creative innovation is likely to develop additional opportunities.

10.1 AREAS OF HEDLP SCIENCE: ASSESSMENT

The assessment of the six areas of fundamental HEDLP science is carried out according to the evaluation criteria discussed in Sec. 3 and reported below.

(1) IMPORTANCE: to the fundamental understanding and development of high energy density science
(2) POTENTIAL: for important practical applications (other than IFE)
(3) POTENTIAL: for resolving major issues in other fields of science
(4) READINESS: progress expected in the next five to ten years

The HEDLP areas are ranked with respect to each evaluation criterion on a three-level scale: high, medium, and marginal. Each area is first characterized by an overarching question and by an overview of the underlying themes. A short paragraph describes the potential of each area for attracting graduate students and stimulating the interest of scientists from other fields. This is followed by the assessment with respect to the four criteria. The specific scientific issues and opportunities for research are discussed in Sec. 10.2. **Fundamental science relevant to the energy applications of HEDLP is not considered here. Energy related issues and opportunities are identified in Sec. 9.**

A summary of the assessment levels for the six areas is provided in Table 10.I. Details of the assessment are given in Secs. 10.1.1–10.1.6.

Table 10.I: Assessment of the HEDLP science areas with respect to four ranking criteria

Area/Criterion	(1)	(2)	(3)	(4)
HED hydrodynamics	High	Marginal	Medium	High
Radiation-dominated dynamics and material properties	High	Medium	High	Medium
Magnetized HED plasma physics	High	Medium	High	High
Nonlinear optics of plasmas	High	Medium	Medium	High
Relativistic HED plasma and intense-beam physics	High	High	Medium	High
Warm dense matter physics	Medium	Marginal	High	High

10.1.1 Area: High Energy Density Hydrodynamics

Overarching question: *How do the distinct properties of HED systems alter hydrodynamic behavior?*

The description of flows in HED matter, including instabilities, nonlinear evolution, and turbulence, has broad connections to a wide range of scientific disciplines. Examples include plasma flows in HED and ICF experiments; plastic flows and lattice dynamics in solid-state, high-rate deformations; protostellar jets in star formation dynamics; explosive turbulent flows in supernovae; accretion disk dynamics in accreting compact objects (white dwarfs, neutron stars, and massive black holes); hypervelocity impact (cratering) dynamics; and high-energy, heavy-ion, nuclear collisions, to name a few. HED flows occur in settings having vastly different spatial and time scales, ranging from microns in imploding ICF capsules to $>10^{12}$ meters in exploding massive stars. These HED flows are created by extreme pressures, whether caused by gravity, powerful shocks, intense fluxes of radiation, or intense pulses of current. HED flows can be created in the laboratory using high-power lasers, magnetic pinch facilities, gas or powder guns, high-explosive-pressure sources, or combinations thereof. HED flows are unique from a number of perspectives. First, the flows, including instabilities and turbulence, can be observably influenced or modified by the properties of the HED medium. Strong compression and density gradients can have significant effects on instabilities such as Rayleigh–Taylor, Richtmyer–Meshkov, Kelvin–Helmholtz, and 3-D Widnall (azimuthal) instabilities. Interfaces and volumes that would have otherwise been stable can become unstable because of ionization (entropy) gradients, composition gradients, or temperature gradients. Self-generated electric or magnetic fields can severely modify the flows and instability growth rates.

Well-posed HED experiments allow precise control of the initial conditions by using well-characterized solid targets that are driven by precisely applied energy pulses to flow at extreme pressures. This is in contrast to the challenge of controlling initial conditions in many traditional experiments with fluids, and is an aspect in which HED experiments complement these others. Well-posed HED experiments can be executed in planar geometry, cylindrical geometry, spherical geometry, or complex geometries. The temporal profile of the applied pressures or temperatures can be precisely tailored for specific research needs. The experiments allow excellent diagnostic access, since the targets effectively sit isolated in open space in a vacuum chamber. The dynamics can be probed with high spatial and temporal resolution, using synchronized optical probes, x-ray sources, and particle sources. HED hydrodynamics serves as a reference, against which radiative or magnetized HED effects can be compared for departures in evolution (from this reference). Beyond seeking an understanding of how the properties of HED systems alter hydrodynamic behavior, these precise diagnostics offer the possibility that "known hydrodynamics" might be used as a diagnostic probe of fundamental properties of HED matter, such as viscosity or thermal diffusivity in the warm dense matter regime, where theoretical uncertainties are large.

Potential for stimulating interest in graduate students and scientists from other fields. The potential for stimulating interest in graduate students and scientists from other fields of science is demonstrably very high. The field of HED laboratory astrophysics has a major component that relies upon HED hydrodynamics and, in particular, the rigorous scalability of these results from the laboratory to the cosmos. The interest level is evidenced by the publications, citations, conferences, and invited talks in this area over the past ten to fifteen years, and by the significant number of active collaborations between laboratory scientists and astrophysicists. Students are intrigued by the applicability to high energy astrophysics, planetary physics, and high energy density materials science. This area has led to a long series of invited talks at major scientific conferences by senior graduate students, making it an excellent training ground and attracting students in experiment, theory, and computational sciences.

Assessment. The following assessment of the readiness and scientific importance of HED hydrodynamics is based on the five criteria discussed in Sec. 3.

(1) ***Importance to the fundamental understanding and development of high energy density science***

Assessment level – High

Understanding HED science requires understanding the fundamental properties of HED matter, such as electrical conductivity, thermal diffusivity, and kinematic viscosity, and the dynamics of HED flows. Furthermore, hydrodynamic HED flows are subject to an array of instabilities. Some are familiar, such as Rayleigh–Taylor, Richtmyer–Meshkov, and/or Kelvin–Helmholtz instabilities, but operating in the unfamiliar environment of an HED medium; others are new, such as density-gradient instabilities, composition- or ionization-gradient-driven instabilities, and geometry-specific instabilities (e.g., spherical accretion-shock instability). HED conditions in the laboratory occur over only very short spatial and time scales and can involve dense, strongly coupled, Fermi-degenerate plasmas. Experimentally probing the properties of HED matter is particularly challenging. Hydrodynamics offers a probing technique, whereby carefully tailored flows can be created that are sensitive to these fundamental properties of HED matter. HED hydrodynamics are the quantitative reference against which radiative HED dynamics and magnetized HED flows will be compared to look for telling departures. As such, understanding HED hydrodynamics, including the transition to and development of turbulence, is of high importance.

(2) ***Potential for important practical applications (other than IFE)***
Assessment level – Marginal

There are practical applications in the area of science-based stockpile stewardship, where hydrodynamic drivers generate precision tailored flows for specific applications, such as probing strong shock-driven turbulent flows in complex geometries, or quasi-isentropic compression waves for material property studies. Another potential, but largely unexplored, application could be generating hypervelocity (tens of km/s) micro- or nano-flier plates for impact studies, and durability tests of space hardware. With the exception of stockpile stewardship, we consider these issues of marginal importance as practical applications of HEDLP.

(3) ***Potential for resolving major issues in other fields of science***
Assessment level – Medium

The potential for addressing scientific issues in other fields is significant. In astrophysics, understanding core-collapse supernova (SN) explosion hydrodynamics still eludes us. New models of the deep nonlinear hydrodynamics of SNe continue to emerge, such as the spherical accretion-shock instability, and low-mode/high-mode coupling in deep nonlinear, RM-RT instabilities in divergent 3-D geometries. Another example is the use of HED hydrodynamics to probe the properties of exotic states of solid-state dynamics, phase, and lattice response. Yet another example is the use of strong (high Mach numbers) HED shocks and multiple line-of-sight diagnostic access to understand turbulent mass stripping and mixing of discrete objects, relevant to the shock processing of molecular clouds during star formation.

(4) ***Readiness: progress expected in the next five to ten years***
Assessment level – High

The readiness level for HED hydrodynamics in the coming five to ten years is very high. Multiple HED facilities, such as the OMEGA and Z, are already doing high quality HED hydrodynamics experiments; OMEGA has a mature user program. In the next five to ten years, one can anticipate a broad range of experiments on new facilities, such as the NIF, and on existing facilities as their user programs expand.

10.1.2 AREA: RADIATION-DOMINATED DYNAMICS AND MATERIAL PROPERTIES

Overarching question: *What are the unique properties of radiation-dominated HED plasmas?*

The path to generating regimes of very high energy density matter often involves very strong shocks or other sources of intense heating. This, in turn, generates radiation. Any description of the properties of these states inevitably requires the use of radiation hydrodynamics, where radiation plays a strong, and oftentimes dominant role. For example, radiation can be extremely effective at transporting heat, making radiation a dominant source of energy flux at high temperatures. In even more extreme cases, the radiation pressure itself can become significant. To probe the science under these very extreme conditions will require an understanding of: (1) the structure and dynamics of radiative shocks in regimes that have optically thick layers, (2) ionization waves in HED systems, (3) the rate of absorption of x-rays (the opacity) in HED matter and the associated atomic physics, and (4) the interplay of the treatments of equation of state (EOS) and opacity. This will require implementing and testing computationally efficient radiation-transport models, developing methods to choose or combine radiation-transport methods to get more accurate results, and benchmarking them against well-diagnosed experiments, maintaining self-consistency within the radiation hydrodynamics. This should allow us to: (1) understand the dynamics and structure of radiatively cooled jets, (2) understand the impact of radiative precursors on HEDLP experiments, (3) develop improved coherent-radiation sources, and (4) develop consistent models of ablation (photoevaporation) — driven hydrodynamic evolution and test this experimentally. Radiation-dominated dynamics and material properties have broad and fundamental connections to astrophysics, such as stellar birth and evolution, supernova explosions and supernova remnants, accreting compact objects (neutron stars, black holes, white dwarfs), and radiatively driven, photoevaporation front instabilities in molecular clouds, such as the Eagle Nebula and Rosette Nebula. The ability to produce systems producing large radiative fluxes also translates into an ability to produce bright photon sources, whether coherent, such as soft x-ray lasers or incoherent, such as keV x-ray backlighters.

Potential for stimulating interest in graduate students and scientists from other fields. Analysis of radiatively dominated plasmas is intellectually challenging and requires both good physical intuition and computer skills. If astrophysics-related, this analysis allows one to get insights into some of the most captivating images available from astrophysical observations. Astrophysicists have called for laboratory experiments that can provide physical insight into radiative effects and tests of astrophysical simulation tools. If application-related, this analysis provides opportunities for breakthroughs in the areas like weapons physics, x-ray lasers, novel diagnostic techniques, and material processing. All these opportunities are very attractive for graduate students.

Assessment. The following assessment of the readiness and scientific importance of radiation hydrodynamics is based on the five criteria discussed in Sec. 3.

(1) ***Importance to the fundamental understanding and development of high energy density science***

Assessment level – High

The presence of intense radiation in HED systems introduces the need to understand new aspects of these systems and the potential for new complexities in dynamical behavior. X-ray absorption and the transport of radiation become important, and new dynamical behaviors arise via peculiarities of the radiation heat transport and/or via direct contribution to the pressure. These features are also important in a broad range of astrophysical systems and their laboratory analogues. Without understanding the behavior of radiative blast waves, dynamics of ablatively driven flows, radiative transport in the media with strong velocity variations, both regular and turbulent, one cannot understand the associated astrophysical and laboratory phenomena.

(2) ***Potential for important practical applications (other than IFE)***

Assessment level – Medium

Important practical applications include soft x-ray lasers based on both capillary discharges and optical/infrared laser pumping, backlighters for imaging in a variety of experiments (from weapons physics to biology), and advanced laser-based-machining techniques.

(3) ***Potential for resolving major issues in other fields of sciences***

Assessment level – High

The potential impact on astrophysics is evident from the above discussion and is significant. The impact on other fields of fundamental science will follow from the development of radiation sources (pulsed, "point" radiation sources for wavelengths from the optical range to x-ray range) and material-processing techniques.

(4) ***Readiness: progress expected in the next five to ten years***

Assessment level – Medium

One can expect considerable progress in the development of small-scale (table-top to room-scale) radiation sources. Significant progress will be made in backlighting techniques relying on existing petawatt lasers. A wide range of facilities, from ultrafast lasers to lasers on the scale of Trident or Jupiter, intermediate-scale pulsed power systems, and larger facilities can produce systems with strong radiative energy transport.

Studies of the most complex types of radiative shock waves require lasers of the scale of OMEGA. Reaching the state where radiation pressure is dominant in the optically thick matter would require the use of megajoule-scale facilities.

10.1.3 AREA: MAGNETIZED HIGH ENERGY DENSITY PLASMA PHYSICS

Overarching question: *How do magnetic fields form, evolve, and affect the properties of high energy density plasmas?*

There have been few experiments intended to investigate the fundamental properties of magnetized HED plasmas, in spite of the fact that magnetized HED matter is ubiquitous. As a result, we know very few answers to the obvious questions about how the properties of magnetized plasmas change when the mean free path between collisions becomes comparable to or less than the ion orbit size in the magnetic field (gyroradius) and the radiation penetration distance (collisionless skin depth), or when radiation transport becomes important. Only a small fraction of the experiments to date have had adequately precise diagnostics to, for example, validate the models and computer simulations that are being used to help understand the experiments. Of special interest is the case in which electrons are magnetized and ions are not. Will the electron transport be classical?

The most extreme magnetized HED plasmas (highest B-fields and densities) are typically created by ≤100 ns pulsed-power machines or short-pulse lasers. They are associated with high electric fields, high current densities, and high rates of change of plasma conditions. It is common for the plasma to be initiated from room-temperature solid-density material and to change very quickly to a high-temperature plasma or even a mixture of phases. Exploding wire experiments are one example. Adding to the physics richness of such plasmas is the fact that they are often far from local thermodynamic equilibrium.

Potential for stimulating interest in graduate students and scientists from other fields. The challenges associated with using state-of-the-art pulsed power machines and lasers to produce magnetized HED plasmas, and to determine the properties of those plasmas is already known to be attractive to some of the best graduate students at universities around the country. The opportunity to carry out experiments in totally new regions of plasma parameter space and to discover totally unexpected phenomena is very attractive to graduate students. Condensed matter physicists are interested in the ability of the Z-machine to be used for studies of high-pressure equations of state. Some astrophysicists are excited about some of the data they are able to collect on magnetized jets, opacities, etc., using magnetically driven HED plasmas in the laboratory. Finally, atomic physicists are obtaining ionization, recombination, and radiation-rate data that are being used to validate atomic physics models and computer codes.

<u>Assessment.</u> The following assessment of the readiness and scientific importance of Magnetized HEDLP is based on the five criteria discussed in Sec. 3.

(1) ***Importance to the fundamental understanding and development of high energy density science***
Assessment level – High

The scientific community has the opportunity to break new ground in generating and studying magnetized HED plasmas. Very few experiments, to date, have attempted to understand the fundamental properties of HED plasmas with anisotropy introduced by the magnetic field. In many experiments there is the added complication of significant energy transport through intense radiation fields. This is fertile ground, and well-diagnosed experiments will elucidate new physics, improve the validation of existing models and computer simulation codes, and/or force new ones to be developed.

(2) ***Potential for important practical applications (other than IFE)***
Assessment level – Medium

Magnetically driven HED plasmas are finding several applications as radiation sources even with our limited understanding of their quasi-static and dynamic properties. Achieving a full understanding of such plasmas could lead to their optimization as table-top point-source (x-pinch) x-ray sources for high-resolution imaging; as valuable large-scale radiation sources in several x-ray spectral ranges for application to the stockpile stewardship program; and as potential highly efficient medium-scale UV, VUV, and XUV radiation sources for drying coatings and inducing chemical reactions.

(3) ***Potential for resolving major issues in other fields of science***
Assessment level – High

Laboratory magnetized HED plasmas and plasma jets are believed to have physics in common with some astrophysical objects seen with advanced astronomical observatories. If the laboratory plasmas are well enough understood to enable confident use of scaling laws to connect the laboratory and astrophysical plasmas, this could be a major breakthrough toward achieving an understanding of the distant plasmas by validating the computer codes used to study those plasmas.

(4) ***Readiness: progress expected in the next five to ten years***
Assessment level – High

Pulsed-power machines can produce up to several cubic millimeters of magnetically confined HED plasmas for up to ~10 ns, while ultra-intense lasers can produce short-lived magnetized HED plasmas with huge gradients in all properties. One or both of these two approaches can facilitate different kinds of research in all the above categories, including, for example, radiative shocks in magnetized HED plasmas. The main limitation here is that the accurate, HED-specific plasma diagnostic tools need to understand that experiments must be developed as part of the HEDLP research program.

Small-scale, pulsed-power facilities that can produce interesting HED plasmas can be built with University scale resources so new university research groups with good ideas can easily enter the field. The availability of intermediate-scale laser facilities at both the national laboratories and universities means that new university groups seeking to understand laser-based magnetized HED plasmas can also easily enter the field, as users at those existing facilities.

10.1.4 AREA: NONLINEAR OPTICS OF PLASMAS AND LASER–PLASMA INTERACTIONS

Overarching question: *How does high-intensity coherent radiation alter the behavior of high energy density plasmas?*

The propagation of high-intensity, coherent, electromagnetic radiation in plasmas, and the resulting modifications of the plasma state, is the subject of the nonlinear optics of plasmas. This is a topic of great intellectual challenge as well as one with the potential for broad impact. Coherent radiation can scatter from and decay into collective plasma modes and can create radiation at new frequencies. The plasma oscillations may become self-organized, nonlinear, kinetic states. This subject is very exciting and promising from theoretical, computational, and experimental points of view because of the myriad states made possible by the interaction of multimode fields, together with wave-particle resonances, the non-locality of the self-consistent, plasma-particle dynamics, and the various theoretical descriptions from continuum to discrete required to capture the true nature of plasmas.

Potential for stimulating interest in graduate students and scientists from other fields. The nonlinear optics of HED plasmas is interdisciplinary, involves multi-scale physics, and includes concepts from nonlinear optics, plasma physics, statistical mechanics and nonlinear dynamics, quantum mechanics, and computational physics. It involves close coupling between experiments, theory, and first principles simulation, and has numerous potential opportunities for hands-on experimental access. The attributes are attractive to graduate students. This area of research is of interest to scientists working with nonlinear optics in any context.

Assessment. The following assessment of the readiness and scientific importance of nonlinear optics of plasmas is based on the five criteria discussed in Sec. 3.

(1) ***Importance to the fundamental understanding and development of high energy density science***
Assessment level - High

The nonlinear optics of high energy density plasmas is uniquely challenging due to the myriad of longitudinal oscillations and waves in a plasma, the dispersive properties of plasma waves, the presence of wave-particle resonances, the presence of nonlinear phase space structures, and the possibility of many processes occurring simultaneously. High energy density matter can also exist in a regime where collisionless and collisional damping processes compete. In addition, in partially ionized plasmas, quantum mechanical effects associated with the phase of an electron's wave function as it oscillates in a laser field near an ion can become important. Much of high energy density science involves depositing laser energy onto a target. Without a fundamental understanding of the nonlinear optics of plasmas it will not be possible to accurately describe these experiments and processes, or to make the most effective use of lasers as HEDP drivers.

(2) ***Potential for important practical applications (other than IFE)***

Assessment level - Medium

The nonlinear optics of high energy density plasmas will influence the development of novel photon and particle-beam sources. The theoretical, computational, and theoretical tools developed in this field will also benefit the development of plasma-based radiation and light sources by advancing the understanding of how radiation evolves in plasma and how novel self-consistent structures in phase space can be formed and exploited.

(3) ***Potential for resolving major issues in other fields of sciences***

Assessment level - Medium

The nonlinear optics of high energy density plasmas has the potential to broadly impact other fields of science. There is overlap between it and the nonlinear optics in gases and solids. Nonlinear structures in phase space — such as kinetic electrostatic electron nonlinear (KEEN) waves — are relevant to galaxy formation, to vortex dynamics in liquids and gases, and to emittance preservation of intense beams in accelerators. Understanding the formation of such structures and the rapid release of stored energy is fundamental to particle acceleration and jet formation in plasma-based accelerators and astrophysical objects.

(4) ***Readiness: progress is expected in the next five to ten years.***

Assessment level - High

Much progress is expected in the next five to ten years. New theoretical models are emerging, first-principle kinetic simulations of experimentally relevant time and space scales are becoming possible, and mid-level laser facilities will enable basic science experiments with the capability to deploy novel ultrafast diagnostics to probe fundamental phenomena.

10.1.5 AREA: RELATIVISTIC HED PLASMA AND INTENSE BEAM PHYSICS

Overarching question: *How do plasmas with relativistic temperatures or relativistic flows behave?*

The electric fields from present day lasers and electron beams can cause single free electrons to move with relativistic energies. Future lasers will cause ions to move at relativistic speeds. High-energy lasers can create plasmas with temperatures exceeding an MeV. Understanding how these plasmas behave when either their directed flow or their average energy is relativistic is a fascinating area for research. This includes understanding how to create useful electron-positron plasmas in the laboratory. This topic is important in high energy astrophysics, in the development of compact photon and energetic-particle sources, and in extending the boundaries within which high energy density systems have been explored. A combination of experiments, theory, and simulations will be required to understand the underlying physics of relativistic HED plasmas.

Potential for stimulating interest in graduate students and scientists from other fields. Research in this area is interdisciplinary, building upon plasma physics, nonlinear optics, nonlinear and relativistic particle dynamics, statistical mechanics, quantum mechanics, computational physics, accelerator physics, and laser physics. It involves close coupling between experiments, theory, and simulation, and has many practical applications. It impacts other fields of science, and it is intellectually challenging. Recent progress has been well publicized and future progress is anticipated to be large. These aspects make it an effective attractor for graduate students and scientists from other fields.

Assessment. The following assessment of the readiness and scientific importance of relativistic HEDP is based on the five criteria discussed in Sec. 3.

(1) ***Importance to the fundamental understanding and development of high energy density science***

Assessment level - High

Relativistic HEDP is fundamental to understanding the properties of matter under the most extreme conditions. It includes examining matter at relativistic temperatures and high densities, and how matter behaves under the influence of extremely high-intensity lasers and particle beams. This subject is challenging, since individual particle orbits vary considerably from fluid trajectories, relativistic mass corrections are important, the self-fields in the plasma are very large, and the plasmas are far from equilibrium. Understanding how ultra-intense lasers and particle beams propagate through tenuous plasma and are absorbed in hot dense plasmas is a fundamental challenge of HED physics. Dense relativistic plasmas, including electron-positron plasmas at relativistic temperatures, are a little understood form of matter.

(2) ***Potential for important practical applications (other than IFE)***
Assessment level - High

Relativistic high energy density plasma physics is the foundation for plasma-based acceleration. Plasma-based accelerators could provide both future accelerators at the energy frontier and compact accelerators for use in medicine, materials science, and next generation light sources, at greatly reduced cost. Amplification of short laser pulses via nonlinear Stimulated Raman Scattering could lead to new classes of ultra-high-intensity lasers. Laser-solid-interactions have the potential to lead to a new class of compact ion accelerators and radiation sources.

(3) ***Potential for resolving major issues in other fields of sciences***
Assessment level - Medium

Relativistic high energy density plasma science will have an impact on other fields of science. Since relativistic HEDLP is at the basis of plasma-based particle accelerators, it can indirectly affect those fields of science that make use of particle accelerators, whether directly (high energy physics, oncology) or indirectly (light sources for biology and materials science). In addition, ultra-intense laser-plasma interactions can lead to extremely large magnetic fields, to jets of energetic particles, to relativistic electron-positron plasmas, and to relativistic collisionless shocks. Generating such conditions has the potential to bring breakthroughs in the understanding of astrophysical phenomenon

(4) ***Readiness: progress expected in the next five to ten years***
Assessment level - High

Tremendous progress can be expected in the next five/ten years. Recent progress in plasma-based acceleration has been very impressive and the development of working compact accelerators is expected. Experiments on Raman amplification have begun and the production of electron-positron plasmas will occur soon. Full-scale modeling of some experiments is already occurring and the onset of petascale and exascale computing could broaden this impact. The development of new reduced — but fully nonlinear — models could lead to real-time guiding of experiments. All the ultrafast lasers and electron or positron beams listed in Table 6.I are well-suited for studying relativistic high energy density science. Large facilities (OMEGA and NIF) have or will have the capability to perform experiments combining high-energy, long-pulse lasers, and kilojoule class, short-pulse, high-intensity lasers, which will significantly extend the opportunities for research in this area.

10.1.6 Area: Warm Dense Matter Physics

Overarching question: *What are the state, transport, and dynamic properties of warm dense matter?*

The study of the properties of warm dense matter (WDM) is a very active area of research. WDM is dense matter between the traditional conditions of cold condensed matter and ideal plasmas. (Ideal plasmas are hot enough and sparse enough to have weak particle coupling.) There is no general theory for warm dense matter because the approximations that enable the development of theories in either the condensed-matter or the ideal-plasma regimes are invalid in the warm dense matter regime. Predictive tools such as Quantum Molecular Dynamics become intractable as the electron temperature approaches and exceeds the Fermi energy. Further, the creation and diagnosis of WDM in a laboratory environment is challenging. Precise measurements of quantities such as equation of state, electrical conductivity, and other transport properties are difficult due to the requirement to create and probe this matter under sufficiently homogeneous conditions, in a relatively small volume over rapid time scales. Warm dense matter research is worthy of pursuit not only because of fundamental interest, but also because of its impact in many scientific areas including inertial confinement fusion, pulsed power experiments, formation and evolution of giant planets, and formation and evolution of white dwarfs.

Potential for stimulating interest in graduate students and scientists from other fields. Warm dense matter research can be embraced as an extension of condensed-matter and plasma research by both of these communities. Both theoretical and experimental efforts in warm dense matter are nascent, with much room to develop and improve tools and techniques. This should continue to attract researchers and collaborators in planetary science and astrophysics research.

<u>Assessment.</u> The following assessment of the readiness and scientific importance of warm dense matter is based on the five criteria discussed in Sec. 3.

(1) ***Importance to the fundamental understanding and development of high energy density science***

Assessment level - Medium

A complete understanding of warm dense matter must include knowledge of the degree of ionization, the relation of pressure and internal energy to density and temperature, the transport properties, such as viscosity and heat conduction, and any novel aspects of dynamic behavior. HED science will be fundamentally incomplete unless this is achieved. In addition, most high energy density systems formed in the laboratory, where driven by lasers, pulsed-power, or intense particle beams, transition through the warm dense matter regime, and in this regime have the greatest uncertainty for equation-of-state, transport properties, and ionization. Without a fundamental understanding of warm dense matter, it will not be possible to accurately describe the formation of high energy density matter in the laboratory.

(2) ***Potential for important practical applications (other than IFE)***
Assessment level - Marginal

Outside of inertial fusion energy, warm dense matter has existing and potential applications in materials science. For example, material damage, such as that caused by intense laser light propagating through optical materials, can occur in the temperature-density regime of warm dense matter. More generally, manufacturing techniques that produce HED matter will produce warm dense matter, whether or not they proceed beyond the WDM regime to hotter conditions. Therefore, understanding the limiting behavior of materials under extreme conditions requires an understanding of the warm dense matter.

(3) ***Potential for resolving major issues in other fields of sciences***
Assessment level - High

The behavior of warm dense matter is at the root of important scientific issues concerning the interior of planets and astrophysical objects such as white dwarfs. Properties such as equation of state and particle or heat transport in warm dense matter are critical for understanding the formation of giant gas planets and the dynamics of their interiors. Warm dense matter also occurs in the atmospheres of white dwarfs, and understanding the opacity of warm dense matter in these astrophysical objects is important for accurately predicting their cooling curves, which are used in cosmology to assess galactic ages. Analogies exist between the theory for warm dense matter and for quark-gluon plasmas, in that they are both strongly coupled, and there is potential benefit to both areas of science from exploiting these theoretical similarities.

(4) ***Readiness: progress expected in the next five to ten years***
Assessment level - High

Significant progress is expected in the next five to ten years. The continued development and use of x-ray Thomson scattering from laser-produced plasmas at high energy density physics facilities, together with the advances in x-ray lasers such as at the Linac Coherent Light Source (LCLS) at SLAC, and in intense ion-beam compression and focusing at the Neutralized Drift Compression Experiment (NDCX) at LBNL, promises significant advances in forming and characterizing warm dense matter. In addition, petaflop-scale computing will allow significant advances in the theoretical understanding of the fundamental properties of warm dense matter.

10.2 SCIENTIFIC OPPORTUNITIES FOR RESEARCH WITHIN THE JOINT HEDLP PROGRAM

The scientific issues and opportunities for research are described within the six areas of fundamental HEDLP. Each issue is accompanied by an elucidating question, a detailed description of the scientific content, and a summary of the research opportunities. To address the level of readiness, the research opportunities are framed within the capabilities of existing facilities. At total of twenty four issues that offer exciting opportunities for research are identified. A summary list is provided below and the detailed descriptions in Secs. 10.2.1–10.2.6.

Area: High energy density hydrodynamics
Issue: Turbulent mixing
Issue: Probing the properties of HED matter through hydrodynamics
Issue: Solid-state hydrodynamics at high pressures
Issue: New hydrodynamic instabilities
Issue: Hydrodynamic scaling

Area: Radiation-dominated dynamics and material properties
Issue: Radiative shocks
Issue: Radiation waves and radiation transport
Issue: Radiative cooling
Issue: Opacities and equation of state
Issue: Radiative instabilities
Issue: Radiation pressure

Area: Magnetized high energy density plasma physics
Issue: Basic properties of magnetized HED plasmas
Issue: Coupled dynamics and atomic kinetics
Issue: Phase transitions in the presence of high magnetic fields and current densities.
Issue: Ultrahigh magnetic fields and their measurement
Issue: Radiation-dominated HED dynamo
Issue: Radiation-dominated reconnection

Area: Nonlinear optics of plasmas and laser–plasma interactions
Issue: The interplay between coherent radiation and nonlinear states in a plasma
Issue: Nonlinear-wave–particle interactions
Issue: Multiple coexisting instabilities
Issue: Broadband radiation in plasma
Issue: Quantum phenomena in HED plasmas
Issue: Multiscale predictive simulation tools

Area: Relativistic HED plasma and intense beam physics
Issue: Relativistic wakefields
Issue: Relativistic laser and beam propagation
Issue: Relativistic laser–solid interactions
Issue: Ultrahigh energy density plasmas at the QED limit
Issue: Relativistic thermal plasmas
Issue: Relativistic shocks

Area: Warm dense matter physics
Issue: Phase transitions in and around the WDM regime
Issue: Comprehensive theory connecting different WDM regimes
Issue: Equation-of-state dependence on formation history
Issue: Transport properties of warm dense matter
Issue: Quark-gluon plasma similarities to warm dense matter

10.2.1 Area: High Energy Density Hydrodynamics

Issue: Turbulent mixing
Question: *What determines the dynamics, the rate of mixing or interpenetration of materials, and the development of turbulence in HED flows?*
Description: HED flows have unique properties compared to conventional hydrodynamic flows because they are compressible, dynamically ionizing, potentially supersonic, and can have complex material evolution such as chunk formation and dissolution. These flows are relevant to laboratory HED experiments, exploding stars, stellar birth dynamics, and accreting black holes. The compressibility may be extreme; few other hydrodynamic experiments achieve shock waves with Mach numbers above 2, while HED systems often achieve Mach numbers far above 10. Beyond that, the compression can be greatly increased by radiative energy losses, producing thin layers of very dense material that can flow. The "established rules" of linear, nonlinear, and turbulent hydrodynamics are largely empirical and result from observations of weakly compressible systems. The natural question is whether these "rules" are affected by strong-compression effects. Observations, to date, have seen anomalous mixing, anomalous vertical-structure formation, evidence of turbulent mass stripping, and mixing rates strongly affected by the strength and proximity of strong shocks at high compression.
Opportunities: The research opportunity is to devise experiments and models that will lead to an understanding of and predictive capability for these flows. Relevant experiments are anticipated on large, high-energy facilities such as OMEGA, Z, and the NIF. Creative innovation may enable relevant work on other systems such as subkilojoule, nanosecond lasers, or joule-scale ultrafast lasers.

Issue: Probing the properties of HED matter through hydrodynamics

Question: *How can hydrodynamics be used to probe the unique properties of HED matter?*

Description: One may be able to use hydrodynamic flows to probe the unique properties of the HED medium. Well-known hydrodynamic flows, such as simple instabilities, can be influenced or modified by frequently uncertain properties of the HED medium such as thermal conductivity, electrical conductivity, embedded electromagnetic fields, viscosity, equation of state, phase, and gradients of temperature, density, ionization, and composition. The instability evolution can potentially become a sensitive probe of these properties. For example, 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. Then measurements of the instability growth rate would probe the thermal conductivity of the matter. Similarly, hydrodynamic flows involving instabilities could be designed to be sensitive to the viscosity. At extreme pressures or densities, one can also envision using the flow as a probe of the phase of the matter, e.g., plasma versus liquid versus solid.

Opportunities: The research opportunity is to develop experiments and models of hydrodynamic flows to infer the viscosity, thermal conductivity, or other properties of dense, HED matter. 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 objects, an understanding of warm dense matter, and probing the fundamental properties of matter at extreme densities, potentially including ultrastrong electric or magnetic fields. Relevant experiments are anticipated on large, high-energy facilities such as OMEGA, Z, and the NIF. Creative innovation may enable relevant work on other systems such as subkilojoule, nanosecond lasers or joule-scale ultrafast lasers.

Issue: Solid-state hydrodynamics at high pressures

Question: *How can hydrodynamic conditions be created to infer the properties of solid-state plastic flow and lattice dynamics at extreme pressures and ultrahigh rates of deformation?*

Description: By the tailored application of very high pressures in HED systems, solid-state samples can be compressed, deformed, and made to "flow" plastically without melting or fracturing, creating a unique and unexplored regime of solid-state hydrodynamics and lattice dynamics at ultrahigh pressures and strain rates. The tailored hydrodynamic conditions can be arranged to dynamically freeze a solid out of a dense plasma state, leading to new nanocrystalline or amorphous states of matter with completely unknown properties. Theories in these unique high-pressure regimes are untested and very uncertain; experiments are sparse to nonexistent.

Opportunities: The research opportunity is to devise experiments and models that can reveal the properties of flowing, solid-state matter, and lattice dynamics at extreme pressures and ultrahigh deformation rates. High-rate plastic flows 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). Relevant experiments are anticipated on large, high-energy facilities such as OMEGA, Z, and the NIF and on mega-amp–class pulsed-power facilities. Creative innovation may enable relevant work on other systems.

Issue: New hydrodynamic instabilities

Question: *What new instabilities arise in strongly compressible flows that are not present in ordinary hydrodynamic flows?*

Description: In strongly compressible flows, materials can collapse into thin, dense, sinuous layers and interacting flows can produce bow shocks, bubbles, or other structures that do not form in ordinary hydrodynamic flows. One example is the Vishniac instability identified in astrophysical theory, which has, to date, seen only few and simple laboratory studies. Other examples include hydrodynamic (Rayleigh–Taylor or Richtmyer–Meshkov) instabilities that occur because of ionization or entropy gradients, shock-front instabilities that only occur in very steep density gradients, shock instabilities that occur in settings where the degree of ionization (compressibility) is changing, and shock instabilities that occur in very specific geometries, such as the spherical accretion shock instability, invoked to explain the large-scale structures observed in core-collapse supernovae.

Opportunities: The research opportunity is to devise novel physical systems in which strong compressibility is a dominant aspect of the evolution and to study their evolution. New instabilities in HED flows are relevant to strong shock phenomena in astrophysics, such as supernova remnant evolution, core-collapse supernova-explosion hydrodynamics, and shock evolution in dense molecular clouds. Relevant experiments are anticipated on large, high-energy facilities such as OMEGA, Z, and the NIF, with blast-wave experiments being feasible on subkilojoule or ultrafast lasers. Creative innovation may enable relevant work on other systems.

Issue: Hydrodynamic scaling

Question: *What are the limits of hydrodynamic scaling in HED systems?*

Description: Hydrodynamic-scaling theory and scaling methodologies enable one to devise scaled experiments to examine some of the most extreme phenomena of the universe, including supernova explosions of massive stars, photo-evaporation front (ablation front) dynamics of molecular clouds in stellar "nurseries," hypervelocity asteroid impact dynamics, and a wide variety of other phenomena. A critical question is how far scaled dynamics can be followed until the underlying assumptions are violated sufficiently to affect the results. Two examples are: when does small-scale, turbulent dissipation start to observably affect the global hydrodynamic evolution? What are the limits of using collisional hydrodynamics experiments to test astrophysical hydrodynamics driven by collisionless shocks?

Opportunities: The research opportunity is to use experiments and simulations to establish boundaries within which scaled experiments are valid, and outside of which the scaling breaks down. Understanding the limits of scaling is central to the application of HED laboratory experiments to settings on different spatial and time scales, such as astrophysics, planetary physics, geophysics, and science-based stockpile stewardship. Experiments to address this will involve an essential interplay of experiments and diagnostics and will require innovative design. Relevant work may prove possible on a wide range of facilities.

10.2.2 Area: Radiation-Dominated Dynamics and Material Properties

Issue: Radiative shocks

Question: *What is the structure and dynamical behavior of radiative shocks?*

Description: Radiative shocks are shocks waves so intense that radiative-energy transport determines their structure. They are challenging objects because they may include multiple boundaries in which the behavior of the radiation changes abruptly, they have essential dynamics that occur on a wide range of spatial and temporal scales, they are subject to both lateral and axial instabilities, and they interact with their surroundings in very complex ways. Radiative shocks are present in supernovae, supernova remnants, gamma-ray bursts, and many other astrophysical systems, and are also present in some possible classes of inertial fusion targets.

Opportunities: The research opportunity is to devise experiments that can probe the structure and dynamics of radiative shocks in their various regimes, and to develop accurate theoretical models and computer simulations of their behavior. Systems dominated by radiative cooling can be produced on most or all HED facilities. Relevant experiments involving trapped radiation or complex structures require work at the OMEGA scale. Creative innovation may enable relevant work on smaller systems.

Issue: Radiation waves and radiation transport

Question: *What are the structure, properties, and dynamical behavior of systems involving complex radiation absorption, radiation waves, photoionization waves, and radiative ablation?*

Description: When intense radiation encounters a material, the nature of the transport of radiation and energy through the system depends on the x-ray absorption properties of the medium (opacities), and on the density and velocity structure of the medium. An important challenge is to develop experiments that quantify and test such radiation

transport. The response of the medium may include the formation of a radiation wave, featuring a propagating temperature structure, the formation of an ionization wave, featuring a constant temperature behind a moving surface of ionization, or the formation of an ablation front, featuring material that flows back toward the radiation source while a shock wave penetrates the irradiated matter. Depending on details, both the flow of radiation and the hydrodynamic response of the system may develop structures and instabilities. Such processes are particularly important to radiatively driven molecular clouds and photoevaporation-front instabilities during star formation and cloud evolution.
Opportunities: The research opportunity is to systematically produce, diagnose, model, and understand radiation transport and the range of possible responses of the medium. Systems in which radiation transport can be studied are possible on most or all HED facilities. Relevant experiments involving complex structures require larger facilities, on the scale of OMEGA. Creative innovation may enable such work on smaller systems.

Issue: Radiative cooling
Question: *What is the structure and dynamical behavior of radiatively cooled systems with strong temperature gradients, including radiatively cooled jets and radiatively cooled hot spots?*
Description: When local objects are created with temperatures of the order of a million degrees or more, the intense radiation they produce often has a controlling effect on their subsequent evolution. The interplay of radiative cooling and heat conduction can become complex. These processes have a broad impact, ranging from the dynamics and instability of radiatively cooled jets in the laboratory and in astrophysics, to the modification of key parameters such as resistivity within materials irradiated by ultra-intense lasers, to the dynamics of an igniting ICF capsule.
Opportunities: The research opportunity is to create, diagnose, model, and understand systems with strong temperature gradients and strong radiative cooling. These results are relevant to protostellar jet dynamics that result during the star-formation process. Nearly any HED facility can produce systems relevant to this issue.

Issue: Opacities and equation-of-state
Question: *In what way do equations of state and opacities change when they are forced to arise from a single, self-consistent treatment of high energy density matter, and how can one devise radiation hydrodynamic experiments to assess their accuracy?*
Description: The structure of radiation hydrodynamic systems is affected by opacities, which describe the absorption and emission of radiation, and by equations of state, which describe the relation among pressure, internal energy, and ionization. Opacities are a challenge to calculate in dense, ionized media where both complex properties of the ionic structure and interactions with other particles may matter. An advanced understanding of opacities is relevant to stellar evolution, Cepheid Variable type stellar pulsations, and

supernova light curves, which are key components to understanding the rate of expansion of the universe. Both equations of state and opacities reflect the detailed structure and interactions of the material, yet their historical development has often been independent and even mutually inconsistent. A complete understanding of HED matter will require the development of self-consistent treatments of equation of state and opacity. This will also have important applications to stellar structure in astrophysics.

Opportunities: The research opportunity is to devise experiments to measure opacities, and radiation hydrodynamic experiments that can simultaneously assess the accuracy of equations of state and opacities. Opacity experiments are feasible on subkilojoule, nanosecond laser systems, but become more accurate on larger facilities. Relevant radiation-hydrodynamic experiments seem likely to require work on OMEGA–scale facilities. Creative innovation may enable relevant work on smaller systems.

Issue: Radiative instabilities

Question: *What structural and dynamic changes are produced by radiative thermal instabilities?*

Description: The variation of the opacity with temperature and density produces regimes in which high energy density plasmas can be subject to radiative thermal instabilities, in which structures grow rapidly through runaway radiative cooling. This phenomenon is responsible for the radiative collapse that may develop in *z*-pinch cores, but has also been adduced as the cause of local structures in ablating laser plasmas; and in the long-term structure of plasma flowing from laser-heated targets. In astrophysics, much of the structure observed in old supernova remnants is produced by this process, and thermal instabilities are a fundamental process in accretion disk dynamics and in some radiative shock regimes. An accurate understanding of opacities is necessary to successfully predict the behavior of radiative thermal instabilities.

Opportunities: The research opportunity is to devise experiments in which radiative thermal instabilities can be reproducibly created, diagnosed, modeled, and understood. Some of the instability mechanisms depend primarily on radiative cooling and can potentially be explored in a wide range of HED facilities. Experiments requiring long time scales or large structures will tend to require larger facilities, perhaps on the scale of OMEGA and Z.

Issue: Radiation pressure

Question: *How can HEDLP experiments produce conditions where the radiation pressure exceeds the material pressure in optically thick media?*

Description: The radiation pressure typically is smaller than the material pressure, even in high energy density systems. In contrast, in large enough systems that trap radiation and have high enough temperatures, the radiation pressure can become dominant. This occurs within some stars, in the shocked material produced during core-collapse supernova explosions, and in accreting neutron stars and black holes, such as x-ray binaries. Creating such conditions in the laboratory, and demonstrating that one has done so, is an extraordinary challenge and will likely require the largest experimental systems now contemplated.

Opportunities: The research opportunity is to develop experimental designs that are predicted to produce radiation-pressure-dominated conditions and that can be tested in the intermediate future on megajoule-class lasers such as the NIF.

10.2.3 Area: Magnetized High Energy Density Plasma Physics

Issue: Basic properties of magnetized HED plasmas

Question: *How does a magnetic field affect the transport properties, dynamics, and turbulence in HED plasmas?*

Description: We are just beginning to get a glimpse of magnetized HED phenomena in well-controlled laboratory experiments. An understanding of the issues associated with magnetized HED plasma will require development of precision diagnostics and a great improvement in the rudimentary state of modeling and simulation. These two requirements are closely coupled, of course, through the need for precision data to validate models and computer simulation. Since modeling and simulation of magnetized HED plasmas benefit significantly from recent advances in computational capability, there will be an increasing need for reproducible experiments in simple configurations to facilitate validation of models. Fundamental issues include how the magnetic field affects the transition to turbulence, the subtle interplay between turbulence and magnetic reconnection, and the effects of magnetic fields on the development of shocks in HED plasmas.

Opportunities: The research opportunity is to use experiments and simulations to better understand magnetized plasma whose pressure is comparable to the magnetic field pressure and that might also include a strong radiation field. Combining the non-local energy transport introduced by a strong radiation field and the anisotropy inherent in magnetized plasma is of great interest for such objects as the atmospheres of neutron stars and accretion disks around black holes. The research opportunity in this context is to develop scaled experimental simulation of such conditions with lasers and z-pinches, with necessary numerical support. Relevant experiments are possible on all the pulsed-power facilities listed in Table 6.I. Creative innovation may enable relevant work on some laser systems.

Issue: Coupled dynamics and atomic kinetics

Question: *How does a magnetic field affect the coupled dynamics and atomic kinetics in HED plasmas?*

Description: When plasma properties are changing at a rate comparable to the ionization, recombination, and even atomic transition rates, as they are in femtosecond laser experiments and the final stages of current-driven radiative collapse, the plasma can be far from local thermodynamic equilibrium. A strong magnetic field can even distort the wave functions of the electrons in a multicharged ion, leading to modified emission lines and to multiple ionizations. This is an essential effect in highly magnetized natural environments, such as pulsar nebulae.

Opportunities: The research opportunity here is to develop techniques for probing and understanding how the presence of a magnetic field affects the coupling of plasma dynamics to ionization, recombination, and radiation processes. Relevant experiments are possible on all the pulsed-power facilities listed in Table 6.I and on the highest-intensity lasers such as Hercules. Creative innovation may enable relevant work on other systems.

Issue: Phase transitions in the presence of high magnetic fields and current densities.

Question: *How does transition from the solid state to the plasma state occur at high current densities and ohmic heating rates, with magnetic pressures >> 1 Mbar?*

Description: Current densities in HED plasmas reach unprecedented levels. In a typical experiment, current flow is initiated in solid-state matter, either by a pulsed-power machine or an ultrahigh-intensity laser. For example, a 10-μm-diameter wire exploded by a 10-kA current pulse in ~10 ns has a current density in excess of 10^{10} A/cm^2. The matter passes through a set of phase transitions that occur nonuniformly, with two or more phases coexisting for a time that depend on both the current density and the configuration. For example, in the exploding-wire case, x-ray and visible light images show that a mixed plasma/vapor/condensed matter state can last for microseconds if the current is reduced or cut off, but it can also last for only a few tens of nanoseconds if the current increases. An instability having a very short axial wavelength is seen in the condensed matter phase and is not yet understood. Adequate characterization of this state is a challenging and stimulating problem at the interface between condensed matter and plasma and includes many of the complexities of warm dense matter. In the case of intense laser interaction with solid matter, the origin of the transient fields that are created as the surface becomes a plasma could be the product of multiple competing processes involving laser–plasma interaction as well as laser–condensed matter interaction.

Opportunities: The overarching research opportunity is to understand the interaction of ultrastrong fields with matter in the presence of pressure that is strong enough to exceed the yield strength of the material, and to initiate thermal and fluid instabilities—all at the same time. Relevant experiments are anticipated on all the pulsed-power facilities listed in Table 6.I. Creative innovation may enable relevant work on some laser systems.

Issue: Ultrahigh magnetic fields and their measurement

Question: *What are the limits of magnetic-field strength that we can generate in an HED laboratory plasma and how can we measure them?*

Description: Radiative collapse triggered by MHD instabilities in current-driven HED plasmas could lead to gigagauss quasi-static magnetic fields, at which magnetic dipole forces are comparable in energy to electron-transition energies in the highly ionized ions that are present in hot plasmas. For example, 500 kA flowing through a 1-µm-radius plasma at the cross point of an *x*-pinch plasma implies a 100,000T = 1 gigagauss magnetic field, and such fields can be produced in university laboratories. Ultra high intensity lasers also produce hot, dense plasmas with transient gigagauss magnetic fields. Detailed atomic-physics computational models and extremely well-diagnosed experiments will be necessary to understand observations in this regime. We have not yet fully developed methods to measure such high magnetic fields. It is anticipated that observation of modifications to emission lines together with detailed atomic-physics computational models will eventually provide such measurements. Another possibility is to measure the deflection, even if transitory, of monoenergetic charged particles, as has been developed recently for magnetic fields in HED plasmas.

Opportunities: The research opportunity is to develop techniques to generate, probe, and characterize ultrastrong magnetic fields in HED plasmas. Relevant experiments are anticipated on all the pulsed-power facilities listed in Table 6.I, and on the highest-intensity lasers shown there, such as Hercules. Creative innovation may enable relevant work on other laser systems.

Issue: Radiation-dominated HED dynamo

Question: *How does a magnetic dynamo work in a radiation-dominated plasma*?

Description: Creation and amplification of magnetic fields might be strongly affected by nonlocal transport of a radiation-dominated plasma or by the nonideal effects of a strongly coupled or degenerate plasma. This could be of great importance in astrophysics.

Opportunities: The research opportunity is to develop experimental and simulation techniques for probing how a magnetic dynamo works in a radiation-dominated plasma.

Issue: Radiation-dominated reconnection
Question: *How is magnetic-field reconnection modified in an HED plasma?*
Description: Reconnection is ubiquitous in the laboratory and in space and astrophysics. It seems highly likely that nonlocal transport associated with a radiation-dominated plasma will have an impact on reconnection. Another intriguing problem is the interplay between turbulence and radiation-dominated reconnection, both of which are thought to be common in diverse settings from astrophysics to laboratory HED experiments. In addition, some radiation-hydrodynamic systems, such a stellar convection zones, clearly play a key role in magnetic-field generation.
Opportunities: The research opportunity here is to develop models of such effects in laboratory systems and design experiments in which they can be cleanly observed.

10.2.4 Area: Nonlinear Optics of Plasmas and Laser–Plasma Interactions

Issue: The interplay between coherent radiation and nonlinear states in a plasma
Question: *How does coherent radiation drive self-organized, nonlinear, kinetic states in plasmas?*
Description: When coherent radiation traverses a plasma, it triggers collective excitations in the plasma that can scatter, reflect, focus, and modulate the radiation and also accelerate particles and severely change the character of the plasma in its phase space. These interactions can occur in the presence or absence of external magnetic fields, in multi-species or pure-electron or pure-ion plasmas. In each of these regimes, coherent radiation can generate self-organized, nonlinear, kinetic states that need not be reduced to oversimplified models of stationary modes or linear, resonant single-mode interactions. Recent work shows that simple modes which have linear limits and fluid limits can be strongly manipulated by these more-recently discovered kinetic, nonstationary, multimode nonlinear states of self organization such as KEEN waves. Entirely new methods of nonlinear wave–wave communication and interaction become possible when such states are created and allowed to suppress the natural modes of the plasma, which are otherwise hard to control. Insights gained from the study of such states may impact fields such as fundamental plasma physics in plasma traps, 2-D Euler turbulence, vortex dynamics in fluids, and nonstationary stellar and galactic evolution.
Opportunities: The research opportunity is to systematically explore and exploit these self-organized states through the interplay of experiment, theory, simulation, and experiments. Relevant experiments are possible on any laser facility having several nanosecond-scale beams, such as Janus, Trident, and OMEGA. Creative innovation may enable relevant work on other laser systems.

Issue: Nonlinear wave–particle interactions
Question: *How do particle distributions in laser plasmas redistribute and release their energy at the boundary between continuum and discrete plasma physics?*

Description: A long-standing question in plasma physics is to understand when and how nonlinear plasma waves release their energy. In the 1950s and 1960s collisionless damping of linear waves, nonlinear undamped modes, and wavebreaking of nonlinear waves, to name a few, were explored. Recent advances in theory, simulation, and experimental techniques using lasers, have led to new directions. Within the self-organized states described above, particles can be stored in localized regions of phase space. In addition, high energy density plasmas often exist between the regimes where continuum theories are appropriate and those where discrete-particle effects are dominant. In the latter regime, individual electrons and ions can produce non-thermal noise that can seed new instabilities. Keeping numerical subsampling noise under control while exploring effects driven by physical fluctuations is a significant challenge. The ability to control the rapid, efficient transport in phase space of coherent localized states will be of great value to science and technology. For example, the particle jets or beams that result from this rapid release may be of use in accelerators, in light sources, and in understanding astrophysical and solar observations.

Opportunities: The research opportunity is to understand and control the phase-space concentration and transport of particle energy in HEDLP systems driven by coherent radiation. Relevant experiments are possible on any laser facility having several nanosecond-scale beams, such as Janus, Trident, and OMEGA. Creative innovation may enable relevant work on other laser systems.

Issue: Multiple coexisting instabilities

Question: *How do multiple instabilities co-exist? How do overlapping laser pulses interact via the mediation of mutually accessed plasma modes?*

Description: The mutual interactions of nonlinear waves in plasmas with their concomitant wave-particle interactions affords a very rich field of nonlinear classical field theory where pattern formation, negative feedback chaos control, intertwining, and mutual taming and coherence control can be explored. The interaction of many instabilities and many waves, driven by one or more laser pump beams, may form new states of matter far less unstable, intermittent, and chaotic than a single process would be alone, and far different from the sum of isolated processes. Due to the richness of linear and nonlinear coherent plasma modes, plasma physics will play a leading role in the understanding of multi-mode nonlinear optics in any medium.

Opportunities: The research opportunity is to produce well-designed and well-controlled experiments in which multiple waves interact, and to use these to develop an understanding of the resulting plasma states via statistical theories and reduced models. Relevant experiments are possible on any laser facility having several nanosecond-scale beams, such as Janus, Trident, and OMEGA. Creative innovation may enable relevant work on other laser systems.

Issue: Broadband radiation in plasma

Question: *How does one model the nonlinear coupling of broadband radiation to plasma?*

Description: Under large laser irradiation and astrophysical conditions, broadband fluxes of radiation in the from of energetic photons, radio waves, or neutrinos propagate through extended plasmas. The radiation can excite a spectrum of plasma waves, which, in turn, can accelerate particles and heat the plasma. Such radiation can have wavelengths that are shorter than the inter-particle spacing and, in the case of neutrinos, the interaction is through the weak force. Generating theoretical models for these processes is a long-standing challenge. Viewing the radiation as fluxes of dressed particles whose flux density is described by transport equations is one possibility.

Opportunities: The research opportunity is to develop this theory and seek to identify how HEDLP energy sources could produce intense, broadband fluxes of photons that could excite plasma waves. Relevant experiments are likely to require intense broadband radiation fluxes that can be generated only by very large facilities such as Z and NIF. Creative innovation may enable relevant work on smaller systems.

Issue: Quantum phenomena in HED plasmas

Question: *How can we exploit quantum phenomena in HED environments?*

Description: One intriguing and new research direction in the nonlinear optics of plasmas is to exploit quantum phenomena in high energy density plasmas. At first glance this seems improbable because keV energy electrons might not exhibit their quantum nature. Surprisingly, recent work using table-top femtosecond lasers demonstrate that quantum effects can be extremely strong even in high energy density environments. In this work, a femtosecond laser pulse is upshifted to much higher photon energies (>keV). In this process, called high harmonic generation, electrons are first ripped from atoms, then accelerated in the laser field, before finally recolliding with the parent ions and releasing their kinetic energy as a coherent beam of x rays. While the electrons are propagating in the plasma under the influence of the laser field, their quantum phase evolves in proportion to the local field. The quantum phase of the radiating electron can be controlled by shaping the field of the ionizing laser, or by superimposing additional laser beams. By tailoring both the laser field(s) and the high energy density plasma medium to guide an intense laser beam, it will be possible to manipulate the wave functions of energetic electrons (within a plasma environment) on their fundamental, attosecond, time scales.

Opportunities: This main scientific opportunity is to exploit quantum mechanics in high energy density environments and the implementation of new phase-matching schemes in plasmas, making it possible to create bright coherent beams of hard x rays on a desktop for a myriad of applications in science and technology. It might be possible to use visible laser-light patterns to manipulate the spatial phase of the emitted x-ray beams, allowing new types of light-based x-ray lenses to be developed. Relevant experiments are possible on femtosecond-scale lasers in university laboratories. Creative innovation may enable relevant work on some of the laser systems listed in Table 6.I.

Issue: Multiscale predictive simulation tools

Question: *Can a predictive tool be developed that combines self-consistent radiation and particle-flux-transport physics with instability physics to confidently examine potential frontier research areas in this field?*

Description: The nonlinear optics of plasmas and hot-electron transport involve wave–wave and wave–particle interactions, both of which are nonlinear and complex. Unraveling the corresponding physics requires fully nonlinear and fully kinetic computer models, as well as understanding the statistical properties of these models. Fluid and reduced description approaches are also needed to model the disparate time and space scales. The rapid growth in the microscale and mesoscale physics of the nonlinear optics of plasmas, and the dawn of the petascale and exascale (greater than 1,000,000 processors) age of computation could lead to a revolution in how the nonlinear optics of plasmas is simulated. One can envision new and powerful quasi-static and wave-kinetic models, and other reduced descriptions, which home in on scales and structures that matter and ignore or downplay the rest. This revolution will allow true verification and validation of simulation codes and techniques against experiments.

Opportunities: The research opportunity is to creatively exploit advanced computational systems to produce new models that can accurately compute a far wider range of phenomena than can any single current model.

10.2.5 Area: Relativistic HED Plasma and Intense-Beam Physics

Issue: Relativistic wakefields

Question: *What is the limit of the acceleration of electrons, positrons, and ions in relativistic wakefields?*

Description: An intense, short-pulse laser or particle beam propagating in a plasma creates a wakefield. This wakefield is the result of the expulsion of the plasma electrons by the radiation pressure or space charge force. Wakefields are multidimensional and can accelerate electrons with gradients in excess of 1 GeV/cm. The density in these wakefields can be orders of magnitude larger than the background density and the plasma electrons can flow with nearly light speed. Background electrons can be trapped by these wakefields, so that there is potential for practical, compact GeV-class accelerators. A major issue for many applications is controlling the emittance of the electron beams. With the next-generation lasers, the potentials may exceed $M_{\mathrm{proton}}c^2$, such that ions could be trapped and accelerated in relativistic wakefields.

Opportunities: The major research opportunity is to understand how to control the injection and acceleration of charged particles in wakefields with the energy spread and emittance needed for compact light sources. This can be done through closely coupled experiments and full-scale high-fidelity simulations. Experiments on self-injection can be performed on existing facilities (the short-pulse laser and particle-beam facilities in Table 6.I). Existing computing facilities will be used to study the mechanisms that accelerate ions to relativistic energies.

Issue: Relativistic laser and beam propagation

Question: *How can short-pulse, high-intensity lasers or particle beams be configured to propagate stably over many meter distances in tenuous plasmas?*

Description: Understanding how intense particle beams and lasers evolve as they propagate through underdense plasmas is a great challenge. Intense short-pulse lasers and relativistic particle beams are susceptible to a variety of instabilities and destabilization processes such as hosing, sausaging, asymmetric self-focusing, and longitudinal compression. These are driven by transverse focusing and longitudinal acceleration of photons and charged particles by the wakefields that they create. The challenge is to control and manipulate these processes through the use of temporal shaping and frequency (energy) chirping of the laser (particle) beams.

Opportunities: The research opportunity is to use closely coupled experiments, theory, and simulations to understand and control the evolution of short-pulse high-intensity laser and particle beams. This will involve developing methods for tailoring the temporal shape and energy chirp of the beam. Experiments could be performed on existing femtosecond lasers (Table 6.I), such as LOASIS and Hercules. Experiments with particle beams could be performed at SLAC with an upgrade, and creative innovation may enable experiments with picosecond laser systems.

Issue: Relativistic laser–solid interactions

Question: *How can laser–solid interactions generate gigaAmps of current, GeV-class ion beams, and high harmonics?*

Description: When an intense laser is incident on a solid-density target, a complicated suite of phenomena occurs. The electric field in such lasers is orders of magnitude larger than the fields that bind the electrons to the atoms, single free electrons can oscillate with energies in excess of 100 MeV, and the radiation pressure can exceed 1 Tbar. The absorption of an intense laser at a dense plasma boundary is not completely understood because of the complexity of the electron-distribution function and fields (both electric and magnetic) at the interface. Investigation of radiation pressure effects on density steepening and consequently on electron spectrum and temperature is important. These interactions are critical for generating ion beams for oncology and spallation neutron sources, and soft x-rays from reflected harmonics.

Opportunities: The research opportunity is to investigate the complex absorption mechanisms theoretically, numerically and experimentally. Existing femtosecond lasers (medium-scale and large facilities) such as Trident, Titan, the Texas Petawatt, and OMEGA EP, could be used to investigate these processes.

Issue: Ultrahigh energy density plasmas at the QED limit

Question: *How can multiple-beam–plasma interactions be used to generate ultrahigh energy density conditions where QED effects become important?*

Description: The high-field, QED limit, of colliding laser-beam physics is an interesting scientific frontier in the field of relativistic plasma physics. There is the potential for generating new plasma states at ultrahigh energy densities near 10^{17} J/cm^{-3}, by using multi-beam laser–plasma instabilities, multiple overlapping ultra-intense lasers, or a combination of both, to amplify laser intensities many times. Positron production at these intensities was observed during one experiment. Recent advances in laser- and particle-beam capabilities will make it possible for these ultrahigh energy density environments to be created (ever so briefly) and studied in the laboratory. This may be very relevant to high-energy astrophysical phenomena involving bulk-pair plasmas with interesting magnetic-field topologies.

Opportunities: The main research opportunity is to investigate theoretically and numerically methods for generating ultra high laser intensities and ultrahigh energy density plasmas, which are relevant to astrophysical plasmas with complex magnetic field topologies. High energy laser amplification experiments can be carried out at facilities with long and short pulse beams such as Titan, Trident, OMEGA EP, and on the NIF ARC when completed. Pair production could be carried at facilities such as OMEGA EP, NIF ARC, and SLAC.

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Issue: Relativistic thermal plasmas

Question: *How do plasmas, including electron–positron plasmas, with relativistic temperatures behave?*

Description: The next generation of high-intensity lasers will produce plasmas with electron (and positron) temperatures greatly in excess of one MeV. The nonlinear optics of these plasmas have not been fully explored. Curious features such as a reduction in the ponderomotive force and the relativistic self-focusing rate have been predicted theoretically and observed in simulations. The dispersion relation of plasma waves becomes acoustic-like, with the phase and group velocity near the speed of light. At such temperatures, electron–positron pair production can be prodigious. Plasmas with a mixture of pairs, electrons, and ions will also exhibit rich new behavior. It may be possible to create colliding electron–positron plasmas with lengths in excess of several skin depths so that the relativistic Weibel instability, an essential process in relativistic astrophysical jets, can be studied.

Opportunities: The main area of research is to investigate plasmas with a mixture of pairs, electrons and ions with temperatures in excess of an MeV. Plasmas with electrons with relativistic temperatures could be produced on petawatt facilities such as the Texas Petawatt, Z Beamlet, and OMEGA EP. The next generation of lasers will be required to carry out experiments with relativistic ion temperatures and pairs.

Issue: Relativistic shocks

Question: *What is the nature of relativistic shock waves generated by ultra-intense laser–plasma interactions?*

Description: Relativistic shock waves are a fundamental research area at the intersection of astrophysics and plasmas physics. Current simulations are being performed to understand how such shocks form, their internal structure, and how particles are accelerated in such shocks. In astrophysics the shocks are formed by the relativistic outflow of plasma through the interstellar medium, often in exploding systems such as gamma-ray bursts. In ultra-intense laser–plasmas interactions, it may be possible to create similar physics through the laser pressure at a laser–solid interface. Evidence suggests that the laser first drives energy forward in the form of relativistic electrons. Collisionless dissipation mechanisms such as streaming and Weibel-like interactions heat the plasma to MeV temperatures in front of the laser, making it possible for a high-Mach-number collisionless shock to be launched after a picosecond. These dissipation mechanisms are similar to what is conjectured to occur in astrophysical conditions. High-energy, high-intensity laser systems will allow the shock structure and acceleration mechanisms to be explored in the laboratory. Particle-in-cell methods are being used to study the high-kinetic (collisionless) physics. Rapidly heating a plasma in large magnetic fields may make it possible to generate high-Mach-number Alfvénic shock waves.

Opportunities: The opportunity is to study generation and propagation of relativistic shocks, which connects plasma physics to astrophysics. The light pressures generated by present day petawatt lasers, such as the Texas Petawatt, Z Beamlet, and OMEGA EP, can create conditions to generate such shocks. Creative innovation may enable a wider range of facilities to produce them.

10.2.6 Warm Dense Matter Physics

Issue: Phase transitions in and around the WDM regime

Question: *What phase transitions occur in and around the warm dense matter regime?*

Description: Phase transitions are expected to play a critical role in determining the properties of giant planets that have portions of their interior in the warm dense matter regime. Among these are phase separation, which could lead to helium raining toward the center and converting gravitational energy to heat in the process; the metal-insulator transition, which determines the conductivity profile of the planet and, therefore, its magnetic-field structure; and the transition to a superionic phase of water at high pressures and densities, relevant to the interiors of the ice giants Neptune and Uranus.

Opportunities: The research opportunity here is to develop precision experimental and theoretical techniques to explore phase transitions in warm dense matter. Relevant experiments are anticipated on large, high-energy facilities such as OMEGA, Z, and the NIF and on facilities that can uniformly heat matter into the WDM regime, such as LCLS. Creative innovation may enable relevant work on other systems such as subkilojoule, nanosecond lasers, or joule-scale ultrafast lasers.

Issue: Comprehensive theory connecting different WDM regimes

Question: *How do we develop an accurate theoretical model for warm dense matter?*

Description: Most theoretical methods are optimized to examine physical phenomena in narrow ranges of parameter space. For example, path-integral Monte Carlo is based on a high-temperature expansion, and is limited to low-Z elements because of the difficult Fermion-sign problem. Quantum molecular dynamics, on the other hand, is limited to cool temperatures, with heroic calculations yielding results around 10 eV. Newer forms of density-functional theories, such as orbital-free density-functional theories, may be able to fill such a gap. What is needed is a theory that spans the regions between hot dense matter and low-temperature, condensed matter.

Opportunities: The research opportunity here is to develop advanced theoretical and computational tools appropriate to the warm dense matter regime.

Issue: Equation-of-state dependence on formation history

Question: *How do we accurately measure the properties of warm dense matter?*

Description: Because of its high-pressure state and its high energy density, warm dense matter is typically produced in the laboratory in very small volumes under highly transient conditions that are nonequilibrium both in the hydrodynamic and kinetic scales. It is a challenge to measure simultaneously the entire set of parameters (temperature, density, equation of state, and perhaps others) required to draw quantitative conclusions about the properties of warm dense matter. A central question is whether the properties of warm dense matter are uniquely determined by state variables (density, temperature) or whether they depend on the formation history and subsequent dynamics of the warm dense matter.

Opportunities: The research opportunity here is to develop experimental techniques for making accurate measurements in the warm dense matter regime, and to experimentally and theoretically address the question of whether warm dense matter is satisfactorily described by its state variables, independent of its formation history. Relevant experiments are anticipated on large, high-energy facilities such as OMEGA, Z, and the NIF and on facilities that can uniformly heat matter into the WDM regime, such as

LCLS. Creative innovation may enable relevant work on other systems such as subkilojoule, nanosecond lasers or joule-scale ultrafast lasers.

Issue: Transport properties of warm dense matter

Question: *What are the transport properties of warm dense matter?*

Description: The hydrodynamics of warm dense matter is governed by the equation-of-state and the transport coefficients. Diffusion, for example, determines the rate at which certain elements sink via sedimentation in planetary interiors in well-mixed volumes of material. Viscosity determines the damping of collective motions and the fluid properties in the turbulent regime. Thermal conductivity determines the rate of heat flow from regions of higher temperatures to regions of lower temperatures. Electrical conductivity determines the rate of current's dissipation and is a key parameter affecting planetary dynamos. There are likely to be regimes in which these and other transport coefficients vary strongly with small changes in the state variables. Theories of the transport coefficients in warm dense matter are very uncertain, and experimental data are sparse.

Opportunities: The research opportunity here is to develop experiments and modeling to determine the transport coefficients in warm dense matter. Relevant experiments are anticipated on large, high-energy facilities such as OMEGA, Z, and the NIF and on facilities that can uniformly heat matter into the WDM regime, such as LCLS. Creative innovation may enable relevant work on other systems such as subkilojoule, nanosecond lasers, or joule-scale ultrafast lasers.

Issue: Quark–gluon plasma similarities to warm dense matter

Question: *What analogies exist between warm dense matter and quark–gluon plasmas, and how can those analogies be explored to a mutual benefit?*

Description: The quark–gluon plasma community recognizes that their state of matter is highly viscous and far from the ideal gas state. So far, they have built on the basic strongly coupled plasma literature to develop a deeper understanding of the plasmas they create. However, little connection has yet been made between warm dense matter, which is a partially ionized, strongly coupled state, and quark–gluon plasmas, which are by definition an ionizing state. Such an analogy is much stronger than that between one-component plasmas and quark–gluon plasmas.

Opportunities: The research opportunity here is to explore theoretical similarities between quark–gluon plasmas and warm dense matter.

11 A SCIENTIFIC ROADMAP FOR ENERGY-RELATED HEDLP STUDIES

This section addresses the second part of the FESAC charge (Appendix A) "meant to provide background for a scientific plan for energy-related HEDLP studies." As mentioned in Sec. 2, FESAC is tasked with developing a set of scientific questions "to support the case for energy applications of inertial fusion energy sciences."

The motivation for this second part of the FESAC charge has been well articulated in the Rosner/Brown May 2007 Report of the Workshop on Opportunities for High Energy Density Laboratory Plasma Science:

> "Achieve the grand challenge of fusion energy enabled by high energy density laboratory plasmas – powering the planet. The successful development of inertial fusion energy (IFE) will require fundamental understanding of the behavior of high energy density plasmas. A challenge and obligation for humankind is the development of clean energy sources. Developing the science of high energy density plasmas in the laboratory is a cornerstone for a promising approach for such an energy source, inertial fusion. The achievement of ignition at NIF will focus world attention on the potential of IFE. The science of HEDLP will create the basis for interpreting these ignition results and for developing experimental scenarios that extend laboratory fusion's promise beyond ignition and toward fusion power."

The compelling scientific HEDLP issues identified by this FESAC sub-panel that must be addressed for inertial fusion energy (IFE) are described in detail in Sec. 9, where the opportunities for research within the Joint HEDLP Program are identified. For convenience, a summary list of the HEDLP issues is shown below.

- Intense particle-beam generation by ultra-intense lasers
- Transport and energy coupling of intense particle beams in HED plasmas
- Influence of magnetic fields on HED fusion plasmas
- Laser–plasma instabilities and hot-electron generation
- Implosion hydrodynamics for high energy gains
- Integrated target physics for inertial fusion energy
- Magnetically driven implosions
- Hydrodynamic instabilities and turbulent mix
- Transport properties of strongly coupled plasmas
- Target-system integration
- Nonlocal transport of energy
- Laser/particle beam x-ray conversion
- Radiation hydrodynamics
- Equation of state and opacities of HED plasmas and materials at high pressures

They constitute an exciting subset of the fundamental HEDLP science issues considered by the sub-panel that has a high potential to advance the knowledge of HED physics as well as IFE.

The second element of the FESAC charge requests the panel to develop a prioritized list of "gaps in knowledge and opportunities for research in energy related HEDLP" science. During this process, FESAC should consider "sequential phases of activity focusing" on

1. Exploiting current and near-term facilities to explore energy-related HEDLP science
2. Exploiting the capabilities of the NIF to address ignition-science issues related to inertial fusion energy.
3. Resolving scientific issues to promote a transition from a burning plasma experiment to a fusion-energy-science-development program.

Over the last five months the work of this panel has focused on the primary issues required for IFE target gains to be high enough for the ultimate goal of inertial fusion energy. The required target gains for IFE depend on the prospects for various drivers to achieve a sufficient product of driver efficiency, target gain, and blanket energy multiplication for a reasonably-low recirculating power fraction. It is possible to boost the energy gain of a relatively low gain fusion target by surrounding the chamber with fissile material. The product of target gain with fission gain can then reach the values required for a power plant. This concept has been looked at over the last several decades. Recently, the Sandia group has proposed to use a fusion-fission hybrid system based on the Z-pinch concept. More recently, an energy application of laser indirect drive to produce power in hybrid fusion–fission blankets has been proposed by LLNL. This is based on the same kind of hohlraum targets to be tested in the NIF ignition campaign. The proposed hybrid blanket has a fission energy multiplication of five to ten, which may be sufficient for NIF-like laser hohlraum gains to be used for energy production. While fusion–fission hybrid schemes have been considered over the past decades, the likelihood of achieving ignition on the NIF in the next few years suggests that this concept should be reconsidered with the anticipated NIF conditions. Such a hybrid scheme will still require advances in target physics beyond the initial NIF ignition. Many of the issues for pure IFE described in Sec. 9 will still apply. Since the panel finished its findings before this proposal was made public, it leaves the consideration of target physics and associated development needs for hybrid systems to a future panel.

11.1 USE OF EXISTING FACILITIES TO STUDY ENERGY-RELATED HEDLP SCIENCE

The National Ignition Facility is expected to achieve ICF ignition with indirectly driven implosions and produce modest energy gains of 10 ~ 20 ("gain" is defined as the fusion energy out divided by the implosion driver energy). A gain of 50 ~ 100 is likely to be required for an IFE power plant. There are numerous concepts at various stages of development for achieving gains of this magnitude, including traditional "hot-spot" ignition schemes and two-step schemes. In "hot-spot" or "conventional" ignition schemes, the primary driver provides both the energy to create a central "hot spot" of relatively high temperature (5 ~ 10 keV) and modest areal density (~0.3 g/cm^2) that ignites and then, through alpha-particle deposition, heats the surrounding cold fuel layer with an areal density of ~3 g/cm^2. The peak implosion velocity must be greater than 3×10^7 cm/s to create the appropriate hot-spot conditions. Approximately 50% of the driver energy coupled to the target is contained in the "hot spot," with the remainder used to compress the cold fuel layer. Central hot-spot ignition concepts include high-gain indirect-drive targets driven by lasers, pulsed-power, or ion beams; and direct-drive concepts driven by lasers or ion beams (see Sec. 7 for more details).

Two step-ignition processes reduce the driver-energy requirements by separating the compression of the cold fuel and the creation of the "hot spot." Because the compression driver is not required to produce the "hot spot," the target can be imploded with lower velocity, making it possible for more mass to be assembled for the same driver energy. Figure 20 illustrates a relationship between implosion velocity and target gain for a fixed driver energy of about 1 MJ, indicating the possibility for high gains for two-step-ignition concepts.

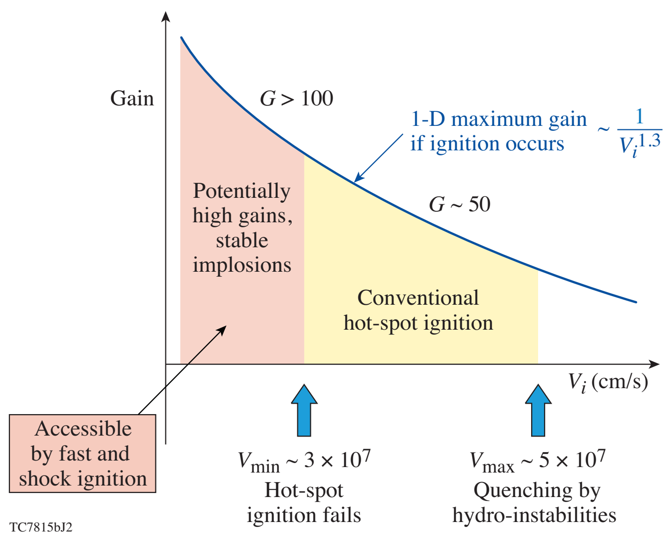

Figure 20. Schematic diagram of the potential increase in target gain for ~1 MJ driver energy with two-step-ignition concepts that use low-velocity implosions.[3]

Two-step processes include shock ignition (Sec. 7.3) that is directly driven with a multistep laser pulse and fast ignition (Sec. 7.2), where the fuel is indirectly or directly compressed by a high-energy laser, pulsed-power, or ion beams, and heated by a high-intensity high-power short-pulse laser. In shock ignition, the final step of the laser pulse has relatively high intensity, launching a converging shock wave into the compressed target to compress the "hot spot." In fast ignition, the short pulse laser energy is converted to energetic electrons or ions that propagate into the target, creating the ignition spark.

Of the alternative IFE concepts, direct-drive is probably the most advanced. Significant effort has been devoted over the past decade to understanding the underlying physics. Recent work[1] has provided a clear understanding of how non-ignition experiments can be hydrodynamically scaled to ignition conditions. Figure 21 shows an example from recent experiments on OMEGA. The implosion performance is assessed through the values of the burn-averaged areal density and ion temperature (in the absence of alpha-particle heating). The solid black line represents a series of hydrodynamically equivalent states for varying driver energies. The blue line represents the ignition threshold for direct-drive targets on the NIF. The red dot represents results recently[2] obtained on the OMEGA laser facility, and the yellow-shaded area represents the parameter space corresponding to energy gains above unity.[3] When the conditions in the yellow dot are achieved on OMEGA in the near future, one will be able to confidently predict that an hydrodynamically equivalent direct-drive target will ignite when scaled up in size and energies on the NIF.

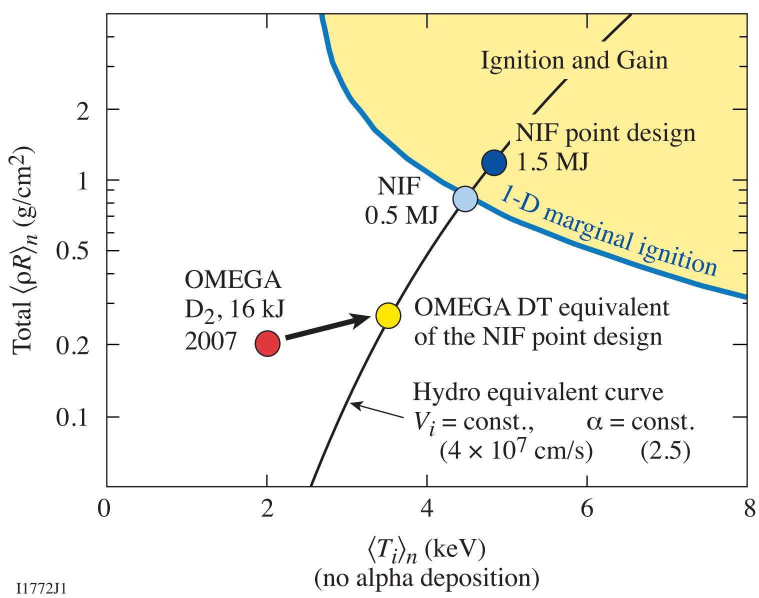

Figure 21. Example of the use of hydrodynamic scaling from non-igniting implosions to ignition conditions on the NIF. This provides a roadmap from recent results during recent direct-drive implosions (red dot) to those hydrodynamically equivalent to ignition (yellow dot).[3]

The scaling laws described above for direct-drive ignition could (and should) be extended to other advanced IFE concepts. These scaling laws make it possible for experiments performed on non-ignition facilities to be directly relevant to IFE opportunities on the NIF, and will guide the future use and modifications of the NIF.

NNSA's current suite of non-ignition facilities (Z and OMEGA are the largest) will be able to develop these concepts and determine those that show the greatest promise for an IFE power plant. There will be a continuing need to use the non-ignition facilities to explore advanced IFE concepts. For example, both OMEGA and Z have recently added high-energy short-pulse laser systems that will allow a critical assessment of the fast-ignition concept. The OMEGA Facility has the pulse-shaping capabilities to test the shock-ignition concept. Smaller facilities can also be used to study specific aspects of IFE-related HEDLP physics through dedicated experiments designed to emphasize relevant features of important physical phenomena, e.g., the generation of focused electron and ion beams for fast ignition.

The non-ignition facilities will remain crucial for supporting NNSA's mainline indirect-drive-ignition concepts. Questions will arise during the initial ignition attempts on the NIF. These will often be resolved on the non-ignition facilities at lower cost (both shot and opportunity). A recent example measuring the equation of state (EOS) of the plastic ablators that are the backup indirect-drive-ignition targets. A large number of shots on OMEGA were quickly carried out to measure the EOS and allow the ignition design to be refined. Novel ignition diagnostics will be developed on the non-ignition devices to further the achievement of ignition.

The national ICF program will rely on non-ignition experimental facilities to support the ignition effort and develop the advanced concepts that will be essential to provide the Nation with a viable approach to inertial fusion energy. These facilities provide the avenue for university users to participate in this area of extreme national interest.

> **Finding:** *The NIF is likely to be oversubscribed during the next decade and the exploration of some of the IFE concepts would require significant modifications of the NIF, with associated costs of the new hardware and a loss of shot time while modifications are being performed. These concepts should be developed on existing HED facilities, with the most promising transferred to the NIF for a high-gain-ignition demonstration.*

Many HEDLP science issues relevant to IFE can be addressed with existing non-ignition facilities. There are three ways of utilizing existing facilities:

1. Studying specific IFE-science issues: Specific IFE-science issues can be investigated through experiments designed to identify the features of a specific phenomenon in isolation to facilitate the measurements and the interpretation of the results. A prioritized list is provided in Sec. 11.1.1.
2. Fielding integrated-implosion experiments with surrogate targets: Some aspects of implosion physics can be studied with room-temperature (warm) surrogate targets that can be easily manufactured and fielded at a relatively high rate. Warm targets

are a practical surrogate for the cryogenic capsules required for IFE. A prioritized list of warm-target-implosion experiments is provided in Sec. 11.1.2.

3. Fielding ignition-scalable integrated-implosion experiments: Fast ignition and direct-drive cryogenic-implosion experiments on existing facilities can be designed to scale in target size and driver energy to ignition conditions on the National Ignition Facility (Sec. 11.1.3)

11.1.1 Investigating Specific HEDLP Science Issues on Existing Facilities

Specific HEDLP science issues relevant to IFE can be explored on existing facilities. Many IFE issues can be investigated through experiments designed to identify the features of a specific phenomenon in isolation. For example, many aspects of the Rayleigh–Taylor instability are better studied and better diagnosed through dedicated experiments on planar foils rather than in ICF spherical implosions. Many examples can be provided to show that advances in IFE research can be made through simplified experiments designed to facilitate measuring and interpreting the results.

This section highlights the most important outstanding IFE science issues that can be addressed through dedicated experiments on existing facilities. Details on the underlying HEDLP science can be found in Sec. 9. The IFE concepts affected by each science issue and the available facilities capable of addressing them are listed together with the priority level from Sec. 9. A brief statement is included to identify whether the science issue is adequately addressed within the NNSA-ICF program or if it represents a scientific opportunity for the Joint HEDLP Program.

1. Linear and nonlinear growth of the Rayleigh–Taylor instability in cryogenic ablators

Description: Sec. 9.1.1
IFE concepts: direct drive, fast ignition, shock ignition
Facilities: OMEGA, ZR, NIKE
Opportunity for the Joint Program, partially addressed by the NNSA-ICF program
Priority for the Joint Program: Medium

2. Equation of state of hydrogen and ablator materials

Description: Sec. 9.1.5
IFE concepts: All
Facilities: OMEGA, ZR, NIKE
Adequately addressed within the NNSA-ICF program
Priority for the Joint Program: Low

3. **Fast-electron and ion generation by intense lasers in solid targets**
Description: Sec. 9.1.3
IFE concepts: fast ignition
Facilities: OMEGA EP, Texas Petawatt, Titan, Trident, Z-Beamlet
Opportunity for the Joint Program
Priority for the Joint Program: High

4. **Hot-electron generation by laser-plasma instabilities in long scale-length plasmas**
Description: Sec. 9.1.2
IFE concepts: laser direct and indirect drive, fast and shock ignition
Facilities: OMEGA, NIKE
Opportunity for the Joint Program, only partially addressed by the NNSA-ICF program
Priority for the Joint Program: High

5. **Relativistic electron transport in metals and plasmas**
Description: Sec. 9.1.3
IFE concepts: fast ignition
Facilities: OMEGA EP, Texas Petawatt, Titan, Trident, Z-Beamlet
Opportunity for the Joint Program
Priority for the Joint Program: High

6. **Shock propagation in solid targets and dense plasmas**
Description: Sec. 9.1.1
IFE concepts: direct and indirect drive, fast and shock ignition
Facilities: OMEGA, NIKE, ZR
Adequately addressed within the NNSA-ICF program
Priority for the Joint Program: Low

7. **Strong shock generation at intensities ~10^{16} W/cm^2**
Description: Sec. 9.1.1 and 9.1.2
IFE concepts: shock ignition
Facilities: OMEGA, OMEGA EP
Opportunity for the Joint Program
Priority for the Joint Program: High

8. Self-generated magnetic-field in laser– and beam–plasma interactions and its effect on energy transport

Description: Sec. 9.1.4
IFE concepts: laser direct and indirect drive, fast and shock ignition
Facilities: OMEGA, OMEGA EP, NIKE
Opportunity for the Joint Program
Priority for the Joint Program: High

9. Magnetohydrodynamic Rayleigh–Taylor instability and its effect on the current flow

Description: Sec. 9.1.4
IFE concepts: Z-pinch, magneto-inertial fusion with metal liners
Facilities: ZR, Zebra, Cobra, Shiva Star
Opportunity for the Joint Program, partially addressed by the NNSA-ICF program
Priority for the Joint Program: Medium

10. Optimization of the fuel assembly for fast ignition

Description: Sec. 9.1.1
IFE concepts: fast ignition
Facilities: OMEGA, ZR
Opportunity for the Joint Program
Priority for the Joint Program: High

11. Energy coupling of heavy-ion beams to surrogate planar targets

Description: Sec. 9.1.3
IFE concepts: heavy-ion fusion
Facilities: requires an upgrade of NCDX
Opportunity for the Joint Program
Priority for the Joint Program: High

12. Compression of externally applied magnetic fields in laser- and pinch-driven implosions and their effects on the compressed-plasma temperature

Description: Sec. 9.1.4
IFE concepts: magneto-inertial fusion
Facilities: Shiva Star, ZR, Zebra, Cobra, OMEGA
Opportunity for the Joint Program
Priority for the Joint Program: High

13. Nonlocal energy transport in laser direct drive

Description: Sec. 9.1.2
IFE concepts: laser direct drive
Facilities: OMEGA, NIKE
Adequately addressed within the NNSA-ICF program
Priority for the Joint Program: Low

14. Laser-to-x-ray-conversion efficiency in hohlraums

Description: Sec. 9.1.5
IFE concepts: laser indirect drive
Facilities: OMEGA
Adequately addressed within the NNSA-ICF program
Priority for the Joint Program: Low

15. Generation of fast particles in *z*-pinch implosions

Description: Sec. 9.1.4
IFE concepts: *z*-pinch-driven hohlraums
Facilities: ZR, Saturn, Zebra, Cobra
Opportunity for the Joint Program
Priority for the Joint Program: Medium

16. Scaling of the x-ray yield in *z*-pinch implosions

Description: Sec. 9.1.4
IFE concepts: *z*-pinch indirect drive
Facilities: ZR, Saturn
Adequately addressed by the NNSA-ICF program
Priority for the Joint Program: Low

11.1.2. Using Existing Facilities to Field Integrated Implosion Experiments with Surrogate Targets

The designation of *integrated implosion experiments* is used here to identify those experiments requiring the integration of all the basic elements of the IFE system under consideration. They require targets of the appropriate geometry and characteristics, a suitable driver (or multiple drivers as in fast ignition) to implode and heat the target, and the necessary diagnostics. OMEGA and ZR are the only implosion facilities currently operating in the U.S. for direct- (OMEGA) and indirect- (OMEGA and ZR) drive-implosion experiments. The National Ignition Facility will be the nation’s premier implosion facility and will start operation in 2009. Shiva Star will be able to perform integrated implosion experiments of magneto-inertial fusion with an imploding metal liner compressing a preformed FRC plasma. If realistic IFE targets are difficult to make and/or to handle, initial implosion experiments are typically performed using surrogate targets. This is the case for all the high-gain IFE concepts that rely on cryogenic capsules. The only facility currently equipped to field implosion experiments with spherical cryogenic capsules is OMEGA. The NIF will also have cryogenic-target capability by 2010. Because of the difficulty in handling cryogenic targets at ~18 K, the shot rate for cryogenic implosions is low (up to four cryogenic spherical implosions per day on OMEGA). Some aspects of implosion physics can be studied with room-temperature (warm) surrogate targets that can be easily manufactured and fielded at a relatively high rate (up to about 12 spherical warm-target implosions per day on OMEGA). The Laboratory for Laser Energetics will be able to field cryogenic cone-in-shell targets in 2010 for fast-ignition integrated experiments. Until then, integrated cone-guided fast-ignition experiments can be carried out using only surrogate warm targets. Below is a list of important outstanding IFE science issues that can be addressed through integrated implosion experiments with surrogate targets on existing facilities.

1. **Compression of surrogate cone-in-shell targets and heating by a petawatt pulse**
   IFE concepts: fast ignition
   Facilities: OMEGA and OMEGA EP, ZR, and Z-Beamlet
   Opportunity for the Joint Program
   Priority for the Joint Program: High
   HEDLP science issues to be studied:
   a. electron transport in imploded targets (Sec. 9.1.3)
   b. optimization of the fuel assembly and short pulse timing (Sec. 9.1.1)
   c. energy coupling of the fast electrons to the dense core (Sec. 9.1.3)

2. **Compression and heating of a magnetized plasma**
   IFE concepts: magneto-inertial fusion
   Facilities: Shiva star, OMEGA
   Priority for the Joint Program: High
   Opportunity for the Joint Program
   HEDLP science issues to be studied:
   a. magnetic-flux compression (Sec. 9.1.4)
   b. magnetic thermal insulation of the heated central plasma (Sec. 9.1.4)
   c. liner-plasma mixing (for MIF with metal liners) (Secs. 9.1.1 and 9.1.4)

3. **Compression of surrogate spherical targets and heating by a late shock**
   IFE concepts: shock ignition
   Facilities: OMEGA
   Opportunity for the Joint Program

Priority for the Joint Program: High

HEDLP science issues to be studied:

a. implosion uniformity (Sec. 9.1.1)
b. late shock strength and uniformity (Sec. 9.1.1)
c. the role of hot electrons produced during the intensity spike (Sec. 9.1.2)

4. Compression and heating of indirect-drive surrogate targets

IFE concepts: indirect drive

Facilities: OMEGA, ZR

Adequately addressed within the NNSA-ICF program

Priority for the Joint Program: Low

a. pulse shaping with *z*-pinches (Sec. 9.1.4)
b. hot-electron preheat in indirect drive (Sec. 9.1.2)
c. implosion performance and scaling studies in *z*-pinch indirect-drive (Sec. 9.1.4)

5. Compression and heating of laser direct-drive surrogate targets

IFE concepts: laser direct drive

Facilities: OMEGA

Adequately addressed within the NNSA-ICF program

Priority for the Joint Program: Low

a. Shock timing and optimum compression (Sec. 9.1.1)
b. Adiabat shaping and reduction of the Rayleigh–Taylor growth rates (Sec. 9.1.1)
c. Hot-spot distortion, turbulent mixing, and fusion-yield degradation (Sec. 9.1.1)
d. Areal-density degradation from hot-electron preheat (Sec. 9.1.2)

11.1.3. Ignition-Scalable Integrated-Implosion Experiments

As highlighted in the introduction to this section, scalable-implosion experiments with IFE-relevant targets are the most accurate tools to assess the future performance of a given concept. If most aspects of the physics do not significantly change when an implosion experiment is scaled in target size and driver energy (hydroequivalent implosion) to ignition conditions, then the results can be scaled—with some confidence—to the performance on larger facilities. This is a reasonable way to move forward with the development of IFE concepts. This requires fielding implosion experiments with IFE-relevant targets using existing drivers. Laser direct drive is approaching a "NIF-equivalent" demonstration of ignition on OMEGA through ignition-scalable cryogenic-implosion experiments. If successful, a "NIF-equivalent" demonstration of ignition implies that such implosions would likely achieve ignition and burn if scaled to NIF energies, while keeping the essential physics unchanged. Below is a summary of ignition-scalable-implosion experiments with IFE-relevant targets that can be fielded on existing implosion facilities.

1. Laser-direct-drive cryogenic-implosion experiments

Cryogenic implosions on OMEGA are designed as scaled-down versions of NIF ignition targets. For instance, the OMEGA scaled version of the direct-drive NIF point design[4] consists of a ~65-µm-thick DT layer inside a 2- to 3-µm-thick CH shell, driven by 25 kJ of UV laser energy at a velocity of about 4.2×10^7 cm/s and an adiabat of about 2.7. The performance of such targets can be assessed by measuring areal densities, ion temperatures, and fusion yields.

IFE concepts: laser direct drive
Facilities: OMEGA
Adequately addressed within the NNSA-ICF program
Priority for the Joint Program: Low

2. Fast-ignition integrated cryogenic-target experiments

Integrated fast-ignition experiments with cryogenic targets will be fielded on OMEGA in the near future. A test stand for layering cryogenic cone-in-shell targets has been developed at LLE, and such targets should become available by 2010. A point design for ignition and gain on the NIF has not yet been developed. It is expected that cryogenic fast-ignition integrated experiments on OMEGA can be designed to scale to ignition-relevant experiments on the NIF (assuming that an ignition-size petawatt laser becomes available on the NIF).

IFE concepts: fast ignition
Facilities: OMEGA and OMEGA EP
Opportunity for the Joint Program
Priority for the Joint Program: High

Recommendation:

The Joint Program should take advantage of the available non-ignition facilities to support the current ICF ignition program and develop the tools and concepts that will lead to an IFE power plant. The Joint Program should support research activities on existing facilities for

1. *Studying specific IFE-science issues (see Sec. 11.1.1)*
2. *Fielding integrated-implosion experiments with surrogate targets (see Sec. 11.1.2)*
3. *Fielding ignition-scalable integrated implosion experiments (see Sec. 11.1.3)*

11.2 EXPLOITING NIF TO STUDY ENERGY-RELATED IGNITION SCIENCE

One of the advantages of inertial fusion is that many IFE concepts share the same fundamental ignition-physics issues. Laser direct- and indirect- drive, shock ignition, *z*-pinch fusion and heavy-ion fusion are based on central hot-spot ignition, where the "spark" is a central low-density plasma (the hot spot) compressed to high pressures and temperatures by an imploding shell. Shock ignition is somewhat different in that the hot-spot compression is enhanced by a strong convergent shock. In fast ignition, the "spark" is located in the dense fuel and is heated by an intense electron or ion beam generated by a short and intense laser pulse. While the physics of the burn wave propagation through the fuel is the same in all of these schemes, the mechanisms of spark generation are profoundly different. If successful, the NIF will be able to explore the fundamental physics of central hot-spot ignition in its current configuration.

> **Finding**: *Several IFE concepts are based on the same ignition method: central hot-spot ignition. The National Ignition Facility is anticipated to demonstrate central hot-spot ignition and achieve moderate energy gains in the near future through the indirect-drive approach. The fundamental physics of central hot-spot ignition that the NIF will study is relevant to indirect- and direct- drive, z-pinch, shock ignition, and heavy-ion inertial confinement fusion.*

The NIF will be able to study the fuel assembly of ignition-relevant fast-ignition targets. To trigger ignition with an intense laser, NIF will require a high-energy short-pulse petawatt laser system. The most recent estimates[1–3] indicate that a ~10-ps-duration, ~20-μm-radius, ~30- to 40-kJ electron beam is required for electron fast ignition. Assuming a laser-to-electrons conversion efficiency of ~30%, the required short-pulse-laser energy is about 100 to 130 kJ. By contrast, the largest operating short-pulse laser is OMEGA EP at the University of Rochester, with two short-pulse beams having a total laser energy of 5 kJ. FIREX-I at Osaka University is expected to begin operation in 2009 with a short-pulse beam energy of 10 kJ. Based on current technology, building a ~100-kJ short-pulse, high-power laser system would require significant R&D and financial investment. Since advances in the physical understanding of fast-electron generation and transport are expected in the coming years, it is possible that the short-pulse laser-energy requirements for fast ignition will be relaxed as scientists learn more about how to control these complicated physical phenomena. Advances in the technology of short-pulse lasers can reduce the construction costs.

> **Finding**: *According to the most recent results, achieving ignition through the fast-ignition scheme will require a ~100-kJ-scale short-pulse high-power laser system. Advances in fast-ignition physics may reduce the*

short-pulse laser-energy requirements. Advances in high-power laser technologies may reduce the technical challenges and construction costs for building such a large system.

While achieving ignition with fast ignition will require a new laser system or the adaptation of several existing beamlines for short-pulse operation, important advances in fast-ignition research can be made with the current NIF configuration and the ~13-kJ short-pulse capability currently planned. The NIF-ARC (Advanced Radiographic Capability), under development at LLNL, is designed to enable multiframe, hard x-ray radiography of imploding NIF capsules—a capability that is critical to the success of the NIF's mission. Work to adapt the first NIF beamline for short-pulse operation should be completed in 2009 and provide 2.4 kJ of short-pulse energy. The NIF-ARC system will enable integrated studies of fast ignition. These experiments can explore fast-electron heating in ignition-scale targets driven by the NIF.

Recommendation: *The NIF-ARC system should be made available for integrated experiments of compression and fast-electron heating in ignition-scale targets. Results from fast-ignition experiments on NIF-ARC and OMEGA EP will provide the scientific basis for future developments of fast-ignition research including a major upgrade of the NIF short-pulse-laser system to ignition-relevant energies.*

Demonstrating direct-drive ignition on the NIF is of fundamental importance to the development of inertial fusion energy and should be an important goal for the NNSA-ICF and Joint HEDLP Programs. However, converting the NIF into a fully spherically-symmetric laser facility ideal for direct-drive ICF will likely cost several hundred million dollars. An interim, far more economical step might be to attempt a demonstration of direct-drive ignition through the "polar drive" scheme. Polar drive[4] is a variant of the conventional spherically-symmetric direct-drive concept. In polar drive, the current two-sided "polar" beam configuration of the NIF is used to directly drive a spherical capsule. The difficulty with polar drive is maintaining the implosion uniformity required while using the two-sided NIF laser configuration. This is accomplished by repointing the laser beams on targets, by varying their spot size and shape, and by tailoring the laser pulses among different clusters of beams. Through an optimization of the illumination pattern, recent two-dimensional hydro-simulations indicate that it is possible to drive a cryogenic-DT capsule uniformly enough to achieve ignition and moderate gain. Recent experiments[5] using 40 OMEGA beams in a two-sided configuration to drive warm surrogate targets have shown that low-mode-number nonuniformities can be controlled by repointing the beams on targets.

Finding: *Demonstrating direct-drive ignition on the NIF is of fundamental importance to the development of inertial fusion energy and should be an important goal for the NNSA-ICF and Joint HEDLP Programs. Polar drive offers the possibility for achieving direct-drive ignition using the two-sided indirect-drive NIF configuration.*

If low-mode laser nonuniformities are fully controlled, small speckles in the illumination of each laser beam can seed hydrodynamic instabilities and quench the ignition process. Short-wavelength laser nonuniformities are controlled through optical-smoothing techniques. As currently designed, the NIF will not be capable of providing the level of illumination uniformities required for direct-drive ignition. In glass lasers (such as the NIF and OMEGA), laser smoothing is implemented through a technique called "smoothing by spectral dispersion (SDD)."[6] SSD shimmers the beam onto the target to remove the speckling and intensity variation. Although it was originally developed for direct-drive experiments, LLNL researchers have applied it to indirect-drive-target designs. As a result, SSD was modified and implemented on Nova and it will also be used on the NIF. OMEGA uses two-dimensional SSD, where the shimmering occurs in two perpendicular spatial directions. The NIF is designed to implement a less-effective one-dimensional SSD. Even if clever remedies can be found to improve the uniformities of NIF beams, the cost for the laser upgrades required for polar drive ignition will likely be in the range of tens of millions of dollars.

Finding: *As currently configured, the NIF will not be capable of providing the level of single-beam illumination uniformity believed to be required for direct drive ignition.*

Initial polar-drive-implosion experiments can be fielded on the NIF using the less-effective one-dimensional SSD smoothing. These experiments can be used to study the fuel assembly and target compression by measuring the areal density of the dense core. The areal density, ion temperature, and neutron yield are the critical parameters for assessing the implosion performance. While the spatially averaged areal densities are rather insensitive to small-scale perturbations, both ion temperature and fusion yields are strongly dependent on the uniformity of the implosion. To achieve the ion temperatures required for polar-drive ignition and the fusion yields required for moderate energy gains, the NIF laser should be upgraded to improve laser-beam uniformities.

Recommendation: *The funding agencies should develop a plan to facilitate the demonstration of ignition with the direct-drive approach on the National Ignition Facility. This will require upgrades of the laser* *system to improve the laser-beam uniformity as needed for polar-direct-drive ignition.*

11.3 Transition to an Energy Science and Technology Development Program: Remaining Science and Technology Issues

After a successful demonstration of ignition on the National Ignition Facility, difficult technological, engineering, and scientific challenges remain in the path of an attractive inertial fusion energy power plant. All the ICF concepts (direct and indirect drive, heavy-ion fusion, fast and shock ignition) require high target gains to be viable for energy applications. The target gains required for a viable power plant vary for different concepts depending on the driver efficiency. The product of the driver efficiency and target gain must exceed about ten to reduce the recirculating power and minimize the capital cost of an IFE power plant. Heavy-ion and *z*-pinch drivers have higher wall-plug efficiencies than lasers. Laser efficiencies vary according to the type of amplifier medium and pumping technology. Neodymium glass lasers—such as OMEGA and the NIF—have rather low efficiencies, while diode lasers and krypton-fluoride (KrF) lasers have significantly higher ones (see Table 11.I).

Table 11.I: Projected efficiency of ICF drivers. The estimates are based on current R&D and extrapolations of available data.

Driver	Projected efficiency based on current R&D
Nd:glass lasers (flash lamp pumped)	~0.5%
Diode lasers	7-10% @ 351nm, 9-13% @ 528 nm
KrF lasers	7%–8%
Heavy-ion accelerators	~15-30%
z-pinches	~35%

Achieving high gain requires imploding cryogenic targets with a carefully tailored drive pulse. Precise pulse shaping is needed to keep the fuel cold enough to achieve the final compression (e.g., high areal densities) needed for a high burn-up fraction. Lasers have already demonstrated the capability for the high-precision pulse shaping required for high gain. The target gain increases with the amount of fuel assembled by the driver. There is a limit to the amount of fuel that can be compressed to achieve the ignition conditions. For a fixed driver energy, the central hot-spot temperature decreases inversely with the fuel mass because the hot-spot temperature is proportional to the capsule implosion velocity that diminishes as the fuel mass increases (for a fixed capsule kinetic energy). If the temperature falls below a critical value, the hot-spot-ignition process is inhibited and the energy gain drops below unity. Conventional direct- and indirect-drive ICF operates at high-implosion velocities above 300 km/s. Thus, for a given driver energy, only relatively small amounts of fuels can be assembled at such high implosion velocities. For a ~1-MJ UV laser driver (0.35-μm wavelength), the predicted energy gains are limited to about ~10 to 20 for indirect drive and 30 to 40 for direct drive. Higher gains are predicted for direct drive using the deep UV light of KrF lasers, and for indirect drive using green light. Fast and shock ignition take advantage of an externally induced spark to ignite the compressed fuel and, therefore, can achieve higher gains (~140 at 1 MJ) by compressing more fuel at lower-implosion velocities. There are no substantial differences in the fusion burn physics between a moderate- (~10 to 20) and a high-gain target (~100). However, the demonstration of high gains will permit a direct validation of the predictive capabilities and scaling laws for the gain as a function of the driver energy, target specifications, and driver pulse shape. Achieving high gains will increase confidence and enable an accurate evaluation of the target and driver requirements for a power plant.

> **Finding:** *While the underlying burning plasma physics exhibits only minor differences between moderate (~10) and high (~100) gains, achieving higher gains will enable a direct validation of the predictive capabilities and an accurate evaluation of the target and driver requirements for a power plant.*

In the current configuration, the NIF may not be able to create the proper conditions required for many fusion energy target designs. Substantial upgrades of the laser system, or another type of laser or driver will probably be required for achieving gains greater than ~50. Even without a direct demonstration of high gains on the NIF, a credible validation of some IFE target designs can take place with a combination of experiments in relevant physics regimes and multi dimensional, high resolution simulations using codes that have been benchmarked with experiments.

> **Recommendation:** *After the demonstration of ignition, an assessment should be made of the upgrades required for the achievement of high gains on the National Ignition Facility. Possible paths to high gains on the NIF include alternative concepts such as direct-drive, fast and shock ignition. In addition, a strategy should be developed to achieve a credible validation of other plausible IFE-relevant target designs through a combination of experiments in relevant physics regimes with existing and/or new facilities, and multi dimensional, high resolution simulations using codes that have been benchmarked with experiments.*

Achieving high gains will resolve many, but not all, of the IFE target-physics issues. A comprehensive development program should be established that addresses all the remaining key science and technology issues of the integrated IFE system. The establishment of this program should follow from a careful assessment of the benefits of inertial fusion energy, and of the pros and cons of the different IFE concepts.

There are many attractive aspects of inertial fusion energy. For some IFE concepts, there has been considerable progress in addressing the pressing science and technology issues, as well as in identifying the steps to resolve them. A formal DOE program to resolve these issues should be timely coordinated with progress in target physics expected on the National Ignition Facility and/or elsewhere, and with a careful assessment of the economic and technological viability of the specific IFE concept. The same physics standards used in the DOE Magnetic Fusion Program should be applied to a formal DOE Inertial Fusion Program. The progress in target physics required for the establishment of such a program should be based on the validation of a target design through a combination of experiments in relevant physical conditions and multi-dimensional simulations used to extrapolate the results to reactor relevant regimes.

> **Recommendation:** *A formal program to resolve the remaining key science and technology issues of the integrated IFE system should be coordinated with the progress in target physics. The establishment of this program should follow from a careful assessment of the potential benefits of inertial fusion energy, and of the pros and cons of the different IFE concepts.*

The following sections describe the benefits of inertial fusion energy, the key science and technology issues, the progress made with some IFE concepts, and the rationale for a development program.

11.3.1 Benefits of Inertial Fusion Energy

There are several attractive aspects of inertial fusion energy that suggest that an IFE system can lead to a practical fusion power plant, with potentially favorable development cost, development time, and risk.

a. The driver, the most expensive and complex part, is either modular or composed of modular parts. This allows research and development on a small scale before replication to produce a full-scale system.
b. The principal components are physically separated from one another, allowing them to be individually developed before (and modified after) integration into a full system.

c. This separation allows for a staged development program that minimizes the risk in final demonstration systems.
d. In a power plant, this separation will facilitate incremental improvements.
e. The target physics can be established on a single-shot basis using existing or soon to be completed facilities. Many of the underlying physics issues have been addressed and continue to be addressed under the NNSA ICF program. The remaining physics issues, i.e., those endemic to the advanced targets required for fusion energy, can be addressed as described in Sec. 9 of this report
f. Most, if not all, of the fusion-reactor nuclear science, technology, and engineering optimizations can be developed and demonstrated on one repetitively pulsed facility. This includes the target physics, the driver/final optics, the target fabrication and injection, materials and components, and the chamber architecture.

11.3.2 Remaining Science and Technology Issues

The IFE community is developing an integrated approach to fusion energy: The science, technology, and, as needed, the engineering, are developed in concert with one another, while always keeping the goal of an attractive power plant at the forefront. This is the fastest, most efficient, and lowest risk path to realizing fusion energy. With this as a background, we can formulate the top-level scientific and technical issues that must be resolved to allow IFE to transition from a HEDLP science- to an energy science and technology-development program**.**

Issue 1: Target Physics

Description: Produce target designs with sufficient gain for the energy application, while achieving adequate stability. The target design must be compatible with the other components of an IFE system. It must match the driver capabilities; must be compatible with low-cost mass production; must be within the precision capabilities of target-fabrication techniques; must be suited for accurate, repetitive injection/placement; and must produce an emission spectrum that can be resisted by the chamber/first wall. This is a complex, multifaceted challenging task and will require several iterations with the other elements listed below. *Producing an integrated target design suitable for fusion energy is an extreme test of our understanding and control of the underlying HEDLP physics.*

Steps to resolve for transition: Validation of the target design: Credible validation can take place with a combination of experiments in relevant physics regimes and multidimensional, high-resolution simulations using codes that have been benchmarked with experiments. These will be done with the highest fidelity experiments and simulations available. It is realized that in the near term, only the

NIF will be able to access the ignition regime. The NIF may not be able to achieve the high gains required for many fusion-energy target designs. Therefore, using a demonstration of ignition as the "definition" of validation is not justified and, in fact, may be too constrictive. A better definition is to use the same level of confidence in the target designs as was used to justify the construction of the NIF

Issue 2: Driver

Description: Develop the technologies needed to build a driver that can meet the IFE requirements for energy on target, "characteristics", efficiency, repetition rate, durability, and cost. These "characteristics" encompass all that is required by the target physics in Element 1. Examples include wavelength and beam quality for lasers, brightness for lasers and heavy ions, and pulse shaping and power for all approaches. Repetition rate, durability, and cost characteristics would be determined by the integrated power-plant concept.

Steps to resolve for transition: Demonstration of a driver with the required energy, characteristics, efficiency, and repetition rate at subscale. The subscale driver is based on components that are directly scalable to a full-size system. This phase durability would be demonstrated by continuous runs of at least a full day of operation, and the cost goal met by reasonable economic projections of the developed technology.

Issue 3: Driver delivery system

Description: Develop final focusing elements (e.g., optics, magnets, electrical transmission lines) that can focus the driver energy onto the target with the required precision, fidelity (e.g., preserve beam uniformity), damage threshold, and repetition rate. These elements should be resistant to damage from both the target emissions and the driver energy.

Steps to resolve for transition: Demonstration of the above on small-scale systems that can be credibly scaled to full-size components.

Issue 4: Target fabrication, injection, and engagement

Description: Develop methods to mass produce targets with the required precision (as dictated by the target physics), and within the required cost (as determined by the power plant economics.) In many reactor concepts, this requires cryogenic capability. Develop techniques to place these targets in the reaction chamber with the required precision and verify the placement with the required accuracy and/or ensure the driver energy is focused on to the target with the required accuracy. In some cases (laser and heavy ions) this requires injecting the target. In others it is much simpler, and requires only injecting a plasma or neutral gas (magneto-inertial fusion).

Steps to resolve for transition: Demonstrate target-fabrication precision on a batch-production basis. In the interest of keeping costs under control, some of these demonstrations may be done with D_2 rather than DT. Demonstrate target placement with scaled bench tests of non-cryogenic surrogates.

Issue 5: Reaction Chamber

Description: The reaction chamber and its blanket must absorb the emission from the target, convert those emissions to a form that can be used for energy production, and breed tritium to keep the system running. The chamber must provide an environment to make possible the required precision in placement and tracking of the target, and must provide a means to return to that environment on subsequent shots The chamber topology depends on the fusion concept, and the first wall can take a variety of forms including having a replenished liquid, a solid, and a magnetically protected wall. In some cases, the blanket may be filled with a fissile material, to boost the effective gain of an inherently lower gain target, such as for laser-indirect-drive or magneto-inertial fusion.

Steps to resolve for transition: Develop a credible integrated chamber concept using simulations, physics models, and subscale experiments. Experimentally demonstrate a realistic concept for survival/replenishment of the first wall

11.3.3 Past Progress in IFE Research

The U.S. has invested heavily in the physics of inertial fusion energy, both through the Department of Energy's National Nuclear Security Administration's (NNSA's) Science-Based Stockpile Stewardship program and through the Office of Science. These programs have developed designs with the gain needed for energy applications. Among the more mature are central-hot-spot ignition based on direct drive with lasers, indirect drive with *z*-pinches, and indirect drive with heavy ions. As discussed in this report, more advanced approaches such as fast ignition, shock ignition, magneto-inertial fusion, and direct drive with heavy-ion beams are also under investigation.

Significant advances have been made in the fusion nuclear science and technologies needed for IFE. This work has been carried out under the high-average power laser (HAPL) program, the *z*-pinch fusion program, and the heavy-ion fusion program. For example, under HAPL, two durable and efficient laser drivers have demonstrated long duration runs with high-energy-per-pulse, fusion-class repetition-rate capability, and have a credible path to realizing the required efficiency. Meaningful advances have been made with z-pinch– and heavy-ion–based drivers as well. Outside the driver arena, final optic systems have demonstrated impressive durability (>10 million shots at 10 Hz), with the required laser-damage threshold. Experiments have shown the feasibility of mass-producing (the non-cryogenic) targets with the precision required for IFE, and based on these results, the targets are projected to meet the cost requirements. Bench tests have shown that it should be possible to track these targets into the reaction chamber. Several chamber concepts have been evaluated, in particular both solid and thick-liquid walls, and have been or are under experimental evaluation

11.3.4 Rationale for an Energy Science and Technology Development Program

The rationale for proceeding with a formal inertial fusion energy program (apart from the acute global need for a clean, plentiful energy source) is to capitalize on the momentum produced by the significant technical advances described above and to maintain the current research efforts. Since there is no formal program, all of these efforts are at some risk. Within the next two to four years the momentum is expected to get a significant boost if ignition- and fusion-energy gain is achieved on the NIF. To fully take advantage of this opportunity, both technically and politically, an integrated program to resolve the issues for IFE should be coordinate with the progress in target physics.

A program in inertial fusion energy sciences should make it possible for sufficient resources to take the most mature/promising concepts to the next stage of development, as listed in the "Steps for Transition" sections above. This will establish the technical basis to determine which (if any) warrant advancing to a major initiative, such as an Integrated Research Experiment[1–5] or another facility that demonstrates long-term production of meaningful fusion power. The program must be oriented along integrated concepts to develop the science and technology for all the components, including the driver, final optics, chamber, target fabrication, and target injection/engagement. The program must have sufficient resources and flexibility to encourage innovations to solve problems. Examples of this are fast and shock ignition for laser fusion, direct-drive targets for heavy-ion fusion, or targets based on magnetic fields. It is equally important that this program allow room for the pursuit of advanced ideas that are outside the main concepts. Achieving the balance between fostering new ideas and developing complete integrated concepts will be challenging, but achievable.

> **Recommendation:** *A program in inertial fusion energy science and technology should have sufficient resources to take the most mature/promising concepts to the next stage of development. This program should be oriented along integrated concept lines and make room for the pursuit of advanced ideas that are outside the main approaches. Achieving the balance between fostering new ideas and developing complete integrated concepts will be challenging, but achievable.*

REFERENCES

SECTION 1

1. National Research Council (U.S.) Committee on the Physics of the Universe, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (National Academies Press, Washington, DC, 2003).
2. National Research Council (U.S.) Committee on High Energy Density Plasma Physics, *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science* (National Academies Press, Washington, DC, 2003).
3. "Frontiers for Discovery in High Energy Density Physics," prepared for the Office of Science and Technology Policy, National Science and Technology Council Interagency Working Group on the Physics of the Universe and prepared by the National Task Force on High Energy Density Physics (20 July 2004). This paper can be found at http://www.ofes.fusion.doe.gov/News/HEDPReport.pdf.
4. R. Rosner and J. C. Browne, "Summary of a Workshop on Opportunities for High Energy Density Laboratory Plasma Science," presented at Argonne National Laboratory, Argonne, IL, 23–24 May 2007.
5. National Research Council (U.S.) Plasma 2010 Committee, *Plasma Science: Advancing Knowledge in the National Research* (National Academies Press, Washington, DC, 2007).
6. "Report of the Interagency Task Force on High Energy Density Physics," prepared by the National Science and Technology Council, Committee on Science, Interagency Working Group on the Physics of the Universe (August 2007).

SECTION 7.1.1

1. S. E. Bodner, D. G. Colombant, J. H. Gardner, R. H. Lehmberg, S. P. Obenschain, L. Phillips, A. J. Schmitt, J. D. Sethian, R. L. McCrory, W. Seka, C. P. Verdon, J. P. Knauer, B. B. Afeyan, and H. T. Powell, "Direct-Drive Laser Fusion: Status and Prospects," Phys. Plasmas **5**, 1901-1918 (1998).
2. A. J. Schmitt, D. G. Colombant, A. L. Velikovich, S. T. Zalesak, J. H. Gardner, D. E. Fyfe, and N. Metzler, "Large-Scale High-Resolution Simulations of High Gain Direct-Drive Inertial Confinement Fusion Targets," Phys. Plasmas **11**, 2716-2722 (2004).
3. L. J. Perkins, M. Tabak, C. Bibeau, R. Beach, A. Ladran, C. Barty, J. Harte, J. Sethian, A. Schmitt, R. Betti, and C. Zhou, "HAPL Reactor Targets: Baseline Specifications and Future Options," presented at the 13th High Average Power Laser Program Workshop, Rochester, NY, 8–9 November 2005; see http://aries.ucsd.edu/HAPL/MEETINGS/0511-HAPL/program.html.
4. D. Colombant, A. J. Schmitt, S. P. Obenschain, S. T. Zalesak, A. L. Velikovich, J. W. Bates, D. E. Fyfe, J. H. Gardner, and W. Manheimer, "Direct-Drive Laser Target Designs for Sub-Megajoule Energies," Phys. Plasmas **14**, 056317 (2007).
5. A. J. Schmitt, J. W. Bates, S. P. Obenschain, S. T. Zalesak, D. E. Fyfe, and R. Betti, "Direct Drive Fusion Energy Shock Ignition Designs for Sub-MJ Lasers," presented at the 18th TOFE Conference, San Francisco, CA, 28 September–2 October 2008; to be published in Fusion of Science and Technology.
6. R. Betti, C. D. Zhou, K. S. Anderson, L. J. Perkins, W. Theobald, and A. A. Solodov, "Shock Ignition of Thermonuclear Fuel with High Areal Density," Phys. Rev. Lett. **98**, 155001 (2007).

SECTION 7.1.2

1. M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilks, J. Woodworth, E. M. Campbell, M. D. Perry, and R. J. Mason, “Ignition and High Gain with Ultrapowerful Lasers,” Phys. Plasmas **1**, 1626-1634 (1994); N. G. Basov, S. Yu. Gus’kov, and L. P. Feokistov, “Thermonuclear Gain of ICF Targets with Direct Heating of Ignitor,” J. Sov. Laser Res. **13**, 396-399 (1992).
2. D. Strickland and G. Mourou, “Compression of Amplified Chirped Optical Pulses,” Opt. Commun. **56**, 219-221 (1985).
3. J. D. Lindl, *Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive* (Springer-Verlag, New York, 1998); M. D. Rosen, “The Physics Issues that Determine Inertial Confinement Fusion Target Gain and Driver Requirements: A Tutorial,” Phys. Plasmas **6**, 1690-1699 (1999).
4. R. Kodama, K. Takahashi, K. A. Tanaka, M. Tsukamoto, H. Hashimoto, Y. Kato, and K. Mima, “Study of Laser-Hole Boring into Overdense Plasmas,” Phys. Rev. Lett. **77**, 4906-4909 (1996).
5. S. P. Hatchett and M. Tabak, “Cone-Focused Target Design for Fast Ignition,” presented at the 30th Annual Anomalous Absorption Conference, Ocean City, MD, 21–26 May 2000; R. Kodama, H. Shiraga, K. Shigemori, Y. Toyama, S. Fujioka, H. Azechi, H. Fujita, H. Habara, T. Hall, Y. Izawa, T. Jitsuno, Y. Kitagawa, K. M. Krushelnick, K. L. Lancaster, K. Mima, K. Nagai, M. Nakai, H. Nishimura, T. Norimatsu, P. A. Norreys, S. Sakabe, K. A. Tanaka, A. Youssef, M. Zepf, and T. Yamanaka, “Nuclear Fusion: Fast Heating Scalable to Laser Fusion Ignition,” Nature **418**, 933-934 (2002).
6. M. Roth, T. E. Cowan, M. H. Key, S. P. Hatchett, C. Brown, W. Fountain, J. Johnson, D. M. Pennington, R. A. Snavely, S. C. Wilks, K. Yasuike, H. Ruhl, E. Pegoraro, S. V. Bulanov, E. M. Campbell, M. D. Perry, and H. Powell, “Fast Ignition by Intense Laser-Accelerated Proton Beams,” Phys. Rev. Lett. **86**, 436-439 (2001).
7. S. Atzeni, A. Schiavi, and C. Bellei, “Targets for Direct-Drive Fast Ignition at Total Laser Energy of 200–400 kJ,” Phys. Plasmas **14**, 052702 (2007).

SECTION 7.1.3

1. R. Betti, C. D. Zhou, K. S. Anderson, L. J. Perkins, W. Theobald, and A. A. Solodov, “Shock Ignition of Thermonuclear Fuel with High Areal Density,” Phys. Rev. Lett. **98**, 155001 (2007).
2. A. J. Schmitt, J. W. Bates, S. P. Obenschain, S. T. Zalesak, D. E. Fyfe, and R. Betti, “Direct Drive Fusion Energy Shock Ignition Designs for Sub-MJ Lasers,” presented at the 18th TOFE Conference, San Francisco, CA, 28 September–2 October 2008; to be published in Fusion of Science and Technology.
3. S. E. Bodner, D. G. Colombant, A. J. Schmitt, J. H. Gardner, R. H. Lehmberg, and S. P. Obenschain, “Overview of New High Gain Target Design for a Laser Fusion Power Plant,” Fusion Eng. Des. **60**, 93-98 (2002).
4. W. Theobald, R. Betti, C. Stoeckl, K. S. Anderson, J. A. Delettrez, V. Yu. Glebov, V. N. Goncharov, F. J. Marshall, D. N. Maywar, R. L. McCrory, D. D. Meyerhofer, P. B. Radha, T. C. Sangster, W. Seka, D. Shvarts, V. A. Smalyuk, A. A. Solodov, B. Yaakobi, C. D. Zhou, J. A. Frenje, C. K. Li, F. H. Séguin, R. D. Petrasso, and L. J. Perkins, “Initial Experiments on the Shock-Ignition Inertial Confinement Fusion Concept,” Phys. Plasmas **15**, 056306 (2008).

5. W. R. Meier and C. W. Von Rosenberg, Jr., "Economic Modeling and Parametric Studies for SOMBRERO—A Laser-Driven IFE Power Plant," Fusion Technol. **21**, 1552-1556 (1992).

SECTION 7.1.4

1. S. S. Yu, W. R. Meier, R. P. Abbott, J. J. Barnard, T. Brown, D. A. Callahan, C. Debonnel, P. Heitzenroeder, J. F. Latkowski, B. G. Logan, S.J. Pemberton, P. F. Peterson, D. V. Rose, G-L. Sabbi, W. M. Sharp, and D. R. Welch, "An Updated Point Design for Heavy Ion Fusion," Fusion Sci. Technol. **44**, 266-273 (2003).
2. B. G. Logan, L. J. Perkins, and J. J. Barnard, "Direct Drive Heavy-Ion-Beam Inertial Fusion at High Coupling Efficiency," Phys. Plasmas **15**, 072701 (2008).
3. P. K. Roy, S. S. Yu, E. Henestroza, A. Anders, F. M. Bieniosek, J. Coleman, S. Eylon, W. G. Greenway, M. Leitner, B. G. Logan, W. L. Waldron, D. R. Welch, C. Thoma, A. B. Sefkow, E. P. Gilson, P. C. Efthimion, and R. C. Davidson, "Drift Compression of an Intense Neutralized Ion Beam," Phys. Rev. Lett. **95**, 234801 (2005).
4. J. E. Coleman, D. Ogata, P. A. Seidl, P. K. Roy, E. P. Gilson, A. B. Sefkow, and D. R. Welch, "Bunching and Focusing of an Intense Ion Beam for Target Heating Experiments," in *Proceedings of the Particle Accelerator Conference 07* (IEEE, New York, 2007), pp. 3516-3518.
5. Seven reviews: The 1979 Foster Committee. The Jason Report of January 1983 (JSR82-302). The National Academies of Sciences Report of March 1986 "Review of the Department of Energy's Inertial Confinement Fusion Program." The 1990 Report of the Fusion Policy Advisory Committee (Stever Panel). The 1993 Fusion Energy Advisory Committee (Davidson Panel). The 1996 FESAC (Sheffield) Report. The 1999 Secretary Energy Advisory Board Review (Richard Meserve Panel).
6. M. Tabak, "What is the Role of Tritium-Poor Fuels in ICF?," Nucl. Fusion **36**, 147-157 (1996).
7. I. D. Kaganovich, E. A. Startsev, A. B. Sefkow, and R. C. Davidson, "Charge and Current Neutralization of an Ion-Beam Pulse Propagating in a Background Plasma Along a Solenoidal Magnetic Field," Phys. Rev. Lett. **99**, 235002 (2007).
8. R. C. Davidson, I. Kaganovich, H. Qin, E. A. Startsev, D. R. Welch, D. V. Rose and S. M. Lund, "Survey of Collective Instabilities and Beam-Plasma Interaction in Intense Heavy Ion Beams," submitted for publication, (2008).
9. I. D. Kaganovich, E. Startsev, and R. C. Davidson, "Scaling and Formulary of Cross-Sections for Ion–Atom Impact Ionization," New J. Phys. **8**, 278 (2006).

SECTION 7.1.5

1. M. K. Matzen, M. A. Sweeney, R. G. Adams, J. R. Asay, J. E. Bailey, G. R. Bennett, D. E. Bliss, D. D. Bloomquist, T. A. Brunner, R. B. Campbell, G. A. Chandler, C. A. Coverdale, M. E. Cuneo, J.-P. Davis, C. Deeney, M. P. Desjarlais, G. L. Donovan, C. J. Garasi, T. A. Haill, C. A. Hall, D. L. Hanson, M. J. Hurst, B. Jones, M. D. Knudson, R. J. Leeper, R. W. Lemke, M. G. Mazarakis, D. H. McDaniel, T. A. Mehlhorn, T. J. Nash, C. L. Olson, J. L. Porter, P. K. Rambo, S. E. Rosenthal, G. A. Rochau, L. E. Ruggles, C. L. Ruiz, T. W. L. Sanford, J. F. Seamen, D. B. Sinars, S. A. Slutz, I. C. Smith, K. W. Struve, W. A. Stygar, R. A. Vesey, E. A. Weinbrecht, D. F. Wegner, and E. P. Yu, "Pulsed-Power-Driven High Energy Density Physics and Inertial Confinement Fusion Research," Phys. Plasmas **12**, 055503 (2005).

2. M. K. Matzen, “Overview of Fusion Research at SNL,” presented at the Fusion Power Associates Annual Meeting and Symposium, Livermore, CA, 3–4 December 2008.
3. D. D. Ryutov, M. S. Derzon, and M. K. Matzen, “The Physics of Fast *Z* Pinches,” Rev. Mod. Phys. **72**, 167-223 (2000).
4. M. G. Mazarakis, W. E. Fowler, D. H. McDaniel, C. L. Olson, S. T. Rogowski, R. A. Sharpe, K. W. Struve, and A. Kim, “High Current Fast 100-ns LTD Driver Development in Sandia Laboratory,” presented at the 15th IEEE International Pulsed Power Conference, Monterey, CA, 13–17 June 2005 (Session W-O-am-A: Accelerators III).
5. S. A. Slutz, C. L. Olson, and Per Peterson, “Low Mass Recyclable Transmission Lines for Z-Pinch Driven Inertial Fusion,” Phys. Plasmas **10**, 429-437 (2003).
6. J. W. Schumer, P. F. Ottinger, and C. L. Olson, “Power Design Constraints for a Recyclable Transmission Line for *Z*-Pinch IFE,” Fusion Sci. Technol. **52**, 901-905 (2007).
7. T. J. Nash, C. Deeney, G. A. Chandler, D. B. Sinars, M. E. Cuneo, E. M. Waisman, W. A. Stygar, D. Wenger, S. Speas, R. J. Leeper, J. F. Seaman, J. McGurn, J. Torres, D. Jobe, T. Gilliland, D. Nielsen, R. Hawn, H. Seaman, K. Keller, T. Moore, T. C. Wagoner, P. D. Lepell, J. Lucas, D. Schroen, C. Russell, and M. Kernaghan, “Comparison of a Copper Foil to a Copper Wire-Array *Z* Pinch at 18 MA,” Phys. Plasmas **11**, L65-L68 (2004).
8. C. A. Coverdale, C. Deeney, A. L. Velikovich, R. W. Clark, Y. K. Chong, J. Davis, J. Chittenden, C. L. Ruiz, G. W. Cooper, A. J. Nelson, J. Franklin, P. D. LePell, J. P. Apruzese, J. Levine, J. Banister, and N. Qi, “Neutron Production and Implosion Characteristics of a Deuterium Gas-Puff Z Pinch,” Phys. Plasmas **14**, 022706 (2007).

SECTION 7.1.6

1. For a survey of early work see F. L. Ribe and A. R. Sherwood, “Fast-Linear-Compression Fusion Systems,” in *Fusion*, edited by E. Teller (Academic Press, New York, 1981), Vol. 1, pp. 59-78.
2. I. R. Lindemuth and R. C. Kirkpatrick, “Parameter Space for magnetized Fuel Targets in Inertial Confinement Fusion,” Nucl. Fusion **23**, 263-284 (1983).
3. F. Winterberg, “The Magnetic Booster Target Inertial Confinement Fusion Driver,” Z. Naturforschg. **39A**, 325-341 (1984).
4. R. P. Drake, J. H. Hammer, C. W. Hartman, L. J. Perkins, and D. D. Ryutov, “Submegajoule Liner Implosion of a Closed Field Line Configuration,” Fusion Technol. **30**, 310-325 (1996).
5. S. F. Garanin, V. I. Mamyshev, and V. B. Yakubov, Proceedings of the 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, p. 37 (2006).
6. R. E. Siemon, I. R. Lindemuth, and K. F. Schoenberg, “Why Magnetized Target Fusion Offers a Low-Cost Development Path for Fusion Energy,” Comments Plasma Phys. Control. Fusion **18**, 363-386 (1999).
7. R. W. Moses, R. A. Krakowski, and R. L. Miller, “A Conceptual Design of the Fast-Liner Reactor (FLR) for Fusion Power,” Los Alamos National Laboratory, Los Alamos, NM, Report LA-7686-MS (1979).
8. M. G. Mazarakis, W. E. Fowler, D. H. McDaniel, C. L. Olson, S. T. Rogowski, R. A. Sharpe, K. W. Struve, and A. Kim, “High Current Fast 100-ns LTD Driver Development in Sandia Laboratory,” presented at the 15th IEEE International Pulsed

Power Conference, Monterey, CA, 13–17 June 2005 (Session W-O-am-A: Accelerators III); J. W. Schumer, P. F. Ottinger, and C. L. Olson, "Power Design Constraints for a Recyclable Transmission Line for *Z*-Pinch IFE," Fusion Sci. Technol. **52**, 901-905 (2007).

9. D. D. Ryutov, D. C. Barnes, B. S. Bauer, J. H. Hammer, C. W. Hartman, R. C. Kirkpatrick, I. R. Lindemuth, V. Makhin, P. B. Parks, D. B. Reisman, P. T. Sheehey, and R. E. Siemon, "Particle and Heat Transport in a Dense Wall-Confined MTF Plasma (Theory and Simulations)," Nucl. Fusion **43**, 955-960 (2003).
10. J. G. Linhart and L. Bilbao, "Z Pinch Spark of an Axial Detonation in DT," Nucl. Fusion **40**, 941-954 (2000).
11. C. A. Coverdale, C. Deeney, A. L. Velikovich, R. W. Clark, Y. K. Chong, J. Davis, J. Chittenden, C. L. Ruiz, G. W. Cooper, A. J. Nelson, J. Franklin, P. D. LePell, J. P. Apruzese, J. Levine, J. Banister, and N. Qi, "Neutron Production and Implosion Characteristics of a Deuterium Gas-Puff Z Pinch," Phys. Plasmas **14**, 022706 (2007).
12. J. H. Degnan, *et al*., Proceedings of the 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, p. 93 (2006)
13. Y. C. F. Thio, "Supersonic Plasma Jet Driven MIF Fundamentals," presented at the LANL Plasma Jet Workshop, Los Alamos, NM, 24–25 January 2008; http://wsx.lanl.gov/Plasma-Jet-Workshop-08/workshop-talks.html (Session 1: MIF/HED and Plasma Jets).
14. G. A. Wurden, T. P. Intrator, P. E. Sieck, L. Dorf, S. C. Hsu, R. M. Renneke, W. J. Waganaar, Z. Wang, J. H. Degnan, E. L. Ruden, M. Domonkos, P. Adamson, C. Grabowski, D. G. Gale, M. Kostora, W. Sommars, M. H. Frese, S. D. Frese, J. F. Camacho, S. K. Coffey, N. F. Roderick, P. Parks, R. E. Siemon, T. Awe, and A. G. Lynn, "FRCHX Magnetized Target Fusion HEDLP Experiments," presented at the 22nd IAEA Fusion Energy Conference, Geneva, Switzerland, 13–18 October 2008 (Paper IC/P4-13).
15. O. V. Gotchev, R. Betti, P. Chang, J. P. Knauer, D. D. Meyerhofer, J. A. Frenje, C. K. Li, M. Manuel, R. D. Petrasso, and F. H. Séguin, "Magnetized Hot-Spot Implosions Via Laser-Driven Flux Compression," Bull. Am. Phys. Soc. **53**, 247-248 (2008).

SECTION 8.1

1. S. J. Rose, "High-Power Laser-Produced Plasmas and Astrophysics," Laser Part. Beams **9**, 869-879 (1991).
2. R. P. Drake, "Laboratory Experiments to Simulate the Hydrodynamics of Supernova Remnants and Supernovae," J. Geophys. Res. **104**, 14,505-14,515 (1999).
3. B. A. Remington, D. Arnett, R. P. Drake, and H. Takabe, "Experimental Astrophysics—Modeling Astrophysical Phenomena in the Laboratory with Intense Lasers," Science **284**, 1488-1493 (1999).
4. D. Ryutov, R. P. Drake, J. Kane, E. Liang, B. A. Remington, and W. M. Wood-Vasey, "Similarity Criteria for the Laboratory Simulation of Supernova Hydrodynamics," Astrophys. J. **518**, 821-832 (1999).
5. H. Takabe, "Astrophysics with Intense and Ultra-Intense Lasers 'Laser Astrophysics'," Prog. Theor. Phys. Suppl. **143**, 202-265 (2001).
6. B. A. Remington, R. P. Drake, and D. D. Ryutov, "Experimental Astrophysics with High Power Lasers and *Z* Pinches," Rev. Mod. Phys. **78**, 755-807 (2006).

7. R. I. Klein, K. S. Budil, T. S. Perry, and D. R. Bach, "The Interaction of Supernova Remnants with Interstellar Clouds: Experiments on the Nova Laser," Astrophys. J. **583**, 245-259 (2003).
8. U. Hwang, K. A. Flanagan, and R. Petre, "*Chandra* X-Ray Observation of a Mature Cloud-Shock Interaction in the Bright Eastern Knot Region of Puppis A," Astrophys. J. **635**, 355-364 (2005).
9. C. C. Kuranz, R. P. Drake, E. C. Harding, M. J. Grosskopf, H. F. Robey, B. A. Remington, M. J. Edwards, A. R. Miles, T. S. Perry, T. Plewa, N. C. Hearn, J. P. Knauer, D. Arnett, and D. R. Leibrandt, "2D Rayleigh–Taylor Instability: Experiment and Simulation," Astrophysical Journal, in press (2009).
10. A. B. Reighard, R. P. Drake, K. K. Dannenberg, D. J. Kremer, M. Grosskopf, E. C. Harding, D. R. Leibrandt, S. G. Glendinning, T. S. Perry, B. A. Remington, J. Greenough, J. Knauer, T. Boehly, S. Bouquet, L. Boireau, M. Koenig, and T. Vinci, "Observation of Collapsing Radiative Shocks in Laboratory Experiments," Phys. Plasmas **13**, 082901 (2006).
11. A. S. Moore, E. T. Gumbrell, J. Lazarus, M. Hohenberger, J. S. Robinson, R. A. Smith, T. J. A. Plant, D. R. Symes, and M. Dunne, "Full-Trajectory Diagnosis of Laser-Driven Radiative Blast Waves in Search of Thermal Plasma Instabilities," Phys. Rev. Lett. **100**, 055001 (2008).
12. J. M. Foster, B. H. Wilde, P. A. Rosen, R. J. R. Williams, B. E. Blue, R. F. Coker, R. P. Drake, A. Frank, P. A. Keiter, A. M. Khokhlov, J. P. Knauer, and T. S. Perry, "High-Energy-Density Laboratory Astrophysics Studies of Jets and Bow Shocks," Astrophys. J. Lett. **634**, L77-L80 (2005).
13. D. R. Farley, K. G. Estabrook, S. G. Glendinning, S. H. Glenzer, B. A. Remington, K. Shigemori, J. M. Stone, R. J. Wallace, G. B. Zimmerman, and J. A. Harte, "Radiative Jet Experiments of Astrophysical Interest Using Intense Lasers," Phys. Rev. Lett. **83**, 1982-1985 (1999).
14. S. V. Lebedev, A. Ciardi, D. J. Ampleford, S. N. Bland, S. C. Bott, J. P. Chittenden, G. N. Hall, J. Rapley, C. A. Jennings, A. Frank, E. G. Blackman, and T. Lery, "Magnetic Tower Outflows from a Radial Wire Array *Z*-Pinch," Mon. Not. R. Astron. Soc. **361**, 97-108 (2005).
15. J. E. Bailey, G. A. Rochau, C. A. Iglesias, J. Abdallah, Jr., J. J. MacFarlane, I. Golovkin, P. Wang, R. C. Mancini, P. W. Lake, T. C. Moore, M. Bump, O. Garcia, and S. Mazevet, "Iron-Plasma Transmission Measurements at Temperatures Above 150 eV," Phys. Rev. Lett. **99**, 265002 (2007).
16. Hui Chen, Scott Wilks, James Bonlie, Edison Liang, David Meyerhofer, Jason Myatt, Dwight Price, Peter Beiersdorfer, "Relativistic Positron Creation Using Ultra-Intense Short Pulse Lasers," Phys. Rev. Lett., in press (2009).

SECTION 8.2

1. G. H. A. Cole, "The Physics of Planetary Interiors," Rep. Prog. Phys. **58**, 755-820 (1995).
2. R. P. Butler, J. T. Wright, G. W. Marcy, D. A. Fischer, S. S. Vogt, C. G. Tinney, H. R. A. Jones, B. D. Carter, J. A. Johnson, C. McCarthy, and A. J. Penny, "Catalog of Nearby Exoplanets," Astrophys. J. Lett. **646**, 505-522 (2006).
3. T. Guillot, "Interiors of Giant Planets Inside and Outside the Solar System," Science **286**, 72-77 (1999).
4. S. T. Weir, A. C. Mitchell, and W. J. Nellis, "Metallization of Fluid Molecular Hydrogen at 140 GPz (1.4 Mbar)," Phys. Rev. Lett. **76**, 1860-1863 (1996).

5. S. Ichimaru and H. Kitamura, “Pycnonuclear Reactions in Dense Astrophysical and Fusion Plasmas,” Phys. Plasmas **6**, 2649-2671 (1999).

SECTION 8.3

1. R. N. Boyd, *An Introduction to Nuclear Astrophysics* (University of Chicago Press, Chicago, 2008).
2. G. Gosselin and P. Morel, “Enhanced Nuclear Level Decay in Hot Dense Plasmas,” Phys. Rev. C **70**, 064603 (2004).
3. M. R. Harston and J. F. Chemin, “Mechanisms of Nuclear Excitation in Plasmas,” Phys. Rev. C **59**, 2462-2473 (1999).
4. P. Morel, V. Méot, G. Gosselin, D. Gogny, and W. Younes, “Evaluation of Nuclear Excitation by Electronic Transition in ^{235}U Plasma at Local Thermodynamic Equilibrium,” Phys. Rev. A **69**, 063414 (2004).
5. E. I. Moses *et al.*, “The National Ignition Facility: Ushering in a New Age for High Energy Density Science,” submitted to Physics of Plasmas (2008).
6. G. Imbriani, H. Costantini, A. Formicola, D. Bemmerer, R. Bonetti, C. Broggini, P. Corvisiero, J. Cruz, Z. Fülöp, G. Gervino, Z. Guglielmetti, C. Gustavino, G. Gyürky, A. P. Jesus, M. Junker, A. Lemut, R. Menegazzo, P. Prati, V. Roca, C. Rolfs, M. Romano, C. Rossi Alvarez, F. Schümann, E. Somorjai, O. Straniero, F. Strieder, F. Terrasi, H. P. Trautvetter, A. Vomiero, and S. Zavatarelli, “The Bottleneck of CNO Burning and the Age of Globular Clusters,” Astron. Astrophys. **420**, 625-629 (2004).
7. A. Lemut, D. Bemmerer, F. Confortola, R. Bonetti, C. Broggini, P. Corvisiero, H.. Constantini, J. Cruz, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino, Gy. Gyürky, G. Imbriani, A. P. Jesus, M. Junker, B. Limata, R. Menegazzo, P. Prati, V. Roca, D. Rogalla, C. Rolfs, M. Romano, C. Rossi Alvarez, F. Schümann, E. Somorjai, O. Straniero, F. Strieder, F. Terrasi, and H. P. Trautvetter, “First Measurement of the ^{14}N(p,γ)^{15}O Cross Section Down to 70 keV,” Phys. Lett. B **634**, 483-487 (2006).
8. L.A. Bernstein, Lawrence Livermore National Laboratory, private communication (2008).
9. M. Limongi and A. Chieffi, “The Nucleosynthesis of ^{26}Al and ^{60}Fe in Solar Metallicity Stars Extending in Mass from 11 to 120 $M_\odot$: The Hydrostatic and Explosive Contributions,” Astrophys. J. **647**, 483-500 (2006).

SECTION 8.4

1. T. Tajima and J. M. Dawson, “Laser Electron Accelerator,” Phys. Rev. Lett. **43**, 267-270 (1979).
2. E. Esarey, P. Sprangle, J. Krall, and A Ting, “Overview of Plasma-Based Accelerator Concepts,” IEEE Trans. Plasma Sci. **24**, 252-288 (1996).
3. C. Joshi, “Plasma Accelerators,” Sci. Am. **294**, 40-47 (2006).
4. N. Patel, “Accelerator Physics: The Plasma Revolution,” Nature **449**, 133-136 (2007).
5. J. B. Rosenzweig, B. Breizman, T. Katsouleas, and J. J. Su, “Acceleration and Focusing of Electrons in Two-Dimensional Nonlinear Plasma Wake Fields,” Phys. Rev. A **44**, R6189-R6192 (1991).
6. A. Pukhov and J. Meyer-ter-Vehn, “Laser Wake Field Acceleration: The Highly Non-Linear Broken-Wave Regime,” Appl. Phys. B **74**, 355-361 (2002).

7. W. Lu, M. Tzoufras, C. Joshi, F. S. Tsung, W. B. Mori, J. Vieira, R. A. Fonseca, and L. O. Silva, "Generating Multi-GeV Electron Bunches Using Single Stage Laser Wakefield Acceleration in a 3D Nonlinear Regime," Phys. Rev. Spec. Top., Accel. Beams **10**, 061301 (2007).
8. W. P. Leemans, B. Nagler, A. J. Gonsalves, Cs. Toth, K. Nakamura, C. G. R. Geddes, E. Esarey, C. B. Schroeder, and S. M. Hooker, "GeV Electron Beams from a Centimeter-Scale Accelerator," Nat. Phys. **2**, 696-699 (2006).
9. I. Blumenfeld, C. E. Clayton, F.-J. Decker, J. M. Hogan, C. C. Huang, R. Ischebeck, R. Iverson, C. Joshi, T. Katsouleas, N. Kirby, W. Lu, K. A. Marsh, W. B. Mori, P. Muggli, E. Oz, R. H. Siemann, D. Walz, and M. Zhou, "Energy Doubling of 42 GeV Electrons in a Meter-Scale Plasma Wakefield Accelerator," Nature **445**, 741-744 (2007).

SECTION 8.6

1. S. Fritzler, V. Malka, G. Grillon, and J. P. Rousseau, "Proton Beams Generated with High-Intensity Lasers: Applications to Medical Isotope Production," Appl. Phys. Lett. **83**, 3039-3041 (2003).
2. C.-M. C. Ma and R. L. Maughan, "Within the Next Decade Conventional Cyclotrons for Proton Radiotherapy will Become Obsolete and Replaced by Far Less Expensive Machines Using Compact Laser Systems for the Acceleration of the Protons," Med. Phys. **33**, 571-573 (2006).
3. V. Malka, S. Fritzler, E. Lefebvre, E. D'Humières, R. Ferrand, G. Grillon, C. Albaret, S. Meyroeinc, J.-P. Chambaret, A. Antonetti, and D. Hulin, "Practicability of Protontherapy Using Compact Laser Systems," Med. Phys. **31**, 1587-1592 (2004).
4. M. Schollmeier, S. Becker, M. Geißel, K. A. Flippo, A. Blažević, S. A. Gaillard, D. C. Gautier, F. Grüner, K. Harres, M. Kimmel, F. Nürnberg, P. Rambo, U. Schramm, J. Schreiber, J. Schütrumpf, J. Schwarz, N. A. Tahir, B. Atherton, D. Habs, B. M. Hegelich, and M. Roth, "Controlled Transport and Focusing of Laser-Accelerated Protons with miniature Magnetic Devices," Phys. Rev. Lett. **101**, 055004 (2008).
5. Z. Chang, A. Rundquist, H. Wang, M. M. Murnane, and H. C. Kapteyn, "Generation of Coherent Soft X Rays at 2.7 nm Using High Harmonics," Phys. Rev. Lett. **79**, 2967-2970 (1997).
6. B. Dromey, M. Zepf, A. Gopal, K. Lancaster, M. S. Wei, K. Krushelnick, M. Tatarakis, N. Vakakis, S. Moustaizis, R. Kodama, M. Tampo, C. Stoeckl, R. Clarke, H. Habara, D. Neely, S. Karsch, and P. Norreys, "High Harmonic Generation in the Relativistic Limit," Nat. Phys. **2**, 456-459 (2006).

SECTION 8.7

1. National Research Council, Committee on AMO 2010, *Controlling the Quantum World: The Science of Atoms, Molecules, and Photons* (National Academy of Sciences, Washington, DC, 2006).
2. DOE/BES *LCLS: The First Experiments* (2000) and National Research Council (U.S.) Committee on High Energy Density Plasma Physics, *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science* (National Academies Press, Washington, DC, 2003).
3. H. C. Kapteyn, M. M. Murnane, and I. P. Christov, "Extreme Nonlinear Optics: Coherent X Rays from Lasers," Phys. Today **58**, 39-44 (2005).
4. H. Kapteyn, O. Cohen, I. Christov, and M. Murnane, "Harnessing Attosecond Science in the Quest for Coherent X-Rays," Science **317**, 775-778 (2007).

5. A. S. Sandhu, E. Gagnon, R. Santra, V. Sharma, W. Li, P. Ho, P. Ranitovic, C. L. Cocke, M. M. Murnane, H. C. Kapteyn, "Observing the birth of electronic Feshbac resonances in soft x-ray induced O_2 dissociation," Science **322**, 1081 (2008).

SECTION 11

1. C. D. Zhou and R. Betti, "A Measurable Lawson Criterion and Hydro-Equivalent Curves for Inertial Confinement Fusion," Phys. Plasmas **15**, 102707 (2008).
2. T. C. Sangster, V. N. Goncharov, P. B. Radha, V. A. Smalyuk, R. Betti, R. S. Craxton, J. A. Delettrez, D. H. Edgell, V. Yu. Glebov, D. R. Harding, D. Jacobs-Perkins, J. P. Knauer, F. J. Marshall, R. L. McCrory, P. W. McKenty, D. D. Meyerhofer, S. P. Regan, W. Seka, R. W. Short, S. Skupsky, J. M. Soures, C. Stoeckl, B. Yaakobi, D. Shvarts, J. A. Frenje, C. K. Li, R. D. Petrasso, and F. H. Séguin, "High-Areal-Density Fuel Assembly in Direct-Drive Cryogenic Implosions," Phys. Rev. Lett. **100**, 185006 (2008).
3. R. L. McCrory, D. D. Meyerhofer, R. Betti, R. S. Craxton, J. A. Delettrez, D. H. Edgell, V. Yu Glebov, V. N. Goncharov, D. R. Harding, D. W. Jacobs-Perkins, J. P. Knauer, F. J. Marshall, P. W. McKenty, P. B. Radha, S. P. Regan, T. C. Sangster, W. Seka, R. W. Short, S. Skupsky, V. A. Smalyuk, J. M. Soures, C. Stoeckl, B. Yaakobi, D. Shvarts, J. A. Frenje, C. K. Li, R. D. Petrasso, and F. H. Séguin, "Progress in Direct-Drive Inertial Confinement Fusion Research," Phys. Plasmas **15**, 055503 (2008).
4. P. W. McKenty, V. N. Goncharov, R. P. J. Town, S. Skupsky, R. Betti, and R. L. McCrory, "Analysis of a Direct-Drive Ignition Capsule Designed for the National Ignition Facility," Phys. Plasmas **8**, 2315-2322 (2001).
5. A. A. Solodov, K. S. Anderson, R. Betti, V. Gotcheva, J. Myatt, J. A. Delettrez, S. Skupsky, W. Theobald, and C. Stoeckl, "Simulations of Electron Transport and Ignition for Direct-Drive Fast-Ignition Targets," Phys. Plasmas **15**, 112702 (2008).
6. S. Atzeni, A. Schiavi, J. J. Honrubia, X. Ribeyre, G. Schurtz, Ph. Nicolaï, M. Olazabal-Loumé, C. Bellei, R. G. Evans, and " J. R. Davies, " Phys. Plasmas 15, 056311 (2008) (invited). "Fast Ignitor Target Studies for the HiPER Project," Phys. Plasmas **15**, 0563111 (2008).
7. J. J. Honrubia and J. Meyer-ter-Vehn, "Ignition of Pre-Compressed Fusion Targets by Fast Electrons," J. Phys., Conf. Ser. **112**, 022055 (2008).
8. S. Skupsky, J. A. Marozas, R. S. Craxton, R. Betti, T. J. B. Collins, J. A. Delettrez, V. N. Goncharov, P. W. McKenty, P. B. Radha, T. R. Boehly, J. P. Knauer, F. J. Marshall, D. R. Harding, J. D. Kilkenny, D. D. Meyerhofer, T. C. Sangster, and R. L. McCrory, "Polar Direct Drive on the National Ignition Facility," Phys. Plasmas **11**, 2763-2770 (2004).
9. J. A. Marozas, F. J. Marshall, R. S. Craxton, I. V. Igumenshchev, S. Skupsky, M. J. Bonino, T. J. B. Collins, R. Epstein, V. Yu. Glebov, D. Jacobs-Perkins, J. P. Knauer, R. L. McCrory, P. W. McKenty, D. D. Meyerhofer, S. G. Noyes, P. B. Radha, T. C. Sangster, W. Seka, and V. A. Smalyuk, "Polar-Direct-Drive Simulations and Experiments," Phys. Plasmas **13**, 056311 (2006).
10. S. Skupsky, R. W. Short, T. Kessler, R. S. Craxton, S. Letzring, and J. M. Soures, "Improved Laser-Beam Uniformity Using the Angular Dispersion of Frequency-Modulated Light," J. Appl. Phys. **66**, 3456-3462 (1989).
11. C. Olson, "Inertial Fusion Concepts: Summary," Snowmass Fusion Summer Study, 23 July 1999; http://www.ap.columbia.edu/fusion/snowmass/inertial_summary.pdf.

12. “A Plan for the Development of Fusion Energy,” Final Report of the Fusion Energy Sciences Advisory Committee, Fusion Development Path Panel, DOE/SC-0074 (U.S. Department of Energy Office of Science, March 2003).
13. S. P. Obenschain, D. G. Colombant, A. J. Schmitt, J. D. Sethian, and M. W. McGeoch, “Pathway to a Lower Cost High Repetition Rate Ignition Facility,” Phys. Plasmas **13**, 056320 (2006).
14. Y. Kozaki, “Way to ICF Reactor,” Fusion Eng. Des. **51-52**, 1087-1093 (2000).
15. C. D. Orth, S. A. Payne, and W. F. Krupke, “A Diode Pumped Solid State Laser Driver for Inertial Fusion Energy,” Nucl. Fusion **36**, 75-116 (1996).

APPENDIX A

CHARGE LETTER TO FESAC

Department of Energy
Washington, DC 20585
March 6, 2008

Professor Stewart C. Prager
Chair, Fusion Energy Sciences Advisory Committee
Department of Physics
University of Wisconsin
1150 University Avenue
Madison, Wisconsin 53706

Dear Professor Prager:

Steady increases in the energy, power, and brightness of lasers and particle beams and advances in pulsed power systems have made possible the exploration of matter at extremely high energy density in the laboratory. In particular, new experimental regimes could be realized by exploiting fully the scientific capabilities of existing and planned Department of Energy (DOE) facilities, as well as the relevant Department of Defense (DOD) and university facilities. Progress in the exploration of extreme states of matter has also been facilitated by advances in computer simulation and diagnostic techniques. Japan, China, Russia and the European Union also have growing programs in high energy density sciences.

A recent interagency task force report found that stewardship of high energy density laboratory plasmas (HEDLP) should be improved, and recommended that the DOE National Nuclear Security Administration (NNSA) and the DOE Office of Science (SC) establish a joint program in HEDLP. NNSA and SC have now established a joint program in HEDLP. Initially, this program is a combination of work that was funded as part of the NNSA's Stewardship Sciences Academic Alliances Program and Inertial Confinement Fusion Program and the SC's HEDLP Program and Innovative Confinement Concepts Program. Depending on availability of funds, the joint program budget is expected to be in the $30-50 million range over the next several years.

To assist in planning this program, we request that the Fusion Energy Sciences Advisory Committee (FESAC) work with the HEDLP community to provide information that will inform a scientific roadmap for the joint HEDLP program in the next decade or so. This study should be done in the context of both OFES and NNSA programmatic interests and the need to steward the field of HEDLP. Specifically, FESAC should: 1) identify the compelling scientific opportunities for research in fundamental HEDLP that could be investigated using existing and planned facilities in support of the OFES and NNSA/DP missions; and 2) identify the scientific issues of implosion and target design that need to be addressed to make the case for inertial fusion energy as a potential future energy source. The recent National Academies of Science reports [1-2], the two community Workshop reports [3-4], and the Report of the Interagency Task Force on HEDP [5], provide seminal information for addressing this charge.

The first element of this charge is focused on stewardship of HEDLP by the Joint Program. It should provide a description of, and rationale for, scientific interest in investigating this unique physical regime. A prioritized list of issues and opportunities that could be pursued over the next decade or so in this program is desired.

The second element is meant to provide background for a scientific plan for energy-related HEDLP studies. Specifically, FESAC should identify and examine the underlying science questions that need to be addressed to obtain the product of fusion gain and driver efficiency, together with suitable or attractive targets, to support the case for energy applications of inertial fusion energy sciences (IFES). These questions should help develop the knowledge base for inertial fusion energy with a goal of motivating future initiatives in IFES (e.g., an Integrated Research Experiment as discussed in past FESAC Reports). It should identify and prioritize the gaps in knowledge and opportunities for research in energy-related HEDLP research. It should consider sequential phases of activity focusing on: 1) exploiting available capabilities to address HEDLP science in anticipation of future studies on NIF; 2) exploiting the expected new capability of ignition on NIF, and associated approaches, to address scientific challenges of ignition science with increasing relevance to IFES; and 3) resolving scientific issues to establish the basis for justifying a transition from a laboratory ignition feasibility experiment to a program focused on fusion energy science development.

In summary, FESAC should identify the scientific opportunities for a proposed HEDLP program that is exciting, challenging, and puts the United States in the position of a world leader in this field of research. FESAC should complete its work on this charge by October 2008.

Sincerely,

Raymond L. Orbach

Raymond L. Orbach
Under Secretary for Science

Thomas P. D'Agostino
Under Secretary for Nuclear Security

APPENDIX B

HEDLP FESAC PANEL

FARHAT BEG
UNIVERSITY OF CALIFORNIA SAN DIEGO

RICCARDO BETTI (CHAIR)
UNIVERSITY OF ROCHESTER

RONALD DAVIDSON
PRINCETON UNIVERSITY

PAUL DRAKE
UNIVERSITY OF MICHIGAN

ROGER FALCONE
UNIVERSITY OF CALIFORNIA BERKELEY

DAVID HAMMER
CORNELL UNIVERSITY

MARCUS KNUDSON
SANDIA NATIONAL LABORATORIES

GRANT LOGAN
LAWRENCE BERKELEY NATIONAL LABORATORY

DAVID MEYERHOFER
UNIVERSITY OF ROCHESTER

DAVID S. MONTGOMERY
LOS ALAMOS NATIONAL LABORATORY

WARREN MORI
UNIVERSITY OF CALIFORNIA LOS ANGELES

MARGARET MURNANE
UNIVERSITY OF COLORADO

RICHARD PETRASSO
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

BRUCE REMINGTON
LAWRENCE LIVERMORE NATIONAL LABORATORY

DMITRI RYUTOV
LAWRENCE LIVERMORE NATIONAL LABORATORY

JOHN SETHIAN
NAVAL RESEARCH LABORATORY

RICHARD SIEMON
UNIVERSITY OF NEVADA AT RENO

APPENDIX C

WORKSHOP ON SCIENTIFIC OPPORTUNITIES

IN HIGH ENERGY DENSITY LABORATORY PLASMA PHYSICS

August 25-27, 2008

Washington DC

Presentations available at http://fsc.lle.rochester.edu/hedlp/panelmeetings.php

Opening Presentations

- Office of Fusion Energy Sciences (OFES) Perspective
  G. Nardella (Office of Fusion Energy Sciences)

- NNSA Perspective on Scientific Opportunities in High Energy Density Laboratory Plasma Physics
  M. Donovan (National Nuclear Security Administration)

Invited Presentations on Fundamental HEDLP Science

- High Intensity Laser and Energetic Particle–Matter Interaction
  C. Ren (University of Rochester)

- Nonlinear Hydrodynamics, Instabilities and Turbulent Mix
  G. Dimonte (Los Alamos National Laboratory)

- Nonlinear optics of HED Plasmas and Laser–Plasma instabilities
  B. Afeyan (Polymath Research)

- HEDLP Applications to Astrophysics: The Next Decade
  D. Arnett (University of Arizona)

- Radiation and Magneto-Hydrodynamics of HED Plasmas
  M. Herrmann (Sandia National Laboratory)

- A New Generation of Material Science
  R. Collins (Lawrence Livermore National Laboratory)

Invited Presentations on HEDLP Science for Inertial Fusion Energy

- Advanced Target Design for ICF/IFE and the Physics of High Gain
  J. Perkins (Lawrence Livermore National Laboratory)

- Laser Inertial Fusion Energy
  A. Schmitt (Naval Research Laboratory),

- Ion Beam Driven Heavy Ion Fusion Science
  J. Barnard (Lawrence Livermore National Laboratory)

- Magneto-Inertial Fusion and Magnetized HED Physics
  B. Bauer (University of Nevada at Reno)

- Review of Fast Ignition
  M. Key (Lawrence Livermore National Laboratory)

- Z-Pinch Inertial Fusion Energy
  K. Matzen (Sandia National Laboratory)

Contributed Presentations

- Laboratory Astrophysics at Z: Stellar Interior Opacities
  J. Bailey (Sandia National Laboratories)

- Indirect Drive Fast Ignition Target Designs for the National Ignition Facility
  D. Clark (Lawrence Livermore National Laboratory)

- Laser Acceleration of MeV-GeVIon Beams: the Next Generation of High-Current Accelerators
  J. C. Fernández (Los Alamos National Laboratory)

- Proton Generation and Focusing for FI Applications
  M.E. Foord (Lawrence Livermore National Laboratory)

- The Collective Effects of Intense Ion and Electron Beams Propagating Through Background Plasma
  I.D. Kaganovich (Princeton Plasma Physics Laboratory)

- HED Physics of Advanced Z-pinch Loads Including Multi-Planar and Compact Cylindrical Wire Arrays on University-scale Generators
  V. L. Kantsyrev (University of Nevada at Reno)

- Ultrafast High Energy Density Plasma Science using High Harmonics
  H. Kapteyn and M. Murnane (University of Colorado)

- Intense Terahertz Generation and Spectroscopy of Warm Dense Plasmas
  K. Kim (University of Maryland at College Park)

- The Nevada TeraWatt Facility
  J. M. Kindel (University of Nevada at Reno)

- Magnetized, Hot-Spot Implosions on OMEGA
  J. P. Knauer (University of Rochester Laboratory for Laser Energetics)

- High Energy Density Science and Free-electron Lasers
  R. W. Lee (Lawrence Livermore National Laboratory)

- Proton Radiography of Electromagnetic Fields in Laser-Produced High Energy Density Plasmas
  C. K. Li (MIT)

- Experiments and Modeling of Photoionized Plasmas at Z
  R.C. Mancini (University of Nevada at Reno)

- Advanced Transport Studies for HED Science
  A.J. Mackinnon (Lawrence Livermore National Laboratory)

- Energy Coupling in Non-Equilibrium ICF Plasmas with OMEGA and NIF,
  A. R. Miles (Lawrence Livermore National Laboratory)

- Pair-Plasma Creation on kJ-class High-Intensity Lasers
  J. Myatt (University of Rochester Laboratory for Laser Energetics)

- A Laser Based Fusion Test Facility (FTF)
  S.P. Obenschain, (U.S. Naval Research Laboratory)

- Creating Warm and Hot Dense Matter
  S. P. Regan (University of Rochester Laboratory for Laser Energetics)

- Soft X-Ray Laser Interferometry of Dense Plasmas
  J.J. Rocca (Colorado State University)

- HEDP Produced on the University-scale Z-pinch generator: from X-pinches to Planar Wire Arrays
  A. S. Safronova, (University of Nevada at Reno)

- Connecting Simulations and Experiments in HEDP
  R. Stephens (General Atomics Corporation)

- Fast Ignition on OMEGA/OMEGA EP
  W. Theobald (University of Rochester Laboratory for Laser Energetics)

- Driving Gigabar Shocks With High-Power Lasers and Their Applications to Shock Ignition
  W. Theobald (University of Rochester Laboratory for Laser Energetics)

- Trapping and Destruction of Long Range High Intensity Optical/Plasma Filaments by Molecular Quantum Wakes
  S. Varma (University of Maryland at College Park)

- Recent Numerical Advances for Beam-Driven HEDP Experiments
  S.A. Veitzer (Tech-X Corp.)

- Strategy and Issues for Solid Liner MIF Energy
  G. A. Wurden (Los Alamos National Laboratory)

- Direct Laser Acceleration of Electrons in the Corrugated Plasma Waveguide
  A. York (University of Maryland at College Park)

APPENDIX D

SUBCOMMITTEE ON PLANNING

FOR ENERGY-RELATED HEDLP STUDIES

(PART 2 OF THE CHARGE)

RICCARDO BETTI (CHAIR)
UNIVERSITY OF ROCHESTER

DAVID HAMMER
CORNELL UNIVERSITY

GRANT LOGAN
LAWRENCE BERKELEY NATIONAL LABORATORY

DAVID MEYERHOFER
UNIVERSITY OF ROCHESTER

JOHN SETHIAN
NAVAL RESEARCH LABORATORY

RICHARD SIEMON
UNIVERSITY OF NEVADA AT RENO

APPENDIX E

ACRONYMS

1-D	One-dimensional
AFRL	Air Force Research Laboratory
AGB	Asymptotic giant branch
CPA	Chirped-pulse amplification
D	Deuterium
eV	Electronvolt
FESAC	Fusion Energy Science Advisory Committee
FI	Fast ignition
GA	Giga-Ampere
HAPL	High Average Power Laser
HEA	High energy astrophysics
HED	High energy density
HEDLP	High energy density laboratory plasmas
IC	Internal conversion
ICC	Innovative confinement concepts
ICF	Inertial confinement fusion
IFE	Inertial fusion energy
IFES	Inertial fusion energy sciences
ITER	International Thermonuclear Reactor
KEEN	Kinetic Electrostatic Electron Nonlinear
keV	Kiloelectronvolt
KrF	Krypton fluoride
LHC	Large Hadron Collider
LLNL	Lawrence Livermore National Laboratory
LTD	Linear transformer driver
LUNA	Laboratory for Underground Nuclear Astrophysics
LWFA	Laser wakefield acceleration
MFE	Magnetic fusion energy
MeV	Megaelectronvolt
MG	Megagauss
MIF	Magneto-Inertial Fusion
MTF	Magnetized Target Fusion

NEEC	Nuclear excitation by electron capture
NEET	Nuclear excitation by electron transition
NIC	National Ignition Campaign
NIF	National Ignition Facility
nm	nanometer
NNSA	National Nuclear Security Administration
NRL	Naval Research Laboratory
ns	Nanosecond
OFES	Office of Fusion Energy Sciences
PET	Positron emission tomography
PIC	Particle-In-Cell
ps	Picosecond
PWFA	Plasma wakefield acceleration
T	Tritium
UV	Ultraviolet
WDM	Warm dense matter