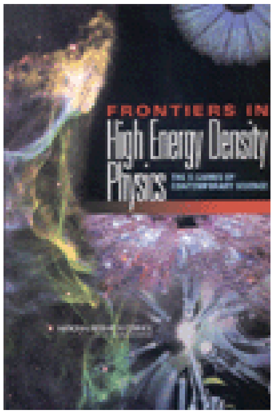

Frontiers in High Energy Density Physics: The X-Games of Contemporary Science

Committee on High Energy Density Plasma Physics, Plasma Science Committee, National Research Council

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FRONTIERS IN High Energy Density Physics

THE X-GAMES OF CONTEMPORARY SCIENCE

Committee on High Energy Density Plasma Physics
Plasma Science Committee
Board on Physics and Astronomy
Division on Engineering and Physical Sciences

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Back Cover: The target chamber at the National Ignition Facility, courtesy of Lawrence Livermore National Laboratory; and three-dimensional PIC simulation of a plasma wakefield accelerator, courtesy of R. Fonseca, Instituto Superior Técnico of Portugal, and the E-162 collaboration.

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Preface

The Committee on High Energy Density Plasma Physics was established in April 2001 by the National Research Council's (NRC's) Board on Physics and Astronomy to identify scientific opportunities and develop a unifying theme for research on matter under extreme high energy density conditions. Specifically, the committee was charged with the following tasks: (a) to review recent advances in the field of high energy density plasma phenomena, on both the laboratory scale and the astrophysical scale; (b) to provide a scientific assessment of the field, identifying compelling research opportunities and intellectual challenges; (c) to develop a unifying framework for diverse aspects of the field; (d) to outline a strategy for extending the forefronts of the field through scientific experiments at various facilities where high energy density plasmas can be created; and (e) to discuss the roles of national laboratories, universities, and industry in achieving these objectives.

While this is a challenging set of tasks, the committee recognizes that now is a highly opportune time for the nation's scientists to develop a fundamental understanding of the physics of high energy density plasmas. The space-based and ground-based instruments for measuring astrophysical processes under extreme conditions are unprecedented in their accuracy and detail. In addition, a new generation of sophisticated laboratory systems ("drivers"), now existing or planned, creates matter under extreme high energy density conditions (exceeding 10^{11} J/m^3), permitting the detailed exploration of physical phenomena under conditions not unlike those in astrophysical systems. High energy density experiments span a wide range of areas of physics including plasma physics, materials science and condensed matter physics, nuclear physics, atomic and molecular physics, fluid dynamics and magnetohydrodynamics, and astrophysics. While a number of scientific areas are represented in high energy density physics, many of the high energy density research techniques have grown out of ongoing research in plasma science, astrophysics, beam physics, accelerator physics, magnetic fusion, 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.

Several important findings became apparent during the committee's deliberations; they are detailed in the report. Two key findings are mentioned here. First, a consensus is emerging in the plasma physics and astrophysics communities that many opportunities exist for significant advances in understanding the physics of high energy density plasmas through an integrated approach to investigating the scientific issues in related subfields. Understanding the physics of high energy density plasmas will also lead to new applications and will benefit other areas of science. Furthermore, learning to control and manipulate high energy density plasmas in the laboratory will benefit national programs, such as inertial confinement fusion and the stockpile stewardship program, through the development of new ideas and the training of a new generation of scientists and engineers.

Second, the committee is convinced that research opportunities in this cross-cutting area of physics are of the highest intellectual caliber and are fully deserving of consideration of support by the leading funding agencies of the physical sciences. A broad federal support base for research in high energy density physics, including plasma science, and the encouragement of interagency research initiatives in this interdisciplinary field would greatly strengthen the ability of the nation's universities to have a significant impact on this exciting field of physics.

The committee was very proactive in collecting information for its deliberations, meeting frequently by conference call and through electronic communication and engaging the scientific community through several professional society mailings, expert briefings of the committee, and site visits, and through a "town meeting" held at the October 2001 annual meeting of the Division of Plasma Physics of the American Physical Society in Long Beach, California. The full committee met on three occasions after its formation in April 2001—on May 11–12, 2001, in Washington, D.C.; on November 2–4, 2001, in Irvine, California; and at a final meeting on March 15–16, 2002, in Washington, D.C.

During this assessment, the committee received the encouragement, support, and expert counsel of many individuals to whom it is indebted, including Christopher Keane of the National Nuclear Security Administration; Ronald McKnight of the Department of Energy's Office of Fusion Energy Sciences; Tom O'Neil and the NRC's Plasma Science Committee; and Michael Moloney, Achilles Speliotopoulos, and Donald Shapero of the National Research Council. The committee is also

grateful to the following physicists who made important scientific contributions to the preparation of this report: Jonathan Aarons, Bedros Afeyan, Yefim Aglitskiy, William Barletta, Christopher Barty, Gordon Baym, Richard Berger, Gennadii Bisnovatyi-Kogan, Roger Blandford, Deborah Callahan-Miller, Michael Campbell, Pisin Chen, Stirling Colgate, Christopher Deeney, Todd Ditmire, Jonathan Dorfan, Paul Drake, Jim Dunn, Fred Dylla, Juan Fernandez, Nathaniel Fisch, Alex Friedman, Siegfried Glenzer, Daniel Goodin, Michael Harrison, Stephen Hatchett, Alan Hauer, Mark Hogan, Zhirong Huang, Chan Joshi, Alexander Koldoba, Glenn Kubiak, Dong Lai, Otto Landen, Richard Lee, Wim Leemans, Hui Li, Edison Liang, Steve Libby, Grant Logan, Dennis Matthews, Keith Matzen, Robert McCrory, Dan Meiron, Paul Messina, Peter Meszaros, George Miller, Warren Mori, Gerard Mourou, Johnny Ng, Stephen Obenschain, Marina Romanova, Francesco Ruggiero, Jack Shlachter, Gennady Shvets, Richard Siemon, Richard Sluten, Paul Springer, Richard Stephens, David Stevenson, James Stone, Galia Ustyugova, Bruce Warner, Ira Wasserman, Bernard Wilde, Alan Wootton, Craig Wuest, and Sasha Zholents.

Additional thanks go to the following individuals, who made an important contribution through the provision of images for inclusion in this report: James Bailey, John Biretta, Kimberly Budil, Robert Cauble, Gilbert Collins, David Farley, Nathaniel Fisch, John Foster, Miguel Furman, Peter Garnavich, Gail Glendinning, Jacob Grun, Walter Jaffe, William Junor, Konstantinos Kifonidis, Manooch Koochesfahani, Christine Labaune, Sergey Lebedev, Mario Livio, Andrew Mackinnon, Vladimir Malkin, Stephen Obenschain, David Reis, Yasuhiko Sentoku, Bert Still, Hugh Van Horn, Shuoqin Wang, Craig West, Scott Wilks, Stanford Woosley, and Simon Yu.

In formulating its findings and recommendations, the committee benefited from extensive discussions with members of the scientific community. The committee was charged with assessing the current status of high energy density physics and identifying the compelling research opportunities. While key facilities and facility upgrades for carrying out this research are identified in the report, the establishment of priorities and ranking of facilities were beyond the committee's charge, but certainly merit a future study.

The reader should note that the committee made the decision early on in the drafting of this report not to include references except for the sources of figures. The committee believed that a partial listing would not be appropriate.

On a personal note, I would like to express my sincere appreciation to all members of the committee for the conscientious efforts that they have devoted to this important study, particularly to David Meyerhofer and Bruce Remington for leading the preparation of the chapter on high energy density laboratory plasmas; to Bob Rosner and David Arnett for the chapter on high energy density astrophysical systems; to Tom Katsouleas and Phillip Sprangle for the chapter on laser-plasma and beam-plasma interactions; and to David Hammer for his critical proofreading of the final draft report.

On behalf of the committee, I would also like to express our appreciation to Michael Turner and the NRC's Committee on the Physics of the Universe (CPU) for recognizing the important role of high energy density physics in their seminal assessment of the key questions and research opportunities at the intersection of physics and astronomy.[1] This committee is particularly gratified that the CPU report identifies the important role that laboratory facilities, such as high-power lasers and high-energy accelerators, can play in simulating the conditions that govern extreme astrophysical environments, ranging from gamma-ray bursts to quark-gluon plasmas in the early universe.

In conclusion, the committee believes that now is a very opportune time to make major advances in the physics of understanding matter under extreme high energy density conditions. A sustained commitment by the federal government, the national laboratories, and the university community to answer the questions of high intellectual value identified by the committee and to implement the recommendations of this report will contribute significantly to the timely realization of these exciting research opportunities and the advancement of this important field of physics.

Ronald C. Davidson, *Chair*
Committee on High Energy Density Plasma Physics

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[1] National Research Council, Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century, Committee on the Physics of the Universe, The National Academies Press, Washington, D.C., 2003.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Roger D. Blandford, California Institute of Technology,
Michael Campbell, General Atomics,
Walter Gekelman, University of California, Los Angeles,
Alice Harding, NASA Goddard Space Flight Center,
Gerard A. Mourou, University of Michigan,
Julia M. Phillips, Sandia National Laboratories,
Dmitri Ryutov, Lawrence Livermore National Laboratory, and
Robert H. Siemann, Stanford University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommenda-

tions, nor did they see the final draft of the report before its release. The review of this report was overseen by Clifford Surko, University of California, San Diego. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Executive Summary

BACKGROUND

Recent advances in extending the energy, power, and brightness of lasers, particle beams, and Z-pinch generators make it possible to create matter with extremely high energy density in the laboratory. The collective interaction of this matter with itself, particle beams, and radiation fields is a rich, expanding field of physics called high energy density physics. It is a field characterized by extreme states of matter previously unattainable in laboratory experiments. It is also a field rich in new physics phenomena and compelling applications, propelled by advances in high-performance computing and advanced measuring techniques. This report's working definition of "high energy density" refers to energy densities exceeding 10^{11} joules per cubic meter (J/m^3), or equivalently, pressures exceeding 1 megabar (Mbar). (For example, the energy density of a hydrogen molecule and the bulk moduli of solid materials are about 10^{11} J/m^3.)

The time is highly opportune for the nation's scientists to develop a fundamental understanding of the physics of high energy density plasmas. The space-based and ground-based instruments for measuring astrophysical processes under extreme conditions are unprecedented in their accuracy and detail, revealing a universe of colossal agitation and tempestuous change. In addition, there is a new generation of sophisticated laboratory systems ("drivers"), existing or planned, that creates matter under extreme high energy density conditions, permitting the detailed exploration of physics phenomena under conditions not unlike those in astrophysical systems.

A consensus is emerging in the plasma physics and astrophysics communities that many opportunities exist for significant advances in understanding the physics of high energy density plasmas through an integrated approach to investigating the scientific issues in related subfields. Understanding the physics of high energy density plasmas will also lead to new applications and benefit other areas of science. Learning to control and manipulate these plasmas in the laboratory will benefit national programs, such as inertial confinement fusion and the stockpile stewardship program, through the development of new ideas and the training of a new generation of scientists and engineers. Furthermore, advanced technologies in the areas of high-speed instrumentation, optics (including x-ray optics), high-power lasers, advanced pulse power, and microfabrication techniques can be expected to lead to important spin-offs.

High energy density experiments span a wide range of areas of physics including plasma physics, laser and particle beam physics, materials science and condensed matter physics, nuclear physics, atomic and molecular physics, fluid dynamics and magnetohydrodynamics, intense radiation-matter interaction, and astrophysics. While a number of scientific areas are represented in high energy density physics, many high energy density research techniques have grown out of ongoing work in plasma science, astrophysics, beam physics, accelerator physics, magnetic fusion, 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 that characterize all of these subfields of physics.

It should be emphasized that while high energy density physics is a rapidly developing area of research abroad, particularly in Europe and Japan, the primary focus of this report is on assessing the present capabilities and compelling research opportunities in the United States.

To illustrate the energy scale of the high energy density regime, some of the systems that deliver the energy in high energy density laboratory experiments in the United States can be considered. Typical state-of-the-art short-pulse lasers and the electron beams generated at the Stanford Linear Accelerator Center can be focused to deliver 10^{20} watts per square centimeter (W/cm^2) on target. The present generation of lasers employed in inertial confinement fusion (on the NIKE facility at the Naval Research Laboratory, on OMEGA at the Laboratory for Laser Energetics at the University of Rochester, and at the TRIDENT laser laboratory at Los Alamos National Laboratory) deliver 1 to 40 kilojoules (kJ) to a few cubic millimeters volume in a few nanoseconds. In Z-pinch experiments on the Z-machine at Sandia National Laboratories, 1.8 megajoules (MJ) of soft x rays are delivered to a few cubic centimeters volume in about 5 to 15 nanoseconds (ns). With the planned upgrades of existing facilities and the completion of the National Ignition Facility (NIF) at the Lawrence

Livermore National Laboratory in the early 2000s, the parameter range of high energy density physics phenomena that can be explored will expand significantly. Complementary technologies, such as gas guns, explosively driven experiments, and diamond anvils, can also generate physically interesting high energy density physics conditions in the laboratory. While the primary purpose of the major facilities sponsored by the Department of Energy's National Nuclear Security Administration (NNSA) is to investigate technical issues related to stockpile stewardship and inertial confinement fusion, increasing opportunities on these facilities are also available for exploring the basic aspects of high energy density physics. These state-of-the-art facilities allow repeatable experiments and controlled parameter variations to elucidate the important underlying physics.

Elucidating the physics of high energy density plasmas through experiment, theory, and numerical simulation presents exciting science opportunities for understanding physical phenomena in laboratory-generated high energy density plasmas and in astrophysical systems. Because the field is developing rapidly, a study of the compelling research opportunities and synergies in high energy density plasma physics and its related subfields is particularly pertinent at the present time.

ASSESSING THE FIELD

In carrying out this assessment, the National Research Council's Committee on High Energy Density Plasma Physics found high energy density physics (pressure conditions exceeding 1 Mbar, say) to be a rapidly growing field of physics with exciting research opportunities of high intellectual challenge spanning a wide range of physics areas. Opportunities for exploring the compelling questions of the field have never been more numerous. The many excellent high energy density facilities—together with a new generation of sophisticated diagnostic instruments, existing or planned, that can measure properties of matter under extreme high energy density conditions—permit laboratory exploration of many aspects of high energy density physics phenomena in exquisite detail under conditions of considerable interest for the following: basic high energy density physics studies, materials research, understanding astrophysical processes, commercial applications (e.g., extreme ultraviolet lithography), inertial confinement fusion, and nuclear weapons research.

Furthermore, a revolution in computational capabilities has brought physical phenomena within the scope of numerical simulations that were out of reach only a few years ago. Numerical modeling is now possible for many aspects of the complex nonlinear dynamics and collective processes characteristic of high energy density laboratory plasmas and for the extreme hydrodynamic motions that exist under astrophysical conditions. The first phase of advanced computations at massively parallel facilities such as those developed in the Advanced Strategic Computing

Initiative (ASCI) is reaching fruition with remarkable achievements, and a unique opportunity exists at this time to integrate theory, experimentation, and advanced computations to significantly advance the fundamental understanding of high energy density plasmas.

Exciting new discoveries in astrophysics have occurred along with dramatic improvements in measurements by ground-based and space-based instruments of astrophysical processes under extreme high energy density conditions. Using the new generation of laboratory high energy density facilities, macroscopic collections of matter can be created under astrophysically relevant conditions, providing critical data on hydrodynamic mixing, shock phenomena, radiation flow, complex opacities, high-Mach-number jets, equations of state, relativistic plasmas, and possibly, quark-gluon plasmas characteristic of the early universe.

A highly cost-effective way of significantly extending the frontiers of high energy density physics research is to upgrade and/or modify existing and planned experimental facilities to access new operating regimes. Such upgrades and modifications of experimental facilities will open up exciting research opportunities beyond those which are accessible with existing and planned laboratory systems. These opportunities range, for example, from the installation of ultrahigh-intensity (petawatt) lasers on inertial confinement fusion facilities to create relativistic plasma conditions relevant to gamma-ray bursts and neutron star atmospheres, to the installation of dedicated beamlines on high energy physics accelerator facilities for carrying out basic high energy density physics studies, such as the development of ultrahigh-gradient acceleration concepts and unique radiation sources extending from the infrared to gamma-ray regimes.

In reviewing the level of support for research on high energy density physics provided by federal program agencies, the committee found that the level of support by agencies such as the NNSA, the nondefense directorates in the Department of Energy, the National Science Foundation, the Department of Defense, and the National Aeronautics and Space Administration has lagged behind the scientific imperatives and compelling research opportunities offered by this exciting field of physics. The NNSA's establishment of the Stewardship Science Academic Alliances program to fund research projects at universities in areas of fundamental high energy density science and technology relevant to stockpile stewardship is commendable and important, particularly because the nation's universities represent a vast resource for developing and testing innovative ideas in high energy density physics and for training graduate students and postdoctoral research associates.

The committee is convinced that research opportunities in this crosscutting area of physics are of the highest intellectual caliber and that they are fully deserving of the consideration of support by the leading funding agencies of the physical sciences. A broad federal support base for research in high energy density physics, including plasma science, and the encouragement of interagency research initiatives in this very interdisciplinary field would greatly strengthen the ability of the nation's universities to have a significant impact on this field.

THE KEY QUESTIONS

In developing a unifying framework for the diverse areas of high energy density physics and identifying research opportunities of high intellectual value, the committee found it useful to formulate key scientific questions ranging from the very basic physics questions to those at the frontier of the field. These are questions that, if answered, would have a profound effect on our understanding of the fundamental physics of matter under high energy density conditions. The following list of questions is not intended to be complete but rather to be illustrative of important questions of high intellectual value in high energy density physics:

- How does matter behave under conditions of extreme temperature, pressure, density, and electromagnetic fields?
- What are the opacities of stellar matter?
- What is the nature of matter at the beginning of the universe?
- How does matter interact with photons and neutrinos under extreme conditions?
- What is the origin of intermediate-mass and high-mass nuclei in the universe?
- Can nuclear flames (ignition and propagating burn) be created in the laboratory?
- Can high-yield ignition in the laboratory be used to study aspects of supernovae physics, including the generation of high-Z elements?
- Can the mechanisms for formation of astrophysical jets be simulated in laboratory experiments?
- Can the transition to turbulence, and the turbulent state, in high energy density systems be understood experimentally and theoretically?
- What are the dynamics of the interaction of strong shocks with turbulent and inhomogeneous media?
- Will measurements of the equation of state and opacity of materials at high temperatures and pressures change models of stellar and planetary structure?
- Can electron-positron plasmas relevant to gamma-ray bursts be created in the laboratory?
- Can focused lasers "boil the vacuum" to produce electron-positron pairs?
- Can macroscopic amounts of relativistic matter be created in the laboratory and will it exhibit fundamentally new collective behavior?

- Can we predict the nonlinear optics of unstable multiple and interacting beamlets of intense light or matter as they filament, braid, and scatter?
- Can the ultraintense field of a plasma wake be used to make an ultrahigh-gradient accelerator with the luminosity and beam quality needed for applications in high energy and nuclear physics?
- Can high energy density beam-plasma interactions lead to novel radiation sources?

These questions cut across the boundaries of this field, and answering them will require new approaches to building a comprehensive strategy for realizing the exciting research opportunities. With this in mind the committee makes the following recommendations.

RECOMMENDATIONS

a. Recommendation on external user experiments at major facilities

It is recommended that the National Nuclear Security Administration continue to strengthen its support for external user experiments on its major high energy density facilities, with a goal of about 15 percent of facility operating time dedicated to basic physics studies. This effort should include the implementation of mechanisms for providing experimental run time to users, as well as providing adequate resources for operating these experiments, including target fabrication, diagnostics, and so on. A major limitation of present mechanisms is the difficulty in obtaining complex targets for user experiments.

b. Recommendation on the Stewardship Science Academic Alliances program

It is recommended that the National Nuclear Security Administration continue and expand its Stewardship Science Academic Alliances program to fund research projects at universities in areas of fundamental high energy density science and technology. Universities develop innovative concepts and train the graduate students who will become the lifeblood of the nation's research in high energy density physics. A significant effort should also be made by the federal government and the university community to expand the involvement of other funding agencies, such as the National Science Foundation, the National Aeronautics and Space Administration, the Department of Defense, and the nondefense directorates in the Department of Energy, in supporting research of high intellectual value in high energy density physics.

c. Recommendation on maximizing the capabilities of facilities

A significant investment is recommended in advanced infrastructure at major high energy density facilities for the express purpose of exploring research opportunities for new high energy density physics. This effort is intended to include upgrades, modifications, and additional diagnostics that enable new physics discoveries outside the mission for which the facility was built. Joint support for such initiatives is encouraged from agencies with an interest in funding users of the facility as well as from the primary program agency responsible for the facility.

d. Recommendation on the support of university research

It is recommended that significant federal resources be devoted to supporting high energy density physics research at university-scale facilities, both experimental and computational. Imaginative research and diagnostic development on university-scale facilities can lead to new concepts and instrumentation techniques that significantly advance our understanding of high energy density physics phenomena and in turn are implemented on state-of-the-art facilities.

e. Recommendation on a coordinated program of computational-experimental integration

It is recommended that a focused national effort be implemented in support of an iterative computational-experimental integration procedure for investigating high energy density physics phenomena.

f. Recommendation on university and national laboratory collaboration

It is recommended that the Department of Energy's National Nuclear Security Administration (NNSA) continue to develop mechanisms for allowing open scientific collaborations between academic scientists and the NNSA laboratories and facilities, to the maximum extent possible, given national security priorities.

g. Recommendation on interagency cooperation

It is recommended that federal interagency collaborations be strengthened in fostering high energy density basic science. Such program collaborations are

important for fostering the basic science base, without the constraints imposed by the mission orientation of many of the Department of Energy's high energy density programs.

To summarize, the committee believes that now is a very opportune time for major advances in the physics understanding of matter under extreme high energy density conditions. A sustained commitment by the federal government, the national laboratories, and the university community to answer the important questions of high intellectual value identified by the committee and to implement the recommendations of this report will contribute significantly to the timely realization of these exciting research opportunities and the advancement of this important field of physics.

1

Exordium and Principal Findings and Recommendations

INTRODUCTION

The time is highly opportune for the nation's scientists to develop a fundamental understanding of the physics of high energy density plasmas. Ground-based and space-based instruments for measuring astrophysical processes under extreme conditions are unprecedented in their sensitivity and detail, revealing a universe of titanic violence and continuous upheaval. In addition, a new generation of sophisticated laboratory systems ("drivers"), existing or planned, is capable of generating extreme high energy density conditions in matter, permitting a detailed exploration of physics phenomena under conditions never before accessible in the laboratory and approaching those in astrophysical systems. A consensus is emerging in the plasma physics and astrophysics communities that many opportunities exist for significant advances in understanding the physics of high energy density plasmas through an integrated approach to investigating the scientific issues in related subfields. Understanding the physics of high energy density plasmas will also lead to new applications and benefit other areas of science and technology. Furthermore, learning to control and manipulate high energy density plasmas in the laboratory will benefit national programs, such as inertial confinement fusion and the stockpile stewardship program, through the development of new ideas and the training of a new generation of scientists and engineers.

Elucidating the physics of high energy density plasmas through experiment, theory, and numerical simulation is of considerable scientific importance in order to understand physical phenomena in laboratory-generated high energy density plasmas and astrophysical systems. Because the field is developing rapidly, a study of compelling research opportunities and synergies among related subfields is particularly pertinent.

Recent advances in extending the energy and power of lasers, particle beams, and Z-pinch generators make extremely high energy density matter accessible in the laboratory. The collective interaction of this matter with itself, particle beams, and radiation fields is a rich and expanding field of physics termed high energy density (HED) physics. It is also a field rich in new physics phenomena and steeped with important applications.

To illustrate the energy scale, let us briefly consider some of the systems (drivers) that deliver the energy in laboratory experiments. Typical state-of-the-art short-pulse lasers and the electron beams generated at the Stanford Linear Accelerator Center can be focused to deliver 10^{20} W/cm^2 on target. The present generation of lasers employed in inertial confinement fusion research (NIKE, OMEGA, and TRIDENT) deliver 1 to 40 kJ to a few cubic millimeters volume, in a few nano-seconds. The Z-pinch experiments at Sandia National Laboratories generate 1.8 MJ of soft x rays in a few cubic centimeters volume in 5 to 15 ns. With the planned upgrades of existing facilities and the completion of the National Ignition Facility (NIF) in the early 2000s, the parameter range of high energy density physics phenomena that can be explored will expand significantly. Complementary technologies, such as gas guns, explosively driven experiments, and diamond anvils can also generate physically interesting high energy density physics conditions in the laboratory. While the primary purpose of the major facilities sponsored by the Department of Energy's National Nuclear Security Administration (NNSA) is to investigate technical issues related to stockpile stewardship and inertial confinement fusion, there are increasing opportunities on these facilities to explore the basic aspects of high energy density physics.

Although a sizable fraction of high energy density physics research is carried out at national laboratories engaged in inertial confinement fusion and nuclear weapons research, university involvement in physics investigations of high energy density plasmas is growing. University involvement has increased as a result of several factors, including the increased openness of national research facilities to collaborators and the development of relatively inexpensive short-pulse lasers and parallel computing clusters that are powerful enough to access high energy density physics regimes on university-scale facilities.

High energy density experiments span a wide range of areas of physics, including plasma physics, laser and particle beam physics, material science and condensed matter physics, nuclear physics, atomic and molecular physics, fluid dynamics and magnetohydrodynamics, and astrophysics. While a number of scientific areas are represented in high energy density physics, many of the techniques used in high energy density research have grown out of ongoing research in plasma science, astrophysics, beam physics, magnetic fusion, inertial confinement fusion, and nuclear weapons research. The intellectual challenge of high energy density physics lies in the complexity and nonlinearity of the interaction processes.

DEFINITION OF HIGH ENERGY DENSITY

The region of parameter space encompassed by high energy density physics includes a wide variety of physical phenomena. Simple estimates of high energy density conditions exhibited in different physical circumstances enable the overlap in conditions to be made readily apparent. Taking advantage of the synergies that can be developed among different areas of research has the potential to greatly increase the fundamental understanding of high energy density physics and to enhance the identification of compelling research opportunities.

The energy density of common, room-temperature materials provides a starting point for a definition of high energy density conditions. Many of these materials (such as hydrogen, carbon, and iron) are ubiquitous in the universe. One definition of high energy density conditions is that these conditions exist when the external energy density applied to the material is comparable to the material's room-temperature energy density. This can be thought of as the condition that exists when typical room-temperature materials become compressible—for example, if a shock wave is sent through the material.

The energy density of a hydrogen molecule and the bulk moduli of solid-state materials are similar, that is, about 10^{11} J/m^3. Table 1.1 lists some of the ways of expressing the energy density corresponding to 10^{11} J/m^3. At this energy density, the pressure is 1 Mbar. The energy density of electromagnetic radiation can be considered either as an effective intensity or as a blackbody radiation temperature. An intense radiation pulse interacting with matter can ablate material, generating a pressure wave in the material. The x-ray and laser drives required for a 1-Mbar ablation pressure wave are shown in Table 1.1. The magnetic and electric field strengths that correspond to this energy density are also shown. In a plasma with a specified electron number density, the temperature required to give an energy density corresponding to 10^{11} J/m^3 is shown in Table 1.1. These different ways of expressing the same energy density facilitate comparisons of different physical conditions and identify similarities and potential synergies.

Figure 1.1 shows a plot in temperature-density space indicating regions encompassed by different physical processes and conditions. Regions that are accessible in various high energy density laboratory facilities are indicated in the figure, and the

TABLE 1.1 Static High Energy Density Definition: Various Quantities That Correspond to an Energy Density of 10^{11} J/m^3

Energy Density Parameter Corresponding to ~10^{11} J/m^3	**Value**
Pressure	1 Mbar
Electromagnetic Radiation	
Electromagnetic wave (laser) intensity (I) ($p \sim I$)	3×10^{15} W/cm^2
Blackbody radiation temperature (T_{rad}) ($p \sim T_{rad}{}^{1/4}$)	4×10^2eV
Electric field strength (E) ($p \sim E^2$)	1.5×10^{11} V/m
Magnetic field strength (B) ($p \sim B^2$)	5×10^2 T
Plasma Pressure	
Plasma density (n) for a thermal temperature (T) of 1 keV ($p \sim nT$)	6×10^{26} m^{-3}
Plasma density (n) for an energy per particle (temperature) (T) of 1 GeV ($p \sim nT$)	6×10^{20} m^{-3}
Ablation Pressure	
Laser intensity (I) at 1 μm wavelength (λ) ($p \sim (I/\lambda)^{2/3}$)	4×10^{12} W/cm^2
Blackbody radiation temperature (T_{rad}) ($p \sim T_{rad}{}^{3.5}$)	75 eV

NOTE: The scaling of the pressure with the appropriate physical quantity is shown parenthetically in the first column.

1-Mbar contour is shown. As is evident from the figure, a wide variety of physical and astrophysical processes and objects have energy densities greater than 1 Mbar.

High energy density systems exhibit a variety of physical properties that can be useful in characterizing such systems. Some of these are summarized below.

- *Nonlinear and collective responses.* One of the defining characteristics of high energy density conditions is their collective response to external stimuli. Examples include wave motions in plasmas and the response of a metal to a strong shock wave. High energy density systems often have a significant nonlinear response to an applied energy source. An electromagnetic wave propagating in a plasma generates many nonlinear responses from the plasma, including stimulated (parametric) instabilities such as Raman and Brillouin scattering, and relativistic instabilities generated at higher intensities. At still higher intensities, the vacuum itself can become nonlinear. (This nonlinear response is discussed in Chapter 4.)
- *Full or partial degeneracy.* High energy density systems can be driven to such extremely high density that their pressure is determined by the Pauli exclusion principle rather than by their temperature. The response of such systems is determined by their quantum-mechanical properties. Many astrophysical and laboratory high energy density systems are partially or fully degenerate. These include the centers of large planets, brown dwarfs, white

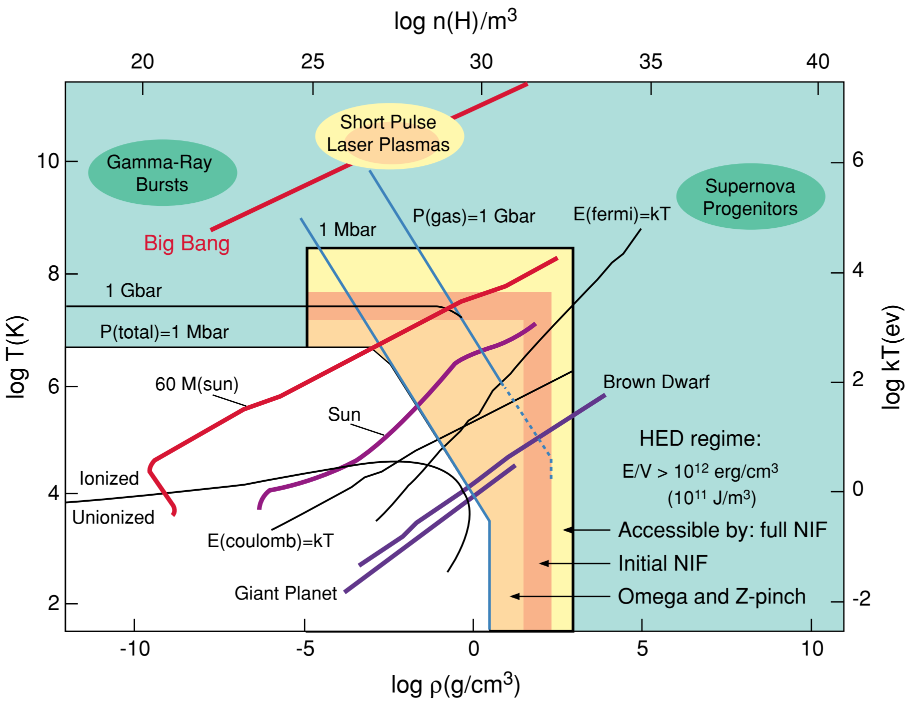


FIGURE 1.1 Overlap between high energy density experimental range and astrophysical conditions. The horizontal axis is logarithmic density (lower axis in grams per cubic centimeter, upper axis in number per cubic meter). The vertical axis is logarithmic temperature (left in degrees Kelvin, right in electronvolts). All shaded regions correspond to the high energy density (HED) regime. The rectangular boundaries in the center enclose the high energy density regimes now accessible on experimental facilities such as OMEGA and Z (smaller, tan box); the National Ignition Facility, or NIF (larger, light-yellow box); and intermediate stages of NIF as it begins operations (orange region). The tan and yellow elliptical regions correspond to short-pulse, ultrahigh-intensity lasers, present and future. A density-temperature plot is only one of many ways to parameterize laboratory systems, and it ignores the trade-offs among the utility of different systems depending on the choice of experiment. Magnetic fusion experiments probe comparable temperatures, but much lower densities. The rectangles overlap most of the extreme conditions for typical stars (stars of 60 and 1 solar mass are shown; the 60-solar-mass star is both burning helium [at the center] and hydrogen [in a shell], while the 1-solar-mass star is a model of the present-day Sun), and a significant fraction of the extreme conditions found in the interior of giant planets and brown dwarfs.

dwarfs, neutron stars, and various phases of an inertial confinement fusion implosion. In the case of the neutron star, the degeneracy of the neutrons determines the system characteristics. (These properties are discussed further in Chapters 2 and 3.) It is noteworthy that some low energy density systems exhibit degeneracy at extremely low temperatures, such as those in single-component plasmas and Bose-Einstein condensates.

- *Dynamic systems.* The Reynolds and Mach numbers serve as yardsticks for hydrodynamic instabilities. At high values of the Reynolds number, turbulence ensues: the ultimate nonlinear response. The Mach number measures compressibility, the ratio of kinetic to thermal energy, and the ability of the flow to form and sustain shocks. The transition to turbulence in a high energy density medium is probably the least understood high energy density condition, either experimentally or theoretically. Figure 1.2 illustrates the various hydrodynamics regimes encountered in high energy density conditions as a function of Reynolds number and Mach number. Compressible turbulence regimes map in the upper-right-hand sector, that is, $Re > 10^4$ and $Ma > 0.5$, and are relevant to larger-scale and, in particular, astrophysical phenomena, as discussed in Chapter 2. These regimes are likely to be within the experimental reach of future facilities such as the National Ignition Facility.

The conditions that are described above are not unique in achieving energy densities of order 10^{11} J/m^3. For example, the ionization of individual atoms or molecules in intense laser fields occurs at similar energy densities. These latter systems do not, however, demonstrate a collective response and are therefore outside the scope of this report. The high energy density interactions with individual atoms are discussed in the National Research Council (NRC) report entitled *Atomic, Molecular, and Optical Science—An Investment in the Future.*[1]

PHYSICAL PROCESSES AND AREAS OF RESEARCH

By way of introduction, this section outlines some, but certainly not all, of the physical processes that are normally included under the descriptor "high energy density physics." This section briefly gives a sense of the field, and subsequent chapters provide considerably more detail, as well as identifying research opportunities of high intellectual challenge.

[1]National Research Council, Atomic, Molecular, and Optical Science: An Investment in the Future, Washington D.C., National Academy Press, 1994.

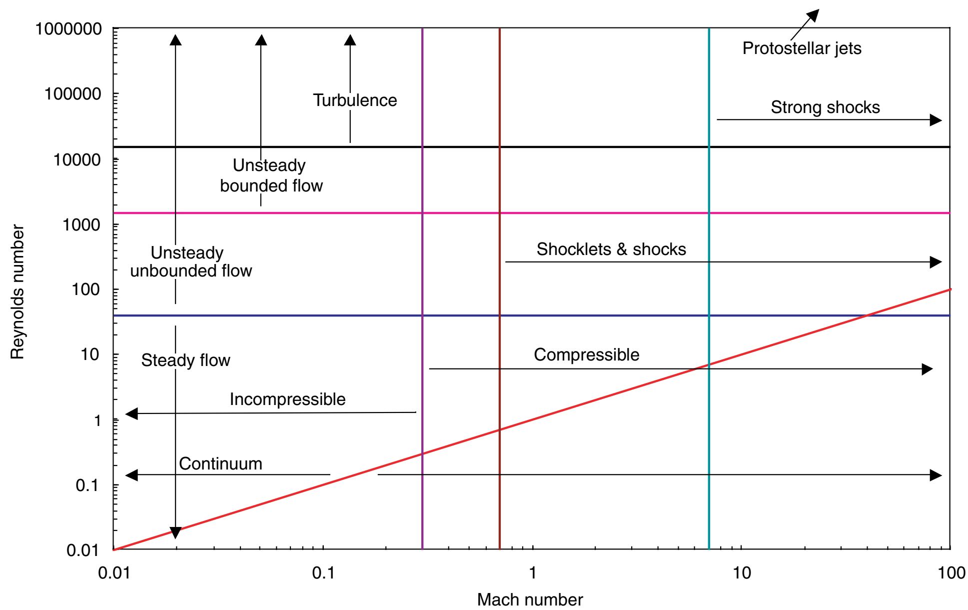


FIGURE 1.2 Mach number-Reynolds number plane indicating various hydrodynamic regimes encountered in high energy density phenomena. The range of astrophysical interest is large. In one event, a Type Ia supernova, the Mach numbers range from less than 0.01 at thermonuclear ignition to more than 100 at emergence of the explosion shock at the stellar surface. The Reynolds number scales with size, so that astrophysical events generally involve much larger Reynolds numbers than those accessible by HED experiments. Astrophysical phenomena generally lie above the top of the graph, at Reynolds numbers greater than 1 million. The experiments sample the region now being explored by direct numerical simulation and are relevant to understanding the tools that will be used to explore more extreme conditions.

High Energy Density Astrophysics

During the past decade, a new subfield of laboratory astrophysics has emerged, made possible by current and planned high energy density experimental facilities, such as large laser facilities and Z-pinch generators. On these facilities, macroscopic collections of matter can be created under astrophysically relevant conditions and their properties measured. Examples of processes and issues that can be experimentally addressed include compressible hydrodynamic mixing, strong-shock phenomena, magnetically collimated jets, magnetohydrodynamic turbulence, radiative shocks, radiation flow, high-Mach-number jets, complex opacities, photoionized plasmas, equations of state of highly compressed matter, and relativistic plasmas. These processes are relevant to a wide range of astrophysical phenomena, such as supernovae and supernova remnants, astrophysical jets, radiatively driven molecular clouds, accreting black holes, planetary interiors, and gamma-ray bursts. There has been a concomitant increase in observational and simulation capabilities that allow a more direct connection between laboratory and astrophysical high energy density conditions.

Laser-Plasma Interactions

The nonlinear optics of intense lasers in plasmas is an exciting area of forefront research. Ultrahigh-power, short-pulse lasers are generating extraordinary fluxes of very energetic electrons and ions and the highest electric and magnetic fields produced on Earth. Another challenging area of research is the collective interaction of multiple, interacting, long-pulse laser beams as they filament, braid, and scatter. Research on laser-plasma interactions impacts plasma physics, astrophysics, inertial confinement fusion, and stockpile stewardship. It may also lead to ultrahigh-gradient particle accelerators, novel light sources, advanced diagnostics, and new approaches to fusion.

Beam-Plasma Interactions

Short-pulse electron beams with densities greater than the plasma electron density can, like the laser pulses described above, be used to drive electron-accelerating plasma waves. In this case, the electron beam ejects all plasma electrons from the propagation channel, and in turn the ion channel that has been formed constitutes a very powerful charged particle lens. High-power charged-particle beam interactions with plasmas produce a wealth of high energy density physics and are of long-standing interest in inertial fusion energy. In addition to external beams interacting with plasmas, interesting electron and ion beams can be generated from within the plasma itself. Relativistic electron beams of unprecedented peak currents, exceeding the Alfvén current by orders of magnitude, have been produced in petawatt-laser–solid-target interaction experiments. High-brightness ion beams with energies exceeding 5 MeV per nucleon have also been produced by petawatt lasers. Their development remains an exciting physics challenge. Ion beams of unprecedented peak current, exceeding the Alfvén current for the ions by orders of magnitude, have been produced in petawatt-laser–solid-target interaction experiments.

Beam-Laser Interactions

Colliding high-brightness picosecond relativistic electron beams with ultrahigh-power, short-pulse lasers enables the study of fundamental electromagnetic radiation processes in the laboratory. These collisions provide a testing ground for relativistic quantum electrodynamics, where the nonlinear quantum electrodynamic production of electron-positron pairs has been observed. They also produce copious quantities of Compton x rays. These experiments can lead to compact, high-spectral-brightness x-ray sources that may be brighter than current synchrotron light sources for materials science research and medical applications.

Free Electron Laser Interactions

The use of relativistic electron beams as a lasing medium is attractive, as it allows the production of very high photon energy densities and operation at nearly arbitrary tunable wavelengths. The development of an x-ray free electron laser is now a major focus of the synchrotron radiation community, as it will provide very powerful "fourth-generation" x-ray sources that are highly coherent. Coherent, high-power imaging is expected to revolutionize molecular, biological, and materials research. Such an x-ray free electron laser at 1 angstrom (Å) is expected to be so powerful that at its focus it may produce conditions that "boil the vacuum" to produce electron-positron pairs. These high-flux x-ray sources can be used to volumetrically heat large amounts of solid-density matter to fully or partially degenerate conditions and/or to probe their properties. The electron beam needed to drive the x-ray free electron laser is of unprecedented brightness, and its production and diagnosis are a frontier research effort.

High-Current Discharges

Research on high energy density, magnetically confined, radiation-dominated plasmas is rapidly advancing because of the availability of pulsed-power sources that can deliver up to 20 mega-amperes (MA) in 100-ns pulses. Discharges through wire-arrays produce copious amounts of soft x rays—as much as 1.8 MJ at the Z-machine at the Sandia National Laboratories—in times of 5 to 15 ns. Soft x-ray fluxes are used to study radiation-matter interaction. High-Mach-number jets of plasma in discharges produced by the MAGPIE pulsed-power facility in the United Kingdom simulate astrophysical jets. This research also plays an important role in stockpile stewardship and inertial confinement fusion.

Radiation-Matter Interaction, Hydrodynamics, and Shock Physics

High-energy laboratory drivers are used to obtain opacities and to study radiation transport. Useful opacity information for astrophysics can be obtained in the laboratory. New experimental techniques have been developed for understanding Rayleigh-Taylor, Richtmyer-Meshkov, and other hydrodynamic instabilities in the linear and nonlinear regimes. High-power laser experiments study shock wave propagation and interaction especially at high Mach numbers $Ma \sim 15$ to 20. These experiments access the regime where the shock pressures exceed the material's bulk modulus. Instabilities of shock waves, shocked matter, compressible turbulent mixing, and radiation interaction with shocks are also being studied. These measurements benchmark codes used in supernova research, inertial confinement fusion, and in defense applications.

Equation-of-State Physics

Recent laser-driven and pulsed-power-driven compression experiments provide new and unexpected data on the equations of state of hydrogen and its isotopes at high pressures (>1 Mbar), and of other materials, such as copper and iron. High energy density drivers create novel states of matter such as metallic hydrogen or complex carbon states. These experiments supply critical data for stellar and planetary interior calculations.

Atomic Physics of Highly Stripped Atoms

High energy density drivers generate highly stripped, near-solid-density, mid-Z and high-Z plasmas at kiloelectronvolt temperatures, with and without magnetic fields. Such plasmas can be used to benchmark atomic physics codes and may contribute to our basic understanding of atomic processes in complex ions in strong electric and magnetic fields.

Theory and Advanced Computations

High energy density physics phenomena are difficult problems to analyze theoretically. The high degree of nonlinearity and complexity of multiple scales make many traditional approaches difficult at best. Advances in scientific computation and computing technology are being utilized with considerable success in modeling many of these systems. The knowledge obtained from laboratory experiments can be used to verify and develop theoretical models needed to more fully understand the fundamental physics and to model astrophysical objects for which we have limited observational data.

Inertial Confinement Fusion

Many of the high energy density physics areas described above are relevant to the development of inertial fusion as an energy source, using either intense heavy ion beams or high-repetition-rate lasers as drivers. The current goal of the inertial confinement fusion program is to achieve ignition in the laboratory, where more energy is produced in fusion reactions than is incident on the imploding deuterium-tritium fusion pellet. It is anticipated that ignition will be achieved on the National Ignition Facility, currently under construction. Conditions in ignited plasmas mimic those in stars. Inertial fusion energy has the further goal of using ignited targets to drive an economical electric power plant.

FINDINGS AND RECOMMENDATIONS

Subsequent chapters in this report describe the compelling research opportunities and questions of high intellectual challenge in high energy density astrophysics (Chapter 2), high energy density laboratory plasmas (Chapter 3), and laser-plasma and beam-plasma interactions (Chapter 4). The research opportunities range from investigating the very largest cosmological systems to exploring at the very smallest scales, with questions such as these—Can astrophysical jets be simulated in laboratory experiments? and Can focused lasers "boil the vacuum" to produce electron-positron pairs? The questions deal with the properties of matter under extreme high energy density conditions, including matter in stars, at the beginning of the universe, and in inertial confinement fusion experiments.

During the course of this assessment of research opportunities and national capabilities in high energy density physics, the Committee on High Energy Density Plasma Physics reached a number of important conclusions that are included here as the principal findings and recommendations of the report. In many respects, the field of high energy density physics is still in its infancy. As would be expected, several of the recommendations identify compelling research opportunities in which an increase in the level of federal research support would lead to significant advances in physics understanding and new discoveries, particularly in research areas in which there are strong synergies among related subfields of high energy density physics.

The findings and recommendations presented here follow not only from the content of the subsequent chapters, but also from the data provided to the committee in the course of this study and the extensive interactions of the committee with the many members of the research community identified in the Preface of this report. In formulating its findings and recommendations, the committee recognized that setting priorities and indicating a quantitative scale (in dollars) for recommended initiatives may be necessary to implement these changes and effectively realize the science opportunities identified in this report. However, the committee considered this undertaking to be beyond its charge. Perhaps a future panel could be charged with this task.

The most exciting questions in high energy density physics cut across many boundaries. Answering the questions will require a new and comprehensive strategy to strengthen the national capabilities necessary to realize the exciting research opportunities. The committee believes that the following findings and recommendations define a framework for building and sustaining such a strategy.

Findings

a. Finding on attributes of high energy density physics

High energy density physics (for example, pressure conditions exceeding 1 Mbar) is a rapidly growing field, with exciting research opportunities of high intellectual challenge. It spans a wide range of physics areas, including plasma physics, laser and particle beam physics, materials science and condensed matter physics, nuclear physics, atomic and molecular physics, fluid dynamics and magnetohydrodynamics, and astrophysics.

Over the past decade, a new class of experimental facilities dedicated to high energy density physics studies has emerged; in these facilities macroscopic collections of matter can be prepared under extreme conditions of density and temperature. These new high energy density facilities fall somewhere between nuclear and high energy physics accelerators (which induce individual particle collisions) on the one hand, and astronomical observatories (which observe integral consequences passively from afar, generally from uncertain initial conditions) on the other. The dynamical evolution of macroscopic collections of matter can be followed, starting from well-characterized initial conditions, in situations where the atomic physics and radiation transport are coupled to the compressible hydrodynamics. In this fashion, the macroscopic response of matter under extreme conditions of compression and temperature can be examined dynamically in the laboratory. Examples of new phenomena that are accessible on existing and future high energy density physics facilities include, for example, pressure ionization of Fermi-degenerate matter; radiatively collapsed, high-Mach-number shocks and jets; lattice response to ultrahigh strain rate compression; thermally relativistic matter and its collective behavior; quantum mechanically relativistic degenerate plasma and its compressibility; kinetically relativistic flows and jets; ultrahigh (greater than gigagauss) magnetic-field generation and its effects on the plasma dynamics; and the transition to turbulence in compressible, high-Reynolds-number flows. Well-designed laboratory experiments in high energy density physics could serve to bring the astrophysics, plasma physics, condensed matter, and spectroscopy communities into many close collaborations, thereby benefiting several subfields of physics through this synergism.

b. Finding on the emergence of new facilities

There is a new generation of sophisticated laboratory facilities and diagnostic instruments existing or planned that create and measure properties of matter under extreme high energy density conditions. These facilities permit the detailed laboratory exploration of physics phenomena under conditions of considerable interest for basic high energy density physics studies, materials research, understanding astrophysical processes, commercial applications (e.g., extreme ultraviolet lithography), inertial confinement fusion, and nuclear weapons research.

An important observation made by the committee was that, in addition to the widely known facilities that already are being, or could be, employed to study matter under extreme high energy density conditions, there also exists a very large number of less-well-known facilities that are operational, under construction, or in the planning stage. Key research facilities are listed in the series of tables in Chapter 3 of this report. While the very brief characterization of each facility presented in these tables is not intended to be sufficient to design an experiment, there is nonetheless adequate detail to show the range of capability that exists for laboratory exploration of high energy density phenomena and to stimulate new ideas.

Not only are there many facilities, but they range in size, capability, and geographic distribution. Some are unique, but other types are widespread. Thus, the opportunity exists to extend the parameter range obtained in "small" (university-scale) experiments at local institutions by using the larger, special facilities. This mode of operation is particularly conducive to university and student participation.

Not only are many high energy density facilities available for research, but sophisticated, and very extensive, diagnostic equipment exists. This equipment allows the exploration, in amazing detail, of many aspects of high energy density physics phenomena. The capabilities that presently exist are described briefly in this report but are far more extensive than can be presented here.

c. Finding on the emergence of new computing capabilities

Rapid advances in high-performance computing have made possible the numerical modeling of many aspects of the complex nonlinear dynamics and

collective processes characteristic of high energy density laboratory plasmas, and the extreme hydrodynamic motions that exist under astrophysical conditions. The first phase of advanced computations at massively parallel facilities, such as those developed under the Advanced Strategic Computing Initiative (ASCI), is reaching fruition with remarkable achievements, and there is a unique opportunity at this time to integrate theory, experimentation, and advanced computations to significantly advance the fundamental understanding of high energy density plasmas.

A revolution in computational capabilities has brought physical phenomena within the scope of numerical simulation that were out of reach only a few years ago. The Department of Energy's Advanced Strategic Computing Initiative (ASCI) has played a major and multifaceted role in this revolution, as has the continued evolution of microprocessor and other technologies. With the ability to perform highly resolved, multidimensional computations, advanced scientific computing has become an enabling tool for first-principles explorations of high energy density phenomena. Many examples of recent breakthrough progress in the numerical simulation of high energy density phenomena can be given. The first three-dimensional simulation of a thermonuclear device has recently been successfully carried out using the ASCI White computer. Such calculations are very important for stockpile stewardship in the absence of nuclear testing. As a complementary example, it has recently become possible for the first time to perform detailed simulations of high energy density beam-plasma experiments using algorithms with minimal approximations in three dimensions using unscaled parameters. Such simulations provide a powerful tool to unveil the physics and to help design future facilities.

Numerical simulation has become a vital and extremely powerful component in the discovery process in high energy density science research. Unprecedented opportunities exist for using numerical modeling to test and advance our understanding of complex physical phenomena and to interpret and design experiments on a variety of impressive high energy density facilities. Many discoveries and new applications lie ahead. There are also very stimulating challenges, such as the need to accurately simulate phenomena occurring over widely disparate space and time scales. Development of the necessary physics-based subgrid-scale models will require theoretical advances and sophisticated, well-characterized experiments that probe the dynamics at small scales and validate the simulations. Such experiments, which are in general unlikely to reproduce the (dimensionless) parameter regimes encountered in astrophysics, can nevertheless reveal or elucidate scaling regimes that may be extended to astrophysical conditions.

d. Finding on new opportunities in understanding astrophysical processes

The ground-based and space-based instruments for measuring astrophysical processes under extreme high energy density conditions are unprecedented in their sensitivity and detail, revealing an incredibly violent universe in continuous upheaval. Using the new generation of laboratory high energy density facilities, macroscopic collections of matter can be created under astrophysically relevant conditions, providing critical data and scaling laws on hydrodynamic mixing, shock phenomena, radiation flow, complex opacities, high-Mach-number jets, equations of state, relativistic plasmas, and possibly quark-gluon plasmas characteristic of the early universe.

There has been an explosion of discoveries in astrophysics as well as dramatic improvements in measurements from new space-based and ground-based instruments. The discoveries include these: evidence for the natural cosmological distance of gamma-ray burst sources, discoveries of giant planets and brown dwarfs, measurements of Type Ia supernovae at cosmological distances, discovery of relativistic jets in stellar mass microquasars, high-resolution observations of radiative shocks, and measurements of rapidly rotating neutron stars with ultrastrong magnetic fields. A proliferation of physical and theoretical problems accompanies these new discoveries. Many of these problems parallel the scientific issues arising in recent and planned high energy density experiments and advanced simulation studies. Laboratory high energy density experiments and simulation studies can provide important new understanding regarding, for example, the equations of state and opacities of high-pressure matter in giant planets and brown dwarfs, nuclear reactions and element formation in stars and supernovae explosions, the behavior of high-Mach-number shocks and the acceleration of charged particles in shocks, the behavior of high-Reynolds-number turbulent plasma flows with and without magnetic fields, the behavior of electron-positron explosions that mimic processes of gamma-ray bursts, and the radiative dynamics of hypersonic flows.

e. Finding on National Nuclear Security Administration support of university research

The National Nuclear Security Administration recently established a Stewardship Science Academic Alliances program to fund research projects at universities in areas of fundamental high energy density science and technology relevant to stockpile stewardship. The National Nuclear Security

Administration is to be commended for initiating this program. The nation's universities represent an enormous resource for developing and testing innovative ideas in high energy density physics and for training graduate students and postdoctoral research associates—a major national resource that has heretofore been woefully underutilized.

The National Nuclear Security Administration's establishment of the Stewardship Science Academic Alliances program comes at a highly opportune time. Following presentations at its meetings on the science opportunities in the field of high energy density physics, and from numerous contacts with the research community on an individual basis, through a town meeting, and through a public solicitation effort for input to the study, the committee concluded that a consensus is emerging in the plasma physics and astrophysics communities that many opportunities exist for significant advances in understanding the physics of high energy density plasmas through an integrated approach to investigating the scientific issues in related subfields. Students and postdoctoral associates have a unique opportunity to be trained on a wide range of new sophisticated laboratory systems, existing and planned, that produce extreme high energy density conditions in matter. Numerous universities have infrastructures that can support high energy density experiments—for example, facilities based on lasers in the multiterawatt to petawatt power range, and 100-kJ pulsed-power systems. Studies of high energy density physics have been proposed or performed at university facilities, at national laboratory facilities supported by the National Nuclear Security Administration, and at nondefense laboratory facilities of the Department of Energy. The Stewardship program is positioned to support this exciting research, which may attract some of the best young minds to the field of high energy density physics and produce a pool of talented scientists for the National Nuclear Security Administration laboratories.

f. Finding on the need for a broad, multiagency approach to support the field of high energy density physics

The level of support for research on high energy density physics provided by federal agencies (e.g., the National Nuclear Security Administration, the nondefense directorates in the Department of Energy, the National Science Foundation, the Department of Defense, and the National Aeronautics and Space Administration) has lagged behind the scientific imperatives and compelling research opportunities offered by this exciting field of physics. An important finding of this report is that the research opportunities in this cross-cutting area of physics are of the highest intellectual caliber and are fully

deserving of consideration of support by the leading funding agencies of the physical sciences. Agency solicitations in high energy density physics should seek to attract bright young talent to this highly interdisciplinary field.

The rapid progress in scientific understanding, creative concepts, and new high energy density physics tools, both experimental and computational, has created an explosion of opportunity for advances in high energy density science that now far outpaces the level of support available to capitalize on them. As noted above, the research opportunities in this crosscutting area of physics are of the highest intellectual caliber and are fully deserving of consideration of support by the leading funding agencies of the physical sciences, such as the nondefense directorates of the Department of Energy, the National Science Foundation, the Department of Defense, and the National Aeronautics and Space Administration. The lack of investment in high energy density physics is particularly apparent through the small representation of plasma physicists on the faculty of U.S. universities. A broad federal support base for research in high energy density physics, including plasma science, and the encouragement of interdepartmental research initiatives in this very interdisciplinary field would greatly strengthen the ability of the nation's universities to have a significant impact on this exciting field of physics.

The astrophysics, plasma physics, and other scientific communities contributing to high energy density physics are highly international, and mechanisms for encouraging open scientific collaborations in high energy density physics on National Nuclear Security Administration facilities should be encouraged to the maximum extent possible, consistent with national security priorities.

g. Finding on opportunities to upgrade existing facilities

Through upgrades and modifications of experimental facilities, exciting research opportunities exist to extend the frontiers of high energy density physics beyond those that are accessible with existing laboratory systems and those currently under construction. These opportunities range, for example, from the installation of ultrahigh-intensity (petawatt) lasers on inertial confinement fusion facilities for creating relativistic plasma conditions relevant to gamma-ray bursts and neutron star atmospheres, to the installation of dedicated beamlines on high energy physics accelerator facilities for carrying out high energy density physics studies, such as the development of ultrahigh-gradient acceleration concepts and unique radiation sources ranging from the infrared to the gamma-ray regimes.

A highly cost-effective way to significantly impact and extend the horizons of high energy density research is to upgrade and/or modify existing and future beam and laser experimental facilities to achieve extreme high energy density conditions. As one example, a significant opportunity exists in utilizing one or more of the beamlines of the National Ignition Facility to produce a single or several 0.1 to 10 picosecond (ps) laser pulses employing chirped pulse amplification technology. The characteristics of such a laser pulse would be unprecedented, opening the path to truly unique and exciting new physics. The power levels would be in the multipetawatt range, perhaps approaching the exawatt level; the pulse energy would be between 10 and 100 kJ, with focused intensities as high as 10^{23} to 10^{24} W/cm^2. Significant high energy density experiments could be carried out with this "one of a kind" national laser facility in a number of areas. Examples include fast ignition for inertial confinement fusion research, simulation of properties of black holes, and ultrahigh-gradient acceleration of electrons and protons. In addition to the NIF laser, the 30-kJ OMEGA laser facility could also be modified to produce multipetawatt short laser pulses for exciting high energy density physics experiments under extreme high energy density conditions.

As another example, the Stanford Linear Accelerator Center (SLAC) electron/positron gigaelectronvolt-class beams also provide unique opportunities for high energy density science. At a relatively modest cost, a dedicated SLAC beamline could be made available for high energy density experiments. With such a beamline, pioneering high energy density experiments would extend our basic physics understanding in such frontier research areas as ultrahigh-gradient wakefield acceleration, novel x-ray radiation sources, and ultrastrong-focusing plasma lenses.

h. Finding on the role of industry

There are active partnerships and technology transfer between industry and the various universities and laboratory research facilities that are mutually beneficial. Industry both is a direct supplier of major hardware components to the high energy density field and has spun off commercial products utilizing concepts first conceived for high energy density applications. Further, it is to be expected that industry will continue to benefit from future applications of currently evolving high energy density technology and that high energy density researchers will benefit from industrial research and development on relevant technologies.

As the direct supplier of laser glass, accelerator components, power supplies, and many other products, industry is critically coupled to the field and benefits from the research and development performed. Many of the relevant fabrication processes and designs were first developed at universities and national laboratories and then transferred to industry for production. Products first developed in this manner often find diverse application in other areas. Additionally, chirped pulse amplification lasers and certain nonlinear optical elements, originally developed for high energy density applications, are now commercially available elements of laser systems. As a result, the technology transfer process has come full circle, and economical tabletop terawatt laser systems are commercially available for university research and development in chemistry and many other fields.

Indirectly, industrial research and development contributes significantly to high energy density physics applications. As examples, rapid advances in diode-pumped laser efficiency and in lithographic manufacturing processes have been driven by the multibillion-dollar research and development investment of the telecommunications and semiconductor industries. Yet these advances are key enablers for recent high energy density schemes for laser acceleration of particles. Similarly, the high average power laser source developed for extreme ultraviolet lithography (EUVL) is ideally suited to meet the high photon flux needed for fluid turbulence diagnostics.

It is to be expected that some of the ongoing research and development will generate new spin-off opportunities for industry. Among these could be advanced laser and optical components such as compact, high-performance optical parametric oscillators, dielectric gratings, more effective and economical radioisotope production or miniature advanced accelerators for medical or material processing applications. Many other applications of high-power lasers can rightly be considered spin-offs to industry from the field, although their performance parameters fall below the threshold definition of high energy density utilized in this report. Examples include solid-state, chemical, and free-electron lasers for defense applications, and "ultrafast" material processing lasers.

Recommendations

a. Recommendation on external user experiments at major facilities

It is recommended that the National Nuclear Security Administration continue to strengthen its support for external user experiments on its major high energy density facilities, with a goal of about 15 percent of facility operating time dedicated to basic physics studies. This effort should include the implementation of mechanisms for providing experimental run time to users, as well as providing adequate resources for operating these experiments, including target fabrication, diagnostics, and so on. A major limitation of present mechanisms is the difficulty in obtaining complex targets for user experiments.

Throughout this study, the committee was told that one of the most positive developments during the past decade has been the engagement of the academic community in pursuing frontier experimental science on major high energy density physics facilities. The scientific return on the investment for about 15 percent of usage time at the national facilities has been enormous. Elegant scale transformations now link strong-shock laboratory experiments with supernova explosions and other large-scale phenomena. The transition to turbulence has been theoretically and experimentally demonstrated in strong-shock-driven hydrodynamic flows. Lattice diagnostics probe the solid-state response of matter to heating and compression in exquisite detail on subnanosecond time scales. The equation of state of hydrogen has been measured under conditions of extreme pressure and density, relevant to the interior of Jupiter. The opacities of plasmas under conditions relevant to Cepheid variable pulsating stars have been measured. The collective behavior of ultrarelativistic electron beams interacting with ambient plasma has been demonstrated. These and many other impressive scientific achievements have resulted from the university outreach programs. The value to major programmatic missions within the NNSA, both near term and far term, is significant and clear. The committee commends the National Nuclear Security Administration for its engagement of the academic community over the past decade on frontier scientific phenomena accessible on its high energy density physics facilities, and it recommends an expansion of this program for the coming decade to include both existing and future Department of Energy facilities.

One limitation in the academic outreach programs brought to the attention of the committee by the outreach participants has been that of obtaining sophisticated targets and potentially unique diagnostics to carry out the experiments on facilities such as the Nova and OMEGA lasers and the Z magnetic pinch facility. Once facility time is awarded through a rigorous proposal selection process, it is recommended that there be a firm commitment to providing the necessary support (target fabrication, diagnostic modification and/or development, and so on) to maximize the scientific return and ultimate value of this program to the National Nuclear Security Administration.

b. Recommendation on the Stewardship Science Academic Alliances program

It is recommended that the National Nuclear Security Administration continue and expand its Stewardship Science Academic Alliances program to fund research projects at universities in areas of fundamental high energy density science and technology. Universities develop innovative concepts and train the graduate students who will become the lifeblood of the nation's

research in high energy density physics. A significant effort should also be made by the federal government and the university community to expand the involvement of other funding agencies, such as the National Science Foundation, the National Aeronautics and Space Administration, the Department of Defense, and the nondefense directorates in the Department of Energy, in supporting research of high intellectual value in high energy density physics.

The arguments for investment in university high energy density research are compelling. First, the productive lifetime of major new facilities, such as the National Ignition Facility, is sufficiently long that the ultimate success of these facilities may well depend on the talent and creativity of a generation of scientists who are yet to enter college, let alone graduate school. Moreover, the degree to which these facilities accomplish their important scientific missions will likely depend on attracting, retaining, and inspiring the very best students and researchers. These students will need to be broadly educated in high energy density science, and the talents of experimentalists, theorists, and modelers will be needed. The field of high energy density science is rich with exciting topics to attract such students, and many of these fundamental problems are tightly coupled to applications of great societal and scientific importance.

Second, the freedom to focus broadly and to pursue curiosity-driven research makes universities a natural home for creativity. Such freedom comes historically from the support of such agencies as the National Science Foundation and the nondefense directorates of the Department of Energy, which seek as their primary criterion research proposals that are innovative. Finally, the strong connections to astrophysics made in this report argue for support for this field from the National Aeronautics and Space Administration, the agency that traditionally has been the leader for such support.

c. Recommendation on maximizing the capabilities of facilities

A significant investment is recommended in advanced infrastructure at major high energy density facilities for the express purpose of exploring research opportunities for new high energy density physics. This effort is intended to include upgrades, modifications, and additional diagnostics that enable new physics discoveries outside the mission for which the facility was built. Joint support for such initiatives is encouraged from agencies with an interest in funding users of the facility as well as from the primary program agency responsible for the facility.

The major high energy density facilities, both existing and planned, are built to pursue specific missions. Though they can also be used directly to pursue new opportunities in basic high energy density science outside their original mission (see "Recommendation on external user experiments at major facilities," above), some of the most exciting scientific opportunities may lie slightly outside the original capability of the facility. Incremental funding to enhance these facilities through added diagnostics and capabilities to access new parameter regimes (such as shorter pulse lengths) would open whole new vistas for high energy density science. Examples of particular interest are the addition of a high-intensity (pulse-compressed) laser to high energy density laser facilities and the addition of a dedicated short-pulse beamline at a major high energy particle beam facility. The addition of short-pulse petawatt lasers are interesting in their own right for the extreme relativistic plasma conditions they can create. However, when synchronized to a high energy density facility, unique new regimes of target physics open up, with possible relevance to aspects of gamma-ray bursts and stellar atmospheres. Similarly, the addition of a beamline at a particle beam facility with the flexibility to customize it to plasma science experiments would open new parameter regimes of potential interest for laboratory astrophysics, novel radiation sources, and particle acceleration techniques.

d. Recommendation on the support of university research

It is recommended that significant federal resources be devoted to supporting high energy density physics research at university-scale facilities, both experimental and computational. Imaginative research and diagnostic development on university-scale facilities can lead to new concepts and instrumentation techniques that significantly advance our understanding of high energy density physics phenomena and in turn are implemented on state-of-the-art facilities.

The primary source of new scientists in high energy density physics is the universities. They educate and train graduate students and postdoctoral research associates in this area of research, and they attract faculty members to this exciting field. While the existence of state-of-the-art high energy density facilities (large lasers, pulsed-power machines, and powerful computers) provide high visibility and facilitate exciting advances in the field, they are not sufficient. It is difficult to attract graduate students to high energy density physics without on-site university facilities. These facilities provide critical training in high energy density physics and can lay the groundwork for research on the state-of-the-art national facilities.

University research in high energy density physics is not limited to the direct study of high energy density physics phenomena—for example, exploiting recent technological innovations such as tabletop high-intensity lasers and/or advanced computational facilities. It also includes the study of phenomena that occur under high energy density conditions but which can be explored in the laboratory at low-to-moderate energy densities. Imaginative research in these areas leads to important insights that significantly advance our understanding of high energy density physics phenomena.

e. Recommendation on a coordinated program of computational-experimental integration

It is recommended that a focused national effort be implemented in support of an iterative computational-experimental integration procedure for investigating high energy density physics phenomena.

The first phase of the Advanced Strategic Computing Initiative and other large-scale computational programs have catalyzed and continue to facilitate remarkable achievements. Recent experimental successes and paradigm shifts in terms of facilities and diagnostics discussed elsewhere in this report are responsible for equally significant contributions. Integration of these contributions into a coordinated program is recommended. Such a coordinated program can be expected ultimately to yield as great a revolution—perhaps even a greater one—in the ability to simulate high energy density phenomena as that generated by the recent increases in computing technology. It would combine experimental components to continue to explore, elucidate, and facilitate the development of physics-based models of the dynamics of matter in high energy density conditions; the incorporation of these models in the next-generation simulation codes; further developments of needed computational-science components; and the closure of the experiment-physics-simulation loop through a concerted validation effort. Only through such quantitative comparisons can there be continued significant advances in understanding the underlying physics.

f. Recommendation on university and national laboratory collaboration

It is recommended that the Department of Energy's National Nuclear Security Administration (NNSA) continue to develop mechanisms for allowing open scientific collaborations between academic scientists and the NNSA laborato-

ries and facilities, to the maximum extent possible, given national security priorities.

The joint endeavor between the NNSA and the academic community to pursue basic scientific questions on major Department of Energy facilities has been a particularly successful and rewarding development. The positive outcomes of this partnership—novel ideas, high-quality scientific articles, new talent sources for the laboratories—drastically outweigh any difficulties or inconveniences this program may cause. For the science resulting from this effort to flourish, in a manner consistent with the scientific method, it is necessary to discuss the scientific results at periodic meetings and workshops of all interested scientists, regardless of nationality. Such workshops are vital to extracting world-class science and understanding from the basic physics data acquired on these facilities. These workshops should be open to all interested scientists (independent of nationality) and should be supported by the NNSA both philosophically and, where appropriate, monetarily.

g. Recommendation on interagency cooperation

It is recommended that federal interagency collaborations be strengthened in fostering high energy density basic science. Such program collaborations are important for fostering the basic science base, without the constraints imposed by the mission orientation of many of the Department of Energy's high energy density programs.

A number of federal agencies besides the Department of Energy have overlapping interests in high energy density plasma physics as well as in related or supporting disciplines. In a few instances, the Department of Energy has engaged in developing jointly funded programs, such as the plasma science program conducted jointly by its Office of Fusion Energy Sciences and the National Science Foundation. As stated, such program collaborations are important for fostering the basic science base, without the constraints imposed by the mission orientation of many of the Department of Energy's high energy density programs. The committee applauds these efforts and encourages both the strengthening of existing programs and the initiating of new interagency collaborations. Examples of exciting research opportunities exist especially in astrophysics, where the high energy density physics explored in the Department of Energy's programs have immediate applications to key astrophysics problems.

To summarize, the committee believes that now is a very opportune time to make major advances in the physics understanding of matter under extreme high energy density conditions. A sustained commitment by the federal government, the national laboratories, and the university community to answer the questions of high intellectual value identified by the committee and to implement the recommendations of this report will contribute significantly to the timely realization of these exciting research opportunities and the advancement of this important field of physics.

2

High Energy Density Astrophysics

INTRODUCTION

In ancient times, the heavens were thought of as perfect, static, and immutable. Today we see the universe as a place of titanic violence and continuous upheaval. The twin engines of gravitational collapse and nuclear fusion power phenomena on a nearly unimaginable scale. Giant black holes consume the fiery hearts of galaxies, sweeping entire star systems into their immense accretion disks; relativistic particle jets, powered by unknown acceleration mechanisms, focus their extreme energies with incredible precision across millions of light years; supernovae shocks sweep up turbulent plasma and dust, creating the seeds for stellar rebirth; neutron stars the size of Manhattan spin at kilohertz rates, weaving their huge magnetic fields through the surrounding plasma and creating brilliant x-ray lighthouses. Meanwhile, in our own relatively placid corner of the Galaxy, we are pelted by cosmic rays of such immense energy that their very existence is difficult to understand, and the formation, structure, and dynamics of the most massive of our solar companions, the giant planets, remain a mystery.

The immense energy densities associated with these phenomena could never be reproduced on Earth. Or could they? Certainly, these conditions can be recreated mathematically using computer models and analytical calculations (if only we had better understanding of the physics!). Perhaps, tiny portions of these extreme environments can be made to flash in and out of existence in accelerator collision chambers, in the focal spots of high-power lasers or particle beams, or at the core of magnetic Z-pinch machines. With the aid of such experiments, and through new analytical, computational, and technical breakthroughs, it may soon be possible to gain improved understanding of the physics underlying some of the universe's most extreme phenomena and to answer some of the fundamental questions outlined in the following sections. Indeed, over the past decade a new genre of laboratory astrophysics has emerged, made possible by the new high energy density (HED) experimental facilities, such as large lasers and Z-pinch generators. On these facilities, macroscopic collections of matter can be created in astrophysically relevant conditions, and their collective properties measured. Examples of processes and issues that can be experimentally addressed include compressible hydrodynamic mixing, strong-shock phenomena, radiative shocks, radiation flow, high-Mach-number jets, complex opacities, photoionized plasmas, equations of state of highly compressed matter, and relativistic plasmas. These processes are relevant to a wide range of astrophysical phenomena, such as supernovae and supernova remnants (see Figure 2.1), astrophysical jets (see Figure 2.2), radiatively driven molecular clouds, accreting black holes, planetary interiors, and gamma-ray bursts. In this chapter these phenomena are discussed in the context of laboratory astrophysics experiments possible on existing and future HED facilities. Key questions in each area will be raised, with the hope and expectation that future experiments on HED facilities will play some role in their resolution.

HIGH ENERGY DENSITY DEFINITIONS FOR ASTROPHYSICS

Stars are plasma. This state requires energy in excess of the binding energy of molecular or solid matter—which for the most abundant element, hydrogen, corresponds to 4.4 electronvolts or to a gas temperature of about 23,000 K.

More extreme conditions abound. They may be classified by equating a thermal kinetic energy (a temperature), or a quantum degeneracy energy (a Fermi energy) to the specified energy. For example, the temperature corresponding to the rest-mass energy of an electron is 6 billion K, and the density at which the electron Fermi energy equals its rest-mass energy is 1 million times that of water.

Another set of extremes can be constructed from velocities. Relativistic conditions are energetically extreme: as the velocity of light is approached, the energy of a particle exceeds the rest-mass energy. For typical conditions in the interstellar medium, the sound velocity is about 10 kilometers per second (km/s), while gas motions often exceed this by factors of 10 to 100. Under these conditions, strong shocks, with Mach numbers of 10 to 100, are generated.

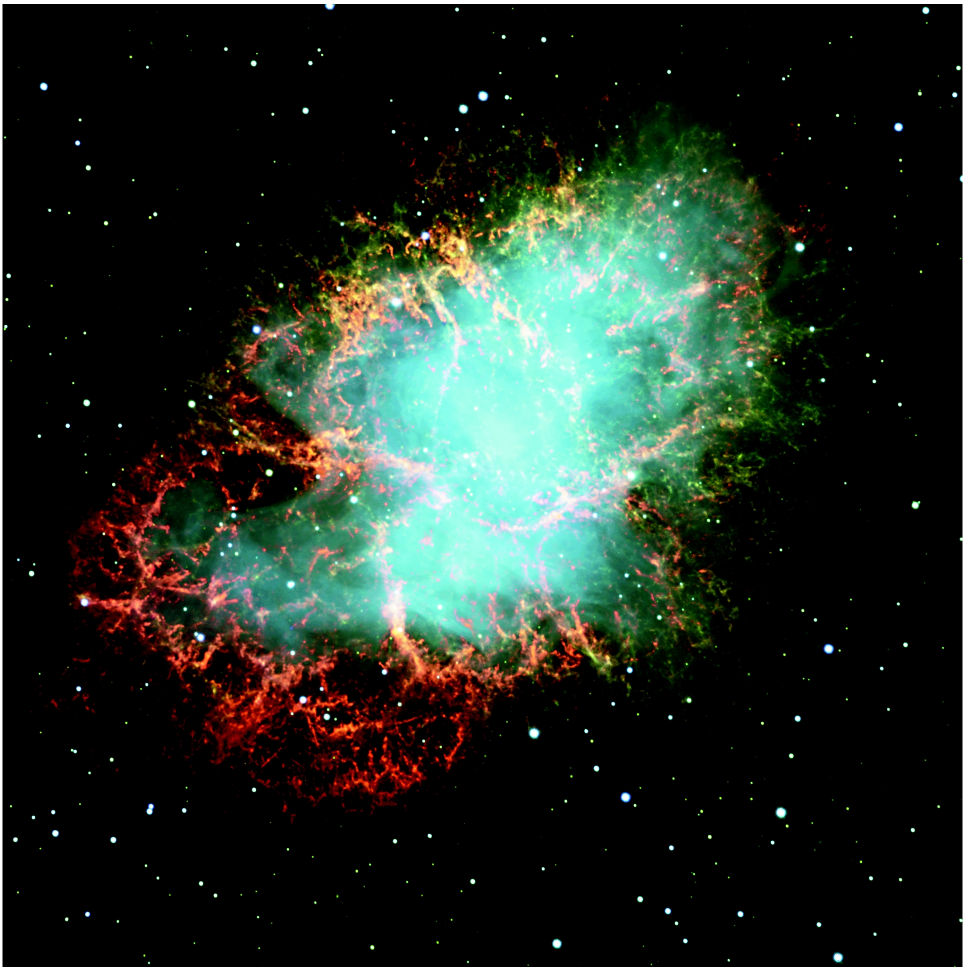


FIGURE 2.1 Crab Nebula in the optical. The Crab Nebula, a supernova remnant whose parent supernova was recorded by Chinese astronomers in the summer of A.D. 1054, is a beautiful example of a relatively young remnant, whose appearance is thought to be largely driven by particle acceleration processes tied to the Crab Pulsar; the observed radiation is due to synchrotron emission from highly relativistic electrons accelerated within the structure seen in this image. The precise nature of the connection between the pulsar and its magnetosphere, and the surroundings, remains uncertain. Courtesy of the European Southern Observatory.

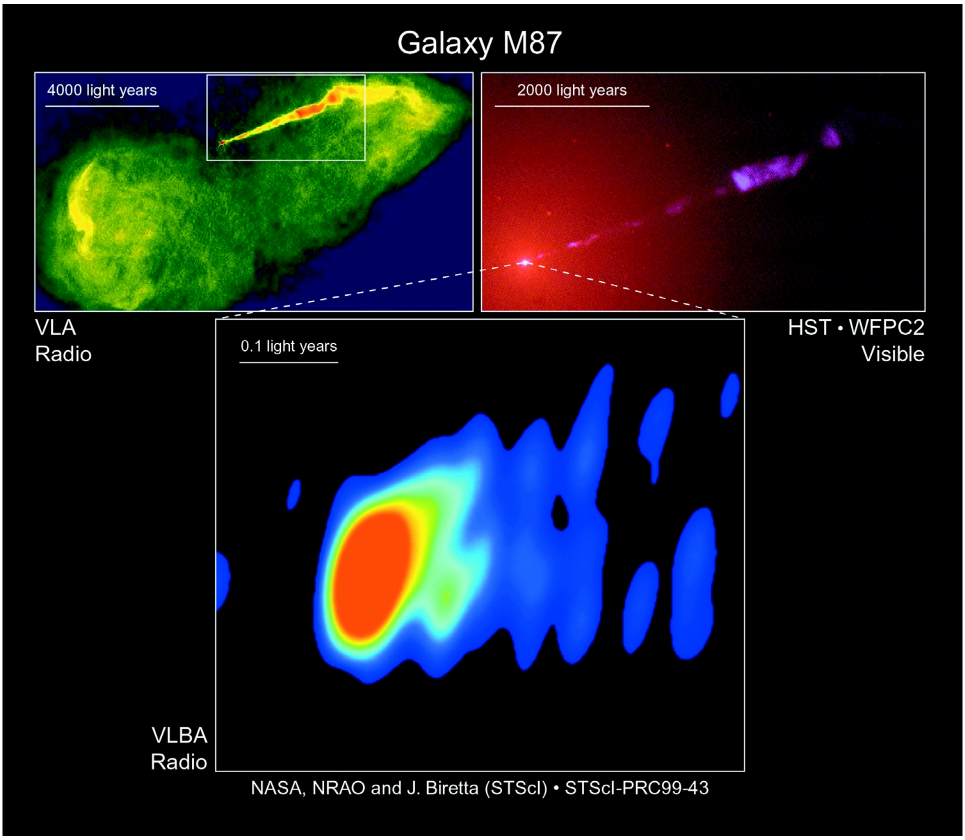


FIGURE 2.2 Jet formation. Images of the active galaxy M87. Using a variety of high angular resolution observations, astrophysicists have been able to disentangle the spatial structure of jets emanating from the core of active galaxies. Such jets present a wealth of unsolved physics problems, ranging from the precise composition of the material composing the jet itself, to its stability, and—most uncertain—its ultimate origin: acceleration to relativistic energies and remarkable collimation. The "engine" producing these jets is most likely one of the most extreme physical environments encountered in astrophysics, namely, the vicinity of a massive black hole lying near the core of active galaxies (see Figure 2.6 in this chapter). Courtesy of W. Junor, University of New Mexico/Los Alamos National Laboratory; and J.A. Biretta and M. Livio, Space Telescope Science Institute.

THE FUNDAMENTAL QUESTIONS FOR HIGH ENERGY DENSITY ASTROPHYSICS

How Does Matter Behave Under Conditions of Extreme Temperature, Pressure, and Density?

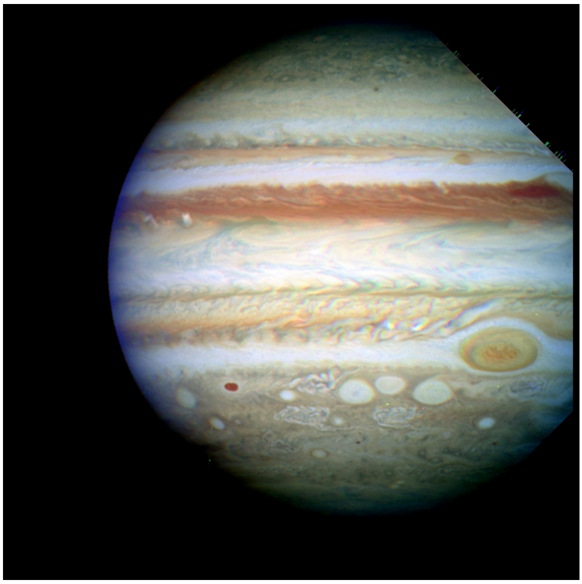
A fundamental quest of physics is to determine the properties of matter—its equation of state, its opacity, and its transport properties (thermal conductivity, viscosity, particle diffusivity, electrical conductivity, and so on). The universe offers a huge range of conditions for matter, far beyond what can be directly obtained in a terrestrial laboratory setting. Following are some examples of new opportunities for studies of matter under extraordinary conditions, spanning both laboratory and astrophysical settings.

The Origin and Evolution of the Giant Planets and Brown Dwarfs and of Planetary Interiors

The discovery of extrasolar planets and brown dwarfs represents one of the most exciting astronomical developments of the decade. The newly discovered planets tend to be giant gas planets with small, highly eccentric orbitals. These new "hot giants" raise many questions about existing models for planetary formation and planetary interiors. Models exist for the interiors of the extrasolar planets as well as for the solar planets, but these models rely upon a quantitative understanding of cold, dense matter at extreme pressures. At such high pressures, the matter is pressed so closely together that the outer electronic orbitals overlap, causing pressure ionization. This serves as an energy sink, which affects the compressibility. Such coupled quantum-mechanical–thermodynamic effects are notoriously difficult to calculate theoretically.

In order to solve the many fundamental questions of planetary formation, evolution, and structure, it is essential to improve our understanding of hydrogen in the ultrahigh-pressure environment found in the interior of brown dwarfs and giant planets. This environment is characterized by moderate temperatures of order 0.1 to 1 eV, and extreme pressures of order 1 to 10 Mbar. Under these conditions, hydrogen is expected to form a degenerate strongly coupled plasma/fluid. The basic thermodynamic properties of such plasmas are still incompletely characterized.

In the specific case of the interior of Jupiter (see Figure 2.3), model calculations predict that molecular hydrogen (H_2) dissociates to atomic hydrogen and ionizes in the mantle, changing from a dielectric to a conductor. The relevant pressure and temperature for this transition is 0.5 to 5 Mbar at temperatures of a fraction of an electronvolt. Deeper in the interior of Jupiter, the pressure and temperature increase to above 40 Mbar and a few electronvolts near the center. For reference, the



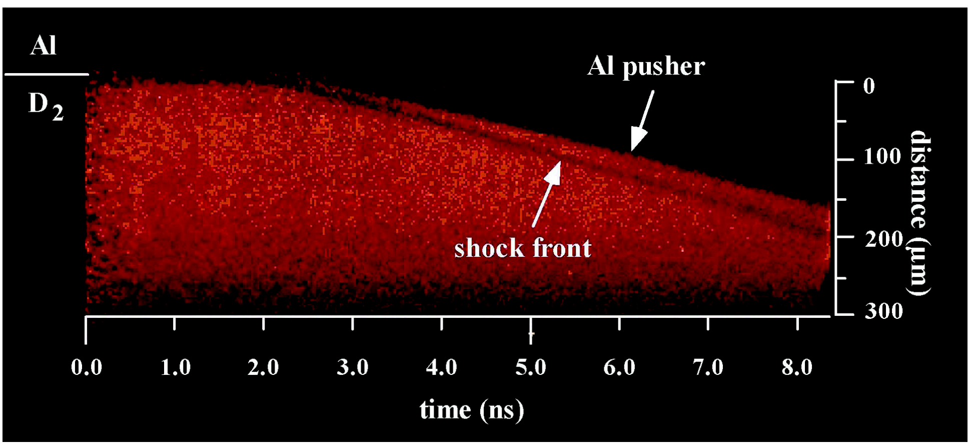


FIGURE 2.3 Planetary interiors and their equation of state. The internal structure of the giant gaseous planets, such as Jupiter shown in the top image, is an ongoing puzzle, primarily because of uncertainties regarding the properties of matter at extreme pressures. One of the few ways to explore such questions experimentally is to probe the relevant materials (primarily hydrogen) in lasers and magnetic pinch facilities, which give us access to the relevant physical regimes; an example of such an experiment is shown in the image on the bottom, drawn from an equation-of-state experiment carried out at a laser facility. The ultimate aim of such studies is to be able to discriminate between different planetary formation models. Courtesy (top) of NASA and Space Telescope Science Institute, and (bottom) R. Cauble and G. Collins, Lawrence Livermore National Laboratory.

corresponding conditions for the brown dwarf GL 229 are similar in the mantle, but 4 orders of magnitude higher in pressures at the core, $P_{core} \approx 10^5$ Mbar. The molecular dielectric to atomic metallic transition in hydrogen ($H_2 \rightarrow H^+ + H^+$) is important because convection of pressure-ionized, metallic hydrogen is thought to create the 10 to 15 gauss magnetic field of Jupiter. Of particular concern is whether a first-order plasma phase transition exists, as this critically affects the internal structure in the important convection zone and the degree of gravitational energy release due to sedimentation of helium (He) and heavier elements. Jupiter and Saturn's atmospheres are observed to be helium-poor, and the energy release from helium sedimentation is required to explain Saturn's intrinsic heat flux.

Among the open questions are these:

- What is the phase diagram of high-pressure hydrogen?
- Is there a (first-order) plasma phase transition?
- Does hydrogen form a metallic state at high pressure?
- What is the solubility of other chemical elements (especially He) in a high-pressure hydrogen plasma? Can H and He become immiscible, with the formation of "He rain," at high pressure and density?

In addition, transport properties in general (such as electrical and thermal conductivity) are poorly understood, but are essential if we are to understand dynamical processes such as magnetic field generation and thermal convection.

An improved understanding of hydrogen in the high-pressure regime would directly impact the following fundamental questions of planetary science:

- What is the structure of a gas giant as a function of depth?
- Where (and what) is the region within which the magnetic field is generated?
- Are such planets fully convective?
- Do these planets form by direct collapse of the solar nebula, or do they form around a preexisting rock-ice core? By inferring the core conditions of Jupiter, can the planetary formation mechanism for the solar system be inferred?
- What high-pressure chemistry goes on within such planets?

While much of the hydrogen equation of state is well known, many of the important questions require accuracy at the 1 percent level in density for a given pressure and temperature. (For example, 1 percent of Jupiter's mass is 3 Earth masses, comparable to the postulated core mass.) Transport properties are currently much less-well understood, and even a factor-of-2 knowledge of the electric and thermal conductivity would be useful. Miscibilities of various cosmically abundant elements in hydrogen within a factor of 2 would also be a great advance relative to current knowledge. It is possible that new experiments involving high energy density plasmas may soon be able to answer these questions, while improved astronomical observations will allow us to explore more fully the mass range of extrasolar giant gaseous planets down to values characteristic of such planets in our solar system.

Another area of interest is the atmosphere and envelope of white dwarfs. Accreting white dwarfs are thought to be the starting point of Type Ia supernovae, which in turn are used as "standard candles" to map out the expansion of the deep universe. Cooling white dwarfs can be used as "clocks," or cosmochronometers, to determine the age of regions of the Galaxy. An understanding of the equation of state, opacity, and heat conductivity in the atmospheres and envelopes of white dwarfs would be very beneficial, and may be experimentally accessible, especially with future facilities, as described in this subsection.

Experimental techniques are being developed on pulsed-power facilities, lasers, gas guns, and diamond anvil cells to probe the properties of matter under extreme conditions of pressure and compression. The conditions achieved to date cover pressure ranges of 0.1 to 40 Mbar in equation-of-state measurements, planar shock pressures of up to 750 Mbar in a proof-of-principle demonstration experiment, and ≈10 gigabars (Gbar) at the core of an imploding spherical capsule. Using modern pulse shaping techniques on lasers and on magnetic pinch facilities, pressures in the megabar regime under quasi-isentropic compressions have been achieved. In the coming decade, with the advent of the National Ignition Facility and Laser Megajoule (LMJ) lasers, this parameter space will be filled in and extended. On these future facilities, quasi-isentropic compressions of well over 10 Mbar should be possible. These laboratory conditions correspond to the interiors of terrestrial and giant gas planets, brown dwarfs, average mass stars, and the envelopes of white dwarfs. Even the simplest case studied experimentally so far, the equation of state of hydrogen, shows the humbling complexity of the behavior of matter under extreme conditions of compression. To develop and have confidence in theoretical and numerical models that pertain to the interiors of the astronomical objects referred to above will require experimental data to guide the way.

Strongly Coupled Plasmas

Most of our understanding of plasmas comes from study of tenuous, ionized gases, in which the electromagnetic behavior is a modest modification of the simpler gas behavior. This Debye (weak coupling) limit breaks down as density increases and/or temperature decreases. At the other extreme, we are familiar with the liquid and solid states. The intermediate condition, "strongly coupled" plasmas, is complex and challenging to understand theoretically. It corresponds to the conditions in giant planets, brown dwarf and white dwarf stars, and the progenitors of Type Ia supernovae. It occurs naturally in HED plasma experiments, and a fertile interaction between astronomy and HED plasma physics has begun in this area. (See Figure 1.1 in Chapter 1 and Figure 3.3 in Chapter 3 for a summary of relevant regimes.) The line labeled E(coulomb) = kT in Figure 1.1 represents the boundary for strongly coupled plasmas: they lie to the right (at higher density).

The Opacities of Stellar Matter

Historically, one of the oldest areas of overlap between HED plasma physics and astronomy has been the radiative opacity of matter. The opacity of stellar plasma controls the rate at which energy leaks from stars, that is, their luminosity. If large enough, opacity causes the onset of mixing currents which, in turn, modifies the structure of stars and their evolution. For example, a well-mixed Betelgeuse would be blue, not red. The bumps in the opacity curves (the changes with temperature and density) can drive pulsations and probably mass loss. Cepheid pulsating stars are the other cosmological yardstick.

Type Ia supernovae provide a particularly fundamental and important challenge: the luminosity and effective temperature we observe is governed by leakage of light from the plasma, but the expansion is so great that the light is red-shifted between emission and absorption, making the probability of its escape too difficult to solve accurately. Observations of these supernovae seem to imply that the universe is expanding at an accelerated rate, contrary to prediction. This conclusion is based on empirical rules for behavior of relatively nearby supernovae, and involves a light curve shape-luminosity correction based on an opacity hypothesis. An understanding based on laboratory experiment would be much more compelling. For example, measurement of the radiation transport in a rapidly expanding, inhomogeneous, fully three-dimensional target would greatly contribute to our understanding of the behavior of Type Ia supernovae.

The error budget for the ages of stellar clusters is dominated by uncertainties in opacity. Continued refinement of our knowledge will allow us to better place a time scale on the formation and development of our Galaxy and nearby galaxies.

Degenerate Plasma Convection

Type Ia supernovae, novae, and the core helium flash are supposed to be initiated under conditions of strong degeneracy of electrons. Thermonuclear burning begins in a degenerate plasma and proceeds to thermal runaway; as the temperature rises in the flame region, a convective instability develops and eventually proceeds to explosion. Similar convective motions under degenerate plasma conditions—

albeit without the local nuclear burning and possible runaway—are thought to occur in the outer regions of brown dwarf stars. Unfortunately, there are no experimental data on convection in an (electron) degenerate plasma; thus, unlike the case of, for example, Boussinesq convection, very little is known about degenerate convection. For this reason, both experiments and fundamental theory and simulations directed at convection under degenerate conditions are very important.

Physics of Nuclear Burning

Historically, the study of nuclear reactions has been based on acceleration of particles and study of their scattering off a target. In a burning plasma, one must also account for the effects of the more complex environment. Instead of bare nuclei, the "projectile" and the "target" have an associated cloud of electrons, and there are other ions and their electrons around. A short term for these additional effects is "screening." At present, a debate rages over the question of whether plasma screening of reacting nuclei is static or dynamic. As plasmas so often exhibit subtle behavior, even sophisticated physical models can be misleading.

In the Sun, the plasma screening only affects the reaction rate at the level of a few percent. However, in progenitors of supernovae, the screening factors are large (a few million), which makes a purely theoretical estimate dubious. A better theory would result from experimental tests, making the necessary extrapolation to more extreme conditions more reliable.

Detailed laboratory measurements could settle these important issues. HED experiments promise to allow the study of a nuclear-burning plasma, that is, the source of stellar energy. Accelerator experiments have provided means to study nuclear reactions in a piecemeal way; HED experiments will allow us to place the phenomena into the context of a burning plasma. In estimating the rate of stellar nuclear reactions, some assumptions about the plasma medium must be made; HED experiments will allow these to be tested directly. As Figure 1.1 shows, the experimentally accessible range already overlaps stellar conditions of temperature and density. Well over 99 percent of the stars in the sky are burning hydrogen and/or helium, and there conditions are mostly in the range that is now available to OMEGA and will be available to NIF.

Stellar burning is slow because the basic fusion reactions that the stars use are slow. Experiments with burning plasmas that are based on faster reactions are feasible—in fact, that is one way of expressing the goal of thermonuclear ignition for NIF. Burning plasma experiments will allow us to study the same process, if not the identical reactions, that powers the stars.

The Nature of Matter at the Extremes

The quark-gluon plasma is a new phase of matter—in the sense that it has not yet been detected in the laboratory—whose elementary constituents are the quarks, antiquarks, and gluons that make up the strongly interacting particles. It is also the oldest phase of matter, the form of matter that filled up the early universe, until the first few microseconds after the big bang. Appropriate for this report, quark-gluon plasmas are the densest plasmas in the universe. They may possibly be present deep in the cores of neutron stars, and may even be made in stellar collapse. To probe the densest states of nuclear matter, the nuclear physics community has embarked on a large-scale program of studying collisions of ultrarelativistic heavy ions, at Brookhaven National Laboratory and the European Organization for Nuclear Research (CERN). A major step in the program is the construction of a large colliding beam accelerator at Brookhaven—the Department of Energy's Relativistic Heavy Ion Collider (RHIC)—which will provide the capability of colliding nuclei as heavy as gold on gold at 100 GeV per nucleon in the center of mass (equivalent to 20 teraelectronvolts [TeV] per nucleon in a fixed target experiment), and should, early in this century, enable one to produce and study quark-gluon plasmas in the laboratory.

The basis for expecting a quark-gluon plasma at high densities or temperatures is that quite generally as matter is heated or compressed, its degrees of freedom change from composite to more fundamental. For example, by heating or compressing a gas of atoms, one eventually forms a plasma in which the nuclei become stripped of the electrons, which go into continuum states forming an electron gas. Similarly, when nuclei are squeezed (as happens in the formation of neutron stars in supernovae where the matter is compressed by gravitational collapse), they merge into a continuous fluid of neutrons and protons. Nucleons and the other strongly interacting particles, or hadrons, are made of quarks that are confined to the individual hadrons. One can thus go a step farther and predict that a gas of nucleons, when squeezed or heated, turns into a gas of uniform quark matter, composed of freely roaming quarks, and at a finite temperature, antiquarks and gluons—the mediators of the strong interaction. The physics is basically the same as that leading to the formation of ordinary plasmas.

The regions in the phase diagram of matter in the temperature-baryon density plane where quark-gluon plasmas are expected to occur are outside the phase space included in Figure 1.1 in Chapter 1. In the low-temperature–low-baryon-density region, the basic degrees of freedom are hadronic, those of nucleons, mesons, and internally excited states of the nucleon, while in the high-temperature–high-baryon-density regions (temperatures above about 200 MeV, equivalent to a few times 10^{12} K, and densities of order 5 to 10 times the density of matter inside a large nucleus, approximately 0.16 particles per cubic femtometer [fm^{-3}], equivalent to

2×10^{14} grams per cubic centimeter [g/cm^3]), the basic degrees of freedom should become those of quarks and gluons. The transition between these regions may be first or second order, or not a sharp transition at all, but washed out. Under any circumstances, the physics between the two regimes changes strongly.

Where are quark-gluon plasmas expected to occur in nature? In the first microseconds of the early universe, the temperature falls as $T \approx 1$ MeV $t_{sec}^{-1/2}$, so that prior to around 5 to 10 microseconds (μs) after the big bang, when temperatures are above hundreds of MeV, matter is in the form of a quark-gluon plasma and follows the downward trajectory practically along the vertical axis of the phase diagram. The matter of the early universe has a relatively small net baryon density, of order 1 part in 10^9 (as inferred from the present photon/baryon ratio). As the universe expands, it cools, and matter hadronizes, undergoing the reverse of the deconfinement transition and emerging primarily in the form of pions, with a slight baryon excess. If the transition is first-order, one expects the formation of bubbles of hadrons—the ordinary neutrons, protons, and pions—in the middle of the plasma.

A second possible astrophysical situation in which quark-gluon plasmas might play a role is in neutron stars. Measured masses of neutron stars are ≈1.4 solar masses, with radii calculated to be about 10 km. Typical temperatures are relatively low, less than 1 MeV. The central density in a neutron star can reach 5 to 10 times the density inside an ordinary atomic nucleus and may be in the form of a quark plasma. Not only may neutron stars have quark cores, but one cannot rule out the possibility that there exists a distinct family of quark stars with higher central densities than that of neutron stars. The order of the quark-gluon phase transition may have important implications for gravitational-wave radiation from stellar collapse.

A third astrophysical situation in which these issues arise is the formation of neutron stars and black holes by the gravitational collapse of stars. Any discussion of the source of energy for gamma-ray bursts (GRBs) and core collapse supernova explosions, as well as of the nature of the formation of the dense remnants, requires assumptions regarding the equation of state of (warm) matter at and above nuclear densities. This regime lies between that of the big bang (hot) and neutron stars (cold), and involves similar questions of physics.

The only reliable approach at present to determine the properties of strongly interacting quark-gluon plasmas and the deconfinement transition is through Monte Carlo calculations of lattice gauge theory. These calculations require very large computing capabilities to achieve good statistics on large lattices. Lattice gauge theory is approaching the point at which it will be able to give quantitative information on the properties of quark matter over large ranges of temperature and also baryon density. Calculations to date have been successful only for the case of zero baryon density at finite temperature, and the results depend strongly on the masses assumed for the quarks. Lattice gauge calculations at nonzero baryon density are beset by technical problems; we do not have a reliable estimate of the transition density at $T = 0$ from nuclear to quark matter, or even compelling evidence that there is a sharp phase transition. In the absence of a good theory of the equation of state at very high densities, the question of whether neutron stars can have quark matter cores remains open, as is the issue of whether a distinct family of quark stars with higher central densities than those of neutron stars can exist.

The Most Energetic Particles in the Universe

It has long been known—since the early 20th century—that Earth is constantly subjected to showers of extraordinarily energetic particles, ranging in energy from kiloelectronvolts up to the remarkable value of over 10^{20} eV.

Collisionless Shocks and Cosmic-Ray Acceleration High-Mach-number collisionless shocks present an environment in which turbulence must have quite a different character from that of ordinary hydrodynamic turbulence. Here suprathermal particles and cosmic rays create a nonlinear wave spectrum through velocity space instabilities that scatter these particles which, in turn, are important in moderating the shock. These instabilities are referred to by the astrophysics community as *magnetic hoop instabilities* and by the laboratory HED community as *hosing instabilities*, *Weibel instabilities*, or *filamentation instabilities*. However, we do not understand the nature of this turbulence or even if it is stationary. Laser and beam instability experiments carried out in large chambers filled with magnetized plasma are quite capable of creating collisionless shocks, the properties of which can be studied.

A key question for many of these fluid issues is the character of the microphysical dissipation at the smallest scale of a turbulence spectrum, in an anomalously resistive reconnection site, and at a shock front. Theories abound, but confident understanding is rare. Turbulence has been proposed to terminate through reconnection, ion cyclotron resonance, or transit time damping. The partition of the dissipated energy between the ions and the electrons controls the dynamics and the radiative properties of the flow. Anomalous resistivity is rarely invoked astrophysically, although much is already understood experimentally. High-Mach-number shock dissipation is barely observed from spacecraft measurements and not understood at all. Relativistic shocks, which are central to the most energetic and interesting phenomena, must be quite different on purely kinematic grounds, as magnetized particles cannot outrun or catch the shock.

What Is the Origin of the Highest-Energy Particles in the Universe? Cosmic rays with energies above 10^{20} eV have been detected by a number of ultrahigh-energy cosmic ray (UHECR) experiments. In 1991, the largest fluorescence detector, the High Resolution Fly's Eye, recorded a surprising event with 3×10^{20} eV, or about 50 joules (J), which is comparable to the kinetic energy of macroscopic objects such as baseballs. Presently, the largest operating ground array, the Akeno Giant Air Shower Array (AGASA), has now measured 10 events above 10^{20} eV, while the Fly's Eye fluorescence detector has observed about 2 events above 10^{20} eV. These events are detected either through the fluorescence light generated by the electromagnetic cascade produced as the UHECR interacts in Earth's atmosphere or by direct detection of the cascade particles in ground arrays. The data were calibrated by numerical shower simulations, and typical energy errors are estimated to be 10 to 20 percent.

These UHECR events have an unexpectedly high flux and a surprisingly isotropic arrival directional distribution. If these particles are protons, the galactic magnetic field is not strong enough to contain them, and the sources are most certainly extragalactic. The flux observed on Earth from extragalactic high-energy proton sources are expected to have a large drop at energies around 10^{20} eV, due to the interaction of UHE protons with the cosmic microwave background radiation. This drop is due to the threshold for pion production by protons interacting with the background radiation; it is known as the Greisen-Zatsepin-Kuzmin (GZK) cutoff. The lack of a GZK cutoff challenges most astrophysical acceleration models and is often claimed as evidence for new physics at the highest energies.

HED plasmas play a key role in many aspects of this problem. First, the observations of such particles are made through the sampling of showers in the atmosphere. Large systematic errors arise from the lack of direct calibration of the shower development codes and from the different techniques used in ground arrays versus fluorescence detectors. Recent studies have shown that validation of shower simulations can be achieved by studying showers in a hybrid high-energy physics and plasma physics laboratory, such as the high-intensity particle and photon beam facility proposed as a Laboratory for Astrophysics at the Stanford Linear Accelerator Center (SLAC).

A second key role for HED plasmas is in explaining the nature of the astrophysical accelerators proposed as the origin of UHECRs. The most common extragalactic accelerator proposals involve shock acceleration in a number of astrophysical sources such as active galactic nuclei (AGN), radio lobes and jets around AGN, cluster shocks, and gamma-ray bursts. One possible resolution for the UHECR puzzle involves a new source of extragalactic UHE protons with a surprisingly hard (high-energy) injection spectrum. It is yet to be shown that shock acceleration can reach the spectral and maximum energy requirements on any known source. Fast reconnection is often invoked, but precise spectrum predictions in these alternative models are still lacking. The hardest predicted spectra are reached by relativistic magnetohydrodynamic (MHD) winds created in unipolar inductors around fast-spinning, highly magnetized neutron stars. These powerful magnets can be sites where heavy nuclei are accelerated in the Galaxy or in the Local Group—a group of galaxies about 3 million light-years in diameter, which contains our Galaxy, the Milky Way. The propagation of heavy nuclei in the Galaxy can still be diffusive at these highest energies, depending on the structure of the galactic magnetic field. Unipolar inductors may also be active in accretion disks around massive black holes. The detailed understanding of these relativistic MHD processes requires both theoretical and numerical advances as well as experimentally validated studies of the numerical simulations.

The propagation of the UHECRs from source to Earth probes magnetized plasmas on the largest scales in the universe, the scales of clusters and superclusters of galaxies. The strength and structure of extragalactic magnetic fields are largely unknown. There is evidence for magnetized large-scale regions in clusters and between clusters, but the origin of magnetic fields on the large scales are still unknown. On the largest scales, the strength and structure of extragalactic fields are loosely constrained by indirect observations such as Faraday rotation of emission from high redshift quasars. The study of the origin and evolution of magnetic fields in galaxies and in clusters and superclusters of galaxies plays a key role in predicting the propagation of UHECR in the extragalactic medium, while observations of UHECR correlations can, in principle, give the strongest constraints on the largest-scale magnetic fields in the universe. AGASA data show a significant correlation of events on small angular scales (about 2°). If these small-scale correlations are confirmed to be extragalactic sources by future experiments such as the international Pierre Auger Observatory project, the extragalactic magnetic field will be most strongly constrained.

In the near future, detection of UHECRs with the Pierre Auger Observatory will greatly improve the data at the highest energies. The broad characteristics of the highest energy accelerators in nature will be unveiled. Detailed understanding of acceleration and propagation of the highest-energy particles ever observed demands a coordinated effort from the plasma physics, particle physics, and astrophysics communities.

Cosmic Magnetic Fields and Their Impact

Observations indicate that the universe is pervaded by magnetic fields, from Earth's interior and immediate surroundings (its magnetosphere) to the interplanetary medium, the Sun itself, the interstellar medium, and even the space between galaxies. The origin of these magnetic fields remains a mystery, including especially the origins of magnetic fields in astronomical objects specifically relevant to HED astrophysics—the magnetic fields of neutron stars and giant gaseous planets.

Over the past few decades, however, substantial progress has been made in the fundamental understanding of the general magnetic-field generation (the "dynamo problem"); and in a specific case, namely Earth, a fairly complete understanding of why it has pervasive magnetic fields appears close. These results are due to a combination of observational, theoretical, and large-scale numerical computational studies. A similarly detailed understanding of the origin of Jupiter's magnetic fields, or of the magnetic fields of neutron stars, is still absent. In these cases, models have been proposed, but the detailed calculations and measurements that would allow an understanding of how these magnetic fields came to be present have not been carried out.

If magnetic fields were simply passive constituents of the universe, then the question of origin would not be particularly pressing. However, magnetic fields are far from passive—indeed, it has been said that magnetic fields are what prevent stars from being simple self-gravitating gas spheres: the phenomenon known as stellar activity, which in the case of the Sun is manifested by its sunspot cycle, its corona, and the dramatic surface phenomenology (ranging from solar flares to coronal mass ejections, see Figures 2.4 and 2.5) all are thought to be a consequence of the interaction between magnetic fields and conducting astrophysical fluids. Indeed, magnetic fields play significant roles in a number of astrophysical phenomena. A few examples of those roles are illustrated below.

Solar and Stellar Activity There has been a revolution in solar physics. We are now able to watch magnetic instability and topological rearrangement of field lines on the surface of the Sun under conditions that are not dominated by solid boundaries, fixed magnets, and initial conditions. The slow winding and squeezing of flux tubes below the photosphere make it restless and explosive. Laboratory experiments interpreted with large numerical simulations are starting to bring out the principles, notably those involving magnetic helicity, that determine how the field rearranges itself.

Astrophysical plasmas are famous for their impressively large magnetic Reynolds numbers, with dissipation almost always and everywhere negligibly small. However, just as in aerodynamics, it is the exceptions that make all the difference. They control the heating of the solar corona and the launching of the solar wind. They determine the circulation of planetary magnetospheres and the emissivity of accretion disks. One key effect is magnetic reconnection, which remains a highly controversial topic. We do not know if and when it is "fast." We do not agree if heating occurs mostly on small scales, in nanoflares, or on large scales. In addition, new modes of reconnection are mathematically possible, but we do not know how relevant they are in practice. It is likely that most of the current flow occurs in thin sheets and filaments, as opposed to uniformly, and this has a major impact on the

FIGURE 2.4 TRACE probe image of solar surface. This image of a portion of the multimillion-degree solar corona, taken through the 171-angstrom passband of the TRACE satellite, shows the characteristic emergence of a large-scale structure—the so-called coronal loops—whose appearance is apparently controlled by physical processes on far smaller spatial scales. Because we can resolve these structures, the Sun's activity can serve as an astronomical Rosetta stone for decoding spatially unresolved observations of much more distant astrophysical objects in terms of physical processes that can be explored in terrestrial laboratories. Courtesy of NASA and Stanford-Lockheed Institute for Space Research.

stability properties. What experience we have from tokamak physics research has not permeated the astrophysical community.

As with regular fluids, turbulence is central to MHD. It can be studied using radio waves propagating through the interplanetary and interstellar media, and it appears to be anisotropic. In the incompressible limit, the governing principle appears to be that as energy cascades to smaller scales, the field gradient becomes more strongly directed perpendicular to the mean magnetic field, with implications for reconnection. Applying these ideas to understanding the nature of dissipation in

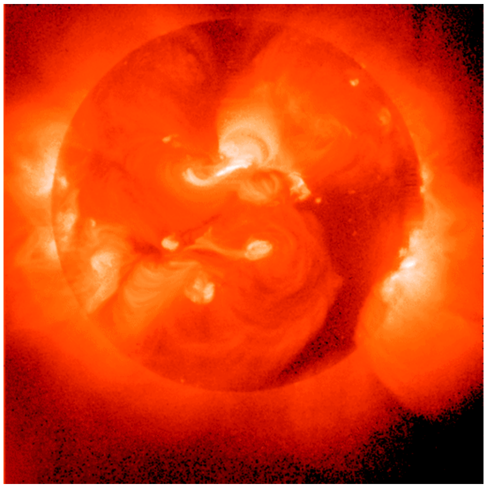


FIGURE 2.5 Yohkoh x-ray image of the Sun. This soft x-ray image of the full-disk Sun, taken by the U.S.-built Soft X-ray Telescope (SXT) onboard the Japanese Yohkoh satellite, illustrates the remarkable propensity of astrophysical objects to produce magnetic fields on spatial scales ranging from the smallest resolvable scales to the scale of the system taken as a whole. In the case of an object such as the Sun, this field generation—the stellar dynamo—leads directly to solar "activity," accompanied by particle acceleration, vigorous (transient) plasma heating, and occasional huge mass ejections into the interplanetary medium. Courtesy of Lockheed-Martin Solar and Astrophysics Laboratory, the National Astronomical Observatory of Japan, the University of Tokyo, the Japanese Institute of Space and Astronautical Science, and NASA.

accretion disks is problematic. We are not sure if an inertial range turbulence develops or if the cascade is to large scales or takes the form of Alfvén waves that escape the disk altogether. Numerical simulations are playing a large role here, but there is an opportunity for beam-plasma experiments in which we generate turbulence at an interface as well.

Accretion Disk Magnetic-Field Dynamics: Magnetohydrodynamic Turbulence and Angular Momentum Transport Accretion is the main source of energy in many astrophysical objects, including binary stars, binary x-ray sources, and quasars and active galactic nuclei. While the first development of accretion theory began a long time ago, intensive development of this theory began after the discovery of the first x-ray sources. Accretion onto stars, including neutron stars, terminates at an inner boundary. This may be the stellar surface or the outer boundary of a magnetosphere for a strongly magnetized star. In this case, all of the gravitational energy of the infalling matter is transformed into heat and radiated outward.

The situation is quite different for accretion to black holes (see Figure 2.6), which are deduced to be present in some binary x-ray sources in our Galaxy as well as in active galactic nuclei. Here, matter falls into the event horizon of the black hole, and no radiation escapes from within it. The radiative efficiency of accretion is not known a priori, in contrast with the case of accretion onto a star, and depends strongly on factors such as the angular momentum of the incoming matter and the magnetic field embedded in it. For spherical accretion of nonmagnetized gas, the efficiency of radiation may be as small as 10^{-8} for low mass accretion rates; the presence of a magnetic field in the accreting matter can increase the efficiency up to

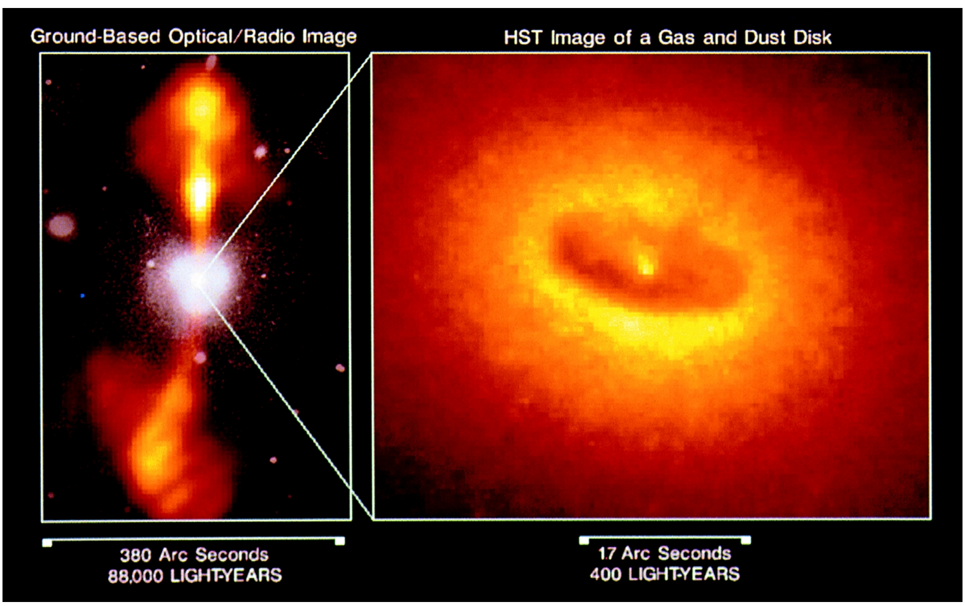


FIGURE 2.6 Spectroscopy of emission from accreting black-hole systems, together with modeling and laboratory experiments (such as on the Z-machine, where similar values of the photoionization parameter to those characterizing the astrophysical system can be achieved), allows us to understand the spectral signatures characterizing the dynamics and conditions of matter as it spirals into a black hole. Courtesy of W. Jaffe, Leiden Observatory, the Space Telescope Science Institute, and NASA.

about 10 percent. Recent attention has focused on advection-dominated accretion flows and convection-dominated accretion flows, where it is possible that the efficiencies are much less than 10 percent. Understanding the low efficiencies is crucial to understanding the very low luminosities of some black holes, such as that in the center of our Galaxy. The low luminosities may also result from jets and outflows.

The viscosity is the most speculative aspect of current accretion disk theory and modeling. The viscosity generally acts to transport angular momentum outward, away from the star or black hole, facilitating the accretion of matter. In the laminar case of microscopic (atomic or plasma) viscosity, which is very small, a stationary accretion disk must be very massive and very thick; in this limit, it is known that the accretion rate onto the central object must be very small. This contradicts observations of x-ray binaries, where a considerable accretion rate is required. This can be explained only when the viscosity coefficient is much larger than the microscopic one; for example, if matter in the disk is turbulent, one can parameterize the viscous stress tensor as $t_{r\phi} = -\alpha\rho v_s^2 = -\alpha p$, where α is a dimensionless constant ≤ 1, v_s is the sound speed, ρ is the density, and p is the pressure. This simple parameterization corresponds to a turbulent viscosity coefficient $\eta_t \approx \rho v_t l$ with an eddy velocity v_t and a length scale of the turbulent element l. The expression for $t_{r\phi}$ with $l \approx h$, with h the half-thickness of the disk, becomes $t_{r\phi} = \rho v_t h r(\mathrm{d}\Omega/\mathrm{d}r) \approx \rho v_t v_s = -\alpha\rho v_s^2$, where the relation between turbulent and sound speeds is $v_t = \alpha v_s$.

The development of turbulence in an accretion disk cannot be explained simply. A Keplerian disk is stable in the linear approximation to the development of axially symmetric perturbations, conserving angular momentum. That is, the disks satisfy the Rayleigh criterion for stability. It has been proposed that in the presence of very large Reynolds numbers, $Re = \rho v\, l/\eta$ about or greater than 10^{10}, the amplitude of perturbations at which nonlinear effects become important is very low, so that turbulence may develop due to nonlinear instability even when the disk is linearly stable. Whether this mechanism works can in principle be tested via simulations; but such studies must await advances in simulation capabilities to allow systematic direct numerical studies of fully turbulent flows.

A magnetohydrodynamic instability as a source of the turbulence in accretion disks has been studied extensively by linear stability studies and MHD simulations during the past several years. The linear instability—the magnetorotational instability—was originally discovered in the late 1950s, but rediscovered and applied for the first time to accretion disks by astrophysicists in the 1980s; it occurs for a weak magnetic field in a differentially rotating disk (Alfvén speed < sound speed). In this context, there has been a considerable development of MHD simulations of turbulence and the associated viscosity coefficient α_{MHD}, and they now involve full three-dimensional parallelized Eulerian grid calculations running on large numbers of processors. This problem represents an important test case for compressible MHD simulation codes and techniques in that the linear theory is well understood. This instability could be important in the absence of any other source of turbulence and if the magnetic fields are sufficiently weak. Stronger fields probably occur in actual disks, and unstable singular modes have been recently discovered in a strongly magnetized accretion disk. This represents a promising area of future study for both linear stability analysis and MHD simulations.

A fundamental limitation on the MHD simulations of accretion flow turbulence is that the flows are only weakly collisional: the smallest scale of the turbulence (about a gyroradius) is much smaller than the mean free path. This is very different from turbulence in, say, the atmosphere, where the Navier-Stokes equations provide in principle a complete description. In fact, the entire issue of the smallest-scale dissipation—heating of electrons versus heating of ions—in MHD accretion flow turbulence is open. This dissipation is a crucial issue for advection-dominated accretion flows, and it requires a particle-in-cell type of simulation.

Laboratory experiments to investigate the MHD instability of differentially rotating liquid metals are under way at the New Mexico Institute of Technology, Princeton Plasma Physics Laboratory, and the University of Wisconsin. The experimental setups are similar to those used to create laboratory dynamos, and they suffer from the same limitation that magnetic Reynolds numbers are only moderately large compared with unity. Other experimental approaches need to be explored. The production of transient megagauss (100 kilotesla [kT]) fields in laser-induced explosions is probably due to inertial forces but may still turn out to be relevant to accretion flows. Large magnetic Reynolds numbers are more difficult to achieve in HED experiments because of the large magnetic diffusivity of these plasmas, though values of Re_M of about 10^2 to 10^3 seem feasible.

In addition to the magnetorotational instability, other processes may be important, such as the macroscale hydrodynamic, Rossby wave instability recently shown to occur in nonmagnetized disks that have nonmonotonic profiles of surface density, pressure, and/or specific entropy. The instability has been found in two-dimensional hydrodynamic simulations and has been shown to give rise to a small number (3 to 5) of long-lived vortices that give outward transport of angular momentum. These vortices may have a key role in planet formation in disks around young stars.

Cosmic Jets Powerful, greater than 10^{46} ergs per second (ergs/s) = 10^{39} watts (W), highly collimated, oppositely directed, relativistic jets are observed in many active galaxies and quasars and in old compact stars in binaries (10^{38} ergs/s). These present us with some of the most visually captivating images encountered in astronomy and astrophysics. In some of the most active quasar sources, the electromagnetic emissions extend from the radio about 10^8 hertz (Hz) to extreme gamma-ray energies of about 10^{27} Hz (~10^{13} eV). Further, well-collimated emission line jets with velocities of 100 to 300 km/s are seen in many young stellar objects.

Recent observations, such as the Hubble Space Telescope images of HH 30, and theoretical and simulation studies support models where the twisting of an ordered magnetic field threading an accretion disk acts to magnetically accelerate the jets. The power in the jets is thought to come from matter accretion in the disk, but it may include power extracted electromagnetically from a spinning black hole. There are two main regimes:

1. The *hydromagnetic regime*, where energy and angular momentum are carried by both the electromagnetic field and the kinetic flux of matter, is relevant to the jets from young stellar objects; and
2. The *Poynting flux regime*, where energy and angular momentum from the disk are carried dominantly by the electromagnetic field, is relevant to extragalactic and microquasar jets and possibly to gamma-ray burst sources.

The theory of the origin of hydromagnetic outflows from accretion disks has been developed by many authors, starting from seminal work carried out in the early 1980s. MHD simulations (axisymmetric)—first done using a Lax-Wendroff method—have greatly increased the physical understanding of these outflows. Stationary MHD outflows have been discovered using a Godunov-type method. These stationary solutions have the five constants of the motion predicted by ideal magnetohydrodynamics. Within the simulation region, the outflows are observed to accelerate from thermal speed in the disk to a much larger asymptotic poloidal flow velocity of the order of 0.5 $(GM/r_i)^{1/2}$, where M is the mass of the central object and r_i is the inner radius of the disk. This asymptotic velocity is much larger than the local escape speed and is larger than the fast magnetosonic speed by a factor of about 1.75. The acceleration distance for the outflow, over which the flow accelerates from about 0 to, say, 90 percent of the asymptotic speed, occurs at a flow distance of about 80 r_i. The flows are approximately spherical outflows, with only small collimation within the simulation region. The distance over which the flow becomes collimated (with divergence less than, say, 10°) is much larger than the size of the simulation region. This lack of collimation conflicts with the common notion that the jets collimate due to the pinching force associated with the axial current flow.

Laboratory experiments on supersonic hydromagnetic jets relevant to understanding astrophysical jets can be done using conical, linear, and radial wire arrays in a Z-pinch facility, and the interaction of these flows—both collisional and collisionless—with target plasmas and with counter-propagating flows can be studied. In collisional systems, one can study the region of kinetic energy deposition, the production of radiation, and the generation of shocks. Reducing the target density allows the study of the collisionless penetration of jets into target plasmas. Indeed, experiments on high-Mach-number, hydrodynamic jets and radiatively collapsing jets have been demonstrated both on lasers and on pulsed-power facilities, with internal Mach numbers of 5 to 10 for purely hydrodynamic jets, and Mach numbers as high as 50 to 60 for strongly radiatively cooled jets. Finally, a new class of very energetic, electrically neutral proton jets has been observed on ultrahigh-intensity, short-pulse lasers. The mechanism behind their formation is still being debated, but their existence at energies of up to 100 MeV is well established.

Poynting jets have been discovered in axisymmetric MHD simulations of the opening of magnetic-field loops threading a Keplerian disk. A typical initial disk magnetic-field configuration is a dipolelike field threading the disk where the field lines are in meridian planes ($B_r B_z$ in cylindrical coordinates). The situation is analogous to a “foil-less,” magnetically insulated diode, because the rotation of the disk gives rise to electric potential variation F across the face of the disk (that is, $E_r = -v_\phi \times B_z/c$, owing to the high conductivity of the disk). The potential variations are much larger than $m_e c^2/e$, and they give rise to an outflow of positive and negative charges from the disk plane.

Laboratory simulations of the formation of Poynting jets can be done using a Z-pinch facility by imposing a pulsed potential difference $\Phi > 10^6$ V between cathode and anode surfaces on the disk plane z = 0. Further, an initial dipolelike poloidal magnetic field can be supplied by a coil in the z = 0 plane. A collimated Poynting jet is predicted to occur under conditions where $B_z(0) \approx \mu u_0 I_z /(2\pi r_C)$, where $B_z(0)$ is the dipole field at the system center, I_z is the current outflow from the cathode, and r_C is the radius of the cathode. Appropriate diagnostics would allow measurements of the collimation and energy outflow of such a diode.

Exciting challenges in future magnetohydrodynamic simulation studies are understanding highly relativistic jets or Poynting flows with Lorentz factors of about 10 that are observed to emanate from some active galaxies, and the jets in gamma-ray burst sources that may have Lorentz factors of about 100. Recent progress has been made in the development of robust relativistic magnetohydrodynamic codes, including the Kerr metric of a rotating black hole. Ultimately, we would like to know the following:

- Is there a universal jet formation mechanism operative for stellar, microquasar, active galaxy, and gamma-ray burst jets?
- How do the jets remain collimated for so long?
- Can the central engine dynamics, energetics, and history be inferred from the jet morphology?

A further puzzle is the nature of the acceleration of the radiating particles (electrons, and possibly positrons) that give rise to the observed synchrotron radiation from jets. It has been long recognized that this acceleration must be in situ in at least some jets (such as those of the quasar 3C 273 and the giant elliptical galaxy M87): the very high energy (up to x-ray) of the synchrotron radiation implies radiative lifetimes much shorter than the travel time from the central source. Lepton acceleration may occur in collisionless shocks distributed along the length of the jet. Alternative ideas such as particle acceleration in sporadic reconnection events have also been discussed. Thus, a remaining puzzle for jets is—

- How are electrons and possibly positrons accelerated in jets?

How Does Matter Interact with Photons and Neutrinos Under Extreme Conditions?

Physics seeks to determine how matter interacts with the nonbaryonic components of the universe—ranging from photons to neutrinos to yet more exotic forms of matter. Here again, recent results from astrophysics have led us into new and unusual domains in which these interactions can be studied.

Intense Photoionization: Accreting Black Holes

One of the most exciting areas of modern astrophysics is understanding the nature of accretion-powered compact objects. Many of these are binary systems in which one of the members is a collapsed object such as a neutron star or black hole, in the case of an x-ray binary, or a white dwarf in the case of a "cataclysmic variable." At the extreme end lie the active galactic nuclei and quasars. Their enormous luminosities are thought to result from the energy conversion of matter falling into supermassive black holes at the center of galaxies. The intense x-ray emissions from these compact objects produce photoionized plasma conditions in the infalling accretion disk. One of the goals of high-energy astrophysics is to understand the dynamics of these black-hole accretion disk systems. The most promising observational tool is high-resolution spectroscopy of the emerging x-ray emissions. Two new space-based x-ray observatories currently in orbit, Chandra and XMM, are acquiring high-quality data of just such x-ray emissions. Turning these data into a better understanding of the dynamics of accreting black holes, however, will require a better understanding of photoionized plasmas, both in equilibrium and in nonequilibrium conditions.

Computer models for photoionized plasmas exist, but these complex codes differ in their predictions and have not been directly validated owing to a lack of relevant laboratory data. Modern Z-pinches and large lasers are now capable of generating intense bursts of photoionizing x rays. Experiments on the Z-machine have shown that astrophysically relevant equilibrium photoionized plasmas can be created and diagnosed. It may also be possible to access photoionized plasma conditions on large laser facilities. These new HED laboratory capabilities will allow complex x-ray photoionization theories and models to be tested under relevant conditions, thereby serving as a critical component in the effort to understand the dynamics of accreting black holes.

Gamma-Ray Bursters

Gamma-ray bursts are among the greatest enigmas in contemporary astrophysics. Detected at a rate of more than one per day from random directions in the sky, GRBs have typical burst durations of a few seconds, but signal variability as short as about 1 ms, at photon energies of 0.1 to 100 MeV. At least some of the GRBs are at cosmological distances of several billion light-years, and their total source energies of 10^{51} to 10^{53} ergs per burst appear to be emitted from very compact sources. Their power law spectral shape is often interpreted as suggesting that the source plasma is optically thin to the radiation observed.

The fireball scenario is the most widely discussed model of GRBs. Here, an initial release of about 10^{52} ergs of energy into a volume of spatial extent about 10^7 cm creates a relativistically hot fireball of photons and leptons, with a small admixture of baryons. This initial fireball of leptons and photons at an initial temperature of 1 to 10 MeV expands relativistically; the gamma rays are produced by synchrotron or inverse Compton radiation from Fermi-accelerated electrons in optically thin shocks in the fireball. A small admixture of baryons is also accelerated to relativistic velocities, thereby transferring the fireball thermal energy to the kinetic energy of the radially expanding baryons. The baryons sweep into the interstellar medium (ISM), creating a system of a forward shock and several reverse shocks, with the observed GRB emission coming from the reverse shocks. The much-longer-lived x-ray afterglow then comes from the forward shock in the ISM, and the prompt optical emission from the corresponding reverse shock. In this scenario, the GRB can be thought of as a relativistic supernova remnant. All of the GRB localized so far with the BeppoSAX satellite belong to the class of long bursts with durations $\Delta t_\gamma \geq 2$ s, and there is increasing evidence that these occur in star-forming galaxies.

For this class at least, comprising nearly two-thirds of all bursts, it is widely assumed that a massive, collapsing star ("collapsar") is the progenitor. The shocks producing the gamma rays must occur after the fireball has emerged from the stellar envelope (and later, also an x-ray, optical, radio afterglow, as the fireball decelerates by sweeping up an increasing amount of matter encountered). The preferred escape route for the fireball is along the centrifugally lightened stellar rotation axis, and the stellar pressure tends to collimate the fireball into a jet.

The second class of "short" bursts with durations $\Delta t_\gamma \sim 2$ s is less well understood—one hypothesis being that they may be caused by mergers of double neutron star or neutron-star–black-hole binaries. These binary mergers would also lead to a central black hole plus a shorter-lived accreting torus, and a (probably less collimated) MHD or pair-dominated jet along the rotation axis. These mergers are prime candidates for producing gravitational waves detectable with the second-generation Laser Interferometer Gravitational-wave Observatory (LIGO) or France's VIRGO detectors (whereas collapsar-type long bursts may be weaker gravitational-wave sources due to a smaller quadrupole moment). The difference between the two classes of bursts will be further probed with spacecraft such as Swift and GLAST, now under construction.

The rest-mass densities that characterize the inner portions of the accretion disk and the jet are $\rho \geq 10^{14}$ g cm^{-3}, comparable to those inside nuclei and in neutron stars. As the fireball expands, inelastic nuclear collisions are expected when the n and p fluids decouple and their relative drift velocity becomes comparable to the speed of light. Inelastic n,p collisions lead to charged pions and gigaelectronvolt muon and electron neutrinos, as well as π^0 decay gamma rays, which should be detectable with the GLAST spacecraft. The relativistic jets from the GRB outflows are inferred to lead to highly relativistic terminal bulk Lorentz factors ($\Gamma \geq 100$), with extremely high energy fluxes (10^{50} to 10^{52} erg s^{-1}, or 10^{43} to 10^{45} W) on the beam, corresponding to an isotropic flux comparable to that of the entire universe over the 10- to 100-s duration of the burst. The energy density at the base of the jet is of order 10^{30} ergs cm^{-3} (10^{29} J/m^3), enough for electron-positron and nuclear processes to be, initially at least, in near-equilibrium.

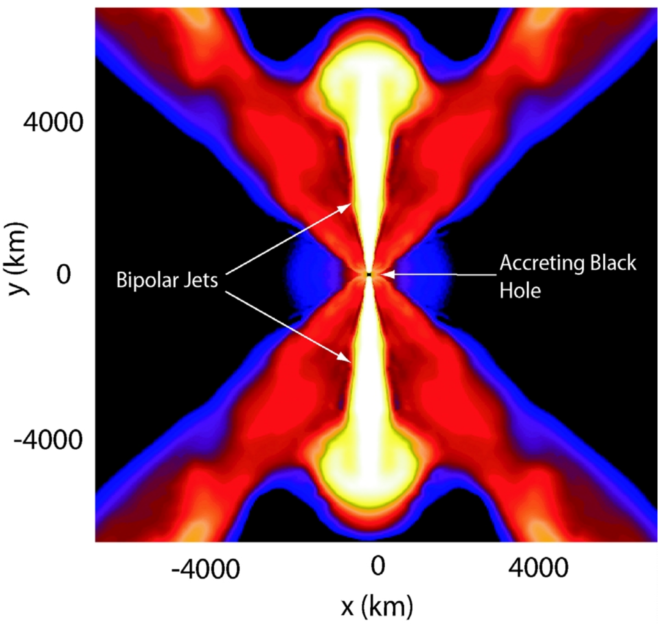
Farther out, at distances of $\geq 10^{11}$ cm, the photon-electron scattering mean free paths become longer than the characteristic dimensions of the flow, and collisionless internal and external shocks in the jet can accelerate electrons via the Fermi mechanism leading to a highly relativistic power law energy distribution. These, interacting with turbulently generated magnetic fields, lead to nonthermal gamma rays and, subsequently, in the jet deceleration phase, to an x-ray, optical, and radio afterglow, which has served to pinpoint the location of dozens of bursts and their distances. The interaction of waste heat bubbles or a decaying jet with the stellar envelope or with external debris can also lead to characteristic x-ray line spectra, in addition to a power law continuum.

Interesting issues of shock physics arise in connection with the GRB fireball radiation mechanism. The nonthermal spectrum in the fireball shock model results from assuming that Fermi acceleration accelerates electrons to highly relativistic energies following a power law $N(\gamma_e) \propto \gamma_e^{-p}$, with $p \approx 2$ to 2.5, in agreement with observations. To get reasonable efficiencies, the accelerated-electron-to-total-energy ratio $\varepsilon_e \sim 1$ must not be far below unity, while the magnetic-to-total-energy ratio $\varepsilon_b \sim< 1$ depends on whether the synchrotron or the inverse Compton spectral peak represents the observed MeV spectral break. The radiative efficiency and the electron power law minimum Lorentz factor also depends on the fraction $\zeta < 1$ of swept-up electrons injected into the acceleration process.

While many afterglow-snapshot or multiepoch fits can be done with time-independent values of the shock parameters ε_b, ε_e, p, in some cases the fits indicate that the shock physics may be a function of the shock strength. For instance, p, ε_b, ε_e or the electron injection fraction ζ may change in time. While these are, in a sense, time-averaged shock properties, specifically time-dependent effects would be expected to affect the electron energy distribution and photon spectral slopes, leading to time-integrated observed spectra that could differ from those in the simple time-averaged picture. The back-reaction of protons accelerated in the same shocks and magnetic fields may also be important, as in supernova remnants. Turbulence may be important for the electron-proton energy exchange, while reactions leading to neutrons and vice versa can influence the escaping proton spectrum.

The same shocks responsible for accelerating the electrons can accelerate protons up to energies of order 10^{20} eV, comparable to the highest-energy cosmic rays measured with the Fly's Eye and AGASA arrays. New experiments under construction, such as the Pierre Auger Observatory array, will provide much stronger constraints on whether GRBs are associated with such events. Relativistic protons can lead also to neutrinos with energies $\varepsilon_\nu \geq 10^{14}$ eV via interactions with the ≈MeV gamma rays, and with energies $\varepsilon_\nu \geq 10^{18}$ eV via interactions with ultraviolet photons. Protons accelerated in internal shocks in the buried jet while it advances through the star interact with thermal x rays to produce teraelectronvolt neutrinos, for which the detection probability is maximized in cubic kilometer Cherenkov detectors such as ICECUBE or ANTARES.

In the laboratory, the most promising means for accessing these relativistic plasma dynamics and flows are with experiments done on ultraintense, short-pulse lasers (see Figure 2.7). Experiments on such lasers have reached intensities of $\approx 10^{20}$ W cm^{-2} and have yielded many fascinating results. Jets of protons with energies of tens of MeV have been created in a very well collimated "beam." Also, less-collimated directional outflows of electrons and positrons with energies of up to 100 MeV have been generated. In terms of an effective temperature, the high-energy electrons have a "slope parameter" of 1 to 10 MeV, making these plasmas thermally relativistic, with $T_e > m_e c^2$, corresponding to a "laboratory microfireball." Similar temperatures are inferred from a fireball analysis of gamma-ray bursts. Another intriguing observation in these ultraintense laser experiments was the generation of ultrastrong magnetic fields. Strong magnetic-field generation (>100 MG = 10^4 T) has



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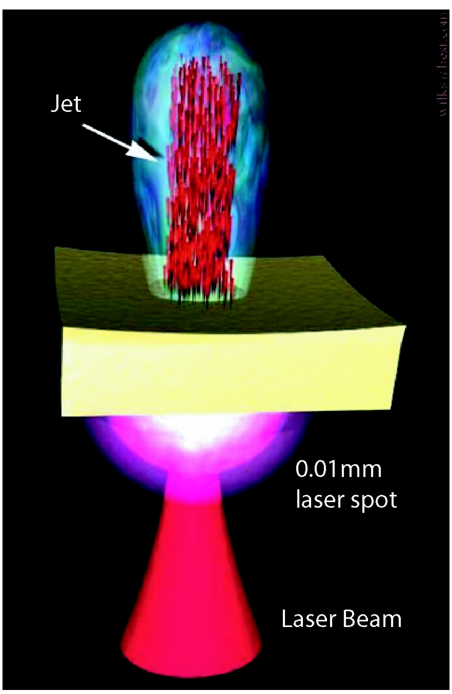

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FIGURE 2.7 A combination of theory, simulation, and laboratory experiments is expected to yield new insights into the physics of gamma-ray bursts (GRB). (a) An example of a current model for gamma-ray bursts; (b) an example of a proposed laboratory experiment exploring aspects of the astrophysical model. SOURCES: Images (a) courtesy of S. Woosley, University of California Observatories/Lick Observatory; and (b) courtesy of S.C. Wilks, Lawrence Livermore National Laboratory.

been experimentally observed on such ultraintense laser experiments, with simulations predicting fields of up to 1 GG (10^5 T) or more. Such extreme conditions, albeit over small volumes and exceedingly short times, may overlap with aspects of the relativistic fireball dynamics thought to occur in gamma-ray bursts.

Pair Plasmas: Pair Creation in Magnetospheres and in the Laboratory

The development of petawatt-class lasers opens the door to the study of relativistic and e^+e^- plasmas in the laboratory. It is well known that lasers with intensities exceeding $\approx 2 \times 10^{18}$ W cm^{-2} couple most of their energy to superthermal electrons with temperature $kT > mc^2$, where m is the electron rest mass. Pairs can then be created when the relativistic electrons interact with high-Z target ions via the trident and Bethe-Heitler processes. Using particle-in-cell (PIC) simulations, the pair production rate for a thin (few micrometers) gold foil has been estimated, with the conclusion that petawatt lasers with sufficient duration can in principle achieve in situ pair densities as high as $\sim 10^{-3}$ of the background electron density, or approximately 10^{22} cm^{-3} for solid gold. Detailed numerical simulations have confirmed this result and have further shown that for a thick gold foil (>20 μm), the positron yield may be even higher.

Subsequent experiments conducted at Lawrence Livermore National Laboratory using a single petawatt laser hitting 250-μm gold foils showed that the positron yield may be higher than even the theoretical estimates cited above. This demonstrates that petawatt lasers are indeed capable of producing copious pairs and has led to a proposal to use double-sided illumination to partially confine the pairs and to create multiple generations of pairs via reacceleration. PIC simulations show that, after the lasers are turned off, the pairs will expand much faster than the heavier gold ions. Hence a miniature fireball of relativistically expanding pure pairs can be created. This pair fireball can be made to collide with another pair fireball to mimic the internal shock model of gamma-ray bursts, allowing us to study how the expansion energy of pair fireballs can be converted into internal energy and gamma rays. Introduction of external equipartition magnetic fields (≈10 T) may be useful in creating collisionless shocks in such plasmas.

Another exotic future application is to study the static pair-balanced plasmas theorized to be the source of the episodic annihilation line flares from black-hole candidates. Two megajoule-class 0.1-petawatt lasers of 10-ns pulse duration, illuminating a gold target on both sides, could in principle create pair densities hundreds of times higher than the background electron density. Such steady-state pair plasmas can then be used to test the BKZS (Bisnovatyi-Kogan, Zel'dovich, Sunyaev) limit of $kT \approx 20\ mc^2$.

Radiative Blast Waves

When a blast wave sweeps up a high-density medium, the optically thin radiative cooling time at the shock front may become shorter than the dynamical time. Such radiative blast waves are expected to occur in the late phase of supernova remnants, gamma-ray burst afterglows, and even young supernova remnants in dense molecular clouds. Such radiative blast waves exhibit over stable radial oscillations when the cooling rate increases sufficiently slowly with temperature. Also the cooled dense shells eventually become unstable against the nonradial thin-shell instability. Numerical simulations in the past two decades consistently found that such thin-shell radiative blast waves in a solar-abundance interstellar medium expand as a power law in time, with an expansion index n ($= d \ln R/d \ln t$) $\approx 1/3$, significantly below the adiabatic Sedov-Taylor limit of 2/5, but higher than the pressure-driven snowplow limit of 2/7. Hence, radiative blast waves remain a major challenge in astrophysics because they couple the complex plasma radiation processes with hydrodynamics.

To simulate radiative blast waves in the laboratory, we need to generate highly radiative yet optically thin shocked gas. Laser experiments with xenon gas first demonstrated that radiative blast waves can indeed be created in the laboratory. Recent experiments using the short-pulse Falcon laser at Lawrence Livermore National Laboratory heating Xe gas jets have allowed probing the detailed physics of radiative blast waves, albeit in a cylindrical, rather than spherical, geometry. The key to such experiments lies in the fact that Xe gas with temperatures around tens to hundreds of electronvolts is highly radiative, yet optically thin for typical laboratory dimensions. The Falcon experiments confirm that Xe radiative blast waves expand as a power law in time, with an index intermediate between the Sedov-Taylor and pressure-driven snowplow limits.

It has been proposed that the $n \approx 1/3$ numerical simulation results and the Xe data are consistent with the theory that the radiative blast waves with temperatures below the cooling peak only radiate away the thermal component of the postshock energy. This hypothesis remains to be confirmed by further experiments and by numerical simulations with gases of different adiabatic indices. Radiative blast waves with radiatively preheated upstream gas and radiative blast waves with magnetic fields are also being investigated analytically and numerically. They will be priorities for future experiments.

Radiatively Driven Molecular Clouds

Cold dense molecular clouds illuminated by bright, young, nearby massive stars serve as the stellar incubators of the universe. The intense stellar radiation incident on the cloud creates a high-pressure source at the surface by photoevaporation (ablation), augmented by the ram pressure from the stellar wind. The result is that the cloud is shock compressed, and subsequently accelerated, as the star clears away the cloud out of which it was born. Well-known examples of such systems are the Eagle Nebula, the Horsehead Nebula, the Rosette Nebula, and NGC 3603. Interest in dense molecular clouds in the vicinity of bright young stars is due in part to the hypothesis that these clouds serve as "cosmic nurseries," harboring and nurturing regions of active star formation.

The Eagle Nebula is intriguing because of its famous columns, the so-called pillars of creation. These "elephant trunk" structures may arise as a result of hydrodynamic instabilities such as the Rayleigh-Taylor instability acting at the photoevaporation front, as first suggested 50 years ago. An alternative explanation, the so-called cometary tail model, attributes the columns to the flow of photoevaporated plasma from and around preexisting dense clumps of matter embedded in the molecular cloud, much like the dynamics that lead to the plasma tail of a comet.

Detailed information about the physical conditions in the hot ionized flow and in the cold gaseous cloud interior of the Eagle Nebula has recently been obtained, using both the Hubble Space Telescope and the ground-based millimeter-wavelength BIMA (Berkeley Illinois Maryland Association Array) interferometer array. In particular, hydrodynamic velocities as a function of position inside the cold gas have been determined by recent observations, allowing models of the dynamics of the columns to be tested. The key questions to be answered include these:

- Are the column shapes seen in the Eagle Nebula and other driven molecular clouds due to hydrodynamic instabilities?
- Do the radiative shocks launched into the molecular clouds trigger star formation?
- Do the shapes of these driven molecular clouds record the history of the star turn-on phase?

Experimentally, aspects of the dynamics of radiatively driven molecular clouds, and therefore aspects of these questions, can be tested in the laboratory. Using the radiation emitted from tiny radiation cavity "point sources" on large lasers and pulsed-power facilities, it appears possible to reproduce the dominant photoevaporation-front hydrodynamics of radiatively driven molecular clouds. Offsetting and collimating the source of Planckian radiation from the simulant cloud (foam foil) mean that the incoming "drive" photons would be sufficiently directional (quasi-parallel) to reproduce the dominant features of radiatively driven molecular clouds. In particular, new modes of radiative-hydrodynamic instability may arise owing to the directionality of the incident photons, an effect that could in principle be reproduced and observed on HED experiments. Also, the strong shock launched into the dense molecular cloud is likely to encounter density inhomogeneities, triggering localized regions of shock-induced turbulent hydrodynamics. Such hydrodynamics can also be reproduced in scaled strong-shock experiments on lasers and Z-pinch facilities. The shock launched into the dense molecular cloud is thought to be radiative. Progress on producing radiative shocks in the laboratory has also been demonstrated on several facilities. A magnetic field embedded in the cloud may be a key component to the dynamics, adding "stiffness" to the compressibility of the cloud. Strong-shock MHD experiments may also be possible on lasers and pulsed-power facilities. The possibility of forming an integrated program of theory, modeling, testbed laboratory experiments, and astronomical observations would be very beneficial, and several groups are moving in that direction.

High-Density Plasma in Strong Magnetic Fields and the Study of Surface Emission from Isolated Neutron Stars

Background The study of thermal radiation from isolated neutron stars can provide important information on the interior physics, magnetic fields, surface composition, and other properties of neutron stars. Such study has been a long-term goal of neutron star physics/astrophysics since early theoretical works indicated that neutron stars should remain detectable as soft x-ray sources for approximately 10^5 to 10^6 years after their birth. The past 35 years have seen significant progress in our understanding of various physical processes responsible for the thermal evolution of neutron stars. The advent of imaging x-ray telescopes in recent years has made it possible to observe isolated neutron stars directly by their surface emission. For example, the ROSAT X-ray Observatory has detected pulsed x-ray emission from about 30 rotation-powered radio pulsars, and some of these clearly show a thermal component in their spectra, indicating emission from the neutron star surface. Several radio-quiet, isolated neutron stars have also been detected in the x-ray and optical bands, and have thermal spectra arising from the neutron star atmosphere. Finally, in the past few years, soft gamma-ray repeaters and anomalous x-ray pulsars have emerged as a possibly new class of neutron stars ("magnetars") endowed with superstrong magnetic fields, $B > 10^{14}$ G ($>10^9$ T). According to the magnetar model, the x-ray luminosity from anomalous x-ray pulsars and the quiescent x-ray emission from soft gamma-ray repeaters are powered by the decay of a superstrong magnetic field. Thermal radiation has already been detected (e.g., by ASCA and Chandra) in several anomalous x-ray pulsars and soft gamma-ray repeaters; fits to the spectra with blackbody or with crude atmosphere models indicate that the thermal x rays can be attributed to magnetar surface emission. Clearly, detailed observational and theoretical studies of thermal emission can potentially reveal much about the physical conditions and the true nature of magnetars.

The new generation of x-ray telescopes (e.g., Chandra and XMM-Newton currently in orbit, and Constellation-X in the future) are bringing great promise to the study of isolated neutron stars (including radio pulsars, radio-quiet neutron stars, and magnetars). The greatly improved sensitivity and spectral/angular resolution in the x-ray band will lead to detailed spectroscopy (and continuum observation) of neutron star surfaces. In order to interpret the future observations properly, it is crucial to have a detailed understanding of the physical properties of the dense (partially ionized) plasma in the outer layers of neutron stars in the presence of intense magnetic fields ($B \approx 10^{11}$ to 10^{16} G), and to calculate the emergent thermal radiation spectra from the neutron star surfaces. This radiation is determined by the physical properties of the surface layers, but the surface composition of the neutron star is unknown. The atmosphere could consist of iron-peak elements formed at the neutron star birth, or it could be composed of light elements such as H and He due to accretion and fallback. The immense gravity of the neutron star makes the atmosphere very thin (0.1 to 10 cm) and dense (0.1 to 100 g cm^{-3}), so that the atmospheric matter is highly nonideal, with interactions between particles nonnegligible. If the surface temperature is not too high, light atoms, molecules, and metal grains or droplets may form in the envelope; if the magnetic field is sufficiently strong, the envelope may transform into a condensed phase with very little gas above it. A superstrong magnetic field will also make quantum electrodynamic effects (e.g., vacuum polarization) important in calculating the surface radiation spectrum. All of these problems present significant challenges to the theoretical astrophysics and dense plasma physics communities. The following subsections provide a few more detailed examples of the kinds of new physics problems that one confronts when studying these extreme objects.

Microscopic Calculations of Atoms, Molecules, and Dense Matter in Strong Magnetic Fields

It is well known that a strong magnetic field can dramatically change the properties of atoms, molecules, and condensed matter. For $B >> B_0 = m_e^2 e^3 c/\hbar^3 = 2.351 \times 10^9$ G, the cyclotron energy of the electron, $\hbar\, \omega_c = \hbar\, (eB/m_e c) = 11.58\ B_{12}$ keV [where $B_{12} = B/10^{12}$ G], is much larger than the coulomb energy. Thus, the coulomb forces act as a perturbation to the magnetic forces on the electrons, and at typical temperatures of isolated neutron stars, the electrons settle into the ground Landau level. Because of the extreme confinement of electrons in the transverse direction, the atom attains a cylindrical shape and a large binding energy. Moreover, it is possible for these elongated atoms to form molecular chains by covalent bonding along the field direction. Interactions between the linear chains can then lead to the formation of three-dimensional condensate. Much work remains to be done to understand the electronic structure of various forms of matter in strong magnetic fields. In particular, the atomic structure of heavy atoms has only been studied for a limited range of field strengths, the excitation energies of molecules (and chains) have only been considered qualitatively, and the cohesive properties of three-dimensional condensed matter are only understood in certain limiting field regimes.

Equation of State and Opacities of Dense Plasma in Strong Magnetic Fields A crucial ingredient in modeling neutron star atmospheres and surfaces is the equation of state (including the ionization-recombination equilibrium) of dense plasma in strong magnetic fields. Besides the usual difficulties associated with strong coulomb interactions in dense, zero-field plasmas, there are additional subtleties related to the nontrivial coupling between the center-of-mass motion and the internal structure of atoms and molecules. So far, only very crude models for the equation of state of dense plasma in strong magnetic fields have been constructed. To apply to neutron star atmospheres, various atomic and molecular opacities must be estimated or calculated. For sufficiently high magnetic fields and low temperatures (but still realistic for neutron stars), the condensed phase is more stable than the atoms and molecules, and there is a first-order phase transition from the nondegenerate gas to the macroscopic condensed state. With increasing field strength and decreasing temperature, the saturation vapor density and pressure of the condensate are expected to decrease, and eventually the optical depth of the vapor becomes less than unity. Therefore, thermal radiation can directly emerge from the nearly degenerate condensed metallic liquid. So far these issues have only been studied using very crude approximations.

Radiative Transfer in Strong Magnetic Fields Recent study of radiative transfer in strong magnetic fields has focused on transport of photon modes in ionized plasma. Incorporating neutral species self-consistently in the atmosphere models is an important challenge for the future. Even for ionized models (valid for sufficiently high temperatures, $T >$ a few $\times 10^6$ K), several important issues related to the superstrong field regime ($B > 10^{14}$ G) remain to be studied. One of these concerns the effect of ion cyclotron resonance at photon energy $0.63(Z/A)B_{14}$ keV, where $B_{14} \equiv B/10^{14}$ G, and Z and A are the charge and mass numbers of the ion, respectively. Another concerns the effect of vacuum polarization. Polarization of the vacuum due to virtual e^+e^- pairs becomes important when $B > B_Q = m_e^2c^3/e\hbar = 4.414 \times 10^{13}$ G. Vacuum polarization modifies the dielectric property of the medium and the polarization of photon modes, thereby altering the radiative opacities. Of particular interest is the "vacuum resonance" phenomenon, which occurs when the effects of vacuum and plasma on the linear polarization of the modes cancel each other, giving rise to a "resonant" feature in the absorption and scattering opacities. The vacuum resonance is located at photon energy $E_V(\rho) \approx 1.0(Y_e\rho)^{1/2} B_{14}^{-1} f(B)$ keV, where ρ is the density (in g cm^{-3}), $Y_e = Z/A$ is the electron fraction, and $f(B)$ is a slowly varying function of B [$f(B) \approx 1$ for $B < B_Q$, and ranges from 1 to a few for $B \approx 10^{14}$ to 10^{16} G]. Because E_V depends on density (which spans a wide range in the atmosphere), proper treatment of this vacuum resonance feature presents a significant challenge for the atmosphere modeling. Another related effect is the resonant mode conversion: a photon propagating down the density gradient in the atmosphere can change its mode characteristics (e.g., an extraordinary mode photon gets converted to ordinary mode) at the density where vacuum resonance occurs; such mode conversion is particularly effective for photons with energies greater than a few kiloelectronvolts. Since the two modes have very different opacities in strong magnetic fields, mode conversion can have a significant effect on the radiative transport and the emergent spectra from the magnetar atmosphere.

Plasma physics with ultrahigh magnetic-field strengths becomes particularly interesting at $B > B_0 = m_e^2 e^3 c/\hbar^3 \sim 10^9$ G. At these field strengths, the orbitals of bound electrons become strongly perturbed by the applied magnetic field, that is, $(\hbar\omega_c)/E_b \geq 1$, where $\hbar\omega_c$ is the energy of the electron at the cyclotron frequency due to the magnetic field, and E_b is the electron coulomb binding energy. The details of plasma emission and absorption spectra will be significantly affected, which could be relevant to emission spectra from neutron star atmospheres. With the new genre of ultraintense, short-pulse lasers, magnetic-field strengths in plasmas of order $\sim 10^9$ G have already been demonstrated, with the promise of higher field strengths on future facilities. If such fields could be sufficiently well understood and controlled, it might become feasible to measure emission spectral modifications due to such strong fields.

THE ROLE OF COMPUTING IN HIGH ENERGY DENSITY ASTROPHYSICS

An essential aspect of numerical modeling in the context of HED astrophysics is that the range of spatial and temporal scale that typically needs to be spanned far exceeds what can be plausibly computed. Another way of looking at this difficulty is that the dimensionless control parameters characterizing astrophysical systems (e.g., Reynolds number, Rayleigh number, and so on) are typically much larger than what can be simulated on existing (or even imagined) computing platforms.

In this sense, computing plays a very different role in HED astrophysics than in HED laboratory physics. HED astrophysics computing is used for the following purposes:

- *To develop models for spatially or temporally unresolved physics.* Astrophysics-focused simulations invariably use subgrid models in order to describe processes not captured by the simulations themselves; common examples of such modeling include the insertion of turbulent viscosity and (in the case of collisionless plasmas) magnetic diffusivity. An important role for joint laboratory and simulation studies is the validation of such (astrophysical) subgrid models.

- *To validate ideas about physical processes thought to take place in an astrophysical context, but which can be explored under less restrictive conditions.* In many instances, physical processes arising under astrophysical conditions have counterparts under laboratory conditions—mixing instabilities such as Rayleigh-Taylor exemplify such processes. In such cases, laboratory experiments can be used to validate astrophysics simulation codes; this is a necessary condition for ensuring that such simulations properly describe the astrophysical situation (albeit not a sufficient condition).
- *To explore and develop intuition for highly nonlinear physical processes.* The challenging problems in astrophysics are largely related to processes that operate in a fully nonlinear regime. In this regime, reasoning based on the behavior of systems in the linear regime usually proves to be very inadequate, but our physical intuitions are generally based on linear theory. For this reason, there is a broad need to inform practitioners about the complexity of possible behaviors in the nonlinear limit; the numerical exploration of the fully nonlinear development of magnetic dynamos is an excellent example of this type of study.

The preceding discussion makes clear that the size (both in memory requirements and computation time) and complexity (in the level of detail of the physics description) of HED astrophysics-oriented simulations are typically set primarily by what is possible: computational HED astrophysicists are rarely heard to say, "We do not need more memory size or computation time." Thus, computational HED astrophysics drives some of the largest simulations that are typically attempted on leading-edge computing platforms. By the same token, computational HED astrophysics has a profound need for access to state-of-the-art computational resources—thus, it is widely believed that major advances in problems such as Type Ia and Type II (core collapse) supernovae will relate to advances in high-end computational capabilities. For example, it is now possible to do two-dimensional hydrodynamic simulations of Type II supernovae, with nuclear reactions and neutrino transport, on a modern personal computer; it will take days to weeks. But full three-dimensional simulations with good resolution are necessary in order to see the development of low-order modes of instability and at the same time to resolve the boundary between the collapsed core and the ejecta. An obvious estimate of the additional computational resources needed is scaling according to the number of zones needed for the new third dimension: roughly 500 to 1,000 personal computers. This translates to at least days or weeks of dedicated time on an ASCI-level parallel system. The Type Ia supernova problem seems to be worse. In addition to demands such as those just mentioned, at least two other issues arise: subgrid models for burning, and grid distortion in the strongly differentially rotating system of a binary merger. These crucial roles played by computations in HED astrophysics have been recognized by the Department of Energy (DOE) and strongly supported within the DOE National Nuclear Security Administration's ASCI Alliances program and the DOE Office of Science's Science Discovery through Advanced Computing (SciDAC) program.

CONCLUSIONS

In summary, there is a wide variety of areas in which theory, numerical simulations, and experiments on HED facilities can address aspects of astrophysical phenomena. Areas of promising overlap include the physics of supernova explosions and supernova remnant evolution, high-Mach-number astrophysical jets, planetary interiors, photoevaporation-front hydrodynamics of molecular clouds, photoionized plasmas around accreting black holes, and relativistic plasmas in gamma-ray burster fireballs. This selection of topics may well be just the "tip of the iceberg" as more experience is obtained in carrying out both large-scale numerical simulations and scaled HED experiments in support of astrophysics.

3

High Energy Density Laboratory Plasmas

INTRODUCTION

Imagine taking the output of the entire global power grid for a few billionths of a second and focusing it with a large laser onto the surface of a hollow capsule no bigger than the head of a pin. Next, imagine filling the capsule with isotopes of hydrogen (deuterium and tritium), then sitting back to "watch the action." The capsule responds by imploding at velocities of up to 300 km/s, that is, at speeds approaching 0.1 percent of the speed of light! (See Figure 3.1.) At peak compression, the temperatures and densities at the center are of order 10^8 kelvin (10 keV) and 100 g/cm^3, with pressures approaching 100 Gbar (~10^{16} P). These conditions mimic those found at the center of the Sun. Not surprisingly, the outcome is a "microsun," for a very brief moment (0.1 ns) spewing forth a miniexplosion of neutrons and alpha particles from nuclear fusion. The pursuit of this "controlled astrophysics in the laboratory" is the routine business of the inertial confinement fusion (ICF) program in the United States, and it forms the focus of an enormous variety of high energy density (HED) physics research.

High energy density physics, as said earlier, is the study of the collective properties of matter under extreme conditions of temperature and density. Not surprisingly, this study of extreme science has considerable overlap with astrophysics and nuclear weapons physics, as well as inertial confinement fusion research. This chapter gives a broad survey of laboratory HED physics, starting in the next section with a list of important scientific questions that could potentially be addressed on

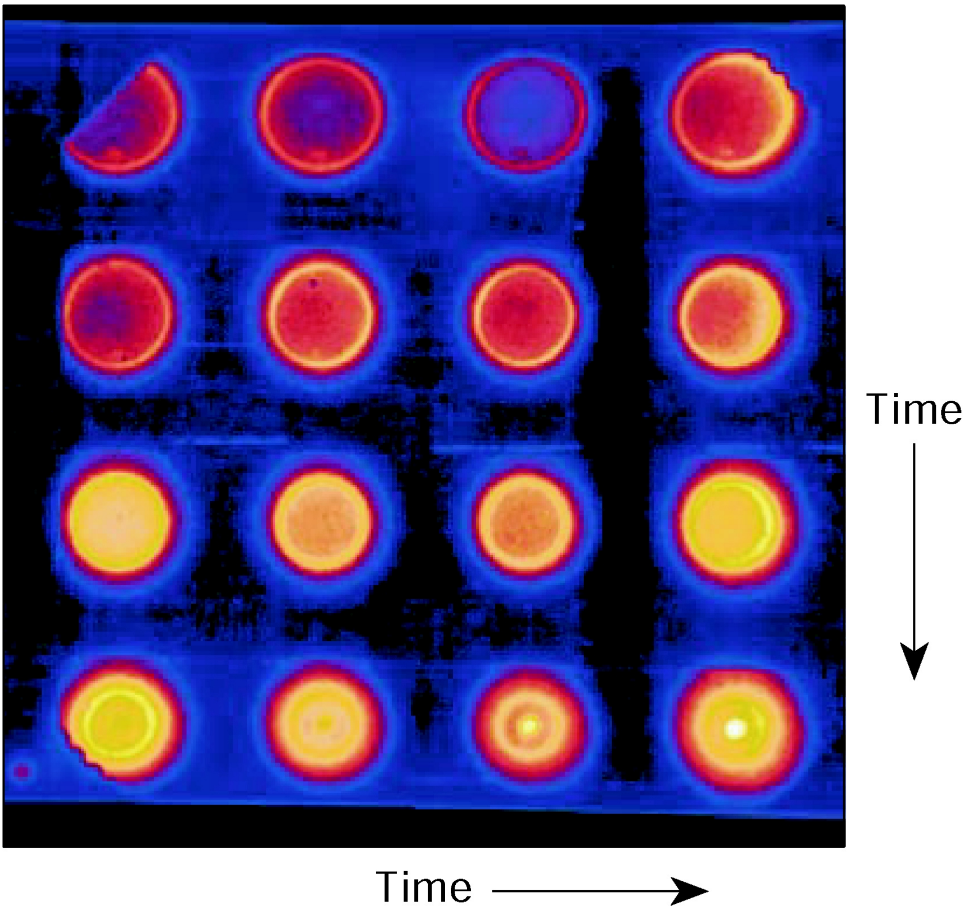

FIGURE 3.1 X-ray pinhole camera "movie" of a directly driven inertial confinement fusion implosion on the OMEGA laser system, from the laser irradiating the shell at early times, to the formation of a hot spot. Each image has ~50-ps temporal resolution, and the total duration of the "movie" is ~3.2 ns. The initial target diameter (upper left image) is ~1 mm, and the final compressed core diameter (third image, bottom row) is <100 μm. Courtesy of the Laboratory for Laser Energetics, University of Rochester.

HED facilities. Then various experimental facilities are described; the section on "Facilities" is devoted to a discussion of a wide range of HED physics phenomena, and areas of overlap with astrophysics and other branches of physics are pointed out. Some applications of HED physics are then described, and the final section of the chapter describes some of the opportunities for high energy density physics studies in the laboratory.

KEY QUESTIONS

It is now possible for experimental science to enter into a regime that has been, until now, largely the exclusive domain of theoretical and computational physics, namely, the collective behavior of matter under extreme conditions of density and temperature. Such conditions are commonplace in astrophysics, yet laboratory experimental mileposts are rare. Indeed, the report of the National Research Council's Committee on the Physics of the Universe, *Connecting Quarks with the Cosmos,*[1] has embraced the need for laboratory exploration of physics under extreme conditions on HED facilities. As a guiding framework for describing this experimental frontier, the Committee on High Energy Density Plasma Physics presents a list of fundamental questions that could potentially benefit from experiments on current or future HED facilities:

- Can thermonuclear ignition be achieved in the laboratory? Can high-yield inertial confinement fusion implosion experiments contribute to our understanding of aspects of thermonuclear supernova explosions? Can nucleosynthesis of the heavy elements ($Z > 50$) be studied using the intense burst of 10^{19} neutrons from high-yield capsule implosions? Can thermonuclear ignition lead to energy production (and possibly then to hydrogen production) through inertial fusion energy?
- Can the transition to turbulence in compressible flows be understood? Can supersonic turbulent flows be generated?
- Is there a fundamentally new, first-order phase transition unique to the plasma state, the so-called plasma phase transition (PPT)? Do mixtures (e.g., He-H, C-O, and so on) undergo phase separation at sufficiently high densities? Can metallic hydrogen ever exist in the solid state, or do quantum zero-point vibrations prevent this?

[1]National Research Council, Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century, Committee on the Physics of the Universe, The National Academies Press, Washington, D.C., 2002.

- Can laboratory experiments help to discriminate among competing models of planetary interiors and planetary formation? Can experiments help establish whether the core of Jupiter is solid or liquid? Is convection not possible in Jupiter's metallic hydrogen layer, and what are the consequences for Jupiter's interior?
- Can intense bursts of thermal electron-positron plasmas be created and studied in the laboratory? Can relativistic jets and shocks be generated from such an electron-positron fireball relevant to gamma-ray burst models? Are the dynamics of such relativistic jets and shocks fundamentally different from those of their nonrelativistic counterparts?
- Can conditions of radiation-dominated matter be created in the laboratory? Can conditions relevant to radiation-dominated black-hole or neutron star accretion disks be generated and probed? At low densities, can an equilibrium photoionized plasma be created in the density-independent, radiation-dominated regime? At high densities, can conditions be created in which radiation pressure dominates particle pressure? Are there new dynamics for this case, such as a photon bubble instability?
- Can macroscopic assemblies of fully degenerate matter (degenerate electrons and degenerate ions) be created, and their thermal and mechanical properties measured? Can plasma transport coefficients be determined under such conditions of extreme degeneracy, where continuum lowering dominates opacities and quantum effects dominate the plasma?
- Can the equation of state of bulk nuclear matter be determined in the laboratory? Can the conditions of "core bounce" (i.e., the nuclear rebound) in core-collapse supernovae be experimentally reproduced? Can the structure of neutron star interiors be experimentally accessed?
- Can a phase transition to the quark-gluon plasma be inferred? Can the properties of a quark-gluon plasma be determined?
- Can sufficiently high densities be created in the laboratory to allow pycnonuclear fusion reactions (genuine cold fusion) to be observed? Can nuclear reactions under highly screened conditions in dense plasmas relevant to the cores of massive stars be studied in the laboratory? Can macroscopic assemblies of relativistically degenerate matter (Fermi temperature, $\Theta_{\mathrm{Fermi}} > m_e c^2$) be created in the laboratory, and their equations of state be determined? Can the boundary between a stable white dwarf core and one that will unstably collapse to a neutron star be verified in the laboratory?
- Can a radiatively collapsed shock be created in the laboratory? Would new thin-shell instabilities be created as a result? Can strong magnetohydrodynamic (MHD) shocks be created? Can a collisionless shock be created, or

its mechanism be inferred? Can shock-induced particle acceleration be demonstrated?

- Can astrophysical jet formation and jet collimation mechanisms be elucidated with laboratory experiments?
- Can ultrastrong magnetic fields, $B > 1$ gigagauss, be experimentally created and their effect on the surrounding plasma be studied? Can magnetic fields relevant to the atmosphere of neutron stars be created, and aspects of the complex radiative MHD processes be experimentally reproduced? Can the so-called radiation-bubble instability be replicated?

FACILITIES

Experimental facilities available for high energy density research include high-energy (relatively long-pulse) lasers, high power (very short pulse) lasers, pulsed-power devices, high-current particle beam accelerators, and combinations of these. New facilities planned or under construction will extend still further the range of high energy density conditions achievable. Tables 3.1 through 3.5 list a variety of HED facilities currently in operation, under construction, or in the serious planning stages. Figure 3.2 is an illustration of the National Ignition Facility (NIF) currently under construction at Lawrence Livermore National Laboratory. When completed, it will produce ~2 MJ of laser energy and will be the flagship high energy density facility in the United States.

TABLE 3.1 Three Currently Operating High Energy Density Facilities That Provide the Highest Energy Densities to Experimental Targets

Existing	OMEGA (University of Rochester—Laboratory of Laser Energetics)	Z-machine (Sandia National Laboratories)		Atlas (Los Alamos National Laboratory; To Be Moved to Nevada Test Site)
Type	Laser	Pulsed power	X-ray source	Pulsed power
Photon energy	3.5 eV	20 MA as Z-pinch driver	50-250 eV (BB)[a]	30 MA as Z-pinch driver
Pulse length	0.1-4 ns (longer with pulse stacking)	~100-ns rise time	5-15 ns	4.5-μs rise time
Spot size	0.1-3 mm	N/A	~1-mm cylinder	N/A
E/pulse	30 kJ	16 MJ stored energy	1.8 MJ	24 MJ stored energy
Repetition rate	1 per hr	A few per day	1 per day	<1 per day
Peak intensity	~1×10^{16} W/cm^2	N/A	X ray: 1×10^{14} W/cm^2	N/A

[a]BB indicates that the given photon energies refer to typical hohlraum temperatures that are achieved.

TABLE 3.2 High Energy Density Facilities, Including Those Typically Associated with Particle Physics

Existing	ICF-Class Lasers	TW-Class Lasers	TW Pulsed-Power System	Electron Linac (SLAC)	RHIC
Energy/photon or particle	1.5 eV	1.5 eV	0.1-10 MeV; 1-5 MA as Z-pinch driver	50 GeV	100 GeV/amu (for Au: 20 TeV/ion)
Pulse length	0.1-10 ns	30-100 fs	50-250 ns	5 ps	~500 ps
Spot size	50-1000 μm	5 μm	~0.1 cm (e-) ~1 cm ions	3 μm	120-240 μm
Energy/pulse	Up to 3 kJ	1-10 J	20-100 kJ	150 J	3 kJ/bunch
Repetition rate	8-10 per day	10 Hz, a few per hour	1-10 per day	100 Hz	Bunches collide at 50 MHz
Typical peak intensity (W/cm^2)	1×10^{15} W/cm^2	1×10^{20} W/cm^2	Application dependent	~1×10^{20} W/cm^2	~6×10^{16} W/cm^2

NOTE: This table includes the large number of laser systems that can achieve HED conditions. While the laser systems are not listed individually, a number of systems nationwide can be used for HED studies.

TABLE 3.3 High Energy Density Facilities Currently Under Construction or Contemplated in the Near Future

Facility	PW-Class Lasers	NIF	Z-R (x ray)	LHC
Energy/particle	1.5 eV	3.6 eV; 600 eV BB[a] for ICF	100-250 eV (BB)[a]	7 TeV
Pulse length	0.5 ps	0.2-20 ns (longer with pulse stacking)	10 ns	0.25 ns (1 bunch)
Spot size	5 μm	0.2-5 mm	1-mm cylinder	16 μm
E/pulse	0.5~5 kJ	1.8 MJ	>3 MJ	334 MJ in 2.8×10^3 bunches
Repetition rate	Up to 2 per hr	2 per day	1 per day	4×10^7 Hz
Peak intensity	1×10^{21} W/cm^2	2×10^{15} W/cm^2	4×10^{14} W/cm^2	1×10^{19} W/cm^2

NOTE: Somewhat lower peak intensities than those listed, in the 10^{12} W/cm^2 range with a ~1-mm target, are planned for the electron beam facility Dual Axis Radiographic Hydrodynamic Test (DARHT) (not listed); similar intensities are planned for future proton drivers as well.
[a]BB means that the given photon energies refer to typical hohlraum temperatures that are expected for ICF experiments.

Table 3.1 shows characteristic parameters for three of the largest currently operating, high energy density facilities: the OMEGA laser; the fast, magnetic pinch Z-machine; and the relatively slow pulsed-power facility Atlas. All three of these facilities were built primarily for high energy density plasma studies relevant to nuclear weapons science, including inertial confinement fusion, but the National

TABLE 3.4 Possible Future High Energy Density Facilities

Future	0.1 Exawatt-Class Lasers	ZX (x ray)	HIF	NLC	LCLS (e^-)	LCLS X rays (coherent)
Energy/particle	1.5 eV	40 MA; up to 280 eV BB for ICF	5 GeV	250 GeV	14 GeV	8 keV
Pulse length	100 fs-1 ps	10 ns (x rays)	10 ns	370 fs	230 fs	230 fs
Spot size	100 μm	N/A	3 mm	250 × 3 nm	28 μm (as FEL driver)	0.1-100 μm
E/pulse	20 kJ	>6 MJ	1-10 MJ	300 J	12 J	2 mJ
Repitition rate	2 per day	0.5 per day	10 Hz	190 pulses at 120 Hz	120 Hz	120 Hz
Peak intensity	$>1 \times 10^{21}$ W/cm^2	$>1 \times 10^{15}$ W/cm^2	1×10^{15} W/cm^2	7×10^{24} W/cm^2	5×10^{17} W/cm^2	$>1 \times 10^{19}$ W/cm^2

NOTE: The facilities listed will significantly expand the range of HED conditions available terrestrially, although significant technological development may be required to achieve these parameters.

TABLE 3.5 Examples of Current and Future International High Energy Density Facilities

Facility	Type of Facility	Country
GSI PW	PW-class laser + ion storage ring	Germany
MAGPIE	TW pulsed power	Great Britain
Vulcan + PW	ICF-class + PW-class	Great Britain
LULI	PW-class lasers	France
LIL	First stage of ignition class	France
Laser Megajoule	Ignition-class laser	France
Gekko + PW	ICF-class + PW-class lasers	Japan

NOTE: The approximate parameters for the various types of facilities can be found in Tables 3.1 through 3.4. Several facilities will have a combination of longer-pulse lasers and ultrahigh-power (petawatt) lasers.

Nuclear Security Administration, which operates them, makes a portion of their time available for fundamental high energy density physics research.

Table 3.2 shows other existing HED facilities. These include ICF-class lasers not listed in Table 3.1, high-intensity (terawatt [TW]) laser and pulsed-power systems typically found in universities, and particle physics facilities that can achieve HED conditions (often in combination with other HED technologies). Many of these smaller laser systems can be operated at a significantly higher repetition rate than is possible with high-energy laser systems. These high-average-power systems can perform hundreds or thousands of experiments, allowing detailed data to be

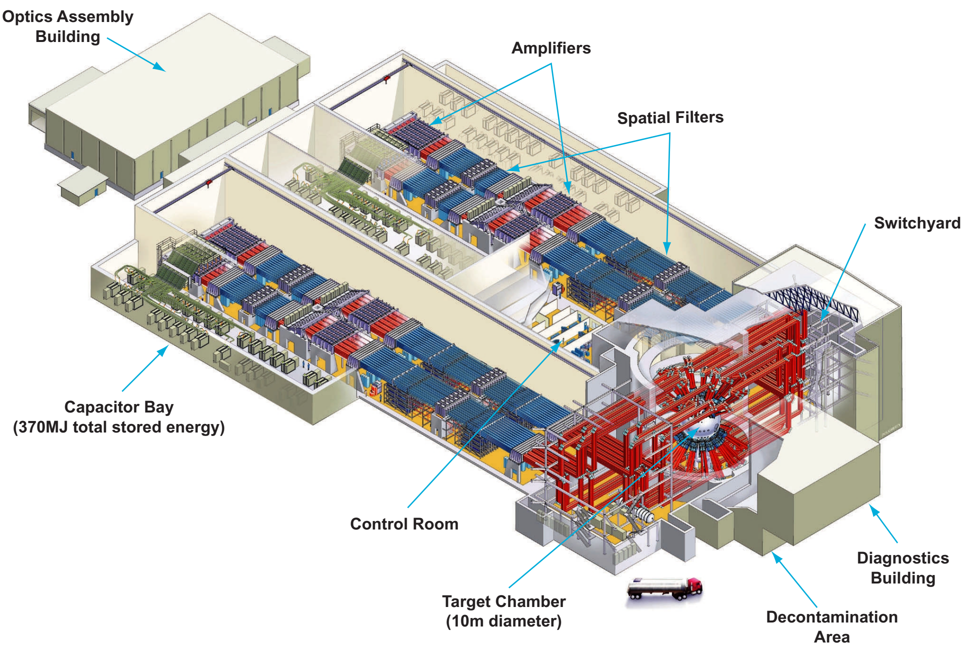

FIGURE 3.2 Rendering of the ~2-MJ National Ignition Facility (NIF) that is currently under construction at Lawrence Livermore National Laboratory, showing the location of various components and support facilities. When completed, the NIF will be the nation's highest-power MJ-class high energy density physics facility, built primarily for weapons-relevant high energy density physics research, including inertial confinement fusion. Up to 15 percent of the laser time is planned to be available for basic science experiments. Courtesy of Lawrence Livermore National Laboratory.

obtained. High-average-power laser systems will also be required for laser-drive inertial fusion energy.

Tables 3.3 and 3.4 list future high energy density facilities, either under construction or being discussed, though significant technological advances may be required to build these advanced systems, which will extend the range of high energy density conditions available for experiments. The National Ignition Facility will be the flagship high energy density facility in the United States. Similar development of high energy density facilities is occurring outside the United States.

Table 3.5 lists some of these facilities. The LMJ laser facility, under construction in France, will have capabilities similar to those of the NIF.

Active foreign research efforts under way and the availability of an increasing suite of international facilities will continue to allow active international collaborations to be pursued. In fact, a number of the experimental results shown in the subsequent sections (particularly in Figures 3.7, 3.9, and 3.10) are the results of international efforts and collaborations involving U.S. researchers collaborating on international facilities or foreign researchers collaborating on U.S. facilities.

HIGH ENERGY DENSITY PHYSICS PHENOMENA

This section describes a number of physics phenomena of wide scientific interest that are unique to HED conditions. The density-temperature phase diagram for hydrogen, shown in Figure 3.3, provides a convenient roadmap through the most important HED regimes. The upper left-hand side of the figure corresponds to extremely high densities and low temperatures where quantum-mechanical degeneracy pressure dominates. The lower right-hand side corresponds to regimes of extremely high temperature and low densities, where radiation effects dominate. Intermediate between these two extremes, radiation, particle, and degeneracy pressures can all contribute to the plasma dynamics. A key distinguishing feature of the HED facilities is that macroscopic volumes of matter can be placed in these extreme conditions for laboratory study.

High Energy Density Materials Properties

When an object (solid, liquid, or gas) is subjected to an increase in external pressure, p, it tends to compress according to $p = -\beta\ (\Delta V/V)$, where β is its bulk modulus, and $(\Delta V/V)$ is the compression. Solids typically have $\beta \approx 1$ Mbar; hence, very high pressures are needed to compress a solid. When $p/\beta << 1$, the material compression is negligible, and its response is well described by elasticity theory. In the HED regime, however, $p/\beta \geq 1$ by definition. Here, the response of matter is no longer a gentle perturbation, but rather a significant, perhaps even violent, compression or deformation. At sufficiently high pressures and densities, molecules can dissociate and atoms can ionize, each of which affects the compressibility and deformation. Solids can undergo phase transitions to reach lower collective energy states and twinning transitions, in response to sufficient applied shear stresses. New techniques for studying the time-resolved response of materials to extreme pressures and applied stresses have been developed in recent years. An illustrative selection of examples is described below.

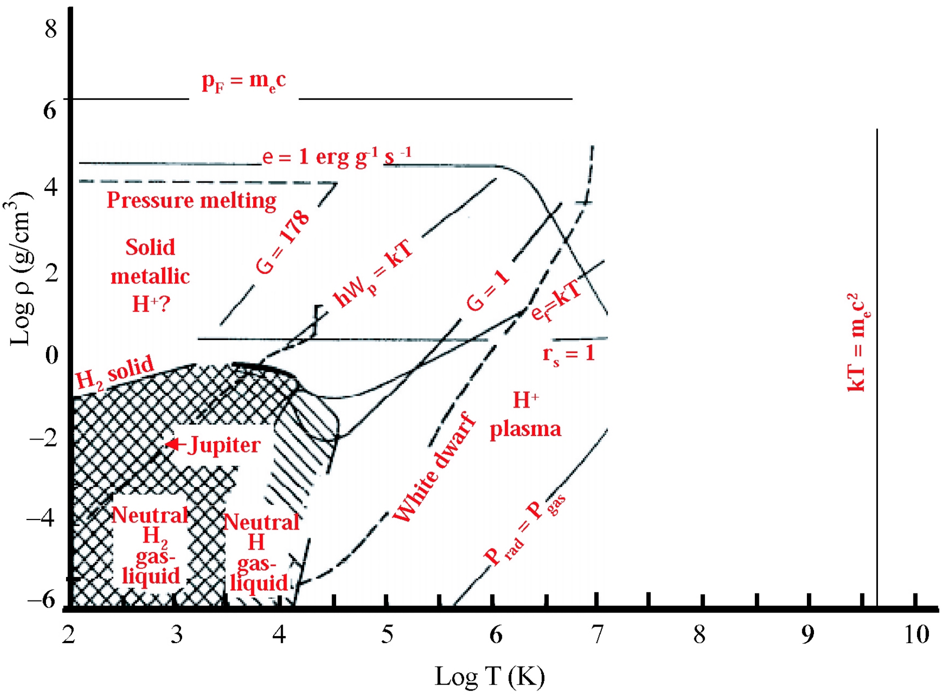

FIGURE 3.3 Phase diagram for hydrogen in temperature-density space showing the great complexity of even the simplest molecule. Courtesy of H.M. Van Horn, University of Rochester, now at National Science Foundation.

High-Pressure Equation of State

The equation of state (EOS) of a material can be experimentally determined by applying a known external pressure to a sample and measuring its volumetric response (compression). If the applied pressure is in the form of a shock, the material response is determined through the Rankine-Hugoniot relations. Modern HED drivers are also capable of delivering shaped pressure pulses that enable isentropic compression experiments, or other off-Hugoniot conditions. High energy density facilities are particularly well suited for EOS studies at high compression, because of the very high pressures possible. A high-energy laser can be used to launch a strong-shock wave by ablation pressure. Pulsed-power devices can launch "flyer plates" with which to shock a sample by impact, or they can produce isentropic compression by applying a tailored magnetic pressure pulse directly to the surface of a conducting sample. Alternatively, by appropriate pulse shaping, compressions to higher density at a given peak pressure can also be achieved, thereby probing off-Hugoniot regimes. Gas guns, explosively driven flyer plates, and electromagnetic launchers can also be used to launch shock waves in materials for compression studies. In addition, static techniques such as diamond anvil cells can be used to generate moderately high pressures in materials.

Hydrogen is the simplest and most ubiquitous element in the universe, and its EOS is critical to planetary structure and planetary formation models, as well as to the performance of inertial confinement fusion capsule implosions and stockpile stewardship. Yet it has an impressively complicated phase diagram, as shown in Figure 3.3. The EOS measurements of hydrogen over the past decade have yielded several surprises. For example, the theoretically predicted plasma phase transition has yet to be experimentally observed. With the recent availability of large high energy density experimental systems (first the Nova laser, and now OMEGA, Z, and NIKE), multimegabar EOS measurements have become possible in liquid hydrogen. As high energy density systems continue to move to higher energies (e.g., the NIF), the parameter space accessible to experiments will be greatly expanded. As mentioned in Chapter 2, new results could significantly impact models of planetary structure and possibly planetary formation models, and they could also affect the modeling of inertial confinement fusion implosions. It should also be noted that in measurements relevant to planetary interiors, the experimental results should be directly applicable, without any scaling (see Figure 1.1 in Chapter 1), provided they are made at the correct density, temperature, and equilibrium states. Measurements of reflectivity and conductivity of shocked hydrogen allow observation of the dielectric-to-metallic transition. The temperature in the shock-compressed material can be determined by various spectroscopic techniques. Taken together, these measurements provide powerful tests of models of the properties of dense, degenerate plasmas. To have significant impact on models of planetary interiors, the accuracy of the experimental measurements needs to approach 1 percent in density, 20 percent in temperature, and factors of 2 in solubility and transport coefficients.

Theories and simulations of the EOS of dense, strongly coupled, Fermi-degenerate plasmas are a very active area of ongoing research. Semiempirical models, such as the "chemical picture," typically use effective pair potentials fit to experimental data. Ab initio simulations using molecular dynamics or Monte Carlo models attempt to calculate the plasma conditions from first principles. Most of these models assume equilibrium conditions. Given that experiments on HED facilities can have rather brief time scales, a few nanoseconds, or sometimes even less, there may be a need for kinetic theories to explicitly calculate the evolution to equilibrium. This remains an open question. Several of the models referred to above predict that pressure ionization of the plasma occurs through a first-order phase transition, called the plasma phase transition (PPT). The PPT has never been experimentally observed, though experimental searches continue. If the PPT were found to exist, it would have a profound impact on models of planetary interiors and planetary formation.

Dynamic Response of Materials

The time-resolved response of a solid-state lattice to an impulsive applied stress is a new area of research. Determining how a lattice responds to a shock requires a combination of quantum mechanics (via an interatomic potential), statistical physics of a large but finite number of discrete objects (lattice points), and continuum dynamics for following material deformation or flows. Knowing which approximations "work" in putting a theoretical treatment together requires comparisons with data. In particular, for an applied stress in a given direction, one would like to know the lattice response in all directions, including the direction of the applied stress. The experimental techniques to make such tensorial measurements are rapidly being developed. It seems very likely that within this decade the fundamental problem of lattice response to a shock will be solved.

The most promising experimental tool for probing the lattice response of a solid-state sample to an impulsive stress is time-resolved hard x-ray diffraction, a technique that measures the lattice spacing. A solid-state lattice has a multitude of options in its repertoire for responding to applied stresses, and which response occurs depends on the magnitude of the stress, the lattice temperature, the strain rate, and the ambient pressure, among other things. A large number of these deformation mechanisms (e.g., uniaxial elastic compression, hydrostatic plastic compression, twinning, solid-to-solid phase transitions, melting) can in principle be inferred from high signal-to-noise ratio, multi-lattice-plane diffraction measurements. An excellent example of such a measurement is shown in Figure 3.4. In this case, matter was impulsively heated at the surface with a ~70-fs laser pulse from a high-repetition-rate (1 kHz) Ti:sapphire laser, and probed with bursts of 10 keV x rays from the Advanced Photon Source. The diffraction signal, which integrates more than 6000 laser shots, shows both the lattice expanding due to the heating from the laser, and an oscillatory pattern due to coherent phonons being launched into the interior of the lattice. As the heat conducts away, the expansion of the lattice subsides over an interval of ~1/2 ns.

Several other techniques exist or are being developed for probing the lattice response to deformation. Among these are extended x-ray absorption fine structure, 2nd harmonic reflectivity, and coherent anti-Stokes Raman spectroscopy. Each

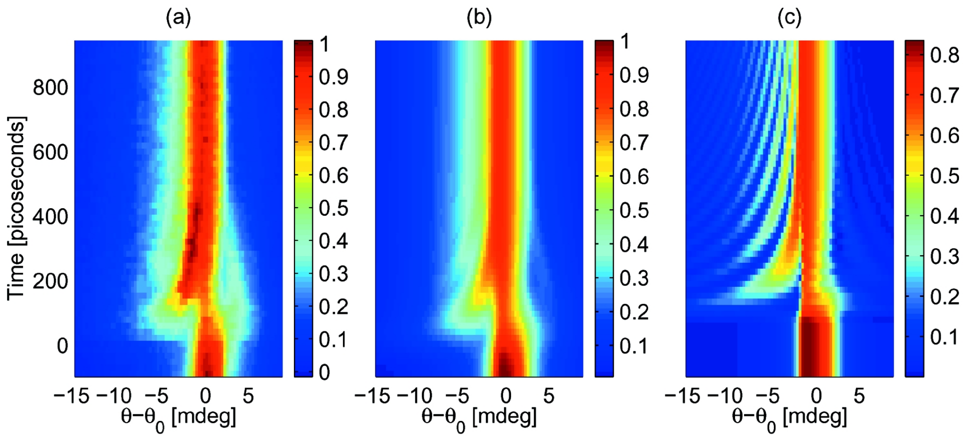

FIGURE 3.4 Time-resolved x-ray diffraction from an InSb crystal that is irradiated with a 70-fs laser pulse from a 1-kHz repetition rate Ti:sapphire laser, synchronized with a burst of collimated 10-keV x rays from the Advanced Photon Source (APS). The pump-probe derived experimental image is shown in (a), and the results from a simulation (with ideal resolution) are shown in (c). Image (b) shows the simulation with the experimental resolution convolved into it. The x-ray scattering angle θ_0 corresponds to the Bragg condition for the 10-keV x rays under ambient conditions. When the laser turns on at t = 0, both lattice expansion ($\theta - \theta_0 < 0$) and lattice compression ($\theta - \theta_0 > 0$) are observed in the diffracted x rays. The oscillations observed vertically, most clearly seen in the simulations, are due to the coherent phonons caused by the acoustic wave launched into the InSb, that is, the crystal is literally "ringing" due to the 70-fs laser-induced impulse. SOURCE: Reprinted, with permission, from D.A. Reis, M.F. DeCamp, P.H. Bucksbaum, R. Clarke, E. Dufresne, M. Hertlein, R. Merlin, R. Falcone, H. Kapteyn, M.M. Murnane, J. Larsson, T. Missalla, and J. S. Wark, 2001, "Probing Impulsive Strain Propagation with X-Ray Pulses," *Phys. Rev. Lett.* 86:3072-3075, copyright 2001 by the American Physical Society.

technique examines different aspects to the lattice response as a function of time, position, and temperature. Taken collectively, these measurements of lattice response to deformation allow a new regime of material science at ultrahigh pressures and strain rates to take root and grow.

Radiation Flow and Material Opacities

The previous section dealt with extreme conditions in cool dense matter, mainly solids, where quantum mechanics dominates. Next let us "turn up the heat" several notches, moving into the right-hand side of the phase diagram of Figure 3.3, where radiation effects dominate. The most interesting effects in this regime often involve gradients that allow thermal energy to flow. At high enough temperature the heat flow is dominated by radiation transport and opacity provides the resistance. The ionization state and opacity of "high-Z" plasma (any Z > about 20) under high-temperature conditions is enormously complex, and can have a dominant impact on the heat flow in ICF hohlraums, stellar interiors, and supernova explosions. The regimes break down into categories such as equilibrium versus nonequilibrium, optically thick versus optically thin, collisional versus radiation dominated, and static versus flowing plasma. Each regime has its own applications and "grand challenge" problems to solve. One of the best examples of laboratory measurements helping to understand an astrophysical object, beat-mode Cepheid variable stars, was a result of accurate calculations and measurements of the opacity of iron under conditions relevant to stellar envelopes.

Partially or Fully Degenerate Matter

Cool dense matter corresponds to conditions where $kT/\Theta_F << 1$, and $\Gamma = e^2/akT >> 1$, where Θ_F is the Fermi temperature and Γ is the plasma coupling constant, that is, the ratio of the interparticle coulomb energy (for typical inter-particle spacing, a) to the particle thermal energy, kT. Here, Fermi-Dirac statistics is the rule. Hot matter corresponds to regimes where degeneracy effects are negligible ($kT/\Theta_F >> 1$), and kinetic energy dominates potential energy ($\Gamma << 1$), where a classical Maxwell-Boltzmann description of the plasma works well. In between lies a theoretical "no-man's land," where $kT/\Theta_F \approx 1$ and $\Gamma \approx 1$. The standard simplifying approximations no longer apply. Quantum effects neither dominate nor are negligible, making this *terra incognita* particularly troublesome theoretically. The scientific community has until now largely set this difficult regime aside for future generations to deal with. A new cadre of scientists, emboldened by a repertoire of new scientific tools—massively parallel computers and new experimental facilities—is now confronting this problem under the innocuous rubric of "warm dense matter."

On the theoretical side, numerical simulation capabilities using massively parallel computing have progressed significantly. The theories, with their numerical implementation, can now begin to model experimental results in this warm dense matter regime, including EOS and opacity studies. On the experimental side, high-explosive techniques can achieve temperatures greater than 1 eV over large (compared to laser-driven systems) volumes of matter. Higher energy densities can be obtained with laser-driven techniques and dense Z-pinches. Development of new high-power, short-pulse sources in the XUV and x-ray regimes look extremely promising to create and diagnose these conditions. These sources, based at high-energy accelerator facilities, include an XUV free-electron laser—the Teraelectronvolt Energy Superconducting Linear Accelerator Test Facility (TTF II) at the Deutsche Elektronen-Synchrotron (DESY) center in Germany—and X-ray FELs—the Linac Coherent Light Source (LCLS) being developed at the Stanford Linear Accelerator Center (SLAC), and the Teraelectronvolt Energy Superconducting Linear Accelerator (TESLA) under development at DESY. Other techniques based on using subpicosecond laser pulses may yield short-pulse x-ray sources as well. A significant advantage in the use of radiation above optical frequencies is that it allows for greatly enhanced diagnostic access, since warm dense matter systems are characteristically opaque to visible light.

One way to access warm dense matter states is through the use of ultrafast laser systems to heat matter on a time scale that is short compared to its hydrodynamic response time. This allows solid-state density materials to be heated to temperatures in the high energy density regime (e.g., densities, temperatures, and energy densities of 10^{24} cm^{-3}, a few electronvolts, and ~10^{12} ergs/cm^3 = 10^{11} J/m^3, respectively). Thus, recent advances in ultrafast laser technology allow the creation of high energy density systems that were previously unattainable.

Dynamic Plasma Evolution

So far, this chapter has described matter solely in terms of static quantities—for example, p/B, kT/Θ_F, $\Gamma = e^2/akT$, and so on. Material flow, however, brings in a whole new dimension and can indeed have dramatic effects on the response of matter to extreme conditions. Under incompressible conditions ($p/B << 1$), the study of material flows constitutes the field of classical fluid dynamics. In HED conditions ($p/B \geq 1$), studies of material flows are new, and experimental mileposts are sparse to nonexistent. The following section discusses dynamic plasma evolution, that is, HED flow dynamics.

Classical Fluid Instabilities, Including Nonlinear Behavior

There are two relevant dimensionless parameters in classical fluid flow. These are the Reynolds number, $Re \equiv \rho uL/\mu = Lu/\nu$, and the Mach number, $Ma \equiv u/a$. Here, ρ is the fluid density, u the relative fluid velocity in the flow frame, L the flow spatial scale, μ the fluid (shear) viscosity, $\nu = \mu/\rho$ is the fluid kinematic viscosity, $a = (\gamma R_u T/W)^{1/2}$ is the (local) speed of sound for a perfect gas, $\gamma = c_p/c_v$ is the ratio of specific heats, R_u the universal gas constant, and W the molecular weight (molar mass).

The Reynolds number (Re) is a measure of the relative importance of viscous damping to inertial or convective forces and gauges hydrodynamic stability when no other (e.g., MHD) forces are important. At low values, *Re* generally serves as a yardstick for the generation of instabilities. At higher values, it characterizes the turbulent state. Typically, values of $Re < 40$ to 50 correspond to stable flow, $Re > 40$ to 50 marks the onset of unbounded (free-shear) flow instabilities, *Re* > a few times 10^3 signals the onset of wall-bounded flow instabilities, and *Re* > a few times 10^4 triggers the transition to fully developed (bona fide) turbulence. The latter transition appears to occur in all high-Reynolds-number flows, and demarks a weaker sensitivity to further increases in Reynolds number. In a turbulent flow, the Reynolds number is also a measure of the range of spatial scales that participate in the dynamics. This can be estimated based on Kolmogorov-scaling arguments, yielding $L_{min}/L_{max} \approx C_L Re^{-3/4}$, where $C_L \approx 16\pi \approx 50$, as also supported by experiment. Post-transitional flows exhibit enhanced mixing relative to pretransitional flows. Figures 3.5 and 3.6 show examples of this transition in turbulent shear layers and jets, and its consequences on scalar (i.e., concentration) fields, as measured by laser-induced fluorescence. As these examples illustrate, there can be significant qualitative and quantitative differences between pre- and post-transitional flows. Inferences from experiments, or simulations, in the pre-transitional regime cannot be applied to fully developed (post-transitional) flows. In the context of future HED experiments

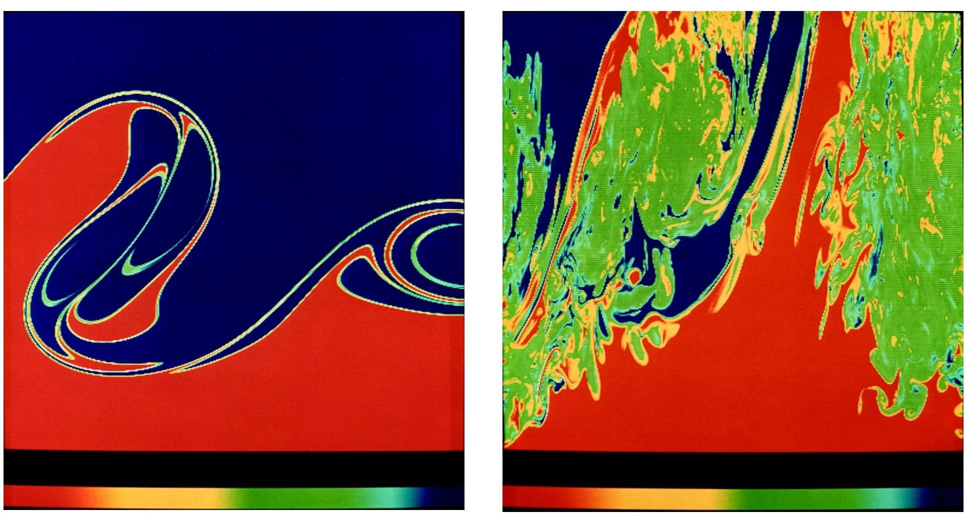

FIGURE 3.5 Shear-layer scalar field. Blue: pure high-speed fluid. Red: pure low-speed fluid. Color bars denote intermediate compositions. Left: $Re = 2.3 \times 10^3$; right: $Re = 2.0 \times 10^4$. Courtesy of P. Dimotakis, California Institute of Technology and M.M. Koochesfahani, Michigan State University.

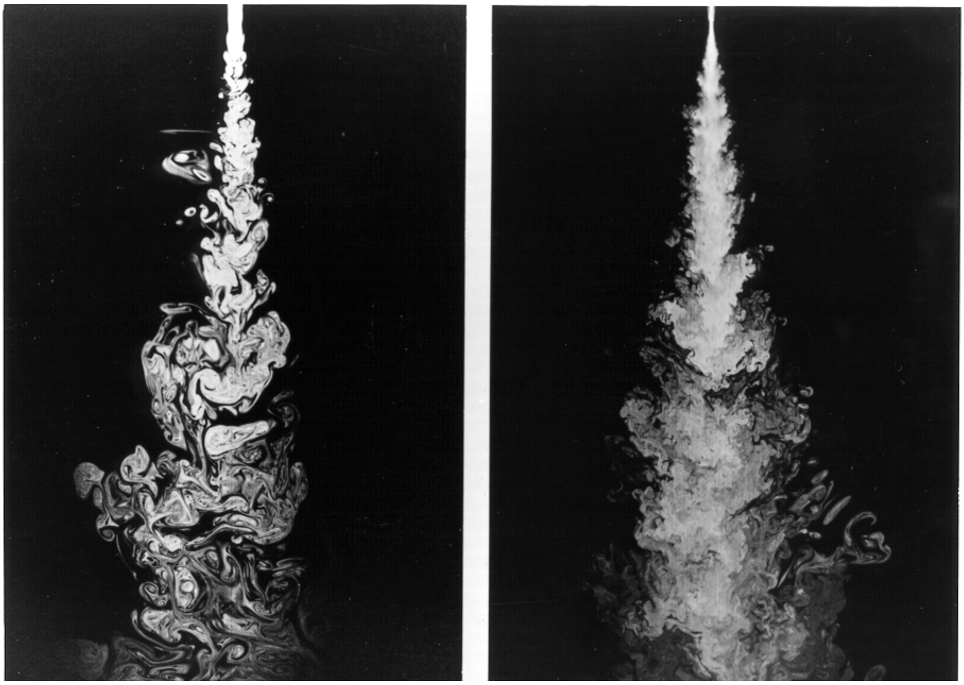

FIGURE 3.6 Jet-fluid concentration field in the plane of symmetry of turbulent jets. Left: $Re = 2.3 \times 10^3$; right: $Re = 10.0 \times 10^3$. Courtesy of P. Dimotakis, California Institute of Technology.

and simulations, especially as length scales and energy density increase in HED laboratory experiments and increases in computational power permit ever-increasing Reynolds numbers to be simulated, post-transitional flows will be encountered. This will mark a major step forward in the experimental and numerical capability to reproduce complex, high-Reynolds-number flows.

The Mach number (Ma) measures compressibility (density variations), the ratio of kinetic to thermal energy, and the ability of the flow to form and sustain shocks. This can be seen by expressing the local, specific thermal energy h (thermal energy per unit mass) in terms of the local sound speed, a, i.e., $h \approx c_p T \approx a^2/(\gamma - 1)$, an exact relation for a perfect gas. The Mach number then expresses the ratio of kinetic energy per unit mass, $K = u^2/2$, to thermal energy per unit mass in the flow, h, since $Ma = [2K/(\gamma - 1)h]^{1/2}$, also exact for a perfect gas. In addition, the Mach number scales the flow density fluctuations, $\Delta\rho$. In particular, for Ma not too large, one can show, with only mild assumptions, that $\Delta\rho/\rho \approx M^2/2$. As the Mach number becomes comparable to unity, the flow will generate shocks, that is, the flow can sustain fluid-property jumps across a few mean free paths.

These relations also indicate that if a significant fraction of the energy density manifests itself as a (specific) kinetic energy, *K*, the flow will be characterized by high Reynolds numbers and must be turbulent. Also, if K/h is large, the Mach number is also large, and the flow will be compressible. If both Reynolds number and Mach number are large, compressibility, shocks, and turbulence will coexist. Compressible turbulence and the coupling and interactions of shocks with turbulence are to a large extent unexplored territory, at present, both experimentally and computationally.

The fundamental instabilities that induce and sustain turbulence are sensitive to compressibility effects. For example, supersonic shear layers grow considerably more slowly than their incompressible counterparts. Further, shocks provide an additional dissipation mechanism, indicating that the Kolmogorov cornerstones of classical incompressible turbulence need to be modified or, at least, augmented. Compressible turbulence must be characterized as an important research area. Pursuits in this important HED regime are limited, as only scant information is available from theory, experiment, or simulations.

Interestingly, the Mach and Reynolds numbers also enter into determining the boundary between a continuum fluid description and a free-streaming, molecular (rarefied) description of the flow. This can be seen from the approximate gas-kinetic expression for the viscosity, $\mu \approx 2\,\rho a \lambda_f/3$, where λ_f is the mean free path. From the relation for the Reynolds and Mach numbers, we see that they can also be expressed as $Ma \approx Re\,Kn$, where $Kn \equiv \lambda_f/L$ is the Knudsen number, that is, the ratio of the mean free path to the flow scale. Continuum hydrodynamics require $Kn \ll 1$, or, $Re \gg Ma$.

This phenomenology is potentially much richer in plasmas where electron and ion velocities can differ, offering additional measures for compressibility and turbulence. As with shocks and turbulence, the corresponding magnetohydrodynamic regimes are not well understood, except in simple cases. Finally, in very energetic plasma flows such as very high Mach number jets or shocks, radiation can significantly alter the dynamics. At sufficiently high temperature and density, the photon "fluid" carries a significant fraction of the energy density. If the scale of the photon mean free path is long compared to characteristic spatial scales of the flow, then radiative cooling can remove thermal energy, lowering the temperature and pressure and increasing the compressibility and Mach number of the flow. High-Reynolds-number, high-Mach-number flows including radiative effects are common in astrophysics (see Figures 3.7(c) and 3.9(a)), but are largely unexplored in laboratory studies. Existing and future HED facilities should be able to make major inroads into this frontier territory.

High-Mach-Number Shocks

The experimental investigation of the dynamics of strong shocks, that is, high-Mach-number shocks, is a relatively new area. Experimental facilities have only recently accessed this hydrodynamic regime. HED facilities, in particular, excel in this respect because they can focus macroscopic energies into microscopic volumes in nanosecond time intervals. Fundamental issues abound, such as what the effect of strong shocks passing through a turbulent medium is, and how radiative emissions and magnetic fields couple to the dynamics. Though difficult to attain in the laboratory, strong shocks in astrophysics are the rule, not the exception. Examples include the enormously energetic shock unleashed by the "nuclear spring" at the core of a supernova (*Ma* ~10), the shocks launched by the passage of high-Mach-number protostellar jets through the interstellar medium (*Ma* ~ 10 to 20), and the shocks created by the stellar winds from newly formed young stars that sweep away the remaining molecular clouds out of which they were born (*Ma* ~ 5), to name a few.

Aspects of strong-shock astronomical dynamics can be scaled down into the laboratory if conditions on certain key dimensionless parameters such as Mach number and also Reynolds number are met. For dynamics that are not dominated by turbulence and turbulent mixing, the equations suggest that such scaling is possible. Figure 3.7 illustrates this point by juxtaposing the results of a computer simulation of a supernova explosion and a Chandra x-ray image of a supernova remnant with images of strong-shock laboratory experiments that capture aspects of the same supernova dynamics.

Those aspects of the supernova dynamics in the explosion phase can be approximated by the inviscid/nondiffusive equations for compressible hydrodynamics, namely, the Euler equations. Two systems will exhibit similar evolution if the dimensionless Euler number, $Eu = L/\tau(\rho/p)^{1/2}$, with L and τ the characteristic length and time scale, and ρ and p the density and pressure, is the same in the two systems. For example, the simulated supernova illustrated in Figure 3.7(a) and the laser experiment illustrated in Figure 3.7(b) differ in spatial scale by 13 to 14 orders of magnitude and 11 orders of magnitude in time. If both are at sufficiently high Reynolds number, Peclet number, and Mach number and if they have similar Euler numbers, important aspects of these two disparate systems will dynamically evolve in a similar fashion.

Several types of HED facilities allow strong shocks to be created and studied. For example, there is a long history of using gas guns, essentially sophisticated, high-tech "gun barrels," for studying strong-shock physics issues. Shock strengths of up to 4 to 5 Mbar (4-5 × 10^{11} Pa) are possible by this technique. An alternate way to generate strong shocks is to use magnetic-pinch facilities, of which the Z-machine is the largest, to accelerate flyer plates (without producing shock waves) to velocities

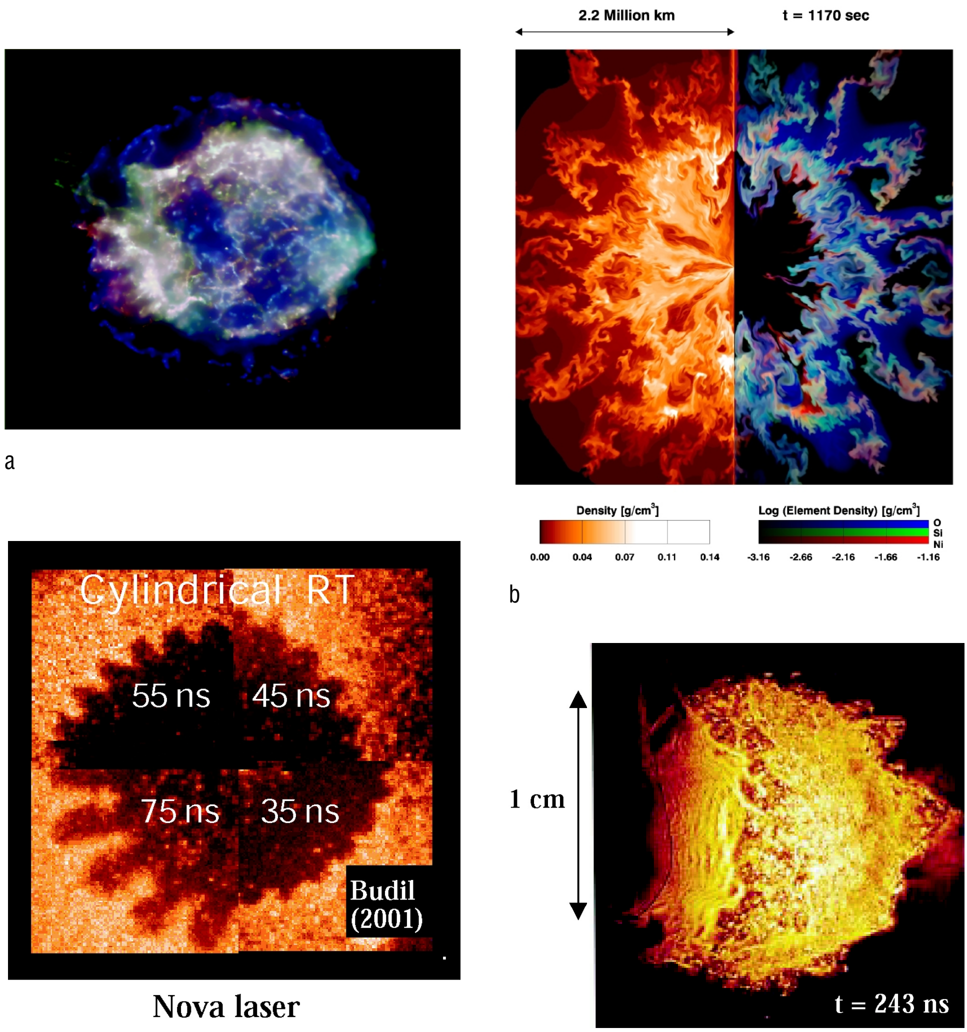

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FIGURE 3.7 Results of a computer simulation of supernova explosion (a) and a Chandra x-ray image of a supernova remnant (b) with images of strong-shock laboratory experiments that reproduce aspects of the same supernova dynamics, (c) and (d). SOURCES: Images (a) courtesy of NASA, the Chandra X-Ray Observatory Center, Smithsonian Astrophysical Observatory; (b) K. Kifonidis, Max-Planck-Institut fuer Astrophysik; (c) K. Budil, Lawrence Livermore National Laboratory; and (d) reprinted, with permission, from J. Grun, J. Stamper, C. Manka, J. Resnick, R. Burris, J. Crawford, and B.H. Ripin, 1991, “Instability of Taylor-Sedov Blast Waves Propagating Through a Uniform Gas,” *Phys. Rev. Lett.* 66:2738-2741, copyright 1991 by the American Physical Society.

of 10 to 20 km/s. The flyer plate then impacts onto samples, triggering shocks of strengths that can exceed 10 Mbar. Planned Z-machine refurbishments and upgrades (turning Z into ZR) will enable both high peak current and tailored current pulse shape. Pressures up to 3 Mbar in liquid deuterium, 15 Mbar in Al, and over 40 Mbar in most high-Z materials will be possible using flyer plates. High-power laser facilities offer the means to reach the highest pressures, albeit over smaller sample sizes and shorter measurement durations. Planar shocks of 50 Mbar, or more, are possible on the OMEGA laser. At the NIF this number will extend into the hundreds of megabars, perhaps even as high as 1 Gbar.

Radiative Hydrodynamics

Very strong shocks and very high Mach number flows invariably enter the regime of coupled radiative hydrodynamics. Indeed, perhaps one of the defining features of HED facilities is their ability to create and probe a wide variety of radiative-hydrodynamic conditions. As discussed in Chapter 2, radiative hydrodynamics is very prevalent in astrophysics. Colliding galaxies, supernovae, and hypersonic jets of particles streaming out of accreting black holes all glow profusely due to radiative hydrodynamics. At extreme temperatures, the matter becomes radiation-dominated, meaning that the pressure from the radiation itself completely overwhelms all other sources of pressure. This is the situation thought to exist in the vicinity of accreting neutron stars and black holes. Theoretical models and computer simulations for radiative hydrodynamic systems abound, but they suffer from large uncertainties due to the complexity of the physics involved and the lack of experimental checkpoints. The field of high energy density physics and astrophysics would benefit greatly from testbed laboratory data in relevant regimes of coupled radiation hydrodynamics.

Over the past 15 years, examples of radiative shock experiments have been demonstrated on a number of HED facilities around the world, including both lasers and magnetic pinch facilities. Strong shocks have been driven into low-density targets of gas or foam, and the radiative characteristics of the shocks measured. An example of a strongly radiative, cylindrical shock from Z is shown in Figure 3.8 (right-hand image), juxtaposed with the glowing shocked circumstellar nebula of Supernova 1987A remnant (Figure 3.8, left-hand image). In dimensionless terms, these two radiative shocks—one in SNR1987A in the Large Magellanic Cloud, our second-nearest neighbor galaxy, and the other at Sandia National Laboratories in Albuquerque—occupy a very similar parameter space in radiative hydrodynamics. In both cases, the shocks are strong, $Ma = v_{shock}/c_{sound} >> 1$, and the radiative cooling time is short compared to a characteristic hydrodynamic time, $\chi = \tau_{rad}/\tau_{hydro} << 1$.

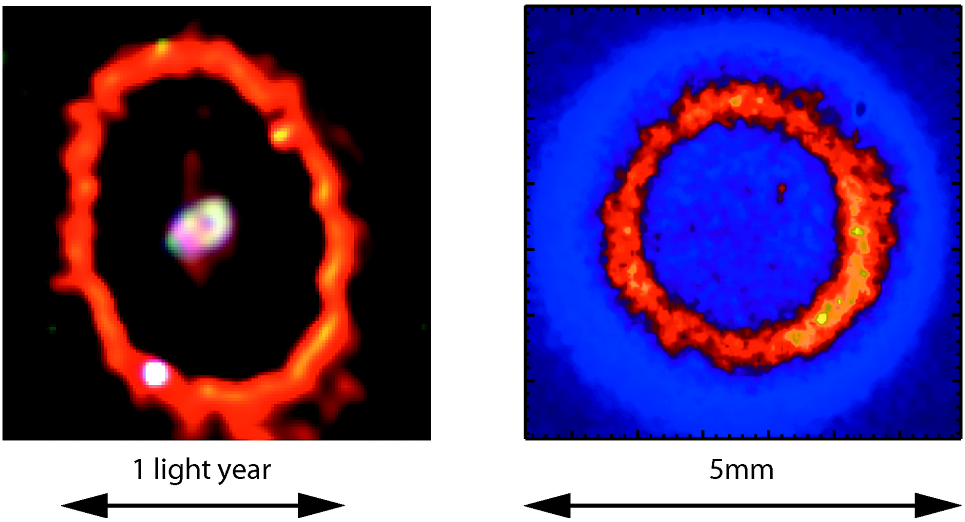


FIGURE 3.8 An example of a strongly radiative, cylindrical shock from Z is shown (right), juxtaposed with the glowing shocked circumstellar nebula of Supernova 1987A remnant (left). Courtesy of (left) P. Garnavich, Harvard-Smithsonian Center for Astrophysics and NASA; and (right) J. Bailey, Sandia National Laboratories.

It may also be possible to experimentally create conditions of radiation-dominated hydrodynamics and turbulence relevant to the vicinities of accreting neutron stars and black holes. This potential is only starting to be explored, but the extraordinary ability to focus macroscopic amounts of energy into microscopic volumes in nanosecond and even picosecond time intervals make this possibility fertile for consideration. It has already been shown on the ultraintense, ultra-short-pulse lasers that temperatures well into the relativistic regime ($T > 1$ MeV) are achievable.

High-Mach-Number Jets

High-Mach-number jets arise in a number of research areas, such as combustion, aerodynamics, fusion research, climatology, and defense research. In astrophysics, high-Mach-number jets and even relativistic jets are at the center of several fundamental unsolved problems, such as how stars form and what drives active galactic nuclei (AGN). An example of a protostellar astrophysical jet is shown in Figure 3.9(a).

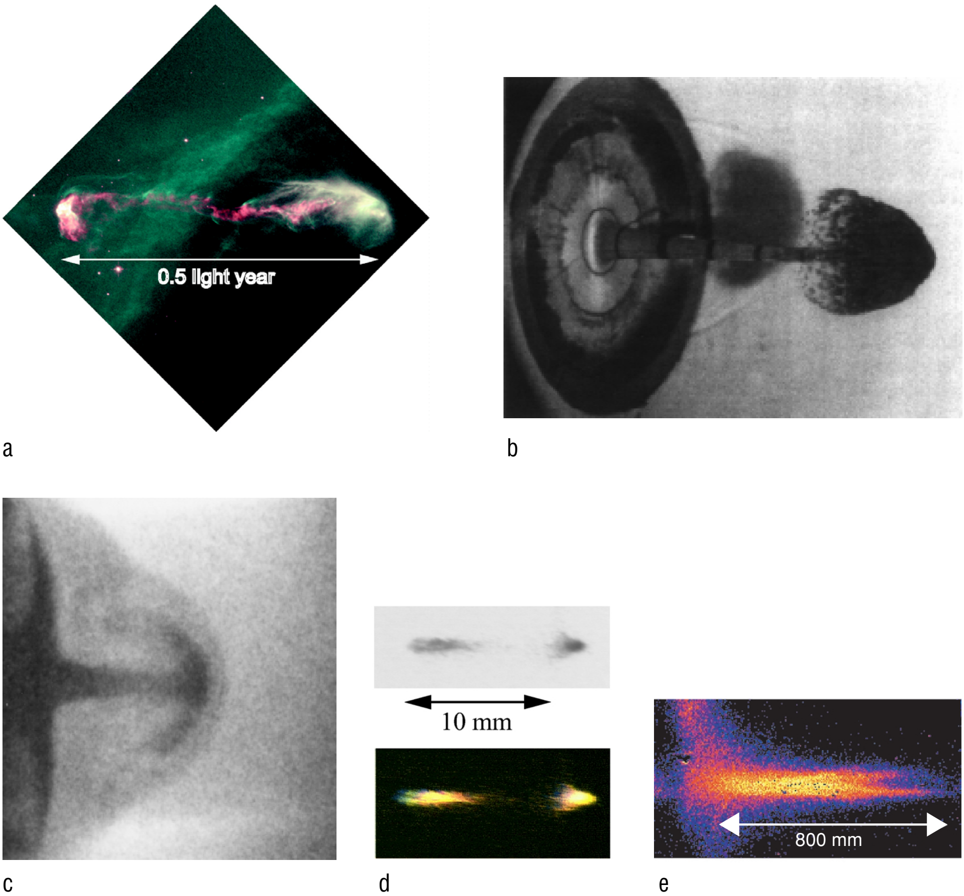


FIGURE 3.9 Examples of high-Mach-number jets: (a) Hubble Space Telescope image of a protostellar astrophysical jet (HH 47); (b) an Mjet ~ 30 jet explosively driven from a conical liner of Cu; (c) laser light converted to an x-ray drive that "imploded" a solid cylindrical pin of Al; the free end of the Al pin was mounted flush against a reservoir of plastic; (d) radiatively cooled jets at Imperial College Z-pinch; and (e) radiatively cooled jets at the Nova laser. SOURCES: Images (a) courtesy of Space Telescope Science Institute and NASA; (b) reprinted, with permission, from L.L. Shaw, S.A. Muelder, D.W. Baum, and K.A. Winer, 1994, "Hypervelocity Explosive-Driven Metal Jet in Air," *Phys. Fluids* 6(9):S10, copyright 1994 by the American Institute of Physics; (c) reprinted, with permission, from J.M. Foster, B.H. Wilde, P.A. Rosen, T.S. Perry, M. Fell, M.J. Edwards, B.F. Lasinski, R.E. Turner, and M.L. Gittings, 2002, "Supersonic Jet and Shock Interactions," *Phys. Plasmas* 9:2251-2263, copyright 2002 by the American Institute of Physics; (d) courtesy of S. Lebedev, Imperial College London; (e) reprinted, with permission, from 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, 1999, "Radiative Jet Experiments of Astrophysical Interest Using Intense Lasers," *Phys. Rev. Lett.* 83:1982-1985, copyright 1999 by the American Physical Society.

In the laboratory, high-Mach-number jets can be generated in a variety of ways, and under an even wider variety of extreme conditions, as illustrated in Figures 3.9(b) through 3.9(e). For example, the Ma_{jet} ~ 30 jet [where jet Mach number is defined as $Ma_{jet} = v_{jet}/c_s$(jet), with c_s(jet) being the speed of sound] shown in Figure 3.9(b) is explosively driven from a conical liner of copper (Cu). This jet of Cu is thought to be in the solid state, meaning that the temperature of the jet is below the melt temperature of Cu. Experiments on high-Mach-number, hydrodynamic jets and radiatively collapsing jets have also been demonstrated both on lasers and on pulsed-power facilities. In the case of the high-Mach-number hydrodynamic jets (Figure 3.9(c)), the laser light was converted to an x-ray drive, which "imploded" a solid cylindrical pin of aluminum (Al). The free end of the Al pin was mounted flush against a reservoir of plastic (CH). The high pressure imploded Al plasma jets out into the CH reservoir, forming an $Ma_{jet} \approx 3$ hydrodynamic jet.

In the case of the radiative jets (Figure 3.9(e)), a conical surface of Au was directly illuminated for 100 ps with high-intensity (~3×10^{15} W/cm^2) laser light. The hot, high-velocity ablated plasma "implodes" onto the cone axis and jets outward from the cone at ~700 km/s. Due to the high initial temperatures, kT ~ 1 keV, the Au plasma very rapidly radiatively cools itself, triggering a radiative collapse over a ~$^1/_2$-ns interval. Due to the radiative cooling, the sound speed in the Au drops, raising the jet Mach number to 50 or more. An x-ray image in emission from this experiment is shown in Figure 3.9(e). An experiment done on a magnetic pinch machine generated a similar radiatively cooled jet, as shown in Figure 3.9(d). In this case, the spatial and temporal scales are over an order of magnitude larger.

Ablation Front Hydrodynamics

Another unique regime accessible on HED facilities is ablation front dynamics. In such a setting, intense radiation bathes a surface, causing ablation or photoevaporation. The absorbing layers become hot and vaporize, in response to which a strong-shock compression wave is launched into the sample. This is the fundamental dynamics of inertial confinement fusion, where millimeter-scale capsules are imploded by this ablation pressure at the capsule surface (see Figure 3.1). Such an ablation front is hydrodynamically unstable, and any surface imperfections grow, due to the Rayleigh-Taylor instability. An example of such a hydrodynamic instability experiment in planar geometry is shown in Figure 3.10(b), and a spherical version of this type of experiment is shown in Figure 3.10(c). A particularly impressive example of ablation front dynamics can be found in astrophysics in radiatively driven molecular clouds. The most notable example here is the Eagle Nebula in M16, otherwise referred to as the Pillars of Creation (Figure 3.10(a)). Here, radiation incident on the dense cloud surface from two nearby bright young UV stars triggers

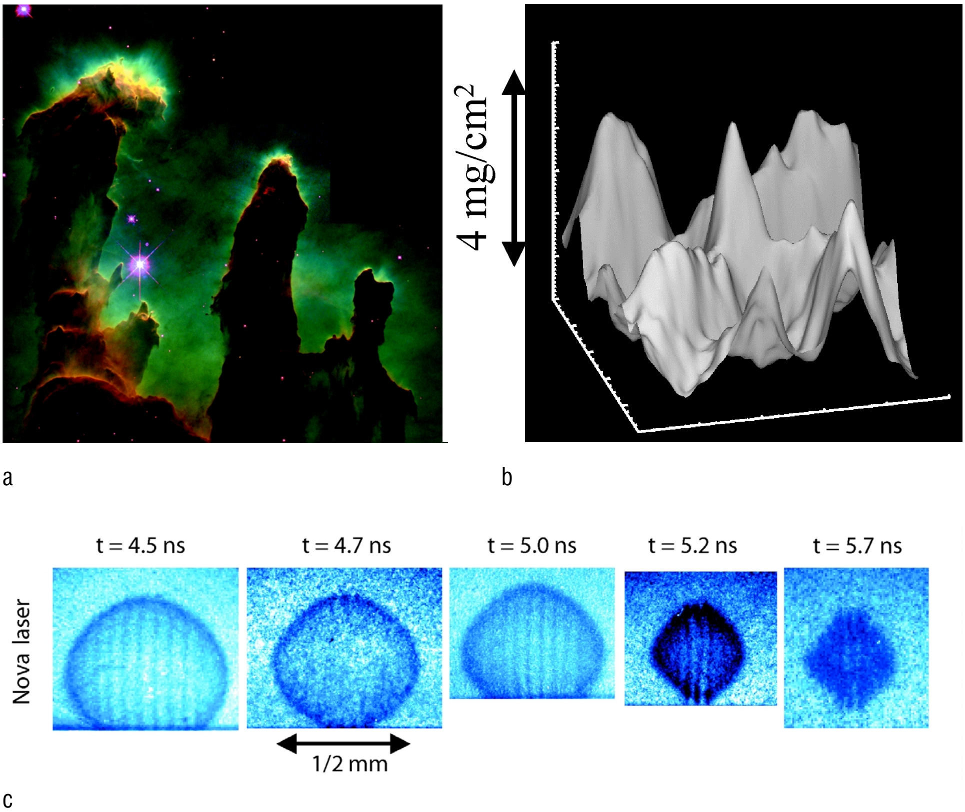


FIGURE 3.10 Ablation front hydrodymanics: (a) the Eagle Nebula in M16, otherwise referred to as the Pillars of Creation; (b, c) x-ray radiography of hydrodynamic instability experiments in (b) planar and (c) spherical geometry. These images show a spherical capsule imploded with a thermal x-ray drive on the Nova laser. The capsules had preimposed ripples imposed on their outer surfaces, to study the hydrodynamic instabilities relevant to ICF capsule implosions in convergent geometry. SOURCES: Images (a) courtesy of NASA; (b) S. Obenshain, U.S. Naval Research Laboratory; (c) reprinted, with permission, from S.G. Glendinning, J. Colvin, S. Haan, D.H. Kalantar, O.L. Landen, M.M. Marinak, B.A. Remington, R. Wallace, C. Cherfils, N. Dague, L. Divol, D. Galmiche, and A.L. Richard, 2000, "Ablation Front Rayleigh-Taylor Growth Experiments in Spherically Convergent Geometry," *Phys. Plasmas*, 7:2033-2039, copyright 2000 by the American Institute of Physics.

photoevaporation or ablation pressure on the cloud surface. This shock compresses the cloud and subsequently accelerates it away from the stars. Theoretical considerations show that several aspects of this radiative dynamic can be scaled to the laboratory for close-up scrutiny.

APPLICATIONS

Besides their fundamental interest and their relevance to astrophysics, laboratory HED plasmas have several important applications. Although not discussed in this report, much of laboratory HED progress to date has been spurred by the relevance of HED plasmas to the nation's nuclear weapons stockpile. In this section, some of the many other applications of HED physics to science and society are described.

Inertial Confinement Fusion

The first goal of inertial confinement fusion (ICF) research is controlled laboratory implosion of fusionable material to a condition of ignition and propagating burn. A further goal of this research is the production of safe, reliable energy in quantities suitable for practical commercial application (inertial fusion energy) by igniting a succession of fusion fuel capsules.

Inertial confinement fusion relies on inertia to confine fusionable material, usually a mixture of deuterium and tritium (DT), for a time long enough for a significant number of fusion reactions to occur. Matter compressed by laser-, x-ray-, or ion-beam-driven ablation can be considered to be a high energy density plasma for essentially all phases of the process from earliest compression, through energy production from fusion reactions, through replete, extinguishing burn.

The canonical ICF implosion scenario is that of central hot spot ignition, in which a hollow DT sphere is symmetrically imploded to a density (ρ) × radius (R) (areal density) of 0.3 g/cm^2 and a temperature (kT) of order 10 keV. In the limit of radial symmetry, success (propagating burn, i.e., spread of DT fusion reactions to the fuel surrounding the central hot spot) is predicted for a wide range of driver-capsule configurations.

The two most commonly envisioned central hot spot systems are direct and indirect drive ICF. In direct drive ICF, the driving beams, usually high-intensity (10^{15} W/cm^2) lasers of short wavelength light (0.35 to 0.25 μm), directly irradiate a spherical capsule surface. As the surface is heated, matter blows off (ablates) and the capsule implodes, accelerating the compressed hollow sphere walls inward to high final velocities (3×10^7 cm/s). For indirect drive ICF, the process is similar, with laser light replaced by a spatially uniform bath of x rays (wavelength ~0.1 μm), characterized by an effective blackbody temperature of hundreds of electronvolts. The x rays are produced and contained in a spherical or cylindrical can, a hohlraum, that is fabricated of high-atomic-number (Z) metals. Drivers used to generate the hohlraum x rays include lasers, Z-pinches, and beams of heavy ions.

It is generally agreed that the following five criteria determine a successful ICF implosion, each with outstanding issues and active research:

1. A sufficient amount of driver energy must be transferred to the shell. Plasma instabilities in the shell corona can inhibit uniform, efficient coupling of driver energy into the target.
2. The imploded capsule must be sufficiently dense for fusion conditions to be achievable with laboratory-scale drivers. Considerable research in equation-of-state, opacity, and other processes is required to be able to quantify this criterion.
3. The implosion must be sufficiently symmetric at length scales long relative to the shell thicknesses for the generation of a well-formed hot spot that will create a DT fusion "spark" at the center.
4. The shell must be sufficiently stable to the short wavelength Rayleigh-Taylor instability to confine the core gas to full compression in order for ignition conditions to be achieved. This instability, which is seeded by all of the small-scale imperfections of the driving beams and shell surface and mass, is the subject of intense ongoing research.
5. The pellet must reach a condition of sufficient ρR and T for alpha-particle-driven ignition of the hot spot and the surrounding fuel (propagating burn) to occur.

As with many systems with well-defined postulates, the relaxation of one criterion can sometimes lead to most interesting alternate systems. In the case of ICF, completely relaxing the fourth criterion has led to the idea of fast ignition. In fast ignition, the ρR for ignition is first achieved with standard drivers and capsules that range from spherical shells to hemispheres of webbed foams. The ignition beam will then be generated from high-intensity, collimated electrons or ions that result from petawatt laser-matter interaction. Thus, the fast ignitor concept reduces the requirements on the compression phase of an inertial confinement target. Any ICF driver could, in principle, be used to assemble the compressed fuel. In addition, driver configurations that would not lead to ICF ignition because of stability or other limitations may produce viable drivers. While compression is relatively easy and has already been demonstrated to a significant level in the laboratory, being able to couple the ignitor "spark" to the compressed fuel is far from determined. The introduction of this concept in the early 1990s, along with the development of very high intensity (~10^{18} W/cm^2 or higher), high-energy (~1 kJ) laser drivers, has resulted in significant active research on very high intensity laser matter and laser plasma interactions.

The body of inertial fusion energy (IFE) research takes as its starting point a single successful ICF implosion with high gain (energy > 100 times driving energy) and seeks to develop from this a system that is commercially viable. For laboratory systems that produce a few hundred megajoules or more of nuclear energy per shot, this means successful ICF implosions at ~1-Hz repetition rates for several years without substantial plant maintenance.

A number of requirements devolve from this highest-level specification: inexpensive mass production of well-characterized targets; high-repetition-rate drivers; a target chamber that will survive years of intense implosions/explosions and also produce reliable, useful heat from the ICF-generated neutrons; a sufficiently accurate target injection system; and some way to deal with radioactive by-products and waste.

Inertial fusion energy systems are postulated for every ICF driver. Ongoing IFE research is focused on the development of full systems that can simultaneously meet all of the requirements for success. The goal of the IFE effort is an end-to-end inertial fusion energy system in a demonstration test phase in the United States within the next few decades.

Spin-offs

The development of high-power lasers for high energy density applications has other applications as well. For example, the class of pump lasers under development for extreme ultraviolet applications would make a significant contribution to turbulence research. Diode-pumped Nd:YAG lasers with ~0.25 to 0.4 J/pulse at 532 nm, 0.5 to 1 kHz, with good beam quality, would permit three-dimensional measurements of fully developed turbulence. These measurements would use laser-induced fluorescence and other laser-diagnostic techniques, coupled with high-resolution, $1{,}000^2$ pixels or better, low-noise, digital-imaging detectors operating at framing rates that match the laser pulse repetition rate. These specifications are dictated by dynamic turbulence scaling at a minimum Reynolds number of 10^4, signal-to-noise considerations for candidate laser diagnostic techniques, and data-acquisition considerations. Such experiments provide significant exploration capabilities in the three-dimensional structure of turbulence, data for subgrid-scale modeling, as well as validation data for the next-generation turbulence numerical simulations.

Other relevant spin-offs for HED include laser machining (manufacture of precision holes for the automotive and airline industries, microelectromechanical systems (MEMS) manufacture, for example), directed-energy lasers for national security (both the technology and lethality). There are also numerous technology spin-offs in the area of diagnostics, lasers, target fabrication, and pulse power.

Extreme Ultraviolet Lithography

Extreme ultraviolet lithography has been identified by International SEMATECH as the leading candidate technology for next-generation lithography. The light sources for these tools consist of a laser interacting with a cold xenon gas jet to produce a high energy density plasma that generates broadband line radiation. The conversion efficiency of the radiated power within the bandwidth of the multilayer optical components centered at 13.4 nm is on the order of 1 percent, and the source power requirement on the first collection optic is nominally 100 W. Typical parameters of the radiating plasma source are $n_e \sim 10^{22}$ cm^{-3}, $T_e \sim 50$ eV, $I = 10^{12}$ W cm^{-2} today, and up to an order-of-magnitude performance increment is planned. However, at ~0.1 Mbar with little evidence of collective effects, extreme ultraviolet lithography is very much at the low end of the high energy density plasma spectrum.

This technology has huge market potential and could prove to be the most significant potential commercial application of high energy density plasmas. The present SEMATECH roadmap calls for market insertion of extreme ultraviolet lithography around 2006, following the 157-nm fluorine dimer source systems, which are presently under active development, to expose chips with 50- to 70-nm critical dimension features. Because of excellent depth of focus, extreme ultraviolet lithography is a multigeneration technology that will carry lithography to the "end of silicon," with respect to achievable minimum smaller feature size. The technology also benefits from ties to existing optical lithography infrastructure and techniques.

Applications to Medical Physics

Researchers are beginning to explore the application of ultrashort-pulse lasers to surgery. Typical operating parameters are 0.1 to 1 TW/pulse and intensities from 0.03 to 3×10^{16} W/cm^2-pulse at millijoule energy levels. Under these conditions, small-volume, high-temperature, short-duration plasmas are created from flash heating of material via multiphoton absorption of the intense laser light. Plasma heating times are so short that photo ablation dominates over thermal ablation. Tissue removal appears insensitive to tissue color and exhibits very little if any collateral damage owing to plasma durations shorter than thermal conduction times. Typical ablation rates are 1 micron/pulse, thus placing a premium on operating lasers at high average power (1 to 10 W) in order to achieve removal rates in the millimeter per second range. In combination with plasma luminescence spectroscopy, this technology can be used to selectively ablate tissue of different mineral content—for example, ablating bone away from sensitive nerves. Medical applications include delicate spinal surgery, tumor resection from brain tissue, corneal sculpting, bone debulking, and hard plaque removal in totally occluded arteries. The development of low-cost, high average power lasers will be required in order to fully exploit the technology for medical applications.

Medical applications of short-pulse lasers include the following:

1. *Femtosecond surgery*. This surgery is based on the absence of collateral damage when femtosecond lasers ablate tissues. Currently more than 10,000 patients a year in the United States are having photorefractive surgery. A spin-off company from the Center for Ultrafast Optical Science at the University of Michigan has developed the tool to perform this surgery.
2. *Precision radiography*. Because the light can be focused on an extremely small spot, a micrometer x-ray source can be created. The small spot size acts as a point source and facilitates radiography with magnification. This could be important for mammography and small animal studies.
3. *Hadron therapy*. High-energy protons that can be created with high-intensity lasers can be used as an inexpensive alternative to the cyclotron for hadron therapy.

OPPORTUNITIES FOR GENERATING AND UTILIZING HIGH ENERGY DENSITY CONDITIONS IN THE LABORATORY

As described in previous sections, many existing and near-term facilities are or soon will be available to produce high energy density conditions in the laboratory. This section describes some of the technologies and capabilities associated with these systems and notes some of the research opportunities afforded by them

Existing and future National Nuclear Security Administration high energy density facilities, such as high-power lasers and magnetic pinch generators, are uniquely capable of probing the behavior of macroscopic collections of matter under extreme conditions. The distinguishing feature of these facilities is their ability to probe macroscopic collections of matter under extreme conditions of compression, deformation, and flow. Conditions relevant to nuclear weapons research, inertial confinement fusion, the center of Earth, the core of Jupiter, the interior of stars, and possibly even the vicinity of black holes can be recreated in the laboratory. The time intervals over which such extreme conditions can be maintained are necessarily brief, typically being measured in billionths of seconds (10^{-9} s). With high temporal- and spatial-resolution detectors and diagnostics designed to operate in this short-pulse mode, high-fidelity measurements of the states and properties of matter under these conditions can be made. The following subsections list a few high-impact physics opportunities that present themselves for pursuit on existing or future HED facilities, briefly pointing out their significance.

High Energy Density Physics Opportunities in the Laboratory

Transition to Turbulence

Turbulence conjures up images of chaotic, unpredictable flows where disorder is the rule, not the exception. Yet, in steady-state flows, phenomenological rules and descriptions for turbulent flows have been developed. A key unsolved question, however, is the transition to turbulence. How do flows "decide" whether they should be turbulent, and over what time span does this transition occur. The high energy density facilities are quite unique in their ability to create high-Reynolds-number flows, over a time span covering their transition to turbulence.

Radiation-Dominated Hydrodynamics

It seems plausible that dynamically evolving flows, and even turbulent flows, could be created on HED facilities such as ZR (the proposed refurbished version of the Z-machine at Sandia National Laboratories) or NIF, in which the pressure is dominated by radiation pressure, P_r. To achieve such conditions requires high temperatures, so that $P_r = 4\sigma T_r^4/3c >> n_e T_e + n_i T_i$, where σ is the Stefan-Boltzmann constant and c is the speed of light in vacuum. Such a flow extended into the turbulent regime would access the conditions that might be found in accretion disks surrounding massive black holes. Another radiation-dominated flow of broad scientific interest is an ablation front. Referred to as a photoevaporation front in astrophysics, the necessary conditions are thought to prevail in the star-forming regions of dense molecular clouds.

There is a potential to combine a megajoule-class laser or magnetic pinch facility with laser heating by a petawatt-class laser to produce matter in a condition of radiation-dominated hydrodynamics. In this regime, the radiation pressure greatly exceeds the thermal particle pressure. Qualitatively unique dynamics can evolve in this regime, depending on the density, temperature, and optical depth of the plasma. Such radiation-dominated hydrodynamics may have relevance to black hole and neutron star accretion dynamics, supernova shocks, and possibly even the dynamics of the early universe in the radiation-dominated epochs.

Dense, Degenerate Plasmas

The properties of dense, Fermi degenerate matter is of broad scientific interest, especially in geophysics and planetary physics, as well as from a fundamental materials perspective. The interiors of planets are at high pressure and are often Fermi degenerate. Understanding the behavior of iron and iron-like alloys at pressures as high as 3 Mbar or more (T ~ 7000 to 8000 K) is relevant to the structure of Earth's interior and the formation of Earth's magnetic field. In the giant gaseous planets and extrasolar planets, the equation of state of H and that of He are the most important quantities. The challenge is to develop the techniques to be able to make equation-of-state measurements to 1 percent accuracy if laboratory experiments are to be able to affect the models of planetary interiors and planetary formation. For example, in the 1- to 10-Mbar pressure regime ($T = 10^3$ to 10^4 K), the structure of planetary interiors depends rather sensitively on the details of how H transitions to the metallic state. This in turn affects whether the cores of gas giant planets such as Jupiter are thought to be a rocky solid or gaseous, a distinction that differentiates two standard planetary formation models (the planetessimal accretion model and the gravitational collapse model). At extreme compressions, matter can be squeezed so close together that the electronic orbitals become grossly distorted, leading to pressure ionization. Theories of this regime are highly uncertain, and measurements would be of great benefit.

If matter is pushed even more tightly together, the electron fluid becomes dominated entirely by the degeneracy pressure, whereas the ions still behave classically. These are the theoretical conditions for the well-known "one-component plasma." Probing this regime tests fundamental theories of very dense, highly degenerate matter. In particular, whether a first-order plasma phase transition exists could be conclusively settled. Also, in a system with a mixture of H and He gases that is compressed until the H becomes metallic, one may be able to determine whether He comes out of solution, a phenomena that is of critical importance to planetary interior models.

Nuclear Burn

If the inertial confinement fusion programs succeed in generating a standard ignition capsule testbed, controlled tests of quantities that affect the nuclear burn wave will become possible. Questions pertaining to the burn dynamics of Type Ia supernovae (SNe) may be accessible, such as how the burn transitions from a deflagration to a detonation, and what role hydrodynamic mixing plays in this. Perhaps even more fundamental is observing nuclear reactions under the appropriate conditions of density, temperature, and electronic screening. Experiments here might allow important thermonuclear reaction rates to be measured under conditions in which plasma screening effects have variable levels of significance: weak screening ($\Gamma << 1$), the intermediate regime ($\Gamma \approx 1$), strong screening ($\Gamma >> 1$), and the pycnonuclear regime ($\Gamma > \Gamma_{solid} \approx 178$). (The corresponding densities and temperatures to these regimes are shown in Figure 3.3.) This would have major impact on stellar modeling. Here, Γ is the ratio of the coulomb interaction energy between neighboring particles and the thermal energy per particle (kT).

Opacities

Measurements of the opacities of materials under scaled conditions relevant to Type Ia SNe would be highly beneficial. The question of the rate of expansion of the universe relies upon "standard candle" observations of Type Ia supernovae light curves. The shape-brightness correction is thought to be due to opacities of dense, high-temperature plasma. Some of these assumptions could be checked by direct experimental measurements. Measuring the opacity of iron at conditions relevant to the core of the Sun would check the theoretical models of continuum lowering, as well as determine a fundamental parameter that controls the heat flow within the Sun and hence affects the internal structure of the Sun. With a combination of convergent implosion geometry and ultraintense short-pulse heating beams, it may be possible to create matter at 100 g/cm^3 at 1-keV temperature in order to study its opacity, with relevance to the opacity at the center of the Sun.

High-Pressure Physics

New states and phases of matter can be created and probed at ultrahigh pressures, using carefully shaped compression pulses and time-resolved lattice structure diagnostics. The time scale for specific phase transitions can also be measured. The time scale for specific phase transitions, which can vary from subpicosecond to tens of nanoseconds or longer, can also be measured.

With carefully shaped drive pulses, it may be possible to accelerate solid-state microflyer plates to velocities in excess of 100 km/s. This would open up new regimes of impact and microcratering studies of possible relevance to shielding Earth-orbiting satellites from space debris, as well as cratering theories.

Parametric Instabilities

At high intensities, a whole variety of parametric instabilities can be investigated (stimulated Raman scattering, stimulated Brillouin scattering, and so on) in large-scale plasmas at high temperatures. These are discussed in Chapter 4.

Generating High Energy Density Conditions in the Laboratory

Laser-Produced Plasmas

High-energy lasers have been one of the workhorses of high energy density experiments. They typically have a flexibility that allows a wide range of high energy density conditions to be achieved. The pulse duration, focal spot size, energy, and, in the case of multiple beam systems, the pointing can all be varied to optimize the experimental conditions. Lasers with energies of even a few joules and nanosecond durations can produce high energy density conditions in targets. Multibeam lasers with energies in the kilojoule range have been used to produce extremely high energy density conditions. Many of these conditions are described in this chapter, with astrophysically relevant high energy density conditions described in Chapter 2. The largest currently operating laser system is the 60-beam, 30-kJ 0.35-μm wavelength OMEGA laser system at the University of Rochester. It can be configured in many ways, allowing a wide variety of high energy density research to be carried out. This research includes inertial confinement fusion (as described above) in both direct- and indirect-drive modes, strongly shocked materials, the evolution of hydrodynamic instabilities relevant to both laboratory and astrophysical plasmas, material opacities under extreme conditions, and generation of intense x-ray radiation sources. The National Ignition Facility, currently under construction at Lawrence Livermore National Laboratory, will extend the available laser energy range by almost 2 orders of magnitude, producing ~2 MJ of laser energy in 192 beams at 0.35-μm wavelength. It will maintain the flexibility afforded by a multibeam laser system but will generate much more extreme conditions than currently possible, including the possibility of obtaining fusion ignition.

Lasers couple their energy to a solid material or a plasma primarily through the collisional and/or noncollisional absorption of the light in the coronal region of the plasma. Electromagnetic radiation cannot propagate at electron densities higher than its wavelength-dependent critical electron density ($n_{cr} \sim 10^{21}\ \text{cm}^{-3}/\lambda^2\ \mu\text{m}^2$). This is a relatively low density region at the edge of a target. Thermal conduction carries the laser energy into the higher density regions. The next step depends on whether the goal is to directly couple the laser energy to the target (direct drive) or to convert the energy to x rays that are subsequently coupled to the target (indirect drive). In direct drive, the hot, high-density region expands (ablates), causing a pressure to be applied to the remaining target material. This ablation process is similar to the process that drives a rocket, acting through the conservation of momentum. This pressure can launch shock waves into the material, bringing it to higher pressure and/or accelerating it. In indirect drive, the laser energy is converted to x rays, often in an x-ray oven (hohlraum) that produces nearly blackbody radiation with temperatures up to hundreds of electronvolts. This x-ray bath can subsequently couple to a target, producing shock waves and acceleration through the ablation process. The x rays can also be used directly to study the opacity of materials under extreme conditions.

Lasers with energies of a few joules or more can also be used to create x-ray lasers that provide a further extension of the HED physics conditions that can be created.

High-Intensity Laser-Matter Interactions

A second class of lasers for HED physics experiments is short-pulse high-intensity laser systems. "Short pulse" typically means a few picoseconds or less and "high intensity" is typically 10^{16} W/cm^2 or greater. Intensities as high as ~10^{21} W/cm^2 have been achieved. The number of such systems has expanded rapidly in the past decade and a half since the revolutionary development of chirped pulse amplification in the late 1980s. This technique involves stretching a pulse, amplifying it, and recompressing it to its original pulse duration. This increases the peak power and focused intensity by many orders of magnitude. There are many applications of this technology (see Chapter 4), from studies of relativistic effects in laser-plasma interactions, to the generation of intense x-ray, electron, and ion sources for both radiography and fusion applications, to the generation of electron-positron pairs and the generation of radioactive isotopes. These lasers can be coupled to other technologies, such as electron beams, to generate short bursts of Compton scattered x rays, or to a high energy density system (laser or pulsed power) to study the fast ignition approach to inertial confinement fusion, or to a target for ultrafast x-ray radiography.

The shortest pulse durations available are just a few optical cycles (~10^{-15} s), giving interaction times comparable to the fastest material response time. The largest high-intensity laser system was the recently decommissioned Nova petawatt-laser facility at Lawrence Livermore National Laboratory, which produced ~600 J in 0.45 ps and peak intensities of a few times 10^{20} W/cm^2. More modest energy systems (up to tens of joules) that can approach similar intensity levels can be built on a few optical tables (4 × 8 feet), making them suitable for university-scale research.

There are unique regimes of high energy density plasma physics that can be accessed in experiments on very modest-scale, short-pulse lasers, with laser energies as low as tens of millijoules per pulse. This remarkable trick involves laser interactions with a jet of atomic or molecular clusters. An intense laser interacting with this gas of clusters sees localized regions of solid density in which the laser absorption is nearly 100 percent. This absorption causes ionization within the cluster and the ejection of electrons, which triggers a "coulomb explosion" owing to the closepacked configuration of positively charged ions. These localized pockets of plasma can be very hot due to the heating from a laser plasma resonance. The hot balls of plasma expand rapidly until they encounter their cluster neighbors, which are also exploding. The end result can be the production of multikiloelectronvolt ions, high-Mach-number blast waves, and even nuclear fusion. A whole range of unique high energy density physics can thus be accessed with tabletop lasers suitable for university-scale laboratories.

Pulsed-Power Plasmas

"Pulsed power generators" deliver $10^5 \sim 10^7$ A to low-impedance loads generating high energy density conditions in a number of different ways. The energy can be directly deposited in a plasma; it can be used to compress a preexisting plasma; it can be converted into extremely large fluxes of x rays that subsequently are coupled to a target material; or the magnetic energy can be used directly to launch shock waves in materials or to launch flyer plates that create high energy density conditions in a target. The largest pulsed-power systems can deliver energies orders of magnitude larger than the energy in current laser systems (though NIF will be comparable), allowing much larger samples to be driven to high energy density conditions. The pulse durations are typically 10^{-8} to 10^{-7} s, an order of magnitude or more longer than high-energy laser systems. Because of the longer durations of the pulsed-power sources, peak pressures of tens of megabars are currently achieved with both types of HED drivers (with higher pressures expected to be available on the NIF). While the pressures and peak radiation temperatures (200 ~ 300 eV) are comparable (though slightly lower on pulsed-power devices), a pulsed-power device can deliver more energy to a larger target.

High Energy Density Z-pinches

A Z-pinch is a technique that converts the energy of the electrical pulse in a pulsed-power system to kinetic energy in a magnetically driven implosion of a plasma column. This thereby generates a hot, dense "Z-pinch" plasma that, in the case of the Z-machine at Sandia National Laboratories, Albuquerque, produces x-ray pulses <10 ns long with >1 MJ total radiated energy. The pinch is caused by a self-generated $j \times B$ body force due to the axial current density, j, flowing in the plasma and the resulting self-magnetic field, B, that is in the azimuthal direction in a cylindrical plasma column, and this force compresses the plasma to the axis. The spatial-scale size of the resulting plasma is determined by the initial density and spatial scale of the load. Application of pulsed-power systems to dense Z-pinches and the achievement of high energy density conditions have occurred with single exploding wire experiments, cylindrical wire-arrays, and gas-puff Z-pinch experiments. Even the lowest density of these plasmas, that generated by a gas-puff Z-pinch, presents unique opportunities for generating strongly radiative plasmas that have important applications. For example, at low enough density for collisional effects to be negligible, important opacities and photoionization rates that are very relevant to astrophysics can be measured directly.

A gas-puff Z-pinch starts with a centimeter-scale cylindrical gas puff at a pressure in the 10^2 to 10^3 pascal (Pa) range, in order to break down quickly when the pulsed-power generator voltage pulse reaches it. To be effective as a radiator, the gas that is imploded by the $j \times B$ force has a high atomic number, which increases the bremsstrahlung yield of the collisions between electrons and ions that are responsible for the x-ray radiation. With a 100- to 200-ns, ~1-MA current source, a few centimeters diameter gas-puff Z-pinch can be imploded to ~1 mm diameter and reach an ion density 20 to 50 times the original gas density. The ohmic and compressional work heats the electrons and generates highly charged ions. Electron densities exceeding $10^{20}/cm^3$ and temperatures of several hundred electronvolts are achieved in plasmas that are a few centimeters long and ~1 mm diameter.

Plasmas generated from fine metal wires and insulating fibers (including fibers made of frozen hydrogen) start from solid density and are exploded by the high-current pulse to form a rapidly expanding plasma. The wire or fiber size is chosen to be small enough that the plasma formation phase takes only a few nanoseconds. As the material expands, the current (and self-magnetic field) is still rising, and the expansion can be arrested by the increasing $j \times B$ force. Current-driven instabilities limit the lifetime of all Z-pinch experiments, preventing long-time magnetic confinement of these dense Z-pinch plasmas.

In the case of the metal wire Z-pinch, radiation can play a major role in allowing the plasma to collapse to a small radius. For example, starting with a single fine wire (~5 to 50 μm initial diameter), the implosion starts with a plasma that has expanded to ~1 mm diameter, and the density can become high enough in the imploded plasma that radiation losses can exceed the rate of ohmic and compressional heating. In that case, as the plasma implodes, it cools ever more rapidly as well as increasing in density, which further increases the radiation loss. This process is known as radiative collapse. Single-wire Z-pinches can, in fact, form micropinches, that is, very small spots at random locations along the wire length where intense kiloelectronvolt x-ray emission occurs, most likely a result of the "sausage instability." The final radius and density reached in those micropinches may be determined at least in part by radiative cooling of the imploding plasma until it becomes optically thick to its own emission.

The conditions in exploding wire micropinches have not, in fact, been directly measured in single-wire Z-pinch experiments, because the location of a micropinch is not known in advance. However, the X-pinch configuration, in which two wires cross and touch at a single point, guarantees that a micropinch will be generated in a known location—close to the original cross point of the wires, where the sum of the current in the two wires acts on the plasma. These micropinches are typically in the ion density range 10^{20} to $10^{22}/cm^3$, or even higher, and have electron temperatures of a few hundred electronvolts to 2 keV. Their size is much smaller than 1 mm, and may be of the order of 1 μm. The plasma remains hot and dense for about 50 to 80 ps.

The gas-puff and single metal wire (or crossed wire) Z-pinches are efficient radiation sources, and can be used for fundamental studies of atomic processes in dense plasmas. They can also be used to validate atomic physics computer codes and radiative-MHD codes. In addition, the X-pinch can be used for x-ray radiography.

A large number of wires in the form of a cylindrical wire-array is necessary to drive a hohlraum to a radiation temperature of interest for inertial confinement fusion or other high energy density science applications requiring megajoules of x rays. This is partly because a high-current pulsed-power generator does not couple energy efficiently into a small number of wires. In addition, arrays with large numbers (300 or even more) of wires have been found to generate a shorter, more powerful radiation pulse upon imploding to the axis than do arrays with a smaller number of wires. The Z-machine at Sandia, with 20-MA peak current and a rise time of about 100 ns, has produced plasmas that radiate close to 2 MJ in less than 10 ns starting from several hundred tungsten (W) wires. Hohlraum temperatures of 150 to 200 eV have been produced. The plasma itself in such a test is estimated to be $\sim 10^{20}$ ions/cm^3 when assembled on axis, with the W ions being ≥ 50 times ionized.

Ultrahigh Magnetic Pressures from Pulsed Power

With 20 MA carried in a 1-cm-diameter cylindrical structure, the magnetic field will be 4 MG (400 T), corresponding to a magnetic pressure of 0.6 Mbar (6×10^5 atm). By using rectangular conductors instead of cylinders and displacing the inner one so that only one face is close to the external conductor, the current per unit width can be increased to close to 7 MA/cm in 1.5-cm-wide conductors. The resultant 800-T magnetic field produces magnetic pressures of up to 2.5×10^{11} P (or 2.5 Mbar). This high pressure can be used directly to launch flyer plates for isentropic compression experiments, or to drive strong-shock waves into materials.

Magnetized Target Physics

Another way that pulsed power can be used to generate high energy density conditions is by compressing a preformed, magnetically confined plasma structure.

In one example, the magnetized target plasma is a field-reversed plasma configuration (FRC) that is produced within a solid, cylindrical conductor. That conductor can be imploded by a high current on a microsecond time scale. The intent is that a stable plasma configuration, the FRC, can benefit from the enormous pressures that can be exerted by a high current without being driven unstable if the current is carried by a collapsing metal conductor instead of the plasma itself. If the inner surface of the imploding conductor remains solid, it will also remain stable. The plasma pressure that can be achieved can substantially exceed the applied magnetic-field pressure as follows. The external magnetic pressure drives the liner inward, converting the magnetic-field energy into kinetic energy of the liner. The liner accelerates inward until the compression of the FRC is sufficient to produce a back-pressure that approximately equals the drive pressure, at which time the liner begins to slow down. It comes to a halt only after all of its inward kinetic energy has been converted to magnetic plus thermal energy of the FRC, taking into account energy loss due to magnetic-field diffusion into the liner. Estimates using reasonable choices of physical parameters, including magnetic and particle diffusion coefficients, suggest that a 30-MA-current driver, such as the Atlas facility, could achieve 1-cm-radius, several-centimeters-long plasmas at 1 Mbar (10^{11} P). This corresponds to a density of $6 \times 10^{19}/cm^3$ at 10-keV temperature, a very interesting plasma for producing deuterium-tritium fusion reactions.

Intense Ion Beams (Heavy and Light)

Intense ion beams can be produced using pulsed-power accelerators or using conventional accelerator technology. The former case is limited to 10 to 20 MeV by the nature of the technology, and high power density is achieved by focusing a beam that might be produced at the mega-ampere level. Intensities achieved using PBFA II Particle Beam Accelerator at Sandia National Laboratories, Albuquerque, before it was converted to the Z-machine exceeded 10^{12} W/cm^2. Heavy ion beams can be generated from conventional ion sources at the ~1-MeV and ~1-A level for about a few microseconds. The power density can then be increased by merging separately generated heavy ion beams, acceleration to the gigaelectronvolt level, and axial bunching. It is expected to be possible to produce beams at 1 to 10 GeV and 10^4 A for ~10 ns and to focus them to ~10^{15} W/cm^2, as is required for inertial confinement fusion, but the proof-of-principle experiments for this are still in the planning stage (as discussed earlier in this chapter).

Because the range of ions at the few megaelectronvolts per nucleon energy level is in the micron range, intense ion beams can be used for many of the same materials science applications for which nanosecond lasers are used, including generating ablation plasmas and driving shock waves into solid materials. Ions have an advantage in that they are absorbed in the volume of a material, penetrating to a depth that is determined by the target material and their energy, whereas a laser interacts with the surface of a solid target and depends on the state of the plasma on the surface.

The beams themselves are high energy density plasmas in their own right. Intense light ion beams must be very close to charge neutral or they cannot propagate, and so they are essentially neutral plasmas moving at high speed in the laboratory frame. A proton beam at 4 MeV and 1 MA/cm^2 represents an energy density of about 3×10^8 J/m^3, although it is largely in directed kinetic energy rather than thermal energy. In a heavy ion beam entering an inertial confinement fusion target chamber, the kinetic energy of the individual ions may be high enough that charge neutrality is not a necessity for propagation. In that case, the kinetic energy density and the energy densities in the electric and magnetic fields are large. For lead ions at 1 GeV and 100 kA focused to 1 cm^2, the kinetic energy density is ~10^{10} J/m^3.

Intense ion beams and their associated self-magnetic fields can also be used in magnetic confinement fusion to generate favorable magnetic confinement configurations.

High-Energy Electron Beams

Similar to ion beams, electron beams can be produced using pulsed-power generators or conventional accelerators. Because the space-charge limit is much higher for electrons than ions in an accelerating gap (by the square root of the ion-to-electron mass ratio), pulsed-power generators can produce electron beams reaching 10^6 A/cm^2 or even more in a 1-MV accelerating gap with self-focusing caused by anode plasma production. Such beams exceed the so-called Alfvén current limit and cannot propagate in vacuum. Because of their large electrostatic and magnetic energy densities, they must be charge and current neutralized. Intense electron beams can, in principle, be used to deliver energy some distance away from the source if their self-fields are neutralized. In an intense electron beam (e.g., 1 MA at 1 to 20 MeV), the self-fields assure that there is as much or more kinetic energy in transverse motion as there is in the direction of propagation. Surface ablation (and shock wave generation) can easily be achieved in solid density materials by focused intense electron beams.

High energy density electron beams can also be produced by conventional accelerator technologies, such as the 50-GeV electron beam produced at the Stanford Linear Accelerator Center. The interaction of these beams with plasmas is described in Chapter 4.

X-ray Lasers

X-ray lasers provide an example of using one type of high energy density system to produce another that can then be used in high energy density experiments. Energy deposited in a plasma by a laser or pulsed-power source leads to a population inversion resulting in x-ray lasing at wavelengths as short as ~40 Å. Because of their short wavelength, soft x-ray lasers have a significantly higher critical electron density (see the subsection above on "Laser-Produced Plasmas") than conventional visible or UV lasers have, and they can propagate through high-density plasmas. They can also be used to volumetrically heat solid materials and high-density plasmas.

Recent developments in soft x-ray laser research have been directed toward utilizing higher-power technology to reduce the pumping source size to tabletop dimensions. Collisional excitation schemes have been very successful and have been adopted worldwide. These include fast capillary discharges and picosecond laser-driven transient schemes. These x-ray lasers operate in the high-efficiency saturation regime with typical pulse durations in the picosecond to nanosecond regime, output energies of tens to hundreds of microjoules, and high repetition rates (a few hertz to 1 shot every few minutes). These x-ray sources have peak powers and brightnesses higher than those of present-day synchrotrons but much lower repetitions rates. They have been used for many applications, including the interferometry of millimeter-scale dense plasmas, characterization of optics, and imaging of biological samples. Future directions include the development of ultrafast x-ray laser schemes operating below 50 Å and the determination of material properties under extreme conditions. The main advantages of these x-ray lasers are their scalability to shorter wavelengths with higher output energy that would allow them to be developed as unique diagnostic tools for picosecond interferometry of other high energy density conditions such as those that the NIF will generate.

Gas Guns and Diamond Anvils

A fundamental goal of geophysics is a basic understanding of the structure and dynamics of Earth's interior in general and of the generation of Earth's magnetic field in particular. Somewhere embedded in the churning, twisting flow patterns of the core-mantle system lies the cause for the dramatic reversals of the dipole geomagnetic field, as shown in paleomagnetic reversal records. The energy source for this dynamo is a combination of heat flow out of the solid inner core and the enhanced rotation rate of the inner core compared to the mantle, which is separated from the inner core by a liquid outer core. The result of this inner turmoil at Earth's surface is as dramatic as the turmoil itself: plate tectonics, earthquakes, volcanoes, and—perhaps triggered by the magnetic-field reversals—possible global climate changes.

Much progress has been made in understanding Earth's interior magneto-rotational dynamics. With the advent of supercomputers, three-dimensional MHD models have begun to reproduce some of the dynamics thought to exist deep below our feet. These simulations have even predicted magnetic-field reversals. Such large-scale three-dimensional MHD code simulations, however, can only be as reliable as the input information, such as the material properties—material strength, phase, melt point, viscosity, and conductivity—at very high pressures (0.1 to 3.6 Mbar), high temperatures (1000 to 6000 K), and high densities.

This leads to the obvious question: How can the properties of the relevant materials be ascertained at such extreme conditions? The answers to questions such as these come from high-pressure laboratory experiments. There are several experimental avenues to such high-pressure conditions. The first, the diamond anvil cell, is the "workhorse" for establishing the phase diagrams of materials at pressures up to several megabars. These devices are essentially a high-tech device that compresses thin samples (10 to 100 μm) between two flat diamond anvil surfaces. When combined with a bright source of x rays in the kiloelectronvolt energy range, such as that supplied by a synchrotron light source, this setup is an extremely powerful tool for determining the phases of materials.

Experiments on diamond anvil cells are static, with strain rates of $<10^{-6}$ s^{-1}. Alternate experimental approaches include gas guns or powder guns. These devices are essentially a large-scale gun barrel. When detonated, a macroscopic "bullet" or sabot is accelerated out the end, impacting a sample, causing shock compression. This allows the equation of state of the shock-compressed sample to be determined with high accuracy, making gas guns a workhorse for dynamic or Hugoniot equation-of-state measurements. Pressures accessible by gas gun experiments can also reach several megabars.

High explosives are a variation on this theme of dynamic experiments. This technique is not as widely used as gas guns are, owing to lower precision. However, high-explosive-driven integral experiments are possible in a wide variety of geometries. Typical pressures achievable are several hundred kilobars.

Diagnostics for High Energy Density Laboratory Systems

As the technologies to produce high energy density conditions have evolved, so have the abilities to diagnose and understand these conditions. This has included development of (1) advanced diagnostics and (2) target fabrication techniques, as well as (3) advances in numerical simulation capability. These technologies form a triad, without which advances in understanding high energy density physics conditions would be severely limited. A few examples of diagnostic development are described in this section, and the other two legs of the triad are described in the subsequent sections.

Many of the advanced diagnostic techniques have been developed as part of the inertial confinement fusion program. As described in the beginning of this chapter, short spatial and temporal scales are characteristic of ICF implosions. The need to diagnose these experiments has led to impressive developments, including time-resolved x-ray spectroscopy and imaging at picosecond time scales with multikiloelectronvolt photon energies. Diagnosis of nuclear reaction products includes detailed spectral and temporal measurements of neutron and charged particle spectra from primary, secondary, and tertiary reactions.

For laser and pulsed-power facilities to be attractive to users for high energy density plasma physics experiments, or for secondary experiments using the high energy density plasmas as drivers, the facilities must have excellent diagnostic systems providing information about the plasma conditions as a function of time. The diagnostics needed by a particular user might include experiment-specific instruments as well, such as shock-breakout instruments when a shock wave is generated in a thin plate attached to a high-temperature hohlraum or by the extremely high magnetic pressure that can be produced by the Z-machine. Another diagnostic requirement for experiments involving high-optical-depth materials is imaging with very high energy backlighter x rays (tens of kiloelectronvolts to even megaelectronvolts), to be able to radiographically see through these targets.

Laser Diagnostics

High energy density facilities rely on a large number of diagnostics to understand the laser or pulsed-power system performance, as well as the laser target interactions or pulsed-power system-driven plasma dynamics. Because of the relatively short time scales of interest (a few nanoseconds or less), much of the emphasis has been on the development of high temporal-resolution diagnostics. These include visible and x-ray streak cameras (producing a continuous record) and time-gated imaging detectors (producing two-dimensional information snapshots). The latter can be used to make movies with ~50-ps frame times and ~50-ps resolution (an example is shown in Figure 3.1). For even better time resolution, short-pulse lasers are often used in a pump-probe scheme, in which the interaction is probed with a second laser, the arrival time of which is varied to build up a time-resolved measurement. Any pump-probe technique using ultrafast lasers is sensitive to the exact pulse shape (prepulse and intensity contrast) of the beam.

Imaging of Target Nonuniformities

The evolution of hydrodynamic instabilities is of paramount importance to understanding inertial confinement fusion and high energy density conditions in general. As energy is deposited in a plasma, shock waves can be launched and the system can be accelerated, leading to conditions in which the hydrodynamic motion is unstable. Diagnostic imaging of perturbed, high-density targets allows the evolution of these instabilities to be measured and compared with numerical simulations and theoretical predictions. Constraints are many and varied, with a goal of simultaneously resolving the space and time evolution of the perturbations with time windows, spatial amplitudes, and perturbation wavelengths that are as small as possible. Here an illustrative diagnostic example for hydrodynamic experiments typical of those performed on the OMEGA or NIKE laser is considered. The diagnostic requires the following: fields of view of more than 1 mm, perturbation amplitude modulations that range from 0.25 μm to tens of microns of solid plastic, objects with diameters of 5 μm or less, and precise time gates that are less than 50 ps. The fundamental enabling diagnostic technology that provides imaging of target mass perturbations in these regimes is x-ray backlighting. The flexibility of high energy density drivers allows part of the energy to be used to generate the probing (backlighting) x-ray radiation. Time resolution is obtained with the help of a framing or streak camera as a detector, or by using an ultrafast laser to generate a short x-ray pulse. To compensate for poor spatial resolution of available detectors, high image magnification (about 10× to 20×) is generally used, which, in turn, requires high system throughput. Experiments with thick targets (e.g., 40 to 100 μm of solid plastic) also require a high efficiency of the diagnostics and a high energy of the probing radiation. For any backlighting scheme, there are two other general requirements: (1) small size of the backlighter source and (2) filtration of imaging radiation from the self-emission of the object. The surface brightness of the backlighter must be larger than the object brightness only in the bandwidth of the spectral line being used to image the object. Examples of x-ray imaging and radiography of HED plasmas produced by lasers and pulsed-power machines are shown in Figures 3.7 through 3.10. High-energy petawatt laser systems may allow high-energy x-ray backlighting of thicker samples at higher x-ray photon energies than are possible with current long-pulse laser systems. Directed jets of protons generated when these lasers interact with matter should allow very opaque targets to be radiographically diagnosed.

There are now available a range of imaging systems that couple well to the x-ray backlighting technique, and which meet many of the criteria described above. These include Kirkpatrick-Baez microscopes, gated x-ray pinhole cameras, point projection imaging, and curved-crystal monochromatic imagers.

Nuclear Reaction Diagnostics

The increased availability of high energy density systems has significantly expanded the range of nuclear and charged particle diagnostics that are used to study them. Part of this expansion is due to the larger energy of the high energy density systems, which produce higher nuclear yields, allowing lower cross-section processes to be observed. In the past, ICF implosions were diagnosed with neutron detectors that measured the primary neutron fusion yield (e.g., $D + D \rightarrow He^3 + n$ or $T + p$) and the secondary (two-step) reaction ($D + T \rightarrow He^4 + n$). As the energy coupled into the implosions has increased, a large number of lower probability reactions have begun to be detectable (e.g., the secondary reaction $D + He^3 \rightarrow He^4 + p$). This has led to the development of a wide array of new neutron and charged particle diagnostics that can provide significantly more information about the target characteristics.

The higher nuclear reaction yields associated with current and future ICF implosions lead to the opportunity to measure astrophysically relevant nuclear reaction rates under conditions that are close to those in astrophysical objects. Nuclear reaction cross-sections are typically measured in beam-target experiments with beam energies of hundreds of kiloelectronvolts or megaelectronvolts. These rates are then extrapolated to the multikiloelectronvolt temperature conditions in stars. Multikiloelectronvolt temperatures are achieved in ICF implosions. The nuclear reaction yields of solar-relevant processes can be measured, providing more accurate reaction rates for stellar processes. An example that may be possible on the OMEGA laser system is to measure the rate of $^3He + {}^3He \rightarrow {}^4He + 2p$ reactions, if the distribution function is sufficiently Maxwellian. The NIF will extend the opportunities for measuring nuclear reaction rates relevant to stellar processes. A particularly intriguing possibility is the potential to use the bursts of 10^{19} neutrons from the $D + T \rightarrow \alpha + n$ thermonuclear yield from an igniting ICF capsule to study reactions relevant to the s, p, and r astrophysical nucleosynthesis processes. For example, the neutron flux from an igniting capsule is high enough to drive 10 to 20 percent of dopant nuclei, say ^{89}Y, into excited states via (n,n′) reactions, and trigger multiple step reactions on those excited states with lifetimes >1 ps.

Special Needs for Pulsed-Power System Diagnostics

The diagnostics needed to study the high energy density plasmas made in pulsed-power systems are essentially the same as those used in comparable laser-based experiments, with the additional need to operate in a high-radiation environment. For example, the bremsstrahlung background at the Z-machine can be 10^6 rads/s as a result of "stray electrons" accelerated in the vacuum feed to the Z-pinch load. In addition, there is the electromagnetic noise generated by the machine, as well as ground motion resulting from the self-closing water switches in the pulsed-power system. Thus, every diagnostic instrument must be placed as far from the vacuum chamber as possible; it may have to be decoupled from the ground motion, and it must be collimated and shielded as well as possible. This said, the extremely interesting and relatively large-volume plasmas generated by the Z-machine and their many applications to high energy density science place a premium on having a large set of diagnostics in place for users. Although smaller pulsed-power machines produce less troublesome background, they also produce much smaller signals. Therefore, the same care in shielding diagnostics from background x rays and electromagnetic noise is necessary on smaller facilities as on the Z-machine. It is noteworthy that the relativistic electron beams generated by petawatt lasers and high irradiance CO_2 lasers can produce large electromagnetic noise pulses that require the same attention to detail in shielding and collimation of detector channels as are required of pulsed-power experiments.

Beam Diagnostics

Intense electron and ion beams generate dense plasmas on surfaces if the deposited energy in a ≤1-μs pulse reaches ~1 kJ/g. Thus, any material placed in the path of such a beam will be rapidly ionized, making it difficult to measure beam properties such as current density and total beam momentum or energy. For example, small apertures in Faraday cups for intense ion beams can be completely blocked by plasma in just a few nanoseconds, and results from a pendulum that is intended to measure the impulse delivered by a beam to a target can be misinterpreted because of the large impulse due to an ablating plasma. The net result is that substantial numerical modeling is often necessary in order to elicit useful information from intense beam diagnostic systems that are straightforward to interpret at more modest energy densities. Beam propagation in a gas or plasma introduces similar problems for direct measurements because, for example, the resulting reverse current induced in the plasma or gas after breakdown can partially or completely eliminate the self-magnetic field of the beam current. Therefore, alternate diagnostic methods must be used to monitor beam properties, such as the intensity of x rays induced in a thin foil as the beam passes through it, for electrons, and nuclear reactions that yield an easily observed reaction product, for ions. Laser-based measurements, including interferometry, laser-induced fluorescence spectroscopy, and laser scattering can provide information on the background plasma and/or the beam.

Advances in Target Fabrication

Target fabrication is an essential enabling technology for high energy density physics. Targets have advanced enormously over the past three decades, not by slow evolution but in true paradigm shifts from early low-tech endeavors to the sophisticated precision materials of today.

The evolution of high energy density systems, both in energy scale and complexity, together with the evolution of diagnostic capabilities and numerical simulations, has led to a concomitant need for more sophisticated and complex targets. Sophistication and control are needed to fabricate targets capable of supporting the intellectual challenges of high energy density plasmas. The extreme complexity of today's targets was achieved as a result of multiple breakthroughs in new technologies and materials science. A critically important step in order to create high-quality spherical shells was that of combining two processes. One process involves density-matched microencapsulation via a droplet generator to produce shells with a highly spherical outer surface. The other process involves a decomposable mandrel technique that allows the actual target shell to be coated onto the mandrel (which is then decomposed and removed). The result is a highly spherical shell with a highly uniform wall that is vital so that defects in the target do not dominate implosion dynamics.

Hohlraums have likewise undergone several stepwise progressions in their manufacture, culminating with today's precision diamond-turning machines that routinely control tolerances to a few microns on complex parts. The ultraprecision characterization of targets continues to evolve with interference microscopy that allows the diameter, wall thickness, and first mode deviations to be measured quickly with modest computing capability. An atomic force microscope traces the shell diameter providing multidimensional quantitative surface analysis for use in simulation codes. Success in the generation of large x-ray fluxes with pulsed-power devices has led to significant advances in the construction of wire arrays and more complicated targets used for equation-of-state studies. The flexibility engendered by high energy density systems has led to even more complicated targets, some that lack any symmetry, others that might be designed to enable multiple backlighting sources, and all requiring extreme precision throughout the manufacturing process.

An important future goal of high energy density physics requiring advances in target fabrication is the production of energy from inertial fusion. Providing billions of precision targets at the low cost needed for energy production will require an intimate understanding of the relevant materials science and additional breakthroughs in the way targets are fabricated. Standardized efficient industrial production technologies must be combined with existing knowledge in the field. An example is the use of fluidized beds to coat hundreds of thousands of targets at once. Initial experiments indicate that one fluidized bed can supply half of the 500,000 targets per day required by a 1,000-MW_e power plant. Additional quantum leaps in the way that targets are manufactured will require a continued effort from industry, national laboratories, and universities, each bringing its unique strengths to this highly challenging field. The high-repetition-rate (driver, targets, and so on) capabilities developed for inertial fusion energy would also be beneficial for many high energy density experiments.

High-Performance Computing

Computational capabilities have been revolutionized in recent years, bringing physical phenomena within the scope of numerical simulation that were out of reach only a few years ago. The Department of Energy's Advanced Strategic Computing Initiative (ASCI) has played a major and multifaceted role in this revolution, as has the continued evolution of microprocessor and other technologies. High-performance computing today is typified by large parallel platforms with 30 gigaflops (Gflops) of sustained performance. High-speed connections enable centralized visualization systems for tasks ranging from debugging to processing of large database results. With the ability to perform highly resolved, multidimensional computations, advanced scientific computing has become an enabling tool for first-principles explorations of high energy density phenomena. Both theory and experiments now typically rely on numerical simulation that comprises an essential component of more-integrated research programs. Ultimately, inputs from theory, laboratory experiments on equations of state, dynamics, explorations of scaled phenomena, and so on, must be integrated in comprehensive computer simulation codes. These incorporate the physics, hydrodynamics, radiation, and other manifestations of high energy density phenomena, along with appropriate algorithms, and explicit or implicit models, in a software environment that must cater to the multiprocessor environment on which it runs. Numerical simulation can now rightfully be considered as an important component in high energy density science discovery.

Large, multidimensional data sets for and from such simulations require preprocessing before they can serve as inputs, postprocessing to digest the results, and, not least, computer visualization. Both the input data that specify initial and boundary conditions and the output data must also be compared against a host of diagnostic data for validation and other purposes. Ideally, this is an integrated, iterative, closed-loop process, with experiment, simulation, and theory each suggesting the next step(s).

The ever-increasing simulation needs of high energy density physics, discussed elsewhere in this report, suggest the need for an assessment of the necessary improvements and capabilities. Even if Moore's law persists for the next decade or so, with DOE's Advanced Strategic Computing Initiative continuing to drive advances at an even greater pace, a number of problems exist that simulations will not be able to completely solve. High-Reynolds-number, radiatively coupled turbulence, in either laboratory or astrophysical environments, for example, is likely to remain beyond the reach of direct numerical simulation—that is, through a solution of the equations of motion with no approximations—for the foreseeable future. The difficulty arises from the combination of the large required spatial and temporal dynamic range and from the three-dimensional dynamics. Considerable insights can, however, be gleaned from simulations that advance the envelope in this fashion, exploiting increases in computational power with simulations relying on the fewest approximations possible. High energy density simulation codes include advection algorithms for the simulation of shocks and also vortical- and magnetic-field-driven instabilities, equation-of-state models that extend from solid to plasma regimes, and detailed electron and radiation transport and opacity packages that can provide an adequate estimate of the energy transport for the full range of high energy density temperatures and densities. Furthermore, some of these codes model the intense electromagnetic wave/particle interaction of high-intensity beams, from plasma coronal nascence through high-density heating. While no codes include all of these effects simultaneously, relevant parts of high energy density physics problems can be simulated, yielding results with predictive value. Such simulations advance our understanding of complex phenomena, yield insights that are fundamental in interpreting and designing experiments, and provide data for new theories and models.

Hardware and computation algorithm advances are required in order to continue to address these problems. Given a span of phenomena in a typical high energy density problem, simulations become tractable as more physics is modeled rather than simulated at every point in space and time. While in a way this is always the case—we rely on continuum and other approximations to simulate hydrodynamics—the complexity of high energy density problems requires an increase in the level of modeling and abstraction. Physics-based subgrid-scale and other phenomenological models that permit a reduction in the number of grid points on which the dynamics must be solved can potentially achieve this. Such models will rely on theoretical advances and special, well-characterized experiments that probe dynamics at small scales and validate the simulations that have incorporated the subgrid-scale models.

4

Laser-Plasma and Beam-Plasma Interactions

INTRODUCTION

The previous chapter was concerned with laser and particle beams insofar as they are used to produce HED plasmas, whereas this chapter is concerned with the physics of the beam-plasma interaction itself.

As can be seen from the tables in Chapter 3, the most powerful focused lasers and particle beams today correspond to remarkable peak intensities—of order 10^{20} W/cm^2 for each. It is perhaps not surprising, then, that the interaction of these powerful beams with plasmas yields a host of new, and often very similar, physical phenomena. For example, both types of drivers may ionize material or create new matter through pair production. They may cause plasma blowout, produce nonlinear plasma wakes, self-focus, filament, scatter, hose or kink, form braided beamlets, generate radiation, accelerate particles to ultrarelativistic energies, and even refract at a boundary in a similar way (see Figure 4.1).

These physical phenomena make up the intellectual theme of this chapter. The questions they raise make up a rich subfield for basic physics research. Answering these questions is of importance for a variety of applications for science and society. The answers may, for example, lead to breakthrough progress toward fusion energy, compact high-energy particle accelerators, and novel imaging techniques. They may also help us to understand the mechanism of ultra-high-energy cosmic ray (UHECR) acceleration and the formation of cosmic jets.

The next two sections outline the fundamental physics questions and phenomena associated with high energy density beams in plasmas. To exhaustively delineate the

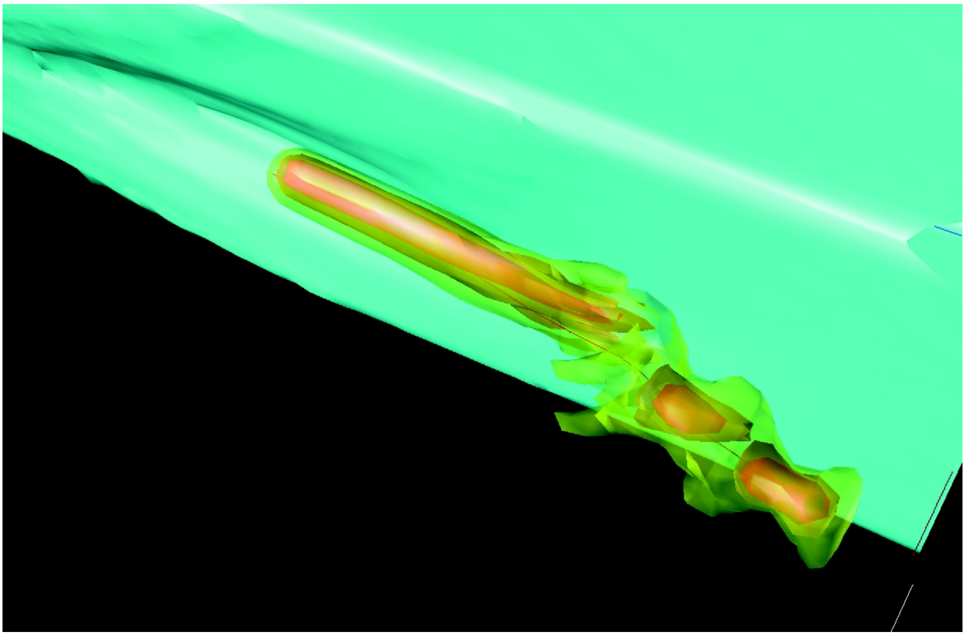


FIGURE 4.1 Refraction and periodic focusing of a particle beam at a plasma boundary. Courtesy of T. Katsouleas, University of Southern California.

full array of phenomena associated with HED beam-plasma interactions is not the intent of this report, but the committee believes that the information provided will give the reader some idea of the wealth of phenomena associated with beams in plasmas. Then, in the secion on applications of HED beam-plasma physics, three applications are described rather extensively, followed by coverage of seven other applications. The final section discusses the opportunities for furthering this field, both experimentally and theoretically/computationally.

QUESTIONS

The intellectual theme of this chapter can be gleaned from the following list of illustrative questions of high intellectual value:

- At what intensities does dense matter become transparent? At what intensities does vacuum become opaque?

- Can focused lasers “boil the vacuum” to produce electron-positron pairs?
- Can macroscopic amounts of relativistic matter be created in the laboratory and made to exhibit fundamentally new collective behavior?
- Can we predict the nonlinear optics of unstable, multiple-interacting beamlets of intense light or matter as they filament, braid, and scatter?
- Can the ultrahigh electric fields produced by laser wakes be used to make a tabletop accelerator with the luminosity and beam quality needed for applications in high energy and nuclear physics?
- Can short-pulse lasers be used to “ignite” a fusion plasma in the laboratory?
- Can lasers and particle beams simulate relativistic shocks and gamma-ray bursts in astrophysics?
- Can high energy density beam-plasma interactions lead to novel “next-generation” light sources?
- Are the same mechanisms responsible for laboratory plasma accelerators and plasma lenses also operating in the acceleration of particles from supernovae and the collimation of cosmic jets?
- Can ion beams produced by relativistic laser-plasma interactions be used as a source for beam-plasma physics, a diagnostic probe, or as a front-end component for accelerators?
- Can such interactions produce novel or economic radioactive ion sources?

HIGH ENERGY DENSITY BEAM-PLASMA PHYSICS: PHENOMENA

In introductory physics, we learn about beam propagation in terms of simple laws—Snell’s law and the laws of reflection and diffraction. In reality, beam propagation is more complex—beams filament, Raman scatter, frequency shift, and so on—even in ordinary media. When the beams reach the high energy densities that are the subject of this report, the medium through which they propagate becomes necessarily a plasma. The nonlinear optics of extreme beams, with their associated gigabar pressures, teravolts per centimeter electric fields, and gigagauss magnetic fields, is no less rich than in regular media. The beams exhibit a wide range of propagation phenomena. These include the familiar, such as focusing and stimulated scattering instabilities, as well as the less familiar, such as braided light and relativistic shocks. In addition, the beam-plasma interactions lead to new radiation-generation mechanisms and to the high-gradient acceleration of particles in the plasma.

Recent advances in experimental and computational capabilities are creating exciting new opportunities on two fronts: first is the use of new tools to address questions that have defied solution for a number of years, and second is the exploration of new regimes opened through advances in beam infrastructure at very high energy densities. In the first category are questions such as: Can we predict the evolution of one or several beamlets propagating through a dense plasma? The importance of this question for laser fusion has been appreciated for more than 30 years. Many advances have been made, yet the answer remains an open challenge. It requires detailed understanding of parametric processes such as Raman and Brillouin scattering in the presence of trapped particles and complex thermal transport. Fortunately, new diagnostics such as x-ray "backlighters" and new computational tools such as advanced algorithms and massively parallel computing offer the possibility of finally answering this question.

At the other end of the spectrum are new questions and opportunities that arise as a result of the tremendous advances in short-pulse laser and particle beam technology. One of these is the fast ignitor: Can a short laser pulse be used to accelerate and deliver hundreds of mega-amperes of plasma electrons in a short burst to the core of a fusion fuel pellet and ignite it? The answer to this question may contribute to realizing the international goal of fusion ignition.

Other questions emerge at still higher laser and beam energy densities. Chirped pulse amplification (CPA) laser technology has enabled a proliferation of multiterawatt laser systems. When focused, their peak fields exceed several gigavolts per centimeter, and the quiver energy of electrons in these fields exceeds several MeV. These HED beams are creating macroscopic amounts of relativistic matter in the laboratory for the first time. Not surprisingly, they are producing a bounty of new relativistic phenomena such as relativistic transparency. In relativistic transparency, the electron mass increases sufficiently in the laser field to reduce the plasma frequency (given by $\omega_p = \sqrt{4\pi q^2 n_p / \gamma m}$, where n_p is the plasma density and γ is the relativistic Lorentz factor) below the laser frequency. At this point, the plasma becomes transparent to the laser pulse it would normally reflect.

Other examples of relativistic phenomena accessible with current laser technology include highly nonlinear plasma wakes in which the plasma is driven to complete blowout, ultrastrong plasma lensing of both photons and particles, and intense radiation generation from the terahertz to x-ray frequency range by various mechanisms. Electron beams with energies up to 100 MeV with small normalized emittance (of order millimeters to milliradians) and nanocoulombs of charge have been generated by plasma wakes in millimeter gas jets. Although the electron beams in these experiments had large energy spreads, the acceleration gradient they achieved was more than a thousand times the gradient of a conventional linear accelerator. This leads to the question: Can wakefield acceleration yield sufficient energies and beam quality so as to enable high-energy physics on a tabletop? Similarly, focusing by plasma lenses has been recently demonstrated at the Stanford Linear Accelerator Center (SLAC) at field strengths of 100 MG/cm. Comparing this to the 5 kG/cm strength typical for quadrupole magnets leads naturally to the question: Can short plasma lenses enhance the final focus of a linear collider?

On the horizon are yet higher density beams and lasers. Chirped pulse amplification technology applied to high-energy lasers is making it possible to consider multipetawatt- to exawatt-class lasers in the near future. The focused field gradients of such lasers will exceed teraelectronvolts per centimeter, and the quiver energies will exceed gigaelectronvolts. As such extreme beams propagate in plasma, they can be expected to create copious electron-positron pairs and possibly heavier pairs. It may be interesting to consider questions such as: Can beams undergo a stimulated pair scattering instability by coupling parametrically to the pairs they create? Can backscatter amplification or other techniques be used to make even higher energy density pulses, exceeding even chirped pulse amplification limits?

Using ultrahigh-intensity lasers, it may become possible to simulate some of the properties of black holes. At an intensity of 10^{26} W/cm^2, an electron will undergo an acceleration of 10^{27} g, comparable to the gravitational acceleration at the event horizon of a black hole. This high acceleration could be used to study Unruh radiation, which is similar in many respects to Hawking radiation, induced by gravitational fields. At modest accelerations, the radiation is described by Maxwell's equations. But it is interesting to study at very large accelerations whether, as Unruh has suggested, there is radiation beyond that predicted by Maxwell. The source of the extra radiation is an effective temperature $k_B T = \hbar a/c$ associated with a particle undergoing acceleration a, causing it to emit blackbody radiation (given by Stefan's law, σT^4).

At sufficiently high intensities, even vacuum can be broken down. The field necessary to achieve pair creation ("boil the vacuum") is the Schwinger field, E_s, which is also equal to the field required to accelerate an electron to its rest-mass energy in a Compton wavelength, $\lambda_c = 2\pi\hbar/mc$. The Schwinger field is $E_s = m^2c^3/q\hbar \approx 10^{16}\ V/cm$ and corresponds to an intensity of $I_s \approx 0.5 \times 10^{30}$ W/cm^2. To reach the Schwinger field would require, for example, a laser pulse having an energy of 100 MJ, pulse duration of 10 fs, focused down to an area of μm^2. Although such fields are beyond the horizon, other nonlinear quantum electrodynamics effects could be accessed at more modest fields. The optical mixing of two pulses in vacuum can produce a standing wave "density grating" composed of a virtual electron-positron plasma. For petawatt, kilojoule-class lasers, a nontrivial pair probability density can be created. It may be possible to scatter off of this grating with a third laser, thereby demonstrating the nonlinear optics of vacuum. Finally, it is noted that an alternate path to the Schwinger field could be an x-ray free-electron laser. If 1.5-Å x rays could be focused to a diffraction-limited spot size of roughly 2 Å, the Schwinger field could be reached with an energy of 2 J at a pulse length of 10 fs.

HIGH ENERGY DENSITY BEAM-PLASMA PHYSICS: APPLICATIONS

Three applications are described below in some detail, followed by discussion of seven more applications in briefer presentations.

Three Important Applications

Multi-GeV Electron Acceleration in Plasma Wakefields

The high cost and size associated with conventional rf accelerator technologies has been a prime motivation in advanced accelerator research for more than two decades. Wakefield accelerators driven by high energy density laser or particle beams promise an entirely new type of technology for building compact high-energy accelerators.

Laser pulses propagating in plasmas can generate large-amplitude plasma waves, that is, wakefields, which can be used to trap and accelerate electrons to high energies. The amplitude of the plasma wave is largest when the laser pulse duration (or its modulation) is on the order of the plasma period. This laser-plasma interaction forms the basis for the laser wakefield accelerator (LWFA). A wealth of new and interesting experimental results on LWFAs has been obtained in recent experiments around the world (see Figure 4.2). On the theoretical and computational front, detailed analyses of the propagation and stability properties of intense laser pulses in plasma channels have been conducted. Recent advances in algorithms and high-performance computing are enabling fully self-consistent modeling of full-scale wakefield experiments in three dimensions for the first time. This work provides a strong foundation for next-generation wakefield accelerator research aimed at producing electron beams with gigaelectronvolt energies and high beam quality.

To reach multigigaelectronvolt electron energies in an LWFA, it is necessary to propagate an intense laser pulse long distances (many Rayleigh ranges) in a plasma without disruption. However, a number of issues associated with long-distance propagation in plasma must be resolved before a viable, practical high-energy accelerator can be developed. These issues include optical guiding, instabilities, electron dephasing, and group velocity dispersion, all of which can limit the acceleration process. The scale length for laser diffraction is given by the Rayleigh range; therefore, the acceleration distance is limited to a few Rayleigh ranges. Since this is far below that necessary to reach gigaelectronvolt electron energies, optical guiding mechanisms such as relativistic focusing, ponderomotive channeling, and preformed plasma channels are necessary to increase the acceleration distance. There is, in fact, ample experimental confirmation showing extended guided propagation in plasmas and plasma channels. The combining of such guiding techniques with a

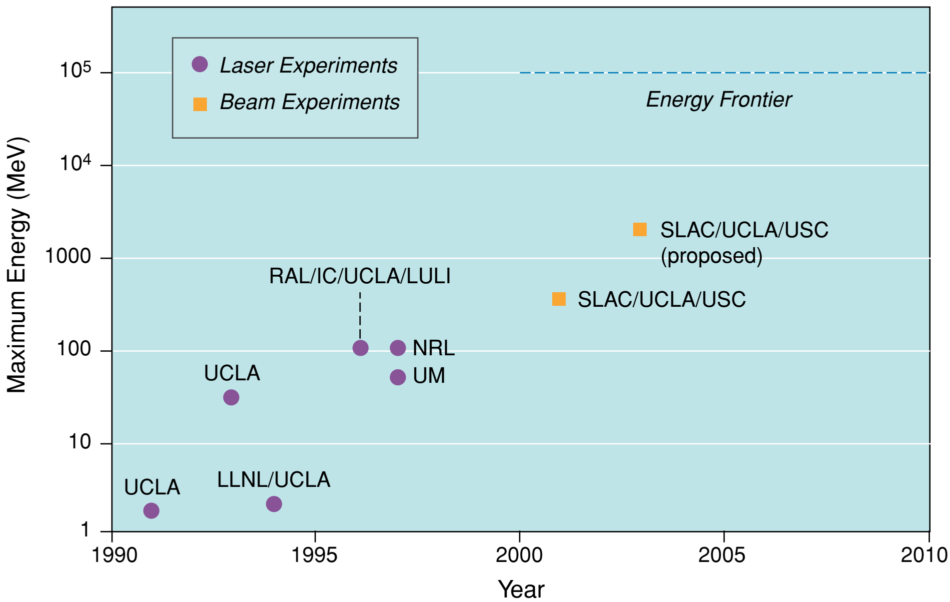


FIGURE 4.2 Progress in plasma accelerator energy: maximum energy gains and laboratories where they were obtained.

suitable injector geometry to achieve controlled acceleration of a monoenergetic beam is the next key step in LWFA development.

Another approach to achieving longer acceleration distances is being pursued at several particle beam facilities. These take advantage of the natural tendency of particle beams to propagate longer distances without spreading, compared to lasers. For example, at the SLAC, electron beams have been used to generate wakefields over a meter and to accelerate electrons by as much as 350 MeV.

Lasers incident on solid targets can also be used to accelerate heavier particles—protons and ions. The petawatt laser at Lawrence Livermore National Laboratory (LLNL), incident on a thin target with intensity approaching 3×10^{20} W/cm^2 has generated ~2×10^{13} protons with energy in excess of 10 MeV, with the highest energy approaching 58 MeV. The generation mechanism has been attributed to the electrostatic field set up by the escaping jet of hot electrons from the back of the target. Experiments with the 50-TW Vulcan laser at Rutherford Appleton Laboratory (RAL), with on-target intensity approaching 5×10^{19} W/cm^2, have demonstrated generation of protons with energies approaching 30 MeV and Pb^{46+} ions of up to 430 MeV energy. The energetic ion production in this experiment has been attributed to a combination of ponderomotive acceleration at the front surface and escaping hot electrons creating "coulomb explosion" at the rear surface.

Intense Laser-Plasma Interactions with Long-Pulse Lasers

High-power lasers with pulse lengths >1 ns have proved to be a remarkably versatile tool for the study of high energy density physics, with important applications ranging from inertial confinement fusion to stockpile stewardship and astrophysics. Over the past four decades, the energy of these lasers has increased at a rate comparable to the growth in computer power, culminating in the National Ignition Facility (NIF) now under construction. This megajoule-class 0.35-μm laser will provide a crucial test of inertial fusion as a future energy source and will also enable a broad study of high energy density science for stockpile stewardship and other applications. The field of laser-plasma interactions is a vital enabling technology for these many applications as well as a remarkable testbed for understanding broadly applicable nonlinear plasma science.

The challenges associated with the interactions of long-pulse high-energy lasers with plasmas is well illustrated by considering the nominal hohlraum target for achieving ignition on the NIF. As shown in Figure 4.3, this hohlraum will be irradiated from two sides by 192 laser beams, arranged into inner and outer cones. The relative power in these cones is tuned to provide the time-dependent x-ray symmetry required for the implosion. The hohlraum is filled with a low-Z plasma with a quasi-uniform density of $\sim 10^{21}$ cm^{-3}, which is needed to prevent radiation asymmetry due to excessive motion of the hohlraum walls. Before collisionally absorbing in the high-Z wall plasma, the laser beams propagate through up to 5 mm ($>10^4$ free space wavelengths) of the low-Z fill plasma at a peak intensity of order 2×10^{15} W/cm^2 (and much larger near the laser entrance holes). Excellent absorption of the laser beams is desired, and excellent temporal and spatial control of the absorption is required for the requisite implosion symmetry.

The interaction physics is extraordinarily rich. As the laser beams propagate through the high-temperature (electron temperature ~5 keV) plasma within the hohlraum, they can filament and spray out in angle, developing additional spatial and temporal incoherence. The beams can undergo enhanced bending in places where the plasma flow is near sonic, where significant energy transfer among crossing beams can also occur. The laser beams can scatter and/or generate high-energy electrons via a variety of instabilities involving either electron plasma waves (the stimulated Raman instability and the two-plasmon decay) or ion sound waves (the stimulated Brillouin instability). These instabilities were controlled in previous

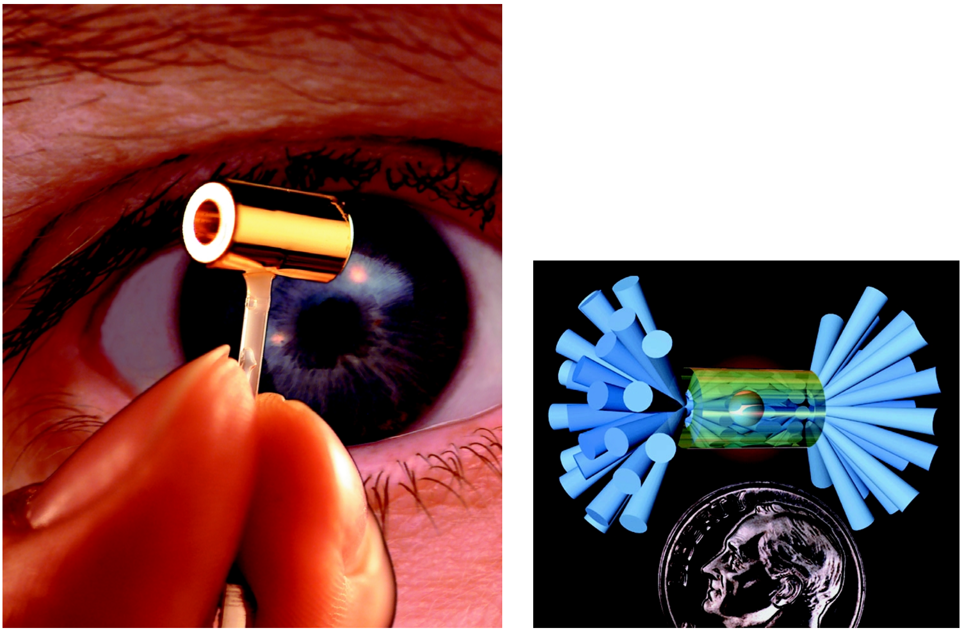


FIGURE 4.3 Images of the type of hohlraum used for ignition experiments. The schematic on the right shows the hohlraum irradiated by 192 NIF beams. Courtesy of Lawrence Livermore National Laboratory.

millimeter-scale experiments at the Nova facility by using significant laser beam smoothing. Understanding and controlling their evolution in new regimes and over the centimeter scales and higher energies at NIF pose a significantly greater challenge. Rarely have questions of such a fundamental physics nature been so directly coupled to a programmatic and societal need.

Fast Ignition

In the past decade, the development of short-pulse, ultrahigh-power lasers has motivated another approach to inertial fusion energy called Fast Ignition. In this case, cold deuterium-tritium (DT) fuel is first compressed to high density, and fusion burn is then initiated by a rapid heating of a portion of the fuel to high temperature. Significantly higher gains are possible compared to the conventional approach.

Furthermore, the Fast Ignition scheme is less sensitive to hydrodynamic instabilities and mix, since the processes of fuel compression and hot spot creation are separated.

The critical issue for Fast Ignition is the efficient generation and transport of a short, ultraintense energy flux to the precompressed fuel, a relatively unexplored topic involving many extremely rich nonlinear physical phenomena and many potential applications. The following estimates illustrate the challenge: The basic requirement is to heat to about 10 keV a volume of cold fuel with a radius equal to the alpha particle range, which will enable a propagating burn into the remaining fuel. For a compressed DT fuel density of 300 g/cm^3, the required radius is about 10 microns and the disassembly time is about 10 ps. To heat this amount of fuel to 10 keV requires delivery of at least 3 kJ in a time less than the disassembly time, which represents a power in excess of 4×10^{14} W and an energy flux of order 10^{20} W/cm^2. The incident laser energy needs to be roughly an order-of-magnitude larger, depending on the efficiency of energy transfer from the laser to the dense fuel and on the size of the hot spot created. Laser-accelerated electrons and/or protons with energies of order 1 MeV and 5 MeV, respectively, offer an attractive means of coupling this energy because their range is similar to that of the alpha particles. Just how efficiently such beams can be generated and transported looms as a key fundamental question.

Intense laser pulses made with chirped pulse amplification technology provide a key tool for investigating physics in this regime. Although at lower energy/pulse and shorter pulse lengths than required for Fast Ignition, CPA lasers have already achieved the requisite powers (up to 10^{15} W) and focused light intensities (up to 10^{21} W/cm^2). These enable important features of this ultraintense laser plasma regime to be explored. The features include relativistic self-focusing and filamentation of the laser light, pronounced hole boring into overdense plasma, and a variety of acceleration processes. Other notable effects include self-generated magnetic fields with an amplitude up to 10^9 G and multi-MeV ion generation.

Computer simulations of this ultraintense regime using two- and three-dimensional electromagnetic, relativistic particle codes have illustrated many of these effects and shown significant absorption (>30 percent) into electrons with energies above 1 MeV. They illustrate several acceleration mechanisms, such as heating due to the oscillating ponderomotive force, conversion of transverse laser fields to longitudinal fields at overdense plasma layers, and electron acceleration at the betatron resonance in relativistic laser channels (an inverse free electron laser (FEL) process). Many of these effects have now been observed in experiments, but much more work is needed for a quantitative understanding.

The transport of ultraintense energetic particle fluxes over distances of hundreds of microns from the laser absorption region to the compressed fuel is another very challenging issue at the forefront of high energy density physics. For example, if a power of 10^{15} W is carried by electrons with an average energy of 3 MeV, the associated current is ~300 MA. Such a current far exceeds the Alfvén critical current (~100 kA) and so requires neutralization by return currents in the dense plasma. Many physical processes then come into play, including strong return current heating, excitation of the Weibel instability, formation and coalescence of current filaments and magnetic channels, as well as various instabilities that can disrupt the beam propagation (see Figure 4.4). Especially encouraging have been experiments at Osaka University in which cold fuel has been assembled to high density and a significant heating of the fuel by a short, very intense, low-energy (60-J) laser pulse has been observed. An energy transfer efficiency from the short laser pulse to the fuel of approximately 20 percent has been inferred.

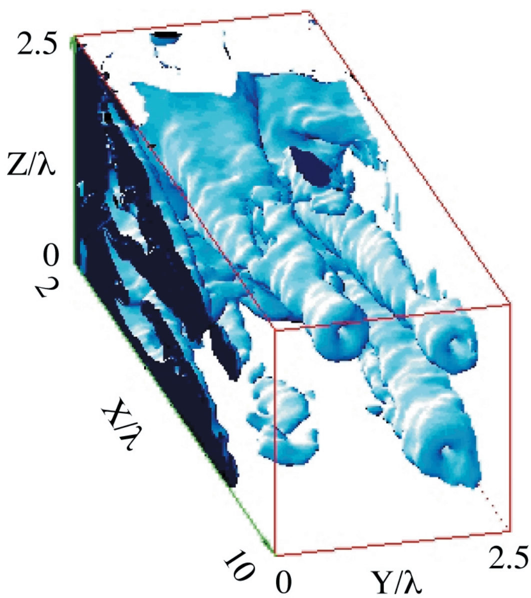


FIGURE 4.4 Three-dimensional particle-in-cell simulations of energetic electron generation and transport with laser pulses in overdense plasmas. Contours of magnetic-field structure due to the Weibel instability are shown. Courtesy of Y. Sentoku, General Atomics.

Other Applications

Ion Beams for Heavy Ion Fusion

Heavy ion drivers are attractive for inertial fusion energy (IFE) because of their efficiency and because the final focusing onto the target is achieved by magnetic lenses. The magnetic lenses can be made robust to the effects of the target explosions, which must repeat at rates of order 5 Hz. To realize heavy ion fusion (HIF), intense beams of heavy ions (with A > 80) must be accelerated to multigigaelectronvolt kinetic energies (several megajoules total), temporally compressed to duration ~10 ns, and focused onto a series of small (few millimeters) targets, each containing a spherical capsule of fusion fuel. Such intense beams represent a significant extension beyond current state-of-the-art space-charge dominated beams. The importance of space charge as reflected in the beam perveance exceeds that in the closest existing beam, Intersecting Storage Rings (ISR) at CERN, by three orders of magnitude. The beams behave as nonneutral plasmas, exhibiting collective processes, nonlinear dynamics, and instabilities that must be understood and controlled if heavy ion fusion is to be achieved.

Major issues arise in two parts of the driver system: (1) the fusion driver accelerator and (2) the final pulse compression, focusing, and transport through the fusion chamber environment onto the target. For example, emittance growth (unwanted increase in beam temperature) in the driver accelerator can take place through complicated distortions driven by collective processes, imperfect applied fields, image fields from nearby conductors, and interbeam forces. To assist in the final transport through the chamber, plasma lenses, as employed in other accelerator applications, are being studied experimentally and theoretically for heavy ion fusion. They offer the promise of stronger focusing with greater chromatic acceptances and reduced demands on beam quality from the driver. However, they introduce beam and background plasma dynamics, including the following: multibeam effects, return current dynamics (streaming and filamentation instabilities), imperfect neutralization, beam stripping, emittance growth, and photoionization of the beam ions and background gas. New opportunities for addressing these challenges are afforded by the development of new experimental facilities and computational tools—an example is shown in Figure 4.5.

Backscatter Laser Amplifier

Chirped pulse amplification techniques have pushed forward the peak intensity of lasers by orders of magnitude and hence have opened a window on a rich array of new physics topics. It is of interest, then, to consider other mechanisms for amplifying lasers that may potentially exceed even the limits of CPA lasers. Because

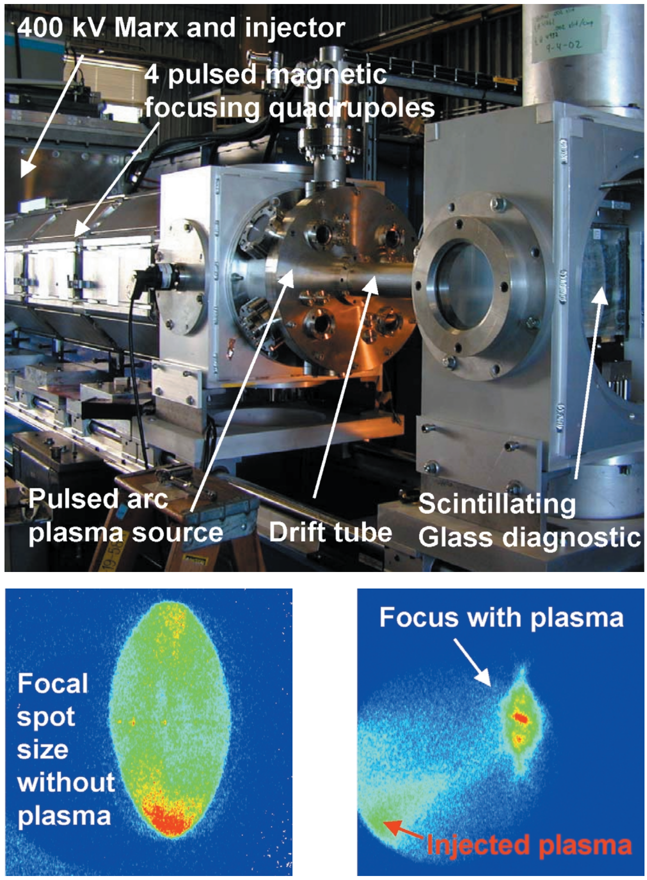


FIGURE 4.5 The Neutralized-Transport Experiment (NTX) addresses many key scientific issues of final focus and neutralized transport in a heavy ion fusion chamber. The concept of neutralized drift of intense ion beams through the target chamber is essential for the viability of an economically competitive heavy ion fusion power plant. The physics of neutralized drift has been studied extensively with PIC simulations. To provide quantitative comparisons of theoretical predictions with experiment, the NTX has been developed at Lawrence Berkeley National Laboratory in collaboration with Princeton Plasma Physics Laboratory. The initial experiment consists of a pulsed metal arc source at the exit of the last pulsed magnet, serving as a "plasma plug," from which electrons are extracted by the positive potential of the traversing beam. The neutralized ion beam drifts for a distance of a meter to converge onto a small focal spot, as witnessed by an image on a glass plate (lower right). The same magnet configuration without plasma yields a large spot at the same location, owing to beam blow-up when the space charge is unneutralized (lower left). Hardware for the full neutralization experiment with a radio-frequency plasma source is also complete and will be installed at NTX near the focal point to study volumetric plasma effects (to simulate the effects of photoionized plasmas in a fusion chamber) and gas interactions. Courtesy of Lawrence Berkeley National Laboratory.

it is impervious to breakdown, plasma is an ideal medium for processing very high power and fluence. One idea is to store energy in a long pump pulse that is quickly depleted by a short counter-propagating pulse, which can be then focused on target (see Figure 4.6).

This counter-propagating wave effect has already been quite successfully employed in Raman amplifiers using neutral gases. But at high power, there appear to be nonlinear effects in plasma that make such methods particularly suitable for high-power pulse compression. The challenge is to evaluate whether these mechanisms in fact produce compression effects. One issue is whether the short pulse can reach

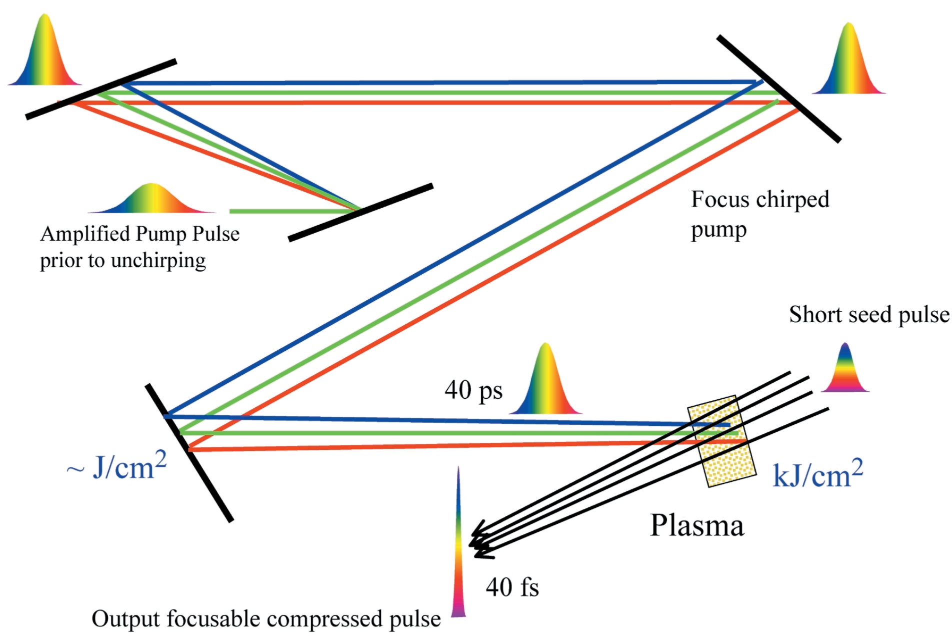


FIGURE 4.6 Example of pulse compression using two optical systems based on Raman backscattering. The first optical system, essentially operating as a flashlamp, delivers energy without providing a strong focus. A chirped pulse emerges from a grating at perhaps 40 ps in length, and then is focused beyond the plasma target, so that the plasma is irradiated by fluence on the order of kJ/cm^2. The second moderate-aperture low-power optical system delivers the short, counter-propagating, focusing pulse that captures, by Raman backscatter in the plasma, the pump fluence, effectively compressing it in time and then focusing it in space. The unfocused output intensity from the plasma can be on the order of 10^{17} W/cm^2; the further focusing in the vacuum can then lead to intensities on the order of 10^{25} W/cm^2. Courtesy of N.J. Fisch and V.M. Malkin, Princeton University.

high intensity before undergoing instabilities. Also undetermined theoretically is the degree to which amplified pulses can retain focus through practical plasmas.

Radioisotope Production

Laser-driven accelerators can be used to accelerate both electrons and ions, offering the possibility for radioisotope production using (γ,n) or (p,n) type reactions. The availability of a compact isotope generator, built around existing or minimally modified target technology, might offer a compact, flexible alternative to cyclotrons. The laser-driven accelerator technology needs to be explored to its full potential in order to determine its global or niche impact in nuclear medicine imaging fields, such as positron emission tomography (PET), one of the fastest-growing imaging modalities in the world today. The Laser Optics and Accelerator Systems Integrated Studies (l'OASIS) group at Lawrence Berkeley National Laboratory has recently used a high-repetition-rate (10 Hz), 10-TW solid-state laser system for experiments on laser-driven acceleration of electrons in plasmas. Several isotopes such as ^{62}Cu, ^{61}Cu were produced using (γ,n) reactions in ^{63}Cu. Experiments are under way to boost activation levels to the tens of millicuries range. Laser-accelerated protons have also been used for isotope production. Experiments to date at LLNL (whose results are shown in Figure 4.7), RAL, and at the University of Michigan have shown proton beams emerging from laser-irradiated solid targets, containing in excess of 10^{12} protons per bunch with energy greater than 2 MeV and peak energies at over 50 MeV.

Imaging and Backlighting

The generation of extremely intense, short-pulse proton beams by very high intensity laser beams interacting with solid targets has great potential for diagnosing dense plasmas, as illustrated in Figure 4.7. Applications for these protons include proton radiography in medicine and weapons programs. To date, the medical application has been generally too expensive for the treatment value added to justify wide deployment of proton beam facilities. This is particularly true in the present climate of medical cost containment. However, a cheaper tabletop proton source, other than a synchrotron or cyclotron, could alter the economics and deliver a new, powerful imaging tool to the physician. The DOE Stockpile Stewardship program is interested in the use of a large synchrotron for time-resolved tomographic imaging of weapon implosion simulations. As another significant application, multikilojoule, 5- to 50-ps laser beams will enable high-quality radiography using 20- to 100-keV x rays. This has potential importance for NIF, where the x rays produced can reach acceptable brightness for backlighting studies of the implosion physics of capsules or for equation-of-state studies.

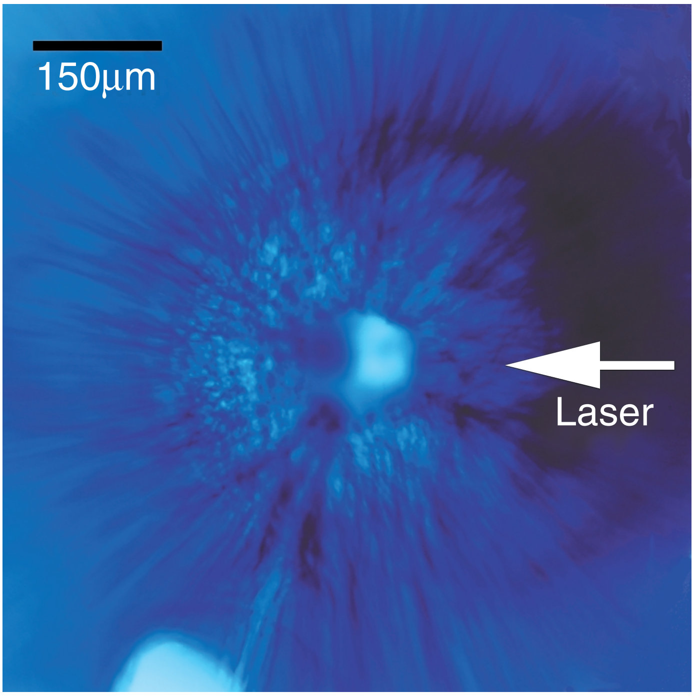


FIGURE 4.7 Image of a laser-heated 150-micron balloon target using proton radiography. The target was heated by a laser; the fine structures shown in the image are due to plasma electric fields that deflect the protons. Courtesy of M. Borghesi, Queen's University, Belfast; O. Willi, A. Schiavi, M. Haines, and H. Campbell, Imperial College, London; S. Hawkes and R.C. Clarke, Rutherford Appleton Laboratory; and A.J. Mackinnon, Lawrence Livermore National Laboratory.

Ultrashort Pulse, High Peak Brightness Light Sources from the Terahertz to X-ray Regime

The infrared (IR) free electron laser at Jefferson National Laboratory has demonstrated simultaneous production of femtosecond x rays from intracavity Thompson scattering of the wiggler IR radiation off the electron beam, regular IR FEL lasing and terahertz (THz) radiation from the recirculating linac bends, at record fluences in all three parts of the spectrum. The IR FEL is also beginning to demonstrate the potential value of such radiation for research and development and in the commercial marketplace. There are a number of ways in which high energy density lasers and beams propagating through plasmas can produce such radiation from more compact systems. The first is to use the laser-accelerated electrons described in the previous sections. These bunches are femtosecond in duration, leading to the possibility of generating ultrashort radiation pulses ranging from the terahertz to the x-ray regime from tabletop devices. Coherent terahertz radiation can be generated by allowing these femtosecond bunches to radiate using, for example, diffraction or transition radiation. X rays are created when these bunches are allowed to interact back with a part of the laser that generated them. An alternative way to make radiation is within the plasma itself. Laser-driven plasma wakes have a frequency in the terahertz regime and can be converted into powerful radiators (up to gigawatt levels in principle). By applying a perpendicular magnetic field, one can give to the wakes a positive group velocity, enabling them to propagate through and emanate from the plasma as radiation.

Coherent light over a broad range of frequencies can also be obtained from an FEL in which the insertion device is a plasma. When a high-brightness electron beam propagates through a plasma of lower density than the beam, the plasma electrons are blown out, leaving a column of positive ion charge. The ion column produces a focusing force (plasma lens) on the beam that causes it to radiate. Thus the plasma acts as a wiggler that is both tunable and strong. The coherent amplification of a signal by this ion channel laser mechanism was demonstrated in the microwave regime in Japan, and spontaneous emission in the x-ray regime was seen recently in the E-162 experiment at SLAC (see Figure 4.8). If this mechanism can be made to lase at higher frequencies, it may provide a simple tunable insertion device for FELs.

Improved Conventional Accelerator Performance: Control of the Electron Cloud and Two-Stream Instabilities

Electron clouds are one of the most significant performance-limiting factors in circular accelerators and storage rings carrying high energy density positively charged beams, and they are a serious concern for future machines such as the Spallation Neutron Source at Oak Ridge National Laboratory, the Large Hadron Collider at CERN, and heavy ion fusion accelerators. Although the clouds themselves are very low density, their creation and their collective effect on the beam are a direct consequence of the high energy density of the beams in such accelerators. These electron clouds arise when the circulating beam emits synchrotron radiation or ionizes residual gas, or when stray beam particles hit the walls of the vacuum chamber. Any of these mechanisms generates electrons, which are attracted toward the center of the chamber by the positive potential of the circulating beam (see Figure 4.9). In addition, the secondary emission process may compound the effect

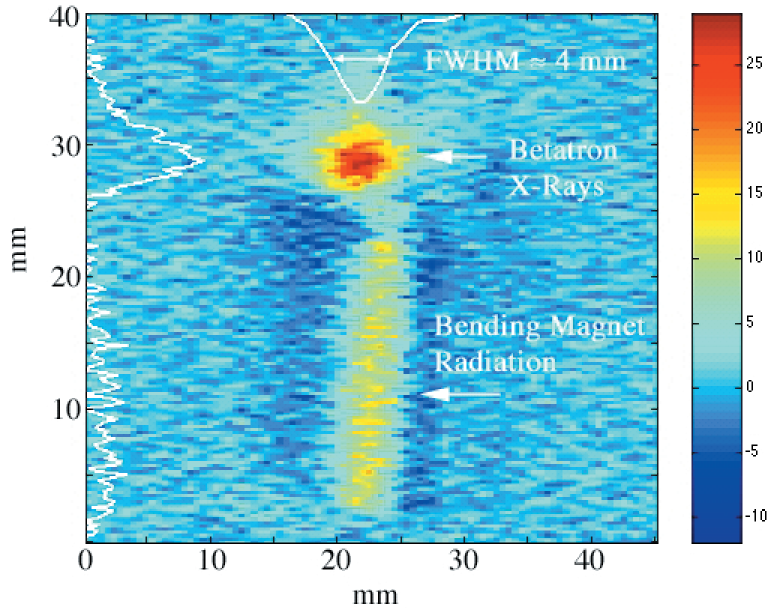


FIGURE 4.8 Spontaneous emission of x rays by a 28.5-GeV beam propagated through a 1.4-m-long plasma of density 10^{14} cm^{-3} in E-162 at SLAC. The peak brightness was 10^{19} photons/s/mm^2/$mrad^2$/0.1 BW at 6.7 keV. The long yellow strip is synchrotron radiation from a bending magnet. SOURCE: Reprinted, with permission, from S. Wang, C.E. Clayton, B.E. Blue, E.S. Dodd, K.A. Marsh, W.B. Mori, C. Joshi, S. Lee, P. Muggli, T. Katsouleas, F.J. Decker, M.J. Hogan, R.H. Iverson, P. Raimondi, D. Walz, R. Siemann, and R. Assmann, 2002, "X-Ray Emission from Betatron Motion in a Plasma Wiggler," *Phys. Rev. Lett.* 88:135004, copyright 2002 by the American Physical Society.

when the electrons, in turn, hit the walls of the chamber. As a result, the electron cloud builds up to equilibrium densities of order 10^5 to 10^7 cm^{-3}, constituting a non-neutral plasma that interacts with the high energy density beams to create two-stream instabilities, potentially leading to particle losses or emittance growth, thus disrupting the beam and degrading machine performance. The collective fields created in such cases are not unlike highly nonlinear wakes excited in wakefield accelerators. Advanced plasma and beam modeling tools are being applied to this problem; an improved understanding resulting from simulation studies will play an important role in controlling the electron cloud and two-stream instabilities.

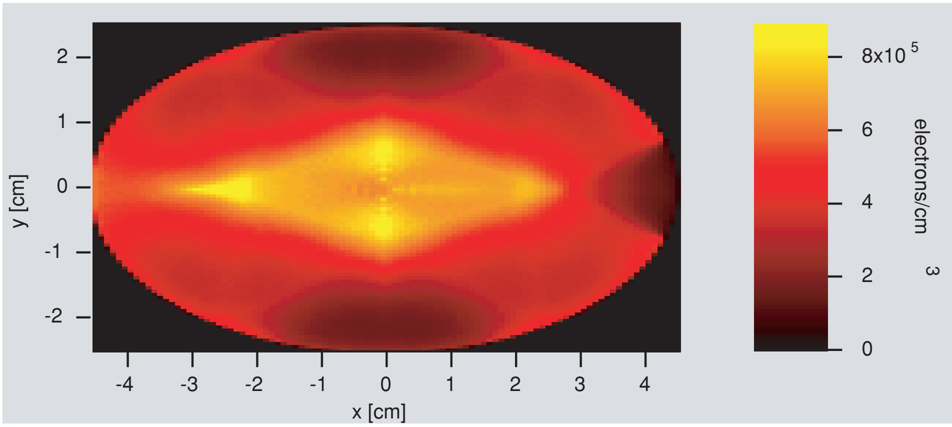


FIGURE 4.9 Simulated time-averaged electron-cloud density in a field-free region in the arcs of the PEP-II positron ring. The beam (not shown) occupies a small region at the center of the chamber, of order 1 mm in diameter. Courtesy of M.A. Furman, Lawrence Berkeley National Laboratory.

Short-Lifetime Particle "Factories"

Laser wakefield acceleration in high-density plasmas produces longitudinal electric fields comparable to the laser transverse field. For next-generation CPA lasers at 10^{23} W/cm^2, this suggests longitudinal fields of the order of ~1 TV/cm. With such fields, particles could be accelerated to relativistic energies in such short distances as to significantly extend their lifetime. Particle-in-cell simulations by A. Pukhov have shown that 5-GeV protons could be produced as the result of the interaction of an ultraintense pulse at the 10^{23} W/cm^2 level with a metallic target. These protons can be used to produce pions, which have a lifetime at rest of 20 ns and are well synchronized to the 10-fs laser pulse. By using a laser-driven acceleration mechanism, one could quickly increase the pion energy and lifetime by roughly 100 times to 15 GeV and 2 μs, in only a few picoseconds, a time much shorter than the pion lifetime. This long lifetime would make it possible to accelerate the pions to higher energy, if necessary, with conventional (i.e., lower gradient) accelerating structures. At the gigaelectronvolt energy level, the pions will decay into a well-collimated beam of muons and neutrinos.

Sources of muons are of interest for a possible muon collider that offers cleaner particle physics interactions than in a proton-antiproton collider (because the muons lack the quark substructure of protons) but lower synchrotron radiation than circular electron-positron accelerators. Another elegant application that combines high-energy accelerators and either high-power lasers or magnetic wigglers is a gamma-gamma collider. By colliding photons instead of charged particles, limits to luminosity arising from beam-beam interactions (so-called bremsstrahlung) can be avoided.

OPPORTUNITIES

This section identifies some illustrative examples of research opportunities for high energy density laser-plasma and beam-plasma physics using existing infrastructure, existing infrastructure with modifications, and future infrastructure. "Infrastructure" includes experimental laser and beam facilities and computational facilities. A number of these were identified in the facilities matrix in Chapter 3 (Tables 3.1 through 3.4), and selected examples are briefly described here.

Beam Facilities: The Stanford Linear Accelerator Center

Fundamental research into the formation, injection, and propagation of short and possibly shaped bunches in long plasmas appears to hold great promise for advancing toward a future device that can benefit high energy physics and other areas of science. There are relatively few beam facilities for high energy density plasma physics. The Accelerator Test Facility at Brookhaven National Laboratory and the Advanced Wakefield Facility at Argonne National Laboratory are significant user facilities with 50-MeV beamlines. Only SLAC has facilities in the gigaelectronvolt class and with positrons. This subsection is limited to describing some of the possibilities available at SLAC.

In order to increase particle beam-driven wakefields to amplitudes similar to the laser wakefield case, the bunch length of the electron beam drivers must be shortened from their present length of a few picoseconds to the subpicosecond range. Presently, work at SLAC is directed toward reducing the bunch length of the beam to 20 fs (a factor of 200 shorter than the present bunch length) for applications such as the Linac Coherent Light Source (LCLS). If this can be done, it becomes possible to consider ultrahigh-gradient acceleration at several gigaelectronvolts per meter over multimeter distances in plasma modules referred to as plasma afterburners. In this concept, the energy of an e^+e^- collider may be doubled in a few meters by splitting each of its bunches into two, with the first bunch exciting a plasma wake that accelerates the second bunch just before the collision point. Appropriate phasing and shaping of the second bunch will be key to keeping the energy spread small, and plasma lenses are key to maintaining the luminosity at the collision point.

High energy density plasma experiments at SLAC thus far have been parasitic with other laboratory programs sharing a single beamline, but the upcoming LCLS may be incompatible with parasitic operation. A dedicated beamline that could be created at modest cost would be a significant opportunity for high energy density plasma physics and other science.

Coupling Physics on Long-Pulse Laser Facilities

As discussed in the subsection entitled “Backscatter Laser Amplifer,” above, fundamental research into the interaction of intense laser light with long-scale-length plasmas is very important for the optimal use of high-power lasers for inertial fusion and high energy density physics in general. Indeed, the time is ripe for significant advances. In recent years, the plasma and laser beam conditions have become increasingly well characterized and controlled in experiments. Furthermore, the diagnostics have become quite sophisticated. For example, Figure 4.10 shows measurements via Thomson scattering of the temporally and spatially resolved amplitudes of both the electron plasma wave due to stimulated Raman scattering and the ion sound wave due to stimulated Brillouin scattering in a laser-plasma experiment. Such detailed measurements provide remarkable tests of the fidelity of simulation models and new insight into relevant behavior.

Development of quantitative models of laser-matter interactions (including, for example, experimentally tested saturation models for laser-plasma instabilities) requires an improved understanding of many basic plasma phenomena and is ideal for university research. University-scale experiments with near-kilojoule lasers can identify and quantify key physical processes. These less expensive facilities enable more numerous experiments to explore parametric dependencies and provide a very important testbed for concept development and discovery. As an example, a new electron-acoustic wave has been discovered in recent experiments with the Trident facility, a 250-J laser at Los Alamos National Laboratory. Unfortunately, there is currently a paucity of kilojoule-class long-pulse length lasers at universities in this country.

Experiments on higher-energy lasers, such as OMEGA, and in the future, the NIF (see Chapter 3 for more about the large laser facilities), allow many important features of coupling physics to be explored in larger and/or hotter plasmas, more relevant to future ignition experiments. For example, on the OMEGA laser new techniques for laser beam smoothing, such as smoothing by spectral dispersion and polarization smoothing, were developed and demonstrated. Reduction of stimulated scattering by these techniques was observed. Beam phasing has been demonstrated as a technique to control radiation symmetry in hohlraums. In ongoing experiments, the interaction physics of multiple crossing laser beams is being studied, and new instability control mechanisms are being developed.

The National Laser Users Facility (NLUF) at the University of Rochester provides facility time on the OMEGA laser for outside users. For several decades, NLUF has

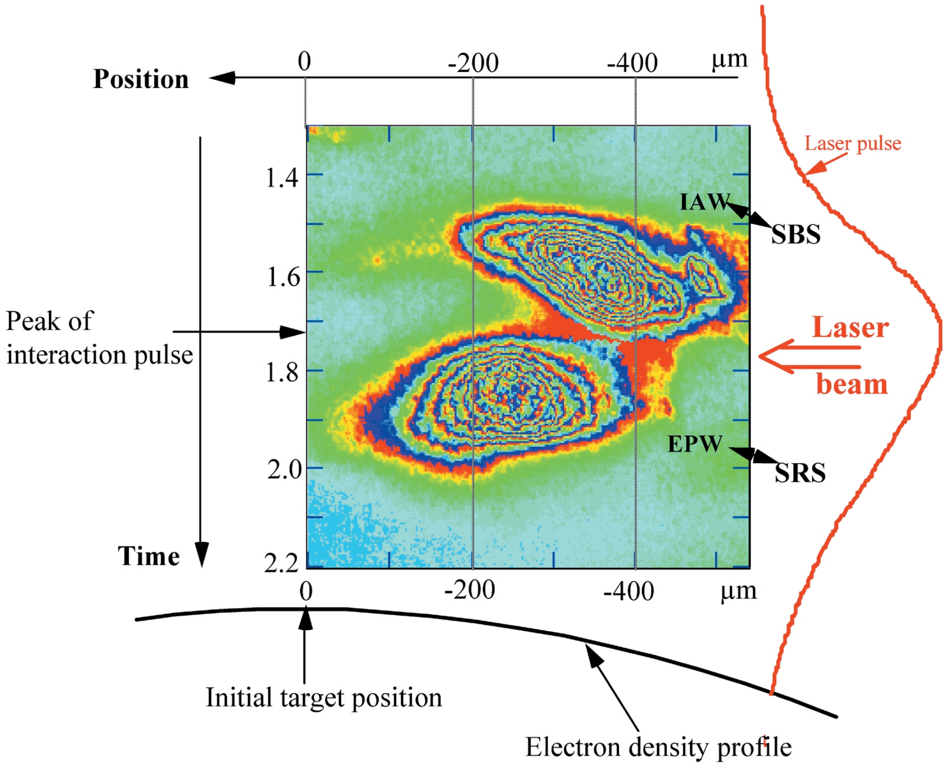


FIGURE 4.10 Measurements in space and time of the amplitudes of both electron plasma and ion sound waves in a laser-irradiated plasma. SOURCE: Reprinted, with permission, from C. Labaune, H.A. Baldis, N. Renard, E. Schifano, and A. Michard, 1997, "Interplay Between Ion Acoustic Waves and Electron Plasma Waves Associated with Stimulated Brillouin and Raman Scattering," *Phys. Plasmas*, 4:423-427, copyright 1997 by the American Institute of Physics.

enabled valuable laser experiments on topics ranging from basic plasma and atomic physics to implosion physics. Another national facility providing a unique resource, an ultrasmooth few-kilojoule laser, is NIKE, at the Naval Research Laboratory. It enables instability studies to be done without worrying about beam seeding of specific modes.

By far the most energetic laser for high energy density physics will be the NIF, described in the Chapter 3. The first quad of beams is anticipated to be available for experiments in fiscal year (FY) 2003, and the entire system is projected for completion later in the decade. As more beams are activated, more sophisticated experiments can be carried out.

NIF experiments on the coupling physics will be vital for the development of quantitative models for the interaction of multiple, crossing laser beams with very long scale length plasmas. In turn, this understanding will enable more efficient use of NIF for applications ranging from inertial fusion to high energy density physics. As a bonus, the concomitant advances in the understanding of nonlinear, kinetic plasma phenomena will benefit other applications of plasma science.

About 10 percent of the NIF laser shots have been allocated for basic science, which is also represented on the facility's Experimental Planning Advisory Committee. A symposium on frontier science with NIF was held in 1999. Finally, a Stewardship Science Academic Alliances program for university users was launched in FY 2002. This program builds on and significantly extends the existing Inertial Fusion Science in Support of Stockpile Stewardship grant program.

Chirped Pulse Amplification Laser Facilities

The generation and transport of ultrastrong energy flows in matter are clearly a very promising frontier of high energy density physics. Applications, many of which have been described above, extend beyond fusion energy, to fast ignition, to stockpile stewardship, and to astrophysics. The studies can also enable improved understanding of many basic relativistic plasma phenomena, such as relativistic shocks. Many relevant experiments can be carried out with university-scale, 100-TW-class lasers. Such lasers are available at a number of universities, including the University of Michigan, the University of Maryland, and the University of Texas at Austin.

The first petawatt laser used a beamline of the Nova laser at LLNL. Petawatt-class lasers are currently under construction at Osaka University in Japan and at the Rutherford Appleton Laboratory in the United Kingdom. Plans are under way for petawatt-class lasers at the University of Nevada at Reno using parts from the LLNL laser, and at both Sandia National Laboratories and the University of Rochester.

However, it is important to develop high-energy, high-power lasers beyond a petawatt. That can be accomplished, for example, by configuring the NIF to provide a chirped pulse amplification pulse in one or more beamlines. In this way, one can move into the multipetawatt, even exawatt, class with 10 to 100 kJ of energy. This would allow x-ray radiography of imploding capsules, testing of fast ignition, and exploration of extreme field science. This development should be of high priority, for it clearly is needed for further advance of this important field.

Novel Light Sources

To date, the study of ultrafast processes has largely relied on femtosecond optical pulses. Since x rays interact with core electronic levels and hence are effective structural probes, the availability of femtosecond x-ray pulses from laser sources and the intrinsic synchronization between laser and x-ray pulses would make it possible to directly probe changes in atomic structure on ultrafast time scales. Such sources could be complementary to recent light source facilities such as that at the Jefferson Laboratory infrared free electron laser. The vast potential of these short-pulse, multicolor operating scenarios for materials and other research and development is only just beginning to be explored.

The Linac Coherent Light Source (LCLS), which is proposed to be constructed in the 2004-2007 time frame, will utilize the last third of the existing SLAC linac. This linac produces a high-current 5- to 15-GeV electron beam that is bunched into 230-fs slices with a 120-Hz repetition rate. When traveling through an ~100-m-long undulator, the electron bunches will lead to self-amplification of the emitted x-ray intensity in the 800- to 8,000-eV energy range and will function as the first x-ray free-electron laser. The emitted coherent x rays will have unprecedented brightness and hence offer a new window on beam-matter interactions.

Two general classes of experiments are proposed for the LCLS. The first class consists of experiments in which the x-ray beam is used to probe the sample without modifying it, as in most synchrotron source experiments today. In the second class, the LCLS beam is used to induce nonlinear photo-processes or to study matter in extreme conditions. The latter experiments will include pump-probe studies of so-called warm dense matter.

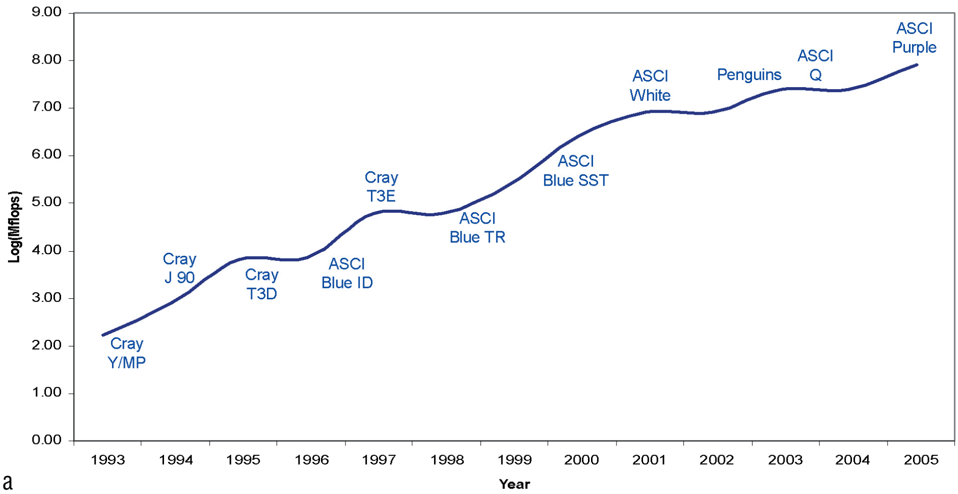
High-Performance Computing

When simulation models were first applied to the study of laser-plasma interactions in the 1960s, lasers were nanoseconds long and computing power was measured in megaflops. The parallel development of femtosecond lasers and teraflop computing has led to a convergence of these factors by more than 10 orders of magnitude! As a result, it has recently become possible for the first time to perform detailed simulations of high energy density beam-plasma experiments using algorithms with very low level approximations in three dimensions with unscaled parameters. It is even possible to begin to use the actual number of particles in simulations that are used in some experiments (e.g., 10^{10} electrons in a beam experiment). This is leading to a significant change in the way that simulations are used to study high energy density beam-plasma interactions. While scaled simulations were previously used to test theoretical concepts that could then be applied to experiments, simulations are now able to unveil the relevant physics in a short-pulse experiment directly. Moreover, by benchmarking the codes against real data, it is possible to build and test a future device at a fraction of the cost otherwise required.

The modeling of laser-plasma interactions is also becoming more powerful and detailed, owing to ongoing advances in model development. Three-dimensional computer models now span the gamut from particle-electron, particle-ion codes, and hybrid codes, in which ions are particles and the electrons are a fluid, to various reduced descriptions that can follow the light-wave propagation over experimental time and space scales. In the modeling of the interaction of subpicosecond laser pulses with plasmas, novel techniques such as moving grids and massively parallel particle codes have been able to directly simulate a number of experiments on laser-plasma acceleration and related phenomena. The codes are in excellent agreement with much data.

For long laser pulses, the modeling is a special challenge, since the key processes occur on widely disparate space and time scales. As an example, consider laser-plasma interactions for inertial fusion. In the mainline approach, laser beams with a pulse length of order 10 ns interact with a target plasma with scale lengths of order 1 cm. The absorption and reflection of the beams are modified by the excitation of plasma waves with maximum frequencies comparable to the laser light frequency ($\sim 6 \times 10^{15}$ s^{-1}) and with scale lengths of order the electron Debye length. (For a plasma with density $\sim 10^{21}$ cm^{-3} and an electron temperature of 5 keV, the Debye length is $\sim 10^{-6}$ cm.) Kinetic modeling using particle or Vlasov codes as well as various reduced descriptions is used to study the growth and saturation of the plasma waves. Ideally, these simulations need to consider a volume of plasma at least equal to that of a laser speckle ($\sim 3 \times 10^4$ λ_o^3, where λ_o is the free space wavelength of the laser light and f/8 optics is taken) and to follow the evolution for many instability growth times (many thousands of laser light periods). These simulations of the microphysics are used to generate saturation models. The models are then input into wave propagation codes that follow the evolution of laser beams with realistic structure over experimental time and space scales and can be coupled with hydrodynamic codes. Accurate incorporation of the fine time and space scale physics is a grand challenge shared with other areas of science.

Although the challenge is great, impressive progress is being made owing to the rapid development of high-performance computing. Figure 4.11 illustrates the remarkable increase in floating point operations per second since 1993 and includes projections to 2005. Note also the increase in the size of the plasma that can be modeled in F3D, the wave propagation code at LLNL. If projected improvements in algorithms are included, it will soon be possible to simulate the propagation of an entire NIF laser beam, including realistic models of laser beam smoothing as well as models for the microphysics due to plasma wave excitation and saturation.



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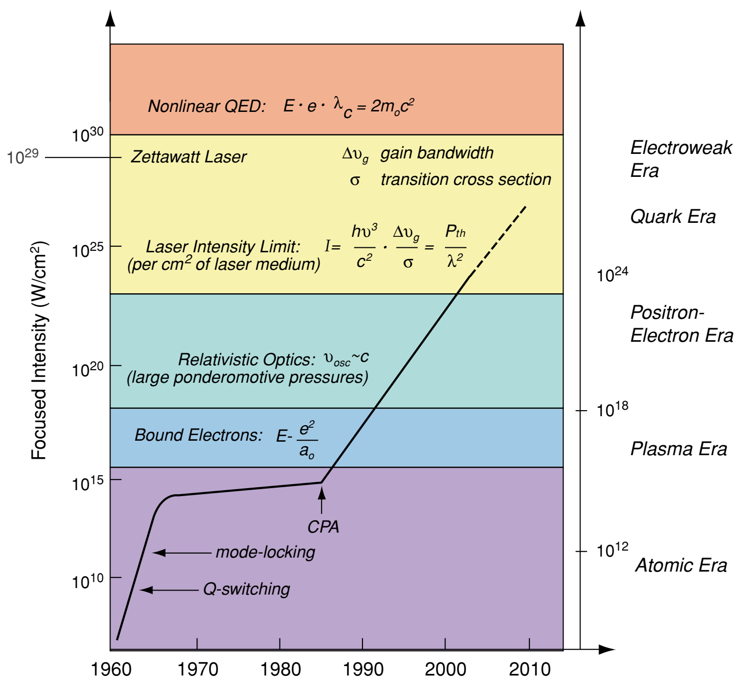

b

FIGURE 4.11 The increase in computer power parallels the increase in laser peak power. (a) The increase in computer power in Mflops from 1993 to 2005 (projected) and (b) the increase in laser peak power from 1960 to 2010. SOURCES: Images (a) courtesy of C.H. Still, Lawrence Livermore National Laboratory; and (b) courtesy of W. Kruer, Lawrence Livermore National Laboratory.

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FIGURE 4.12 Five top supercomputer sites as of November 2001. (a) ASCI Blue-Pacific at Lawrence Livermore National Laboratory is an IBM SP 604e machine capable of 2.14 Tflops; (b) the Terascale System at the Pittsburgh Supercomputing Center is a Compaq Alpha Server machine capable of 4.05 Tflops; (c) the National Energy Research Scientific Computing (NERSC) center at the Lawrence Berkeley National Laboratory is an IBM SP Power3 machine capable of 3.05 Tflops; (d) ASCI Red at Sandia National Laboratories is an Intel processor-based machine capable of 2.37 Tflops; and (e) ASCI White at Lawrence Livermore National Laboratory is an IBM SP Power3 machine capable of 7.22 Tflops. Courtesy of (a) Lawrence Livermore National Laboratory, (b) The Pittsburgh Computer Center; (c) Lawrence Berkeley National Laboratory, (d) Sandia National Laboratories, and (e) Lawrence Livermore National Laboratory.

It is important to note that research in new computer architectures is leading to additional significant performance advances that also are not accounted for in Figure 4.11. These advances are now being realized on the basis of research both within and outside the United States, most notably in Japan, where the Earth Simulator machine has demonstrated, and has re-emphasized, the importance of optimizing memory bandwidth relative to floating point performance.

Physicists can undertake massive calculations in a number of ways. Perhaps the most direct, besides using the National Science Foundation centers, is to access the national laboratory supercomputers. The supercomputers developed by the ASCI program represent a powerful enabling technology for the modeling of high energy density science. Figure 4.12 shows the top five supercomputer sites as of November 2001. The fastest computer is the Advanced Strategic Computing Initiative (ASCI) White machine at LLNL, achieving in excess of 7 Tflops. Supercomputers reaching 100 Tflops are projected for 2005. The ASCI Alliance program is an avenue for unclassified access to the supercomputers at the national laboratories. This program has three levels, ranging from centers of excellence to individual investigator grants.

Glossary

Active galactic nuclei (AGN): Refers to the existence of energetic phenomena in the nuclei, or central regions, of galaxies that cannot be attributed clearly and directly to stars.

Advanced Strategic Computing Initiative (ASCI): Now known as Advanced Simulation and Computing (ASC), this Department of Energy program was established in 1995 to develop the simulation capabilities needed to analyze and predict the performance, safety, and reliability of nuclear weapons and to certify their functionality. To realize its vision, ASC is creating simulation and prototyping capabilities based on advanced weapons codes and high-performance computing.

Akeno Giant Air Shower Array (AGASA): Designed to study the origin of extremely high energy cosmic rays, AGASA covers an area of about 100 km^2 and consists of 111 detectors on the ground (surface detectors) and 27 detectors under absorbers (muon detectors). Each surface detector is placed with a nearest-neighbor separation of about 1 km, and the detectors are sequentially connected with a pair of optical fibers. When an extremely high energy cosmic ray enters the atmosphere, it collides with an atomic nucleus and starts a cascade of charged particles that produce light as they zip through the atmosphere. AGASA and other similar detectors measure the light emitted in these so-called air showers.

Alfvén critical current: The current at which the self magnetic field of a beam reflects the beam particles. The electron Alfvén current, in units of amperes, is $I_A = 17{,}000\ \beta\gamma$, where β is the electron velocity normalized to the speed of light and γ is the relativistic Lorentz factor.

Alfvén wave: A transverse wave that occurs in a region containing a magnetic field and a plasma. The ionized and therefore highly conducting plasma is said to be "frozen in" to the magnetic field and is forced to take part in its wave motion. The existence of these waves was predicted by Hannes Olof Gosta Alfvén in 1942—this work inaugurated the study of magnetohydrodynamics for which Alfvén was awarded the Nobel Prize in 1970. *See **Magnetohydrodynamics**.*

Alpha particle: A helium-4 nucleus emitted by a larger nucleus during a type of radioactive decay known as alpha decay. An alpha particle consists of two protons and two neutrons.

Auger project: The Pierre Auger Observatory project, an international effort to study the highest-energy cosmic rays. Two giant detector arrays, each covering 3,000 km^2, will be constructed in the Northern and Southern Hemispheres. Each will consist of 1,600 particle detectors and an atmospheric fluorescence detector. The objective of the arrays is to measure the arrival direction, energy, and mass composition of cosmic-ray air showers above 10^{19} eV.

Baryon: A class of subatomic particles that includes the proton and neutron. Baryons are a subclass of the class of particles known as hadrons that interact via the strong interaction. Baryons have half-integral spin.

Berkeley Illinois Maryland Association Array (BIMA): A consortium consisting of the Radio Astronomy Laboratory at the University of California, Berkeley; the Laboratory for Astronomical Imaging at the University of Illinois, Urbana; and the Laboratory for Millimeter-Wave Astronomy at the University of Maryland. BIMA operates a millimeter-wave radio interferometer at Hat Creek, California, with support from the National Science Foundation.

Bethe-Heitler process: As an energetic electron slows down in a material, it emits photons via bremsstrahlung. At high electron energies, these photons can be reconverted back to electron-positron pairs. The Bethe-Heitler process describes the bremsstrahlung emitted by an electron in a coulomb field.

Bisnovatyi-Kogan, Zel'dovich, Sunyaev (BKZS) limit: Thermally produced electron-positron plasmas are thought to play an important role in the evolution of the cores of massive stars, neutron-star and black-hole accretion disks, pulsars, quasars, astrophysical gamma-ray bursters, and in the big bang. In the past few years, discoveries of intense, broadened 511-keV annihilation lines from several galactic black-hole candidates suggest that, in addition to transient-pair production, steady-state thermal pair plasmas exist. Since pairs annihilate on short time scales, maintaining such steady-state conditions requires the copious production of pairs in order to balance the annihilation rate. Such pair-balanced steady-state plasmas represent a new state of matter, with unique radiative and thermodynamic properties. For a plasma to be in a steady state, the heating rate must be balanced by the cooling rate, which consists of bremsstrahlung, inverse Compton scattering, and pair annihilation. It turns out that for a pair-balanced plasma, there exists a fundamental limit to the temperature of approximately 10 MeV for hydrogen, above which pair creation can no longer be balanced by annihilation and pair density will exponentiate rapidly, leading to a pair-dominated plasma and net cooling of the system. This limiting temperature is referred to as the BKZS limit.

Black hole, accreting: A black hole is an object with such a strong gravitational field that its escape velocity exceeds the velocity of light. When a black hole attracts matter from the space around it, it is said to be an "accreting black hole." The matter falling into the accreting black hole radiates energy mostly in the x-ray regime, due to momentum conservation.

Bose-Einstein condensation: A phenomenon occurring in a macroscopic system consisting of a large number of bosons (particles with integral spin) at sufficiently low temperature, in which a significant fraction of the particles occupy a single quantum state of lowest energy (the ground state). Bose-Einstein condensation can only take place for bosons whose total number is conserved in collision.

Bose-Einstein statistics: *See* ***Quantum statistics***.

Boussinesq convection (approximation): In his attempts to explain the motion of the light in the ether, Boussinesq (in 1903) opened a wide perspective on mechanics and thermodynamics. With a theory of heat convection in fluids and of propagation of heat in deforming or vibrating solids, he showed that density fluctuations are of minor importance in the conservation of mass. The motion of a fluid initiated by heat results mostly in an excess of buoyancy and is not due to internal waves excited by density variations. In other words, the continuity equation may be reduced to the vanishing of the divergence of the velocity field, and variations of the density can be neglected in the inertial accelerations but not in the buoyancy term. Although used before him, Boussinesq's theoretical approach established a cardinal simplification for a special class of fluids that fundamentally differ from gases and may eliminate acoustic effects.

Bremsstrahlung: The x rays emitted when a charged particle, especially an electron, is rapidly slowed down, as when it passes through the electric field around an atomic nucleus.

Bulk modulus: A parameter associated with the elastic properties of isotropic solids. It is the ratio of the pressure to the fractional change in volume necessary to produce that pressure.

Cepheid variable: One of an important group of yellow giant or supergiant pulsating variable stars whose period of pulsation is directly related to their absolute magnitude. The resulting period-luminosity relationship is used to determine cosmological distances.

CERN: European Organization for Nuclear Research (originally the European Center for Nuclear Research), located near Geneva, Switzerland.

Chirped pulse amplification: Allows one to avoid the strong nonlinear effects that can destroy an amplifier when attempting to build a high-power laser pulse. To overcome the nonlinearities, the input pulse to the amplifier is stretched in time so that the peak power is decreased. This "chirped" pulse is then amplified and subsequently compressed to obtain a high-power pulse with a duration nearly equal to the input pulse.

Compact objects: Remnants of stars that have burned all of their nuclear fuel, forming white dwarfs, neutron stars, or black holes. The extreme gravitational fields near these objects make them valuable as physical laboratories for studying the gravitational force itself.

Compton effect: The change in wavelength and direction of a photon when it collides with a particle, usually an electron; also known as Compton scattering. Some of the photon's energy is transferred to the particle, and the photon is reradiated at a longer wavelength in the electron's initial rest frame.

Compton wavelength (λ_c): $\lambda_c = h/mc$, where h is Planck's constant, m is the electron rest-mass, and c is the speed of light. The length scale below which a particle's quantum-mechanical properties become evident in relativistic quantum mechanics.

Cosmic rays: The term for a broad class of energetic particles that bombard Earth from space. Featuring a variety of energies and constituent particles, cosmic rays have been found at energies less than an MeV and as great as approximately 3×10^{20} eV. Cosmic rays consist mostly of protons, electrons, and some heavier nuclei. The term ultrahigh-energy cosmic rays (UHECRs) is used to describe cosmic rays with energies exceeding approximately 5×10^{19} eV.

Cyclotron radiation: The electromagnetic radiation emitted by a charged particle circling in a magnetic field substantially below the speed of light.

Degeneracy: Several states of an atom that differ in many of their properties but nevertheless have the same value of some particular quantity, usually the total energy. Frequently an external influence such as a magnetic or an electric field can "remove" the degeneracy, which means that the energies become slightly different. An example is the splitting of lines that occurs when atoms are placed in a magnetic field.

Detector, ANTARES: An undersea neutrino detector under development in the Mediterranean Sea. It consists of an array of approximately 1,000 photomultiplier tubes in 10 vertical strings, spread over an area of about 0.1 km^2 and with an active height of about 0.3 km.

Detector, IceCube: A neutrino detector under development. It consists of 4,800 photomultiplier tubes buried in a 1-km^3 block of clear ice deep below the South Pole Station.

Detector, LIGO: The Laser Interferometer Gravitational-wave Observatory; a

National Science Foundation-sponsored project to build and operate two 4-km laser interferometers to detect gravitational waves.

Detector, VIRGO: A 3-km gravitational wave observatory under development in France.

Dwarf, brown: An object that, because of its low mass (less than 0.08 solar masses), never becomes hot enough to begin hydrogen fusion in its core; hence it is not considered to be a star.

Dwarf, white: A very small star that is the remnant core of a star which has completed fusion in its core. The Sun will become a white dwarf. White dwarfs are typically composed primarily of carbon, have about the radius of Earth, and do not significantly evolve further.

Energy, Fermi: Synonymous with the electron chemical potential at absolute zero, the Fermi energy represents the energy level that the next electron into the system must have, to be at the lowest-possible freely available state.

Energy, nuclear binding: The energy release when protons and neutrons bind together to form an atomic nucleus, or the energy required to break up that nucleus.

Energy, rest-mass: A body's mass expressed in energy terms when the body is at rest, when measured by an observer in the same frame of reference. The energy is given by the relationship $E_0 = m_0c^2$, where m_0 is the rest mass and c is the speed of light.

Equation of state: A description of a material's properties, for example, its mass or energy density as a function of applied pressure.

Faraday cup: Allows a beam of charged particles (electrons, ions) to be measured accurately. A Faraday cup collects all the particles that enter it, measuring the current with an ammeter.

Faraday rotation: The rotation of the plane of polarization of electromagnetic radiation upon passing through an isotropic medium with an embedded magnetic field; also known as the Faraday effect.

Fermi-Dirac statistics: *See* ***Quantum statistics***.

Free electron laser (FEL): The amplification of a photon beam via the electromagnetic interaction between the photon beam and a relativistic electron beam that passes through a spatially periodic magnetic field (a so-called undulator). Unlike a conventional laser in which the lasing frequency is determined by the properties of the lasing medium, the frequency of a FEL is determined by the speed (energy) of the electron beam and the period of the magnetic field and hence can be varied (or tuned) over a wide range.

Gamma-ray burst (GRB): A burst of gamma rays from a cosmic source. Several hundred gamma-ray bursts are detected per year, and they range in duration from fractions of a second to several seconds. Most of them come from objects at cosmological distances.

Greisen-Zatsepin-Kuzmin (GZK) cutoff: Constrains ultrahigh-energy cosmic rays above a certain energy to have been produced within a certain distance of where they were detected—namely, particles above 4×10^{19} eV should not be able to propagate in the cosmic microwave background more than about 160 light-years.

Hohlraum: In radiation thermodynamics, a hohlraum is a cavity whose walls are in radiative equilibrium with the radiant energy within the cavity. This idealized cavity can be approximated in practice by making a small perforation in the walls of a hollow container of any opaque material. The radiation escaping through such a perforation will be a good approximation to blackbody radiation at the temperature of the interior of the container.

Inertial confinement fusion (ICF): Uses powerful energy beams, such as lasers or particle beams, to compress and heat hydrogen fuel to fusion temperatures, and uses the inertia of the fuel to confine it long enough for fusion to occur.

Instability, filamentation: The tendency of a single beam of particles or light to break into smaller beamlets or filaments.

Instability, hosing: The tendency of a beam of particles or light to kink like a firehose carrying high-pressure water.

Instability, magnetic hoop: The pinching or narrowing of a beam of charged particles due to its self-magnetic field, which encircles the beam like a hoop.

Instability, parametric: The driving of a resonance in a system by varying some property (or parameter) of the system in a periodic way. For example, a laser of frequency w_0 can go parametrically unstable to a mode (wave) at frequency $w_0 - w_p$ due to the presence of background plasma modulations (i.e., noise) at frequency w_p.

Instability, Rayleigh-Taylor: Classical hydrodynamic interface instability that occurs when a high-density fluid is supported against gravity by a lower-density fluid.

Instability, Richtmyer-Meshkov: Classical hydrodynamic interface instability of a shock-driven system with a density discontinuity.

Instability, Weibel: The electromagnetic instability of a plasma due to anisotropic distribution of velocities in the plasma—in the case of a wide beam flowing through a plasma, it leads to filamentation of the beam into beamlets of diameter of the order of c/ω_p, where c is the speed of light and ω_p is the plasma frequency.

Interstellar medium (ISM): The material between the stars.

Inverse Compton effect: The gain in energy of a photon when it is struck by a fast-moving electron; also known as inverse Compton scattering. The electron passes on a small proportion of its energy to the photon, and the photon's wavelength decreases. The electron must suffer a large number of collisions before it loses an appreciable fraction of its energy due to this process.

Isentropic process: Takes place without a change of entropy (a measure of the unavailability of a system's energy to do work).

Isotope: One of two or more atoms of the same element that have the same number of protons in their nucleus but different numbers of neutrons.

Jet, astrophysical: A stream of fast-moving material flowing outward from an object such as a young star or a massive central black hole in a galaxy. Jets are detected by the radiation emitted by the fast-moving matter.

Knudsen number (*Kn*): The ratio of the mean free path to the flow scale in a medium. Knudsen or molecular flow scale in a medium occurs for a gas when the mean free path is large compared to the dimensions of the flow.

Laser Megajoule (LMJ): A large solid-state laser facility in France similar in design and scale to the U.S. National Ignition Facility.

Lattice gauge theory: A formulation of a gauge or quantum field theory—used to explain fundamental interactions—in which space and time are taken to be discrete rather than continuous. At the end of lattice gauge theory calculations, it is necessary to take the continuum limit. Lattice gauge theory is used to make calculations for gauge theories with strong coupling, such as quantum chromodynamics.

Local group: A group of galaxies about 3 million light-years in diameter, which contains our Galaxy, the Milky Way.

Lorentz factor: $\gamma = (1 - v^2/c^2)^{1/2}$, where v is the particle speed and c is the speed of light, the Lorentz factor is a parameter that indicates if a particle is moving at relativistic velocities. If the Lorentz factor is much greater than unity, the particle is moving at speeds close to c. If the Lorentz factor is close to unity, the particle's speed is nonrelativistic, much less than c.

Mach number (*Ma*): The ratio of the speed of an object to the speed of sound. Shock waves result when an object or flow has a Mach number greater then unity.

Magnetars: Neutron stars with the largest-known magnetic fields in the universe.

Magnetic reconnection: In a plasma, the process by which plasma particles riding along two different field lines find themselves sharing the same field line: for instance, solar-wind particles on an interplanetary field line, and magnetospheric particles on a field line attached to Earth, finding themselves united on an "open" field line, which has one end anchored on Earth and the other in distant space. Magnetic reconnection can occur when plasma flows through a neutral point or a neutral line where the intensity of the magnetic field is zero and its direction is not defined.

Magnetohydrodynamics (MHD): The study of the interactions between a conducting fluid or plasma and a magnetic field. Plasmas, being ionized, are good electrical conductors. An electric current is induced in a plasma when the plasma tries to cross lines of magnetic force, and the plasma tends to follow the magnetic field lines; alternatively, the magnetic field may be dragged along by the plasma. The plasma is said to be "frozen in" the magnetic field or vice versa.

Maxwell-Boltzmann distribution: A function describing the distribution of speeds among the molecules of a gas in thermodynamic equilibrium.

Metallic hydrogen: A form of hydrogen in which the atoms are highly compressed, as in the interiors of massive gaseous planets such as Jupiter and Saturn. Under such conditions, hydrogen behaves like a liquid metal and hence can conduct electricity and generate a magnetic field.

Monte Carlo simulation: A type of calculation involving random sampling for the mathematical simulation of physical systems. Monte Carlo simulations are applied to problems that can be formulated in terms of probability.

National Ignition Facility (NIF): A 192-beam, 1.8-MJ solid-state laser under construction by the Department of Energy's National Nuclear Security Administration at Lawrence Livermore National Laboratory. NIF will create conditions of extreme temperature and pressure in the laboratory that can be used for stockpile stewardship research, high energy density physics research, and inertial confinement fusion ignition.

Navier-Stokes equation: Describes the flow of a Newtonian fluid; also known as Gaussian distribution.

Neutron star: A star at such high density and pressure that its atoms have been completely crushed so that the nuclei merge and most of the electrons have been squeezed onto the protons, forming neutron-rich material.

NIKE: Named after the Greek goddess of victory, NIKE is a krypton-fluoride (KrF) gas laser that produces 4,000 to 5,000 J of ultraviolet light out of the large amplifier in a 4-ns pulse. NIKE is a facility at the Naval Research Laboratory.

Nucleosynthesis: The process of creating elements in nuclear reactions, such as in a nuclear fission reactor, the interior of a star, or at the time of the big bang.

OMEGA: Situated at the Laboratory for Laser Energetics at the University of Rochester, OMEGA's 60 laser beams focus up to 40,000 J of energy onto a target that measures less than 1 mm in diameter in approximately 1 billionth of a second.

Opacity: The extent to which a medium is opaque to electromagnetic radiation. Opacity is the reciprocal of transmittance.

Particle-in-cell (PIC) simulation: A simulation method that follows the self-consistent nonlinear dynamics of a large number of charged particles interacting with applied and self-generated electric and magnetic fields.

Pauli exclusion principle: The quantum-mechanical principle, applying to fermions but not to bosons, that no two identical particles in a system, such as electrons in an atom or quarks in a hadron, can possess an identical set of quantum numbers. The origin of the Pauli exclusion principle lies in the spin-statistics theorem of relativistic quantum field theory.

Perveance: A measure of the importance of self fields to the dynamics of a particle beam. The perveance K is proportional to $I/V^{3/2}$, where I is the beam current and V is the voltage.

Phase transition: A change in a feature that characterizes a system. Examples include the changes from solid to liquid, liquid to gas, and the reverse transitions. Other examples include the transition from being a normally conducting material to being a superconductor. Phase transitions can be classified by their order. If there is a nonzero latent heat (i.e., the quantity of heat absorbed or released when a substance changes its physical phase at constant temperature) at the transition, it is said to be a first-order transition. If the latent heat is zero, then it is said to be a second-order transition.

Pion: A member of a hadron subclass called mesons. A pion (or pi-meson) is an elementary particle that exists in three forms: neutral, positively charged, and negatively charged. The charged pions decay into muons and neutrinos. The neutral pion decays into two photons.

Plasma: A state of matter consisting of free (unbound) ions and electrons moving freely.

Plasma, quark-gluon: Quarks are bound together in nucleons (protons or neutrons), though during the first 10 μs of the big bang the temperature of the universe was so high that unbound quarks moved freely in a state of matter called quark-gluon plasma. It may also be possible to artificially create a quark-gluon plasma by colliding two heavy nuclei at very high energies so that the nucleons dissolve into their quark and gluon parts.

Ponderomotive channeling: The process by which a beam of light forms a channel in a plasma due to its radiation pressure, or so-called ponderomotive force.

Principle, Hugoniot: The regions of parameter space (density, pressure, and so on) that can be accessed by a shock wave passing through a material.

Quantum statistics: A statistical description of a system of particles that obeys the rules of quantum mechanics rather than those of classical mechanics. In quantum statistics, energy states are considered to be quantized. *Bose-Einstein statistics* apply if any number of particles can occupy a given quantum state; such particles are known as bosons. *Fermi-Dirac statistics* apply when only one particle may occupy each quantum state; such particles are called fermions.

Quasar: A very compact and extraordinarily luminous source of radiation in the nucleus of a distant galaxy. Quasars are believed to be powered by the accretion of gas onto massive black holes (*see* ***Black hole, accreting***).

Radiative shocks: Nonlinearly steepened waves or shocks in which the electromagnetic field pressure or radiation pressure dominates over the usual thermal pressure.

Radio lobes: Bright, diffuse areas of radio emission seen on one or both sides of the nucleus of a galaxy. The emission is mainly synchrotron radiation (electromagnetic radiation emitted by charged particles in circular orbits at relativistic speeds in a magnetic field), and the lobe is thought to consist of material ejected from the nucleus of a galaxy and transported into intergalactic space along a jet.

Rankine-Hugoniot relations: The relationship between a material's properties on either side of a shock wave. The relationship is based on conservation of energy and momentum.

Rayleigh scattering: The elastic scattering of photons (light) by particles smaller than the wavelength of light, in which the photons do not lose any energy but do change phase. Rayleigh scattering of sunlight by the atmosphere is responsible for daylight and for the sky's being blue.

Relativistic speed: When the speed of a body is such that its mass becomes significantly greater than its rest mass, it is said to be moving at relativistic speed. Relativistic speed is usually expressed as a proportion of the speed of light and is typically greater than 80 percent of the speed of light. A body traveling at these speeds exhibits significant relativistic effects such as an apparent increase in mass, length contraction, and so on.

Reynolds number (*Re*): The ratio of the inertial forces to the viscous forces in a fluid. $Re = \frac{\rho v L}{\mu}$, where ρ is the fluid density, v is the characteristic fluid velocity, L is a characteristic length, and μ is the viscosity. Fluids with low values of Re are stabile to laminar flow.

Reynolds number, magnetic (*Rm*): $Rm = \frac{v\tau}{L}$, where v is the characteristic fluid velocity, τ is the magnetic diffusion time, and L is a characteristic length. When Rm is large compared to unity, the magnetic field lines are frozen to the moving fluid. The Reynolds number can be very large for astrophysical situations. In magnetic stars, $Rm \sim 10^{10}$, whereas for ionized hydrogen the magnetic Reynolds number is small, $Rm \sim 10^{-2}$.

Scattering, Raman: Similar to Brillouin scattering except that the scattering is off electron plasma density waves rather than ion waves.

Scattering, stimulated Brillouin: Scattering in a plasma of a light wave off of ion acoustic wave density fluctuations (noise). A positive feedback can then develop such that the scattered wave and the unscattered photons beat to further enhance the ion fluctuation, leading to an instability (stimulated scattering). Such processes are important loss mechanisms in the attempt to get laser light to penetrate far enough to heat a fusion pellet.

Schwinger field: The focused electric field strength sufficient to break down vacuum; given by $(m^2c^3)/(e\hbar) = 10^{16}$ V/cm.

Stefan's law: Also known as the Stefan-Boltzman law, Stefan's law states that the total energy radiated per unit surface area of a blackbody (i.e., a perfect emitter or transmitter of energy) in unit time is proportional to the fourth power of its thermodynamic temperature.

Synchrotron radiation: The electromagnetic radiation emitted by charged particles in circular orbits at relativistic speeds in a magnetic field.

Thermonuclear ignition: The point at which the energy generated in a plasma is sufficient to sustain continued nuclear fusion.

Tokamak: Doughnut-shaped magnetic confinement configuration with toroidal symmetry, where the magnetic field in the toroidal direction is much stronger than that in the transverse direction.

TRIDENT: A neodymium-glass laser (1,054-nm fundamental wavelength) facility at Los Alamos National Laboratory providing three beams, with the two main drive beams frequency-doubled to a 527-nm wavelength with energies up to 250 J/beam.

Twinning transition: A deformation mechanism in solid-state samples that occurs when a region in the crystal changes its collective orientation along a line of reflection symmetry.

Unruh radiation: Radiation from an accelerated charge which exceeds that predicted by Maxwell. The source of the radiation is an effective temperature $kt = \hbar a/c$ associated with a particle undergoing acceleration *a*, causing it to emit blackbody radiation (given by Stefan's law, σT^4).

Vacuum polarization: A process in which an electromagnetic field gives rise to virtual electron-positron pairs that effectively alter the distribution of charges and current that generated the original electromagnetic field.

Viscous damping: Damping of a wave in fluid due to the viscosity or friction in the fluid that is supporting the wave.

VULCAN: The main high-power laser facility operated by the United Kingdom's Central Laser Facility is a neodymium-glass laser system capable of delivering up to 2.6 kJ of laser energy in nanosecond pulses and over 100 TW power in subpicosecond pulses at 1,054 nm. Frequency conversion to the second harmonic gives 1 kJ at 527 nm. Pulse durations between 700 fs and 5 ns are available. The subpicosecond pulse is produced using the technique of chirped pulse amplification.

Wakefield acceleration: A mechanism of particle acceleration whereby particles surf on the (electric field) wake left by a laser or electron pulse in a plasma. The wake is formed as a result of radiation pressure displacing plasma electrons in the path of the laser. Laser wakefield acceleration is particularly promising for generating beams of short-pulse, high-energy electrons for applications in femtosecond electron diffraction, medical imaging, and miniature free-electron x-ray lasers.

Warm dense matter: A region of parameter space in which the plasma temperature is close to Fermi temperature and where the plasma temperature is comparable to interparticle coulomb energy.

Z-pinch: A plasma device with cylindrical symmetry carrying a large current in the axial (z) direction, often created by an electric discharge in a low-pressure gas tube. The self-magnetic field of the plasma in the azimuthal direction causes the plasma to pinch.