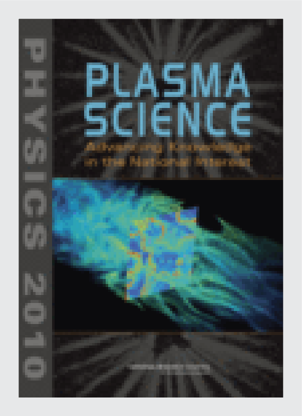

Plasma Science: Advancing Knowledge in the National Interest

DETAILS

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PLASMA SCIENCE

Advancing Knowledge in the National Interest

Plasma 2010 Committee

Plasma Science Committee

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

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Cover: Magnetic energy density in a relativistic collisionless shock. In astrophysical plasmas, propagating shocks such as this one are thought to accelerate particles to very high energies. Courtesy of A. Spitkovsky, Princeton University.

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Preface

The National Research Council (NRC) convened the Plasma 2010 Committee in mid-2004, with substantial input from the Plasma Science Committee concerning the committee, to prepare a new decadal assessment of and outlook for the broad field of plasma science and engineering. Support for the project was provided by the Department of Energy, the National Science Foundation, and the National Aeronautics and Space Administration. The committee was asked to assess the progress in plasma research, identify the most compelling new scientific opportunities, evaluate the prospects for broader application of plasmas, and offer guidance to the government and the research community on realizing these opportunities; the complete charge is reproduced in Appendix A. In addressing that charge, the committee maintained an optimistic, demand-side perspective, working to identify the most compelling scientific opportunities and the paths to realizing them. Decadal surveys experience a strong urge to discuss about the need for funding—the supply side of the workforce equation; this committee worked hard to be forward-looking in its analysis of what plasma research can do for this nation. In light of the ongoing national discussion of U.S. competitiveness, the committee recognized the value of a prospective "international benchmarking" exercise that would compare the U.S. plasma science and engineering enterprise to analogous enterprises in other parts of the world. However, the committee realized that it had neither the time nor resources to undertake such a task.

The committee's membership included not only experts in the many subdisciplines of plasmas (low-temperature, magnetic fusion, high energy density physics, space physics and astrophysics, and basic plasma science), but also several experts from outside plasma science enlisted by the NRC to help place the field of plasmas in a broader context (see Appendix G for biographical sketches of committee members). It was important to the committee from the outset to prepare a report that reflected the scientific connections among the plasma subdisciplines in a clear and compelling manner.

This report represents the third volume in the *Physics 2010* series, a project undertaken by the NRC's Board on Physics and Astronomy. Each volume examines a subfield of physics, assesses its status, and frames an outlook for the future.

Because the committee's full published report is about 250 pages long, the committee will also make available an extract that includes only the front matter, the Summary, and the first chapter, "Overview."

The full committee met three times in person and used a fourth smaller meeting to prepare the first full draft of the report (see Appendix F for meeting agendas). To best address its task, the committee divided the broad field of plasma science and engineering into topical areas and formed subcommittees to study each topic in greater depth. Hundreds of conference calls and e-mail messages kept the work coordinated between the full meetings of the committee. The committee carefully studied trends in federal support for plasma science and the organization of this support (see Appendix D for a short summary) and reviewed past NRC reports on plasma science, with a reprise given in Appendix E.

The committee pursued several mechanisms to engage the broader community of researchers in plasma science and engineering. Site visits by small teams from the committee to the major centers of plasma research were conducted all over the United States. Among the places visited were the Massachusetts Institute of Technology, Princeton University, the University of Wisconsin, the Naval Research Laboratory, the University of Rochester, Sandia National Laboratories, Los Alamos National Laboratory, Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, the University of California at San Diego, General Atomics, and others. The committee appreciates the time and effort expended by its hosts at each of these visits; the discussions were enlightening and invaluable. The committee also held a series of town-hall meetings in conjunction with conferences of the various professional societies, including meetings of the American Physical Society's Division of Plasma Physics and its Division of Atomic, Molecular, and Optical Physics; the University Fusion Association; the American Geophysical Union; the IEEE International Conference on Plasma Science; the AVS: Science and Technology of Materials, Interfaces, and Processing; the International Symposium on Plasma Chemistry; and the Gaseous Electronics Conference. The committee thanks the organizers of each of these meetings for their support and encouragement. Finally, the committee also developed a written questionnaire that was electronically distributed; more than a hundred responses provided valuable contributions to the committee's discussions.

The committee thanks the speakers who made formal presentations at each of the meetings; their presentations and the ensuing discussions were extremely informative and had a significant impact on the committee's deliberations. As co-chairs, we are grateful to our colleagues on the committee for their patience, wisdom, and deep commitment to the integrity of this report. We are especially grateful to the outsider members of the committee for their commitment and dedication to helping prepare this report. Their shrewd questions and creative suggestions substantially elevated the level of its discussions. Finally, the committee also thanks the NRC staff (Timothy Meyer, Michael Moloney, Don Shapero, and Pamela Lewis) for their guidance and assistance throughout this process.

Steven C. Cowley, *Co-chair* John Peoples, Jr., *Co-chair*
Plasma 2010 Committee

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:

Paul Bellan, California Institute of Technology,
Riccardo Betti, University of Rochester,
Amitava Bhattacharjee, University of New Hampshire,
Patrick Colestock, Los Alamos National Laboratory,
Ronald C. Davidson, Princeton University,
Cary B. Forest, University of Wisconsin at Madison,
Edward Frieman, Scripps Institution of Oceanography,
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W.G. Graham, Queen's University, Belfast,
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Arnold Kritz, Lehigh University,
J. Patrick Looney, Brookhaven National Laboratory,

Thomas M. O'Neil, University of California at San Diego,
Robert Rosner, Argonne National Laboratory,
Alvin W. Trivelpiece, Oak Ridge National Laboratory (retired),
Jonathan S. Wurtele, University of California at Berkeley, and
Michael C. Zarnstorff, Princeton Plasma Physics Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by John F. Ahearne of Sigma Xi and Duke University and Nathaniel J. Fisch of Princeton University. Appointed by the National Research Council, they were 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.

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APPENDIXES

Summary

Plasma science is on the cusp of a new era. It is poised to make significant breakthroughs in the next decade that will transform the field. For example, the international magnetic fusion experiment—more exactly, the International Thermonuclear Experimental Reactor (ITER)—is expected to confine burning plasma for the first time, a critical step on the road to commercial fusion. The National Ignition Facility (NIF) plans to ignite capsules of fusion fuel to acquire knowledge necessary to improve the safety, security, and reliability of the nuclear stockpile. Low-temperature plasma applications are already ushering in new products and techniques that will change everyday lives. And plasma scientists are being called on to help crack the mysteries surrounding exotic phenomena in the cosmos. This dynamic future will be exciting but also challenging for the field. It will demand a well-organized national plasma science enterprise. This report examines the broad themes that frame plasma research and offers a bold vision for the future.

Principal Conclusion: The expanding scope of plasma research is creating an abundance of new scientific opportunities and challenges. These opportunities promise to further expand the role of plasma science in enhancing economic security and prosperity, energy and environmental security, national security, and scientific knowledge.

Plasma science has a coherent intellectual framework unified by physical processes that are common to many subfields. Therefore, and as this report shows, plasma science is much more than a basket of applications. The Plasma 2010 Committee believes that it is important to nurture fundamental knowledge of plasma science across all of its subfields in order to advance the science and to create opportunities for a broader range of science-based applications. These advances and opportunities are, in turn, central to the achievement of national priority goals such as fusion energy, economic competitiveness, and stockpile stewardship.

The vitality of plasma science in the past decade testifies to the success of some of the individual federally supported plasma science programs. However, the emergence of new research directions necessitates a concomitant evolution in the structure and portfolio of programs at the federal agencies that support plasma science. The committee has identified four significant research challenges that the federal plasma science portfolio as currently organized is not equipped to exploit optimally: fundamental low-temperature plasma science; discovery-driven, high-energy-density plasma science; intermediate-scale plasma science; and crosscutting plasma research.

Notwithstanding the success of individual federal plasma science programs, the lack of coherence across the federal government ignores the unity of the science and is an obstacle to overcoming many research challenges, realizing scientific opportunities, and exploiting promising applications. The committee observes that effective stewardship of plasma science as a discipline will likely expedite the applications of plasma science. The need for stewardship has been identified in many reports over two decades. The evolution of the field has only exacerbated the stewardship problem, and the committee concluded that the need for a new approach is greater than ever.

Recognizing the need both to provide an integrated approach and to connect the science to applications and the broader science community, the committee considered a number of options. After weighing relative pros and cons, the committee recommends as follows:

> **Principal Recommendation: To fully realize the opportunities in plasma research, a unified approach is required. Therefore, the Department of Energy's Office of Science should reorient its research programs to incorporate magnetic and inertial fusion energy sciences; basic plasma science; non-mission-driven, high-energy-density plasma science; and low-temperature plasma science and engineering.**

The new stewardship role for the Office of Science would extend well beyond the present mission and purview of the Office of Fusion Energy Sciences (OFES). It would include a broader portfolio of plasma science as well as the research OFES currently supports. Two of the thrusts in this portfolio would be new: (1) a non-mission-driven, high-energy-density plasma science program and (2) a low-temperature plasma science and engineering program. The stewardship framework would not replace or duplicate the plasma science programs in other agencies; rather, it would enable a science-based focal point for federal efforts in plasma-based research. These changes would be more evolutionary than revolutionary, starting modestly and growing with the expanding science opportunities. The committee recognizes that these new programs would require new resources and perhaps a new organizational structure for the Office of Science.

A comprehensive strategy for stewardship will be needed to ensure a successful outcome. Other guidance for implementing this vision appears in the main report. Among the issues to be addressed in planning such a strategy are these:

- Integration of scientific elements,
- Development of a strategic planning process that not only spans the field but also provides guidance to each of the subfields, and
- Identification of risks and implementation of strategies to avoid them.

There is a spectacular future awaiting the United States in plasma science and engineering. But the national framework for plasma science must grow and adapt to new opportunities. Only then will the tremendous potential be realized.

1

Overview

plas·ma: ʹplaz-mə *(noun)* [German, from late Latin, something molded, from Greek, from *plassein,* to mold]: the most common form of visible matter in the cosmos, consisting of electrically charged remnants of atoms in the form of electrons and ions, moving independently of each other; as a result of their motion, these charged particles generate electric and magnetic fields that, in turn, affect the plasma's behavior.

DEFINITION OF THE FIELD

Plasmas seem simple enough. They're a collection of free electrons and ions governed largely by physical laws known to late 19th-century physicists. Yet the sophisticated and often mysterious behavior of plasmas is anything but simple. This is strikingly evident in, for instance, the dramatic images of solar flares—sudden plasma eruptions from the surface of the Sun. Plasma is found almost everywhere on Earth and in space; indeed only the invisible dark matter is more abundant. The vast regions between galaxies in galaxy clusters are filled with hot magnetized plasmas. Stars are dense plasmas heated by fusion reactions. Computer processors are fabricated using cold chemically reacting plasmas. Powerful lasers make relativistic plasmas in laboratories. And the enormously varied list goes on. None of these plasmas are quiescent; they wriggle and shake with instabilities and turbulence, and sometimes they erupt with spectacular force (Figure 1.1).

One of the great achievements of plasma science has been to show that the bewildering variety and complexity of plasmas is understandable in terms of some

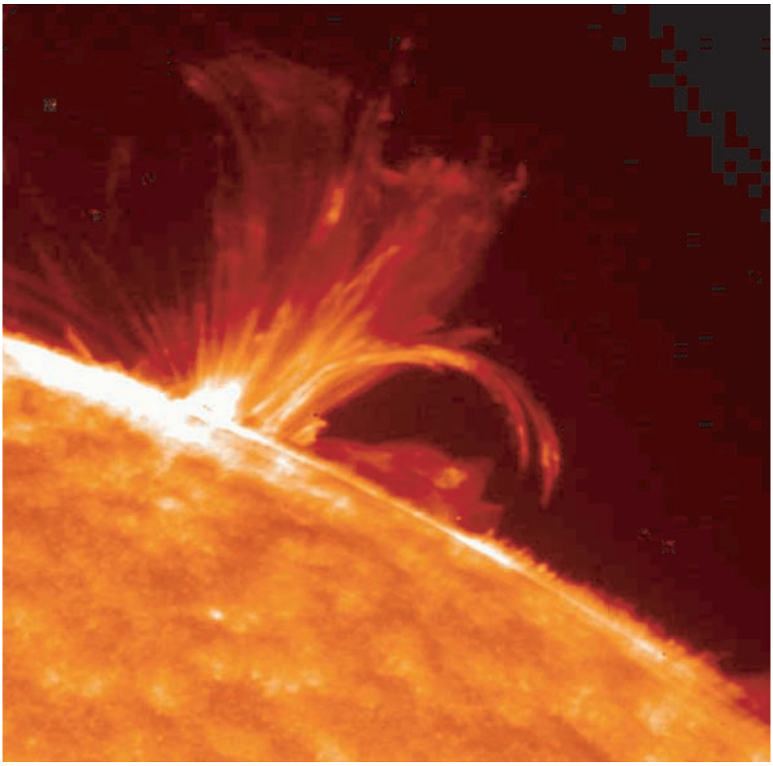

FIGURE 1.1 Exploding plasma on the Sun. X-ray image of one of the most dramatic of natural phenomena, the solar flare, caused by the sudden destabilization of the magnetized plasma in the Sun's outer atmosphere (the corona). The eruption is lifting plasma above the Sun's surface. The bright lines are the illumination of some of the complicated magnetic field lines by plasma emission. Courtesy of Transition Region and Coronal Explorer (TRACE), a mission of the Stanford-Lockheed Institute for Space Research and part of the NASA Small Explorer program.

very elemental ideas that bind the field together (Figure 1.2). This is not to say that all questions have been answered—they have not. Rather, it confirms that the science is evolving rapidly and that there are fundamental principles that organize our knowledge. Much of plasma science seeks to explain the plasma's highly nonlinear behavior and the order and chaos that result. Plasma science has, therefore, much in common with many areas of modern complex system research, from climate modeling to condensed matter studies. Indeed, plasma scientists have played a pivotal role in the development of nonlinear dynamics and chaos theory, which have a multitude of applications to complex systems.

Plasma science has made enormous advances in the last decade. Rapid progress in our ability to predict plasma behavior has been fueled by new diagnostics that

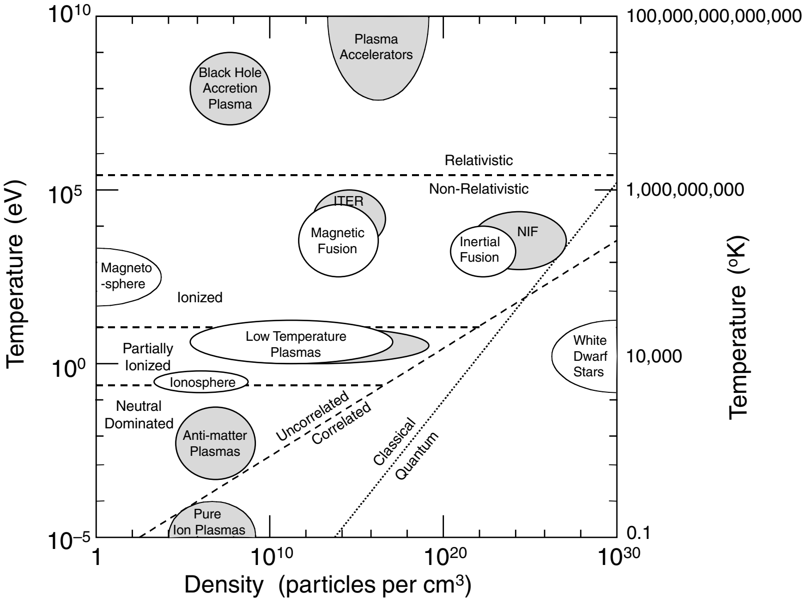

FIGURE 1.2 New regimes—new physics. Plasma science is expanding into new territory and discovering new phenomena. Diagram shows some of the range of plasma phenomena. Regimes that are new areas of study since 1990 are indicated in gray, including the future regimes of the National Ignition Facility (NIF) and the International Thermonuclear Experimental Reactor (ITER).

observe and measure an unprecedented level of detail and by computations that resolve most of the essential physics. In many areas, from fusion plasma science to the manufacture of computer chips, science-based predictive models are replacing empirical rules. What is notable in the research examined for this report, furthermore, is that plasma science is moving beyond the understanding of complicated but isolated phenomena and is entering an era in which plasma behavior will be understood and described as a whole. Growth in fundamental understanding has led to new applications and improved products such as the large-area plasma panel televisions now found in many homes.

This report discusses the scientific highlights of the past decade and opportunities for further advances in the next decade. Detailed analyses are contained in five chapters representing the subfields: low-temperature plasma science and engineering; high-energy-density (HED) plasma science; magnetic fusion plasma science; space and astrophysical plasmas; and basic plasma science. Chapters 2 through 6, the topical chapters, contain in their final sections the committee's conclusion(s) and recommendation(s) pertaining to the particular topic.

The remainder of this chapter, the Overview, summarizes key issues raised by these analyses. The next section shows that plasma research is an essential part of the nation's science and technology enterprise and that its importance is growing. Six scientific highlights of the past decade and the opportunities they create are featured in the section after that. While these examples by no means constitute a comprehensive survey, they give a flavor of the breadth and depth of the field. The fourth section discusses the growth in predictive capability and the emergence of new plasma regimes, two scientific themes that pervade recent advances. Further progress on many applications is predicated on a better understanding of some key plasma processes. These fundamental processes demonstrate the unity of the field by cutting across the applications and the topical areas. They are addressed briefly in the penultimate section, and they appear repeatedly in the topical chapters. The last section of this chapter presents the principal conclusion and the principal recommendation of the entire report.

IMPORTANCE OF PLASMA SCIENCE AND ENGINEERING

The link between scientific development and increased prosperity, security, and quality of life is well documented.[1] Advances in plasma science have contributed enormously to current technology and are critical to many future developments. An effective national research enterprise must have breadth because scientific discovery in any one area is often highly dependent on discovery in other areas. Plasma science is an important part of the web of interdependent disciplines that make up our essential core knowledge base. It contributes to at least four areas of national interest:

- *Economic security and prosperity.* In the past decade, new plasma technologies have entered the home. Many families view entertainment on plasma display televisions and illuminate their homes with plasma lighting. However, the enormous role plasma technologies play in manufacturing remains largely hidden from view (Figure 1.3). Microelectronics devices would not exist in their advanced state if not for the tiny features etched onto semiconductor wafers by plasma tools. Surfaces of materials are hardened, textured, or coated by plasma processes. The value of all this economic activity is hard to estimate, but one small example is that displays and televisions built by plasma tools and lit by special plasma (fluorescent) lights will be a $200 billion market by 2010.[2] The worldwide $250 billion semiconductor

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[1] See, for example, the National Academies report *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, Washington, D.C.: The National Academies Press, 2007.

[2] Alfonso Velosa III, research director for semiconductors, Gartner, Inc., "Semiconductor manufacturing: Booms, busts, and globalization," presentation to the National Academy of Engineering, September 2004.

FIGURE 1.3 Plasmas in the kitchen. Plasmas and the technologies they enable are pervasive in our everyday life. Each one of us touches or is touched by plasma-enabled technologies every day. Products from microelectronics, large-area displays, lighting, packaging, and solar cells to jet engine turbine blades and biocompatible human implants either directly use or are manufactured with, and in many cases would not exist without, plasmas. The result is a better quality of life and economic competitiveness. NOTE: CVD, chemical vapor deposition; HID, high-intensity discharge; LED, light-emitting diode; LCD, liquid crystal display.

industry is built on plasma technology. In the absence of plasma technologies, the $2 trillion telecommunications industry would arguably not exist. (See Chapter 2 for a more detailed discussion of this area of plasma science and its many applications.)

- *Energy and environmental security.* Our prosperity and lifestyle rest on a ready supply of moderately priced energy, but it is well known that fossil fuel resources are limited and the environmental impact of their long-term use is problematic. The search, therefore, for new and sustainable energy sources and new technologies that can reduce energy consumption is, and will remain, a high-priority research goal. Fusion energy has unparalleled potential to meet the need. Deployment of fusion (the fusing of hydrogen nuclei to make helium nuclei, a neutron, and energy) as an alternative energy resource should remain a priority for the nation. The challenge of fusion is that it requires plasmas with temperatures greater than those at the center of the Sun. Plasma science has made great strides in controlling and confining such plasmas (see Chapter 4 for a discussion of the science). ITER, which exploits some of these achievements, aims to explore fusion burning plasmas at the end of the next decade. This is a key and indeed essential step on the path to fusion energy. Research in alternative paths to fusion is also proceeding rapidly. In the meantime, plasma science has contributed to near-term innovations in energy efficiency. For example, the more than 1 billion light sources in operation in the United States use 22 percent of the nation's electrical energy budget. Consumers are switching to the more efficient plasma (fluorescent) lighting as innovations improve the quality of the light and the life expectancy of the lamp. Plasmas also aid the efficient combustion of fuels and the manufacture of materials for solar cells, and they improve the efficiency of turbines and hydrogen production. There is a small but growing use of plasmas to ensure a clean and healthy environment. New applications exploit the ability of plasmas to break down harmful chemicals and kill microbes to purify water and destroy pollutants. (See Chapter 2 for a detailed discussion of the science.)

- *National security.* HED plasma science is central to Science-Based Stockpile Stewardship (SBSS), the DOE program that ensures the safety and reliability of the nation's nuclear stockpile. The study of HED plasma physics has been greatly enhanced by the remarkable progress in producing such plasmas (and copious amounts of x rays) by passing large currents through arrays of wires in Sandia National Laboratories' Z machine. In the next decade, the NIF (the world's most powerful laser facility) at Lawrence Livermore National Laboratory will create plasmas of unusually high energy densities and seek to ignite pellets of fusion fuel. These facilities and experiments are central to the stockpile stewardship program (see Chapter 3 for a discussion of the science). It is perhaps less widely appreciated that plasma technology is also critical to the manufacture of many conventional weapons systems. For example, the turbine blades in the engines of high-performance fighters are coated by a plasma deposition technique to substantially improve their performance. Recently developed plasma-based systems for destroying chemical or biological hazards are answering homeland security needs.

Atmospheric pressure plasma sources are being employed as "plasma hoses" to decontaminate surfaces after a chemical spill or attack.

- *Scientific discovery.* Plasma science raises and answers scientific questions that contribute to our general understanding of the world around us. Unraveling the complex and sometimes strange behavior of plasmas is in itself an important scientific enterprise. The intellectual challenge of explaining the intricacies of collective behavior continues to inspire serious scholarship. Our current understanding is being stretched by, for example, the properties of the curious forms of matter formed when plasmas become correlated at extremely low temperatures (see Chapter 6 for a discussion). Because most of the visible matter in the universe is plasma, many of the great questions in astrophysics and space physics require a detailed understanding of plasmas. For example, while currents in the cosmic plasma must create the magnetic fields that pervade much of the universe, it is not known when these fields and currents first appeared in the universe or how they were generated (see Box 1.1 and Chapter 5 for discussion).

The scientific challenges posed by these important goals are being addressed by a large but diffuse U.S. community of plasma scientists and engineers.[3] The plasma research effort is global, however (see Box 1.2).

SELECTED HIGHLIGHTS OF PLASMA SCIENCE AND ENGINEERING

The committee now describes six highlights of the scientific frontiers of plasma research and development. This is neither an exhaustive survey nor a list of the greatest discoveries—it is, rather, a sampling of exciting and important work. While these examples demonstrate the enormous diversity in plasma research they also illustrate the unity of the underlying science. Fundamental plasma processes are the common threads that weave through all these applications.

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[3] In the United States, many plasma scientists participate in divisional meetings of the American Physical Society (APS), the American Geophysical Union, the American Vacuum Society, and the Institute for Electrical and Electronics Engineers. In 2006, the membership of the APS Division of Plasma Physics numbered about 2,500; at about 5.5 percent of the entire membership, the Plasma Physics Division is the fourth largest. Of course, there are at least as many plasma researchers who are not members of the APS. For more information about the demographics of the plasma science and engineering community, especially the fusion community, please see Fusion Energy Sciences Advisory Committee, *Fusion in the Era of Burning Plasma Studies: Workforce Planning for 2004-2014*, DOE/SC-0086, Washington, D.C.: U.S. Department of Energy, 2004; and E. Scime, K. Gentle, and A. Hassam, *A Report on the Age Distribution of Fusion Science Faculty and Fusion Science Ph.D. Production in the United States*, Washington, D.C.: University Fusion Associates, 2003.

BOX 1.1
Living and Working Inside a Plasma

In 2000, an important human milestone came to pass quietly: Our species became a permanent inhabitant of space. Since then, the human presence in low Earth orbit has been continuous and uninterrupted on board the International Space Station (ISS). Humans now inhabit Earth's ionosphere, where the rain is meteor showers and the wind is plasma, a place of awesome beauty and unforgiving hazards (Figure 1.1.1).

The plasma environment surrounding the ISS is itself a hazard since electrons from the plasma charge up the structure. The pressurized modules of the ISS tend to act as large capacitors storing electrical energy hazardous to space-walking astronauts. Electrical shocks and arcs caused by the charge buildup could puncture spacesuits or damage critical instrumentation with catastrophic consequences. Recent measurements have also shown that the charge buildup varies significantly from day to day as the spacecraft moves from equatorial to polar regions and from daytime to nighttime.

The charge buildup is neutralized (and the astronauts protected) by devices called "plasma contactors," which serve the same function as grounding rods in well-designed homes on Earth. The ISS plasma contactors spray electrons into the surrounding ionosphere by hollow cathode discharges fueled by xenon gas. The rate of electron spray is sufficient to maintain the electrical ground of the station (its metal frame) at the same electrical potential as the surrounding ionosphere.

Space plasma physics knowledge gained in the last few years through our continuous activities in space is teaching us much about the environment in which our planet functions and the important plasma processes that affect our life on the ground.

Biotechnology and Health Care

Dental patients might be surprised to know that their dentist is using a tiny plasma to treat their teeth. Yet the use of plasmas in biological applications is an emerging field that ranges from the surface treatment of human implants to plasma-aided surgery. These applications exploit the fact that plasmas are uniquely dry, hot, and cold, all at the same time. Plasma is dry in that the working medium is a gas and not a liquid, so less material goes into and comes out of the process. The hot electrons can drive high-temperature chemistry while the gas and surface remain near room temperature.

- *Biocompatibility of surgical implants.* Plasma treatment is routinely used to make surgical implants such as joints and stents biocompatible by either

FIGURE 1.1.1 *Left:* Committee member Franklin Chang-Díaz conducting assembly tasks outside the International Space Station (ISS) in June 2002. Courtesy of NASA. *Right:* Aurora australis photographed during a spacewalk on mission STS 111 in June 2002. The ISS routinely flies through the auroral plasma. Courtesy of NASA.

depositing material or modifying the surface characteristics of the material (Figure 1.4).

- *Sterilization.* The goal of plasma sterilization is to destroy undesirable biological activity with absolute confidence. The current workhorse of sterilization is the autoclave, in which medical instruments are exposed to superheated steam for 15 minutes. Autoclaves can damage even metal instruments and cannot be used on many thermosensitive materials. Further, like any single treatment method, it is not universally effective and in fact has been questioned for emerging threats like the prions associated with Creutzfeldt-Jakob (mad cow) disease. Plasmas provide two agents that destroy biological actvity: reactive neutral species and ultraviolet light. Gaseous neutrals can diffuse into complex biological surfaces, whereas

BOX 1.2
Plasma Research Goes Global

The past decade has seen an acceleration of foreign research, investment, and discoveries in plasma physics. Increasing foreign participation testifies to the compelling scientific opportunities.

The committee conducted a primitive exercise to crudely gauge the level of U.S. participation in the global plasma science enterprise. The 200 most frequently cited papers over the past decade from each of six major journals were reviewed and the proportion of foreign-based lead authors was tabulated. The results were as follows: *Nuclear Fusion*, 68 percent foreign; *Plasma Physics and Controlled Fusion*, 78 percent foreign; *Physics Review E* (selecting the plasma-related articles by keyword), 75 percent foreign; *Physics of Plasmas*, 39 percent foreign; *Plasma Sources Science and Technology*, 72 percent foreign; *Physical Review Letters* (selecting the plasma-related articles by keyword), 54 percent foreign. Twenty years ago, the U.S. share would have been much greater.

While these results could be taken to mean that U.S. activity in plasma research is decreasing, the real cause is the large surge in research activities overseas. There are not fewer U.S. papers—there are more and more foreign ones! Because it puts the smallest proportion of U.S. papers at 22 percent, this exercise does after all support the notion that the United States has a globally significant community in basic plasma science and HED physics.

ultraviolet photons can travel only along the line of sight—combined, they could lead to efficient local sterilization techniques. Ongoing research aims to improve the effectiveness of plasma sterilization while minimizing instrument damage through careful selection of the working gas composition and plasma conditions.

- *Plasma-aided surgery.* While plasma sterilization is only beginning to become a commercial process, surgery is already being performed with plasma instruments. It is entirely routine to cut and cauterize tissue with plasma. Emerging—and already in some use—are new plasma "knives" that generate nonequilibrium plasma "streamers" (like miniature lightning bolts) in conducting liquids (saline). These streamers explosively evaporate water in bubbles to cut soft tissue. Here is the convergence of almost all the themes in low-temperature plasma science: selectivity to generate the desired species; interaction with exceedingly complex surfaces; stochastic behavior and multiphase media (bubbles in liquids); and the generation and stability of high-density microplasmas. Most surgical procedures still aim to cut and remove tissue, not modify it in a constructive way. However, there are indications that more selective and constructive processes are possible. For example, plasmas can change the metabolic behavior of cells and trigger cell detachment.

The potential for plasmas in health care might best be viewed as an analog to their use in semiconductor manufacturing. Four-bit microprocessors were manu-

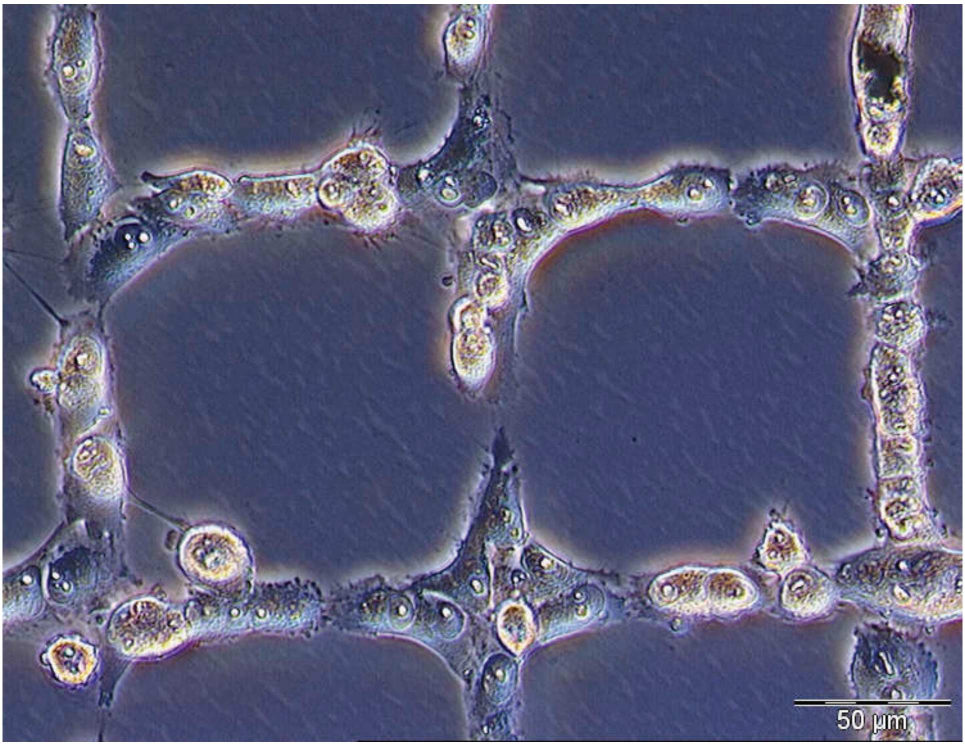

FIGURE 1.4 Plasmas and biology. Using low-temperature, reactive plasmas, the surface of polymers may be functionalized and patterned to allow the cells to adhere. In this example, amine functional groups were patterned on a polymer, resulting in a predetermined network of adhering cells. Courtesy of INP Greifswald, Germany.

factured in liquid acid baths. Plasmas entered the scene and made possible 8- and 16-bit computers with megahertz clock speeds and kilobytes of memory. Today, after two decades of research and development, desktop computers are 64-bit, with gigahertz speeds and gigabyte memories, all enabled by plasmas. If this same physical and chemical precision can be brought to plasmas in health care, will the benefits be any less dramatic?

Accelerating Particles with Plasma Wake Fields

When an electron bunch moves at nearly the speed of light through a plasma, the electrostatic repulsion of the bunch on the stationary plasma electrons pushes them aside, punching a hole in the plasma electron density. The unbalanced positive charge in the hole attracts the plasma electrons back into the hole, setting up plasma oscillations. These plasma oscillations and the hole keep pace with but trail the bunch, providing a plasma wake field that also moves near the speed of light.

Some electrons sitting just at the back of the hole are accelerated forward toward the bunch. These "surfing" electrons can reach energies greater than the energies of the electrons in the driving bunch: This is the principle of the plasma wake field accelerator. An alternative approach employs a laser to excite the plasma in place of the initial electron bunch. The laser's radiation pressure expels the plasma electrons from the pulse. The chief advantage of plasma wake field accelerators is the enormous accelerating force on the electrons—currently greater than 50 GV/m, or a thousand times the force in a conventional accelerator.

From the very beginning of research in plasma accelerators, high-resolution multidimensional computer simulations have helped identify and resolve the scientific issues. Modern massively parallel computer simulations of wake field acceleration (Figure 1.5) are steering the experimental program. The standard com-

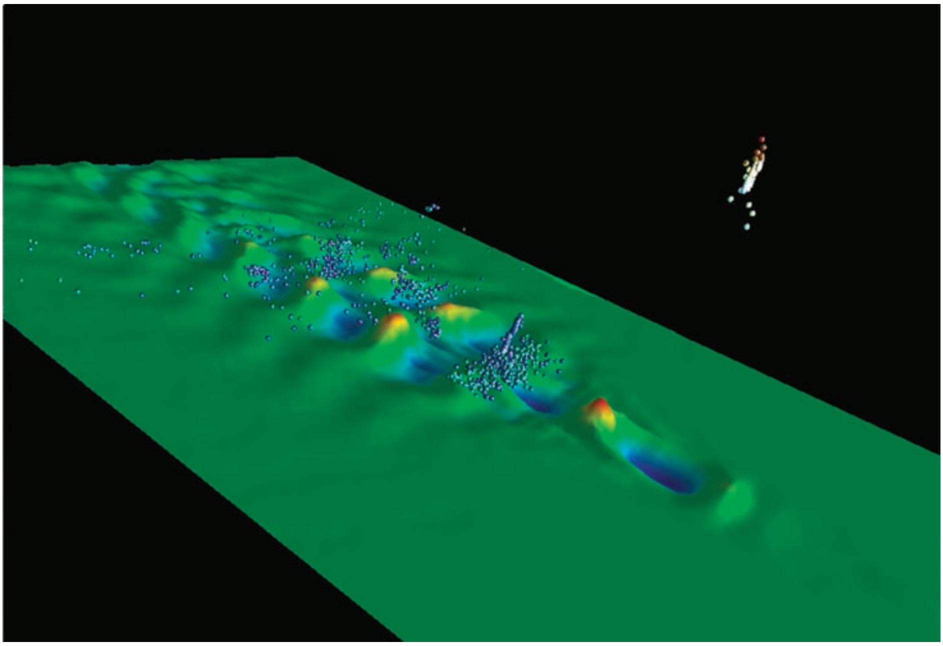

FIGURE 1.5 A computer simulation of laser wake field acceleration. The laser pulse is moving forward, followed by a deficit of electrons, a hole in the electron density. The green sheet represents the electron density with holes colored blue and peaks red. The accelerated electrons are shown and the height above the sheet indicates energy. Most of the accelerated electrons are in the first trailing hole, but some can be seen in the later holes. Courtesy of Tech-X Corp.; simulation, J. Cary; visualization, P. Messmer.

putational tool is particle simulation that follows electrons and ions in the electric and magnetic fields created by the currents and charges of the particles themselves. These simulations have been improved by the theoretical development of new algorithms that exploit the ultrarelativistic nature of the problem. The close interaction of theory, simulation, and experiment in this area has been remarkably productive. Indeed it is a model of the way modern physics (especially plasma science) relies on all three components.

Continuing progress in high-energy physics is hampered by the limits set by conventional accelerator technology. The enormous accelerating fields in a plasma wake field accelerator suggest a path to compact accelerators at a lower cost. Such compact accelerators would have many uses as sources of high-energy particles and photons. However, for the wake field accelerator to be useful, the accelerated electrons must be unidirectional and have uniformly high energy. Rapid progress in the last few years suggests that these criteria are achievable. In 2004, three independent groups demonstrated that laser-driven, plasma-based accelerators are capable of producing high-quality, intense beams with very little angular spread and performance characteristics[4] comparable to state-of-the-art electron sources for accelerators. Within the past 2 years at the Stanford Linear Accelerator (SLAC), a beam-driven plasma wake field accelerator first accelerated particles by over 2.7 GeV in a 10-cm-long plasma module and now has demonstrated doubling of the energy of some of the 42-GeV electrons in a 1-m-long plasma (Figure 1.6).

While recent progress in plasma wake field accelerators has been extraordinary, there are many questions to be answered. For example, what is the optimum shape of the driving electron bunch or laser pulse? How should the background plasma be shaped to produce the best acceleration and beam quality? Can the present success be scaled to much longer plasmas, taking the particles to much higher energies?

Fusion Burning Plasmas in a Magnetic Bottle

The pursuit of a nearly limitless, zero-carbon-emitting energy source through the process of nuclear fusion has been an inspiration to many plasma researchers (Box 1.3). In the magnetic confinement approach to fusion, a 100-million-degree deuterium-tritium plasma is contained in a magnetic bottle where the nuclei collide many times and eventually fuse. The high-energy neutrons born from the fusion reactions are captured in the reactor walls, producing heat that could be converted into electricity.

A principal goal of magnetic confinement fusion is to build magnetic field configurations that contain the plasma stably for long times without much leakage

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[4] With an energy of 100 MeV, an energy spread of 2 to 3 percent, and a pulse length of less than 50 femtoseconds. The charge per pulse was on the order of 0.3 nanocoulombs.

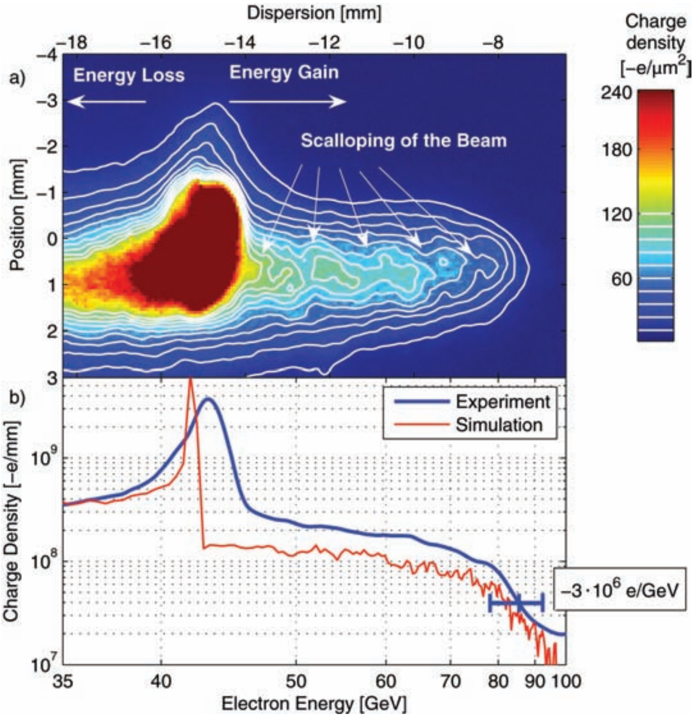

FIGURE 1.6 Demonstration of energy doubling of 42-GeV electrons in a meter-scale plasma wake field accelerator at Stanford Linear Accelerator Center (SLAC). *(a)* The energy spectrum of the dispersed electron beam after traversing an 85 cm long, 2.7×10^{17} cm^{-3} lithium plasma. *(b)* The comparison between the measured and simulated energy spectrum. Reprinted by permission from Macmillan Publishing Ltd.: *Nature* 445: 741-744 © 2007.

of heat to the walls through turbulence (Figure 1.7). Electrons and ions spiral along magnetic field lines, staying inside the plasma. The helium nucleus produced in the fusion reaction is also contained by the magnetic field, and each one deposits its 3.5 MeV of energy in the plasma. Plasmas begin to burn when the self-heating from fusion alpha particles provides most of the heat necessary to keep the plasma hot. Ignition is when the self-heating is sufficient to provide all the heat necessary to keep the plasma hot—that is, enough to balance the heat lost through plasma collisions, turbulence, and radiation.

In the last decade, the Tokamak Fusion Test Reactor (TFTR) at Princeton and then the Joint European Torus (JET) in the United Kingdom provided the first real taste of fusion. These experiments produced substantial fusion power—10 MW in the TFTR and 16 MW in the JET (Figure 1.8). But neither TFTR nor JET had significant heating from the fusion alpha particles and were therefore not in

BOX 1.3
Nuclear Fusion

The easiest fusion reaction to initiate is the fusion of two isotopes of hydrogen, deuterium and tritium, to make a helium nucleus (an alpha particle) and a neutron (Figure 1.3.1). Fusion reactions are hard to initiate because the positively charged nuclei repel until they come close enough for the nuclear force (the strong force) to pull them together and fuse. The nuclei must be slammed together at energies of 100 million degrees, six times the temperature at the center of the Sun, to overcome the repulsion and fuse. The basic process of nuclear fusion is what releases energy in the Sun, causing it to shine and radiate the energy that warms Earth.

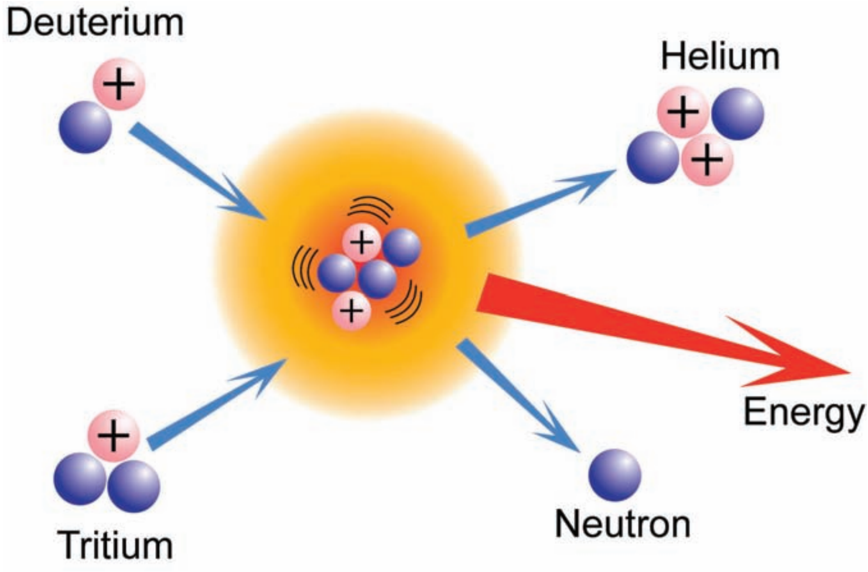

FIGURE 1.3.1 The deuterium-tritium fusion reaction. The helium nucleus (alpha particle) is released with 3.5 MeV and the neutron with 14 MeV. A 1-GW power station would use 250 kg of fuel per year. Published with permission of ITER.

the burning plasma regime. This was, nonetheless, an important milestone on the road to fusion power. Another key achievement of the tokamak program in the last decade was to develop operating regimes that can be extrapolated to a burning plasma experiment. This reflects confidence in the predictive tools and the science that made them possible. It is clear that the next critical step in the development of fusion power is a burning plasma experiment. ITER is that step. It is a large toka-

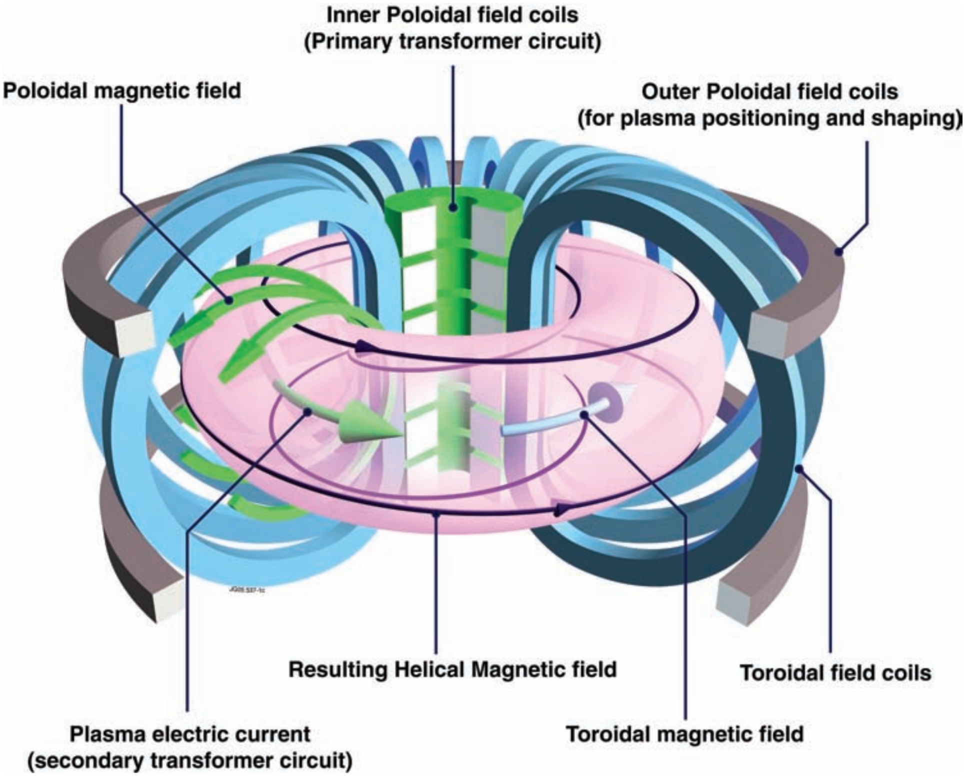

FIGURE 1.7 Plasma confinement in the tokamak magnetic configuration. This type of configuration has produced plasmas at fusion temperatures and densities. The confined plasma is illustrated as the semitransparent pink doughnut-shaped volume. This is the configuration chosen for ITER. Courtesy of the Joint European Torus (EFDA-JET).

mak experiment using superconducting long-pulse magnets that is being built in southern France by an international consortium that includes the United States.[5]

ITER is designed to produce enough alpha-particle heating to replace two-thirds of the heat lost by turbulent transport. It is projected to generate about 500 MW of fusion power. These projections are based on conservative regimes where plasma behavior is well understood. Recent research has uncovered new regimes, called advanced tokamak regimes, where turbulent transport is reduced and the plasma current is driven by the pressure gradient. This has been one of

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[5] The detailed argument for the United States joining this experiment was laid out in the NRC report *Burning Plasma: Bringing a Star to Earth*, Washington, D.C.: The National Academies Press, 2004. The structure of the project is summarized briefly in Appendix B of the current report.

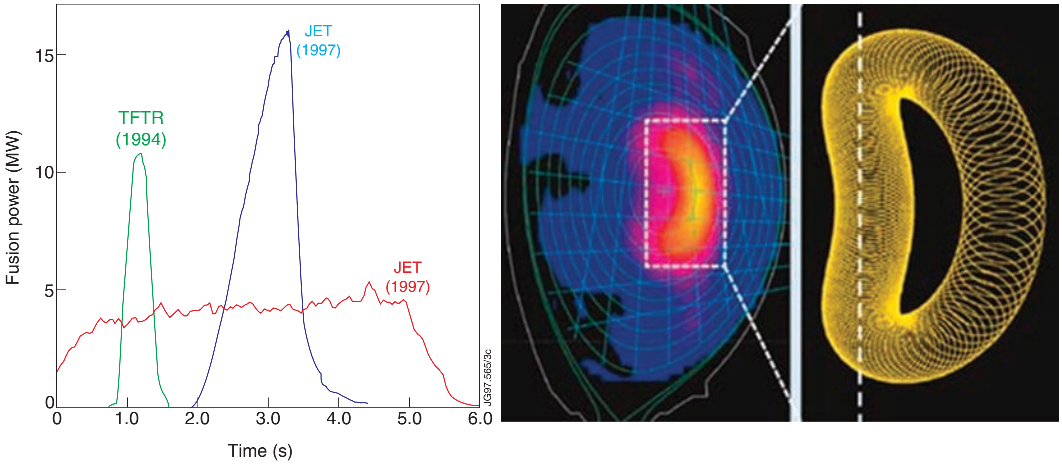

FIGURE 1.8 First fusion. *Left:* Fusion power versus discharge time for the U.S. experiment TFTR in 1994 and two discharges for the European experiment JET in 1997. *Center:* Confining alpha particles. Gamma rays reveal the spatial distribution and temperature of alpha particles in JET. *Right:* The calculated alpha particle trajectory. Courtesy of the Joint European Torus (EFDA-JET).

most remarkable successes of fusion research in the last decade. If ITER can reach such regimes, the performance may considerably exceed expectations, perhaps even approach ignition.

ITER is an experiment and it will investigate important science questions. How does the plasma behave when a substantial fraction of the heating is from fusion? Can it be controlled? Do the alpha particles change the turbulence and/or drive new instabilities? Does the large size of ITER change the physics and scaling of heat and particle transport? Can the walls handle the bursts of heat from edge-localized explosive plasma instabilities and disruptions? Can these explosive events be controlled or minimized? Are there new long-time-scale physical processes that will be revealed in the long pulses of ITER? Do the sophisticated computer models of the turbulence developed in the last decade successfully predict ITER's turbulence? Can the turbulence be reduced and the confinement improved? What is the limit on the plasma pressure in the burning regime?

The scientific advances that ITER will enable will considerably improve our ability to predict the behavior of burning plasmas in all kinds of configurations. But to become economical, fusion power will require developments beyond ITER—perhaps refinements in the magnetic configuration will be needed and certainly it will be necessary to develop the engineering and technology of the first generation of fusion reactors. The importance of hastening the removal of remaining scientific barriers to magnetic fusion power will only grow as the limitations of fossil fuels become ever more apparent.

Magnetic Reconnection and Self-Organization

The magnetic field protruding from the surface of the Sun into the surrounding coronal plasma is impressively complex (Figure 1.9). Nonetheless, the scientific challenge is to explain why it is not far more tangled. The plasma in the Sun's corona is sufficiently electrically conducting that, to a very good approximation, the field lines are frozen into the plasma—that is, the lines move, bend, and stretch with the plasma motion. The turbulent bubbling of the Sun's surface randomly braids the field lines by moving their ends. To break a line and reconnect it to another line—a process called magnetic reconnection—the plasma must slip across the field. This happens most effectively in narrow regions, where the field changes abruptly and oppositely directed components of the field are brought close together. In the solar corona, the random braiding of field lines proceeds until narrow dissipative regions are formed and reconnection releases the magnetic energy stored in the tangled field. Early estimates of the rate and effectiveness of reconnection suggested that the Sun's field should be considerably more tangled than is observed. These same estimates also failed to explain the extremely rapid rates of magnetic reconnection in Earth's magnetosphere and in fusion experiments. However, in the last decade, processes that enable fast magnetic reconnection have been discovered and illumi-

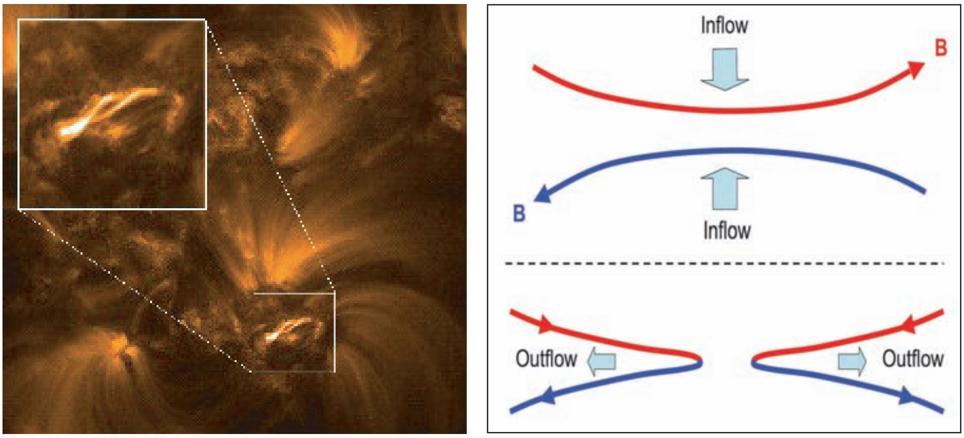

FIGURE 1.9 Magnetic reconnection. *Left:* Image of the Sun's coronal plasma from the TRACE satellite. The striations indicate the direction of the magnetic field. Sometimes TRACE observes coronal loops that are wrapped around each other (generally once, rarely more). Courtesy of Transition Region and Coronal Explorer (TRACE), a mission of the Stanford-Lockheed Institute for Space Research and part of the NASA Small Explorer program. *Right:* Cartoon of red field line reconnecting with oppositely directed blue field line in a narrow region. Outflow removes the field lines from the reconnection region.

nated by new experiments, observations, and a concerted program of theory and simulation. Although magnetic reconnection occurs in many different plasmas, the process has been profitably abstracted from the context, and universal features have been identified.

Simulations of the narrow dissipation region have shown that a key to fast reconnection is the difference in the coupling of ions and electrons with field lines due to the Hall effect. When a field line is forced into the narrow region, it first decouples from the ions and then, in a much narrower region, decouples from the electrons. Field lines reconnect in the narrower electron-decoupling region. Reconnected field lines exit the narrow region dragging plasma outflows (Figure 1.9b). Initially, they move rapidly because they only have to drag the lighter electrons. The ion outflow is slower and over a much wider flaring region. The current in the electron outflow produces a characteristic quadrupole field. This field has been identified in experiments purpose-built to study reconnection (Figure 1.10) and in observations of magnetospheric reconnection.

It is clear that the Hall reconnection mechanism does lead to a dramatic increase in the speed and effectiveness of reconnection. However, laboratory experiments also show that the narrow layers are highly turbulent and that the tur-

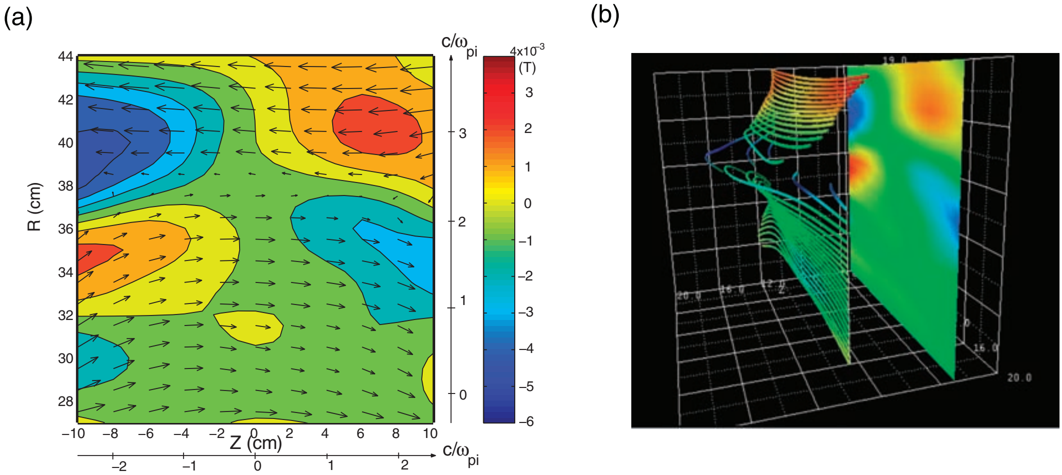

FIGURE 1.10 Hall mechanism for fast magnetic reconnection, the smoking gun. *(a)* Results from a recent laboratory experiment showing color contours of the out-of-plane quadrupole magnetic field (definitive signature of the two-fluid Hall currents that produce the reconnection) superposed on vectors of the magnetic field in the reconnection region. Field lines flow in toward the line R = 38 and outflows are along this line. Ion decoupling begins at a distance of about 2 c/ω_{pi} above and below R = 38, whereas electron decoupling begins at about $\pm 0.8\ c/\omega_{pi}$. *(b)* Three-dimensional plot of reconnecting the field lines showing the way in which they are distorted; color projections are the quadrupole components. Courtesy of M. Yamada, Princeton Plasma Physics Laboratory (PPPL).

bulence is changing the reconnection dynamics. New, probably intermediate-scale experiments that achieve a larger separation of scales are required to distinguish the contributions of the turbulent and Hall dynamics. Furthermore, several important features of reconnection in space and in fusion experiments are not yet seen in the small-scale reconnection experiments or predicted by the theory. For example, reconnection is thought to be responsible for some of the most dramatic and explosive events in nature such as solar flares, magnetic substorms, and certain tokamak disruptions. If reconnection were always fast and effective, however, it would be impossible to store significant energy in the field. That is because reconnection would remove energy as soon as it is built up. Thus reconnection must be triggered, but how or when is not known. Many of the most energetic reconnection events result in a large fraction of the magnetic energy being converted to energetic particles—again it is not clear how. How reconnection works in fully three-dimensional configurations (like the solar corona) is also not yet understood. Extending the advances of the past decade to address these outstanding issues is a difficult but exciting challenge. Clearly, there is an opportunity to make progress on a fundamental problem that has confounded plasma scientists for 50 years. Such progress would enhance predictive capability in a huge number of plasma applications, from fusion to astrophysics.

Fusion Ignition in an Exploding Pellet

In 2009, the 1.8-MJ NIF laser system will begin full-power operation at Lawrence Livermore National Laboratory in California. Its goal is to compress and heat a tiny capsule filled with a deuterium-tritium mixture to the point that fusion burning takes place. In this process a significant fraction of the fuel must react and burn before the capsule expands and cools. This process is called inertial confinement fusion. The data obtained from the experiments at NIF will provide critical information to ensure the safety and reliability of the nation's nuclear stockpile.

The tiny thermonuclear explosions are initiated by squeezing the capsule of fuel by a factor of 20-30 in radius (Figure 1.11). As is obvious to anybody who has tried

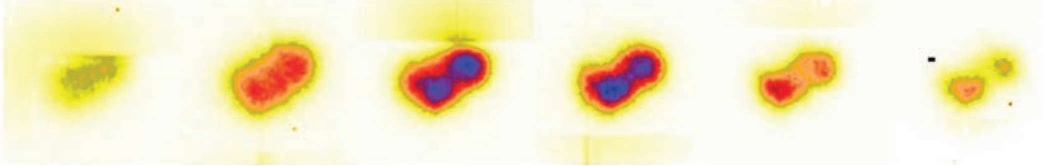

FIGURE 1.11 Images of the last stage of compression of a capsule by the Omega laser at the University of Rochester's Laboratory for Laser Energetics. These x-ray images from argon emission are spaced 35 psec apart and magnified 87 times. This experiment achieved a 15-fold compression in radius. Courtesy of R.E. Turner, Lawrence Livermore National Laboratory (LLNL).

to squeeze a balloon by a factor of two, squeezing a pellet 20- to 30-fold demands a remarkably symmetric and precise squeeze. This can be achieved by very uniform ablation of the surface of the capsule that, by the rocket effect, compresses the capsule. This challenge has driven a deeper understanding of HED plasma science and the development of modern computational tools to design the fuel capsules and to study the many physical processes involved in delivering the laser energy.

The NIF will deliver its 1.8 MJ of energy using 192 convergent laser beams to power the ablation. For the indirect-drive approach, the laser beams will irradiate the inside surface of an enclosure (called a hohlraum) surrounding the capsule, producing a bath of x rays that heat and ablate the capsule surface. In the direct-drive approach, the beams shine on the capsule itself. In both approaches, the basic concept is to heat a central hot spot in the imploded fuel hot enough to initiate fusion reactions that will spread to the surrounding denser but cooler fuel layers. Innovative variants of the basic idea of inertial confinement fusion have been introduced in the last decade. For example, it was shown that the capsule's fusion could be greatly enhanced by delivering a very sudden injection of energy to initiate reactions at the point of maximum compression. This energy might be delivered into the capsule by, for example, relativistic electrons generated by a very short pulse laser. Modeling and experiments have confirmed that this process, called "fast ignition," can indeed significantly improve performance. Additional innovations that will increase the efficiency of inertial confinement fusion are likely to appear once the NIF is in operation.

The huge energy and power of the NIF laser will allow access to many new HED plasma regimes. For example, in some cases the nonlinear interaction of NIF beams with diffuse plasma is expected to produce highly nonlinear (perhaps turbulent) laser–plasma interaction. Ultrashort high-energy laser pulses such as would be needed for fast ignition experiments will accelerate dense beams of relativistic particles and produce novel plasma states. The NIF will also be able to probe the dynamics and stability properties of radiation-dominated plasmas, including processes that, at present, can be seen faintly only in distant astrophysical objects. Finally, the achievement of ignition will release ~10^{18} neutrons in a fraction of a nanosecond from a submillimeter spot, potentially enabling the study of nuclear processes involving more than one neutron. Understanding some of these phenomena does not directly advance the mission of NIF, but it will certainly open new avenues for fundamental research.

Plasma Physics and Black Holes

Black holes are among the most remarkable predictions of theoretical physics. So much mass is compressed into such a small volume that nothing, not even light, can escape. Currently, a black hole can be detected by either its gravitational influence on surrounding matter or the electromagnetic radiation produced when plasma falls toward the black hole and heats up as it is accelerated to nearly the speed of light (Figure 1.12).

There has been a growing recognition over the past 35 years that black holes are ubiquitous and play an essential role in many of the most fascinating and energetic phenomena in the universe. Massive stars that have exhausted their nuclear fuel collapse to form black holes with masses about 10 times that of our Sun—there are perhaps 10 million such black holes in a galaxy like our own. There is now compelling evidence that nearly every galaxy contains, in addition to these roughly solar-mass objects, a much more massive black hole at its center—these range in mass from a million to a billion solar masses.

Accreting black holes power the most energetic sources of radiation in the universe and produce powerful outflows. The central difficulty in understanding

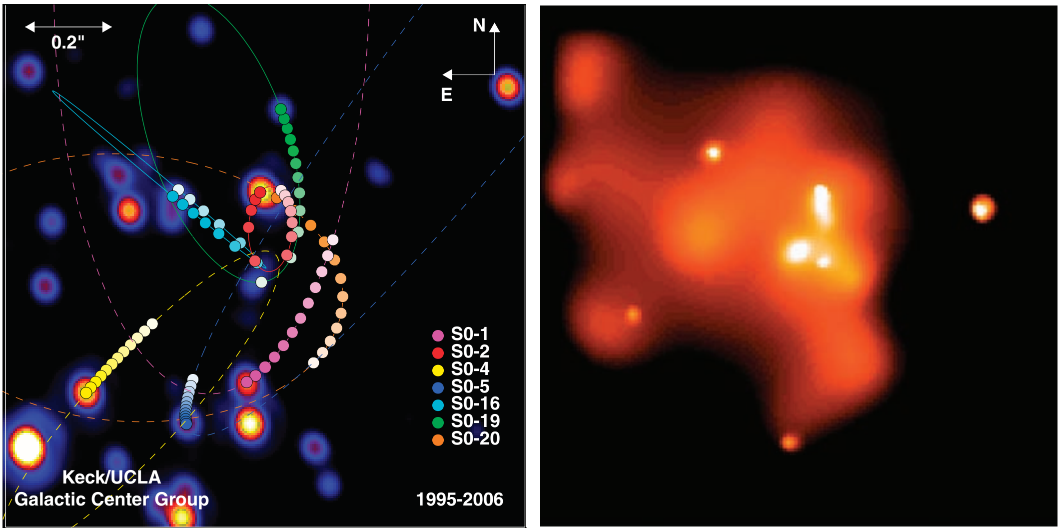

FIGURE 1.12 *Left:* Detecting a black hole by its influence on the orbits of nearby stars. Infrared image of stars in the central 0.1 light-year of our galaxy, a region comparable in size to our solar system. Every star in the image has been seen to move over the past decade. For approximately a dozen stars, this motion can be well fitted by orbits around a central 3.6×10^6 solar mass black hole (indicated by the star at the center of the image). Courtesy of Keck/UCLA Galactic Center Group; based on data from A. Ghez et al., *Astrophysical Journal* 620: 744 (2005). *Right:* Detecting the emission from plasma falling toward a black hole. X-ray image of the central 10 light-years of our galaxy showing diffuse emission from hot plasma and a number of point sources. Some of the ambient hot plasma is gravitationally captured by the black hole at the center of the galaxy. As it falls toward the black hole, this plasma heats up and produces a bright source of radiation. The point source at the lower left of the central three sources is coincident with the location of the massive black hole from the left panel. Courtesy of NASA/MIT/PSU.

black holes as sources of radiation and outflows lies not in understanding the physics of the black holes themselves (as predicted by general relativity) but rather in understanding the physics of the accreting plasma that produces the observed radiation. Further progress on understanding general relativistic plasma physics (i.e., plasma physics in curved space-time) is essential both for interpreting observations of black holes in nature and for achieving the long-sought goal of using such observations to test general relativity's predictions for the strong gravity around black holes. In general, inflowing plasma does not fall directly onto the black hole but instead, because it has angular momentum, orbits the black hole. The orbiting plasma forms a disc called an accretion disc, such as that shown in the numerical simulation in Figure 1.13.

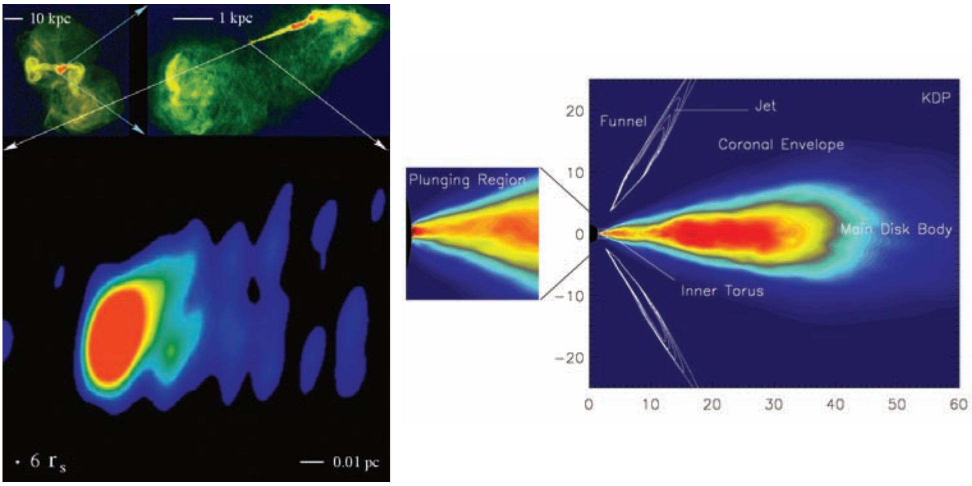

FIGURE 1.13 *Left:* Radio images of the galaxy M87 at different scales (1 kpc = 3,260 light-years) show, *top left*, giant, bubblelike structures on the scale of the galaxy as a whole, where radio emission is powered by relativistic outflows ("jets") from the galaxy's central black hole; *top right*, the jets coming from the core of the galaxy; and *bottom*, an image of the region close to the central black hole, where the jet is formed. The small circle labeled $6R_S$ shows six times the radius of the event horizon for the galaxy's black hole (about 10 times the distance from the Sun to Pluto). Courtesy of National Radio Astronomy Observatory (NRAO)/Associated Universities, Inc. (AUI)/National Science Foundation (NSF); based on data from Junor, Biretta, and Livio, *Nature* 401: 6756. *Right:* The inner regions of an accretion disk around a black hole, as calculated in a general relativistic plasma simulation. The black hole is at coordinates (0,0). The accretion disk rotates around the vertical direction (the axis of the nearly empty funnel region). Its density distribution is shown in cross section, with red representing the highest density and dark blue the lowest. Above the disk is a tenuous hot magnetized corona, and between the corona and the funnel is a region with ejection of mildly relativistic plasma that may be related to the formation of the jets seen in the left panel. Image based on work that appeared in de Villiers et al. (2003), © American Astronomical Society.

Unlike the planets orbiting the Sun, plasma is subject to frictional forces that redistribute angular momentum and allow the plasma to flow inward. In the past decade, it has been realized that magnetic fields in accretion disks are amplified by a powerful instability known as the magnetorotational instability. Such magnetic fields provide the necessary viscous angular momentum transport in most accretion disks and also help generate powerful outflows such as those seen in Figure 1.13.

Much remains to be understood about plasma physics in the vicinity of black holes. What determines the inflow rate of plasma in an accretion disc? How much of the energy of the inflowing plasma is radiated away, ejected in outflows, or swallowed by the black hole? How are jets launched, and why do only some black holes, some of the time, have jets? In addition to progress on the theoretical front, observations are rapidly improving and are providing information about the conditions very close to the event horizon of black holes, by means of both direct images of plasma near the event horizon (e.g., the picture of M87 in Figure 1.13) and the indirect but powerful information about the velocity of the plasma provided by spectral lines. Given the wealth of observational information and the diversity of exciting and difficult problems, black hole plasma physics will remain a vibrant research area in the coming decade.

KEY THEMES OF RECENT SCIENTIFIC ADVANCES

This section examines the overall trends in plasma research. Two themes frame recent advances:

- Plasma science is developing a significant predictive capability.
- New plasma regimes have been found that expand the scope of plasma research and applications.

Both themes are illustrated by the six examples of cutting-edge science in the preceding section. More complete descriptions of the scientific advances and questions are contained in the ensuing topical chapters.

Prediction in Plasma Science

The recent growth of predictive capability in plasma science is perhaps the greatest indicator of progress from fundamental understanding to useful science-based models. It is due primarily to two factors: (1) advances in diagnostics that can probe the internal dynamics of the plasma and yield much greater quantitative understanding and (2) theoretical and computational advances that have led to models that can accurately predict plasma behavior. Good examples are the predictive modeling of turbulence in fusion plasmas, the modeling of reconnection dynamics, and the modeling of industrial plasma processes. The cost of development via an Edisonian approach, where multiple designs and prototypes are tried, is prohibitive for many plasma science applications, notably but not exclusively fusion. Predictive models provide a basis for steering investigation and ultimately reduce development cost and time. Nonetheless, our understanding of many fundamental aspects of plasma behavior remains rudimentary, and further increases in predictive capability require progress in understanding the basic plasma processes outlined in the next section. That is, the next generation of improvements in predictive capabilities will probably be driven by theoretical insights.

New Plasma Regimes

New facilities and experimental techniques have revealed new plasma regimes. The highly relativistic plasma physics in the beam plasma interaction at SLAC is a good example (see the preceding section). The power of the SLAC beam has opened up this regime to study. Another example is the very cold, highly correlated plasmas being studied in basic experiments made possible by the development of new techniques for cooling the plasma. Low-temperature microplasmas that blur the distinction between the solid, liquid, and plasma states are being created to explore novel plasma chemistry. In studying accretion discs, astrophysicists are considering the behavior of plasmas in the curved space around black holes. These new regimes are revealing unexpected new phenomena, challenging and extending our understanding.

In the next decade, more new regimes are expected. For example, ITER will begin studying magnetically confined plasmas heated by alpha particles produced in fusion reactions—the burning plasma regime. The NIF will seek to produce a fusion burn in a pellet compressed by lasers.

COMMON INTELLECTUAL THREADS OF PLASMA RESEARCH

Plasmas occur over a fantastic range of temperatures, densities, and magnetic fields. However, there are a number of issues that are pervasive, and much of plasma behavior can be characterized in terms of universal processes that are, at least partially, independent of the particular context being considered. Some of these processes have been well understood and the behavior can be predicted with near certainty. The propagation of weak electromagnetic waves through plasmas, such as radio waves through the ionosphere, is one example where predictive capability has risen to a level of considerable certainty in the last decade.

However, six critical plasma processes are not well understood. They yield some of the great questions of plasma science. Progress on any one of them would advance many areas of plasma science simultaneously. Indeed they define the research frontier.

- *Explosive instability in plasmas.* Some of the most striking events in plasmas are the explosive instabilities that spontaneously rip apart plasmas. Such instabilities give rise to a massive and often destructive release of energy and accelerated particles. For example, disruptions in magnetically confined fusion plasmas can deposit large fractions of the plasma energy (tens of megajoules) on the solid walls of the experiment in less than a millisecond. Solar flares convert magnetic energy equivalent to billions of nuclear weapons to plasma energy in 10 to 1,000 seconds. It is not understood when and how plasmas explode.
- *Multiphase plasma dynamics.* Multiphase plasmas—plasmas that are interacting with nonplasmas (such as neutral gas, solid surfaces, particulates, and liquids)—are widespread. For example, low-temperature multiphase plasmas are used to perform tasks such as emitting light of a particular color, destroying a pollutant or sterilizing a surface. A host of basic questions about these plasmas have at best been only partially answered.
- *Particle acceleration and energetic particles in plasmas.* In supernova shocks, laser–plasma interactions, the wakes of particle beams, solar flares, and many other phenomena, we observe the acceleration of some plasma particles to very high energies. Particles may be accelerated by surfing on waves in the plasma or by being randomly scattered by moving plasma irregularities. It is still not clear how nature accelerates particles so effectively or what can be learned from this behavior in the laboratory.
- *Turbulence and transport in plasmas.* Magnetic fusion plasmas, accretion discs around black holes, Earth's magnetosphere, laser-heated plasmas, and many industrial plasmas are permeated with turbulence that transports heat, particles, and momentum. The effects of this turbulence often dominate these plasmas, yet many aspects are not understood. For example, can we reduce and control turbulence?
- *Magnetic self-organization in plasmas.* In many natural and laboratory plasmas, the magnetic field and the plasma organize themselves into a structured state. For example, although it is not known how, the Sun's turbulent plasma produces an ordered magnetic field that cycles with an almost constant 22-year period. Laboratory plasmas often seek out preferred configurations called relaxed states. Magnetic reconnection is almost always a key part of the relaxation processes that lead to self-organization.
- *Correlations in plasmas.* In cool, dense plasmas, the electrostatic forces between the ions and electrons begin to dominate the motion of the particles. This induces ordering and structure into the particle positions. The

> behavior of such plasmas in stars, HED systems, laboratory experiments, and industry is of great current interest. Unraveling the properties of highly correlated plasmas is an ongoing challenge.

It is notable that each of these six processes plays a role in four or more of the (five) topical areas treated in Chapters 2-6. A variety of approaches are needed to advance our knowledge of these processes. Some phenomena must be studied at a large scale and therefore can only be addressed in the context of (well-funded) applications or space/astrophysics research. Other phenomena can be best understood through a series of small-scale laboratory experiments whose objectives are to peel back the layers of complexity. Clearly, progress on understanding these six fundamental processes will benefit a broad range of applications. Such advances in understanding will lead (via modeling and simulation) to improvements in predictive capability.

THE REPORT'S PRINCIPAL CONCLUSION AND PRINCIPAL RECOMMENDATION

Plasma science is on the cusp of a new era. It is poised to make significant breakthroughs in the next decade that will transform the field. For example, the international magnetic fusion experiment—ITER—is expected to confine burning plasma for the first time, a critical step on the road to commercial fusion. The NIF plans to ignite capsules of fusion fuel with the goal of acquiring the knowledge necessary for maintaining the safety, security, and reliability of the nuclear stockpile. Low-temperature plasma applications are ushering in new products and techniques that will change everyday lives. And plasma scientists are being called upon to help crack the mysteries of exotic plasmas in the cosmos. This dynamic future will be exciting and challenging for the field. It will demand a well-organized national plasma science enterprise.

> **Principal Conclusion: The expanding scope of plasma research is creating an abundance of new scientific opportunities and challenges. These opportunities promise to further expand the role of plasma science in enhancing economic security and prosperity, energy and environmental security, national security, and scientific knowledge.**

Plasma science has a coherent intellectual framework unified by physical processes that are common to many subfields. Therefore, and as this report shows, plasma science is much more than a basket of applications. The committee believes that it is important to nurture fundamental knowledge of plasma science across all of its subfields to advance the science and to create opportunities for a broader range of science-based applications. These advances and opportunities are, in turn, central to the achievement of national priority goals such as fusion energy, economic competitiveness, and stockpile stewardship.

The vitality of plasma science in the last decade testifies to the success of some of the individual federally supported plasma science programs. However, the emergence of new research directions necessitates a concomitant evolution in the structure and portfolio of programs at the federal agencies that support plasma science. The committee has identified four significant research challenges that the federal plasma science portfolio as currently organized is not equipped to exploit optimally:

- *Fundamental low-temperature plasma science.* The many emerging applications of low-temperature plasma science are challenging and even outstripping fundamental understanding. A basic research program in low-temperature plasma science that links the applications and advances the science is needed. Such a government-sponsored program of long-range research would capitalize on the considerable benefits to economic competitiveness offered by key breakthroughs in low-temperature plasma science and engineering. No such program or federal steward for the science exists at present. The detailed scientific case for this program is presented in Chapter 2.
- *Discovery-driven, HED plasma science.* Fueled by large new facilities and breakthroughs in technologies that have enabled access to previously unexplored regimes, our understanding of the science of HED plasmas has grown rapidly.[6] Mission-driven HED plasma science (such as the advanced accelerator program in the DOE Office of High-Energy Physics or the Inertial Confinement Program in the National Nuclear Security Administration [NNSA]) is thriving. New regimes revealing new processes and challenging our fundamental understanding of plasmas will be discovered in the next decade at the new HED facilities (such as NIF and upgrades elsewhere). It is very likely that some of the science that will emerge in these new regimes and new processes cannot be adequately explored by the current suite of facilities given the specificity of their purposes. By extension, discovery-driven research in HED plasmas cannot grow inside the facilities' parent programs that are dedicated to specific missions. However, there is no other home for this research in the present federal portfolio.

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[6] This science is discussed in Chapter 3 in the NRC report *Frontiers of High Energy Density Physics: The X-Games of Contemporary Science*, Washington, D.C.: The National Academies Press, 2003; and *Frontiers in High Energy Density Physics*, July 2004, prepared by the National Task Force on High Energy Density Physics for the Office of Science and Technology Policy's (OSTP's) interagency working group on the physics of the universe.

- *Intermediate-scale plasma science.* Some of the most profound questions in plasma science are ripe for exploitation right now and are best addressed at the intermediate scale. These questions can only be studied in facilities that are intended for groups larger than single-investigator groups. They do not, however, require the very large national and international experimental facilities on the scale of NIF and ITER. For example, magnetic reconnection research would be advanced significantly by an experiment at an intermediate scale, where the collisionless physics is dominant. Such intermediate-scale facilities might be sited within national laboratories or at universities. The current mandates of the mission-driven programs of the NNSA and OFES do not provide for the development of intermediate-scale facilities that pursue discovery-driven research directions in plasma science that are not clearly applicable to their missions. The discoveries that intermediate-scale facilities would foster are unlikely to happen within the current paradigm of federal support for plasma science.
- *Crosscutting research.* Federal stewardship of plasma research is disaggregated and dispersed across four main agencies—the Department of Energy, the National Science Foundation, the Department of Defense, and the National Aeronautics and Space Administration—and within those, across many offices (e.g., magnetic fusion is primarily supported through DOE's Office of Science, and inertial confinement fusion is primarily supported through DOE's NNSA). This dispersion hinders progress in many areas of plasma science because it does not allow for an intellectual juxtaposition of disparate elements that will force dialogue on common issues and questions. There are significant opportunities at the interfaces between the subfields, but the current federal structure fails to exploit them.

Notwithstanding the success of individual federal plasma science programs, the lack of coherence across the federal government ignores the unity of the science and is an obstacle to overcoming many research challenges, to realizing scientific opportunities, and to exploiting promising applications. The committee observes that the stewardship of plasma science as a discipline will likely expedite the applications of plasma science. The need for stewardship was identified in many reports over two decades.[7] The evolution of the field has only exacerbated the stewardship problem and has driven this committee to conclude that a new, integrated way of managing the federal support for the science is necessary.

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[7] See NRC, *Plasma and Fluids*, Washington, D.C.: National Academy Press, 1986; NRC, *Plasma Science: From Fundamental Research to Technological Applications*, Washington, D.C.: National Academy Press, 1995; and NRC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, Washington, D.C.: National Academy Press, 2001.

The committee considered a wide range of options to provide stewardship without disrupting the vigor and energy of the ongoing plasma research. Recognizing the potentially far-reaching consequences of any recommendation to integrate research programs in plasma science, the committee considered four options in great detail:

- **Option 1:** *Continue the current structure of federal plasma science programs unchanged.* It is apparent that many plasma science programs were very successful in the past and some continue to be successful. Certainly, the pace of discovery would remain high in many areas if the system remains unchanged. However, the status quo option does not position the nation to exploit the emerging new directions in plasma science and their potential applications. Even now, the committee judges, the structure is impeding broad progress in plasma science.
- **Option 2:** *Form a plasma science interagency coordinating organization.* Interagency working groups have facilitated crosscutting science and technology initiatives such as nanotechnology and information technology. With some of the fundamental questions in plasma science being investigated by as many as three agencies (and several offices within those agencies) it is clear that a coordinated effort that is supported at the highest levels within the government would be beneficial. However, while such an approach might stimulate some crosscutting research, it would not, in itself, create research initiatives in fundamental low-temperature plasma science and discovery-driven, HED plasma science. An interagency task force cannot facilitate the development of intermediate-scale facilities for the emerging science if those facilities are all within one large agency. Furthermore, an interagency advisory panel cannot directly provide stewardship nor can it provide advice on coordination if the roles and responsibilities of the participating agencies are too diffuse. Arguably, the future of plasma science requires more than a coordinating effort.
- **Option 3:** *Create an office for all of plasma science, pulling together programs from DOE, NSF, NASA, DOD, and other government agencies.* Such an office would centrally manage all plasma science and engineering in the federal portfolio. It would naturally emphasize the unity of plasma science and the commonality of the physical processes. Certain efficiencies would be realized through common administration and management. However, this move would uproot many successful activities, separating flourishing programs from their applications and isolating others from their related areas of science. It might create more problems than it would solve.
- **Option 4:** *Expand the stewardship of plasma science at DOE's Office of Science.* Since the heart of the science at stake resides within DOE, this op-

> tion would address directly the four problems identified by the committee. As the home of many large plasma science applications (fusion, stockpile stewardship, and so on), DOE has abundant interest in the effective development of the science. It has also successfully nurtured basic plasma science through the NSF-DOE partnership. Furthermore, DOE has experience (and success) in operating large and intermediate-scale science facilities as part of broader research programs. An expanded stewardship of plasma science in the Office of Science would not, however, exploit *all* the connections that the science presents. Nonetheless, by linking together a large part of the core science, the Office of Science could coordinate effectively with other offices and agencies on common scientific issues. Thus a stewardship focused in the Office of Science would be at the heart of a balanced strategy that would bring coherence without sacrificing connections to applications and the broader science community.

The scientific advantages of the fourth option are compelling to the committee. After careful assessment, this is the route the committee recommends. Assessing the bureaucratic and managerial issues involved in effective pursuit of this option, however, is beyond this committee's charge.

Principal Recommendation: To fully realize the opportunities in plasma research, a unified approach is required. Therefore, the Department of Energy's Office of Science should reorient its research programs to incorporate magnetic and inertial fusion energy sciences; basic plasma science; non-mission-driven, high-energy-density plasma science; and low-temperature plasma science and engineering.

The new stewardship role for the Office of Science would extend well beyond the present mission and purview of the OFES. It would include a broader portfolio of plasma science as well as the research OFES presently supports. Two of the thrusts would be new: (1) a non-mission-driven, HED plasma science program and (2) a low-temperature plasma science and engineering program. These changes would be more evolutionary than revolutionary, starting modestly and growing with the expanding science opportunities. The committee recognizes that these new programs would require new resources and perhaps a new organizational structure for the Office of Science. However, the scale and extent should evolve naturally from community proposals and initiatives through a strategic planning process such as outlined below and the usual budget and operation planning within the government.

The committee's intention is not to replace or duplicate the plasma science programs in other agencies. Rather, it would create a science-based focal point for federal efforts in plasma-based research. Space and astrophysical plasma research would remain within the space and astrophysical research programs in NASA and NSF. The NSF-DOE partnership in basic plasma science would continue. HED programs in plasma accelerators would remain in the DOE Office of High Energy Physics. Inertial confinement fusion research enabling the stockpile stewardship mission of DOE's NNSA would remain there. With a renewed and expanded research focus, the Office of Science would also be naturally positioned to accept a lead scientific role in interagency efforts to exploit HED physics.[8] Finally, current programs at NIST and NSF wrestling with the engineering applications of low-temperature plasma science would continue. In fact, they would be substantially enhanced by the inception of the new DOE plasma science programs that could provide directed scientific inquiry on key issues as well as coordination and communication of the most compelling breakthroughs in the basic research.

The committee is aware that there are substantial challenges and risks associated with its chief recommendation. A comprehensive strategy will be needed in order to ensure a successful outcome. The planning should do the following:

- Develop a structure that integrates the scientific elements,
- Initiate a strategic planning process that not only spans the field but also provides guidance to each of the subfields, and
- Identify the major risks and develop strategies to avoid them.

The committee recognizes that there is no optimal strategy without risk. Indeed, the status quo is not without considerable risk. Some things could be done, however, to mitigate the most obvious risks:

- Strong leadership to achieve these ambitious goals and inspire the elements of the program to rise above their particular interests.
- Careful consultation among the communities, their sponsors, and constituencies to build trust and a strong consensus.
- An advisory structure that reflects the breadth and unity of the science.
- Scientific and programmatic connections to related disciplines in the broader physical sciences and engineering.

DOE's magnetic fusion and inertial fusion programs are currently focused on large developing facilities (ITER, NIF, and Z). The next decade will see these facilities mature into vibrant and exciting scientific programs. Looking beyond that

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[8] Under the direction of the National Science and Technology Council's interagency working group on the physics of the universe, an ad hoc National High Energy Density Physics Task Force has been formed to coordinate federal activities in HED physics. A report from this group was expected by mid-2007.

phase, however, the committee has two observations. First, NNSA's support for HED science will become uncertain when NIF and Z complete their stockpile stewardship missions. Yet, by that time, HED science will have flowered and expanded in many directions. Second, if ITER is successful and 15 years from now the nation is actively pursuing the development of fusion energy, DOE's fusion science program is likely to have changed dramatically. The fusion energy effort may move outside the Office of Science. Which entity will then become the de facto steward of plasma science? The committee concludes that the Office of Science would naturally fill this role. A broad-based plasma science program within the Office of Science would explicitly include (among other research programs) the science of magnetic fusion and the science of inertial fusion. Indeed, the Office of Science will steward plasma science long after the current large facilities have come and gone.

There is a spectacular future awaiting the United States in plasma science and engineering. But the national framework for plasma science must grow and adapt to new opportunities. Only then will the tremendous potential be realized.

2

Low-Temperature Plasma Science and Engineering

Low-temperature plasma science and engineering is that area of plasma research addressing partially ionized gases with electron temperatures typically below about 100,000 K (10 eV). Such plasmas are often known as "collisional plasmas" or "weakly ionized plasmas" because input power first couples with the charged electrons and ions and then is collisionally transferred to neutral atoms and molecules, creating chemically active species. The richness of the field comes from the intimate contact between energetic plasmas and ordinary matter in all its phases: gas, liquid, and solid. When these interactions can be accomplished in a stable, reproducible, controlled way, the result can be practical products or processes that benefit society (Figure 2.1).

A particular challenge for low-temperature plasma research is the diversity of parameter space and conditions that are encountered:

- *Size.* From ever larger, stable plasmas ($5\ m^2$ plasmas are used to make liquid crystal display television panels) to tiny ($100\ \mu m^2$) plasmas so intense that the plasma electrons merge with the electrons inside the solid electrodes.
- *Pressure.* From ever lower pressures used in semiconductor processing equipment (<1 millitorr) to increasing pressures, now more than 100 atm (76,000 torr), for the lamps that power projection displays.
- *Chemistry.* From simple rare gas plasmas used to propel spacecraft to ever more complex and reactive hydrocarbon and halogen chemistries for plasma-augmented combustion and material processing.

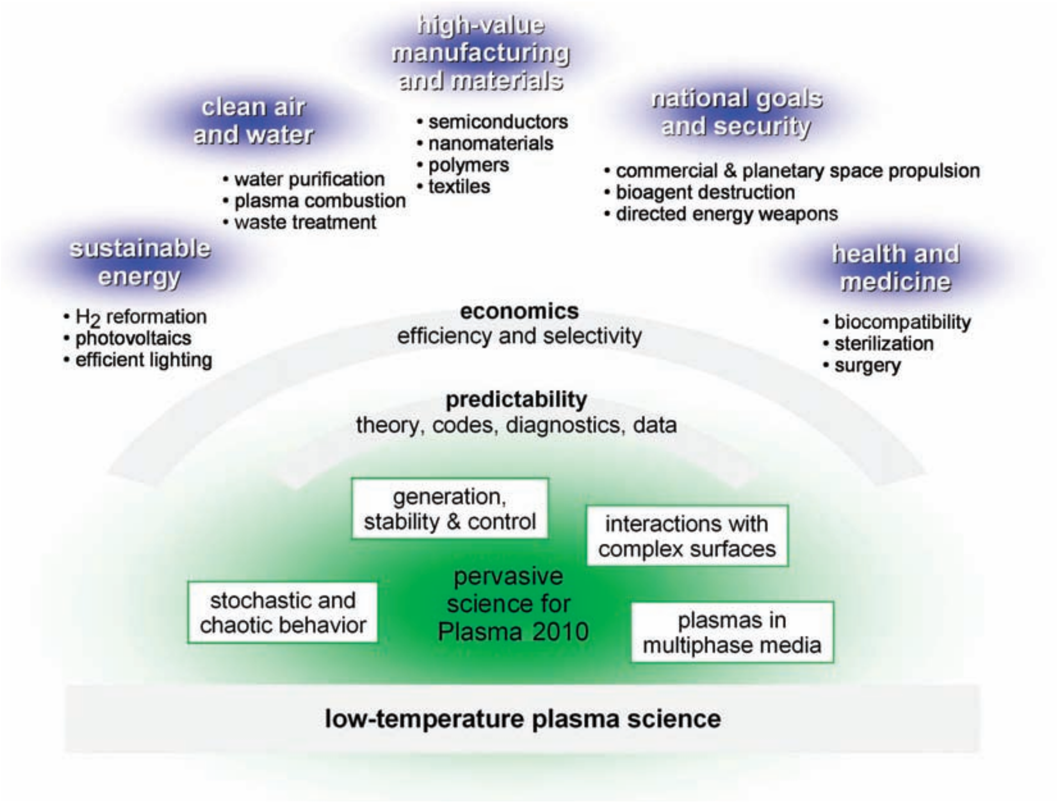

FIGURE 2.1 The many beneficial applications of low-temperature plasmas are realized most effectively when plasma behavior can be accurately, reliably, and rapidly predicted. A robust predictive capability rests, in turn, on a healthy foundation of low-temperature plasma science and a robust effort to improve and extend the scientific understanding in key areas.

Low-temperature plasma science and engineering is a highly interdisciplinary field because of its widespread applications. The field is driven by both fundamental science issues and the societal benefits that result from application of these plasmas. As such, there are often parallel approaches to furthering the state of the art. Like research in other fields of science and engineering, research in low-temperature plasmas strives to gain a deeper understanding of the underlying fundamental principles governing plasmas. At the same time, the research can be motivated by the need to develop detailed understanding of application-specific phenomena that may have important consequences for practical applications. Because the total worldwide effort in applications dwarfs the efforts devoted to basic science, it is typically the case that an application attracts the science in an effort to replace empirical development with scientific rigor. However, the greatest success stories are often found when the science and application advance together.

Advances in the science of low-temperature plasmas have produced great societal benefits. Some of the products and processes include these:

- Computer chips, fabricated using multiple plasma processing steps to deposit, pattern, and remove material at the nanometer scale of modern integrated circuits.
- Plasma television, which has leveraged scientific advances in high-pressure dielectric barrier discharges to become one of the best-selling video displays. They are the forerunners of microplasmas having unique properties approaching quantum effects.
- Textiles and polymers, functionalized by plasmas to produce stain-resistant carpets and waterproof jackets and to prepare plastic surfaces for printing and painting.
- Artificial joints and arterial stents, treated in plasmas to make them biocompatible, reducing the risk of rejection by the patient.
- Fluorescent and high-intensity-discharge lamps, which supply four-fifths of the artificial light for offices, stores, roadways, stadiums, and parking lots. Their higher efficiencies allow them to consume only one-fifth as much power as incandescent lamps.
- Jet engines, which rely on protective plasma spray coatings to protect components subject to the highest temperatures.
- Plasma thrusters and rockets that maintain the orbit of many satellites and propel deep space probes.
- Environmental improvements realized from low-temperature plasma technologies and enabled by improved energy usage and renewable energy sources including plasma-aided combustion, fabrication of large-area photovoltaics, plasma remediation of greenhouse and toxic gases, and plasma destruction of hazardous wastes.
- Low-temperature plasma production of nanoscale materials, from superhard nanocomposites to photonic nanocrystals to nanowires and nanotubes, is one of the key enablers of the nanotechnology revolution.
- Unique materials and coatings for transportation applications, produced using arc-generated direct current and radio frequency thermal plasmas. These range from superhard coatings to nanophase materials that have enabled advances in current and next-generation automotive and aerospace technologies.

The breadth of the science and the importance of the applications place a high premium on the ability to quantitatively predict the behavior of low-temperature plasmas. Obtaining experimental, theoretical, and model-based predictive capability is crucial to integrating the intellectual diversity of the field and speeding advances in low-temperature plasma science that benefits society. Each box in this chapter tells the story of an application of low-temperature plasmas (Boxes 2.1 through 2.7). Each application has its own flavor, giving some idea of the diversity of the approaches that are needed to make effective use of scientific breakthroughs.

The chapter is organized around the scientific topics, issues, and opportunities that underlie the diverse applications of low-temperature plasmas.

INTRODUCTION AND UNIFYING SCIENTIFIC PRINCIPLES

There are recurring and unifying scientific principles behind the extraordinary range of practical uses for low-temperature plasmas. The list of scientific themes is similar to that found in other branches of plasma science, but the details are unique to low-temperature plasmas and their broad range of operating conditions. A notable feature throughout low-temperature plasmas is the close coupling of plasmas with surfaces, leading to unique complexities and feedback mechanisms.

Plasma Heating, Stability, and Control

Depending on the plasma requirements, low-temperature plasmas can be heated by electromagnetic energy ranging from zero frequency (direct current) up to microwave frequency (several gigahertz). The ability to deposit a high density of power is important for many applications, from waste processing to lighting to rockets. The need to control plasmas is illustrated by the extreme cases where plasmas are used to remove a single atomic layer of material or maintain uniformity over square meters of area. *The scientific challenge is to connect charged and neutral particle collisional and collective processes at the atomic level to the behavior of a plasma that can span an area of several square meters.*

Efficiency and Selectivity

The desirable end-product of many low-temperature plasmas is an excited plasma species. In certain environmental applications the goal is to produce ozone, O_3; hydroxyl, OH; or atomic oxygen, $O(^1D)$. For many plasma lamps the goal is to produce mercury atoms in a particular electronic state, $Hg(6^3P_1)$. In fact, 10 percent of all electric power produced in the United States is used to create this one excited atomic state in lamps. *The scientific challenge is to understand the whole of the plasma, quantitatively follow the flow of energy and material, maximize the desirable end product, and minimize deleterious processes.*

BOX 2.1
Reaching the Planets

Plasma-based propulsion systems are already keeping satellites in their proper orbit, and they propelled the Deep Space 1 probe to Comet Borelly. They may also take the first humans to Mars. Plasmas will never launch a rocket into orbit because the instantaneous power requirement is too high, but once in space, the plasma is highly efficient and can reduce fuel requirements by a factor of 100 (Figure 2.1.1). Plasma based electric rockets could have significant commercial advantage over conventional chemical rockets to propel space cargo, said President Bush in his speech, "*The United States Vision for Space Exploration*."[1]

The advantage of plasma propulsion is that its exhaust speed can be very high. This high speed produces a very high efficiency in terms of the momentum that the rocket can give to the spacecraft relative to the mass of fuel consumed (the specific impulse). Instead of being limited by the temperature of a chemical reaction, as in conventional rockets, these devices utilize electric and magnetic fields to provide the driving forces that ultimately accelerate the exhaust particles to much higher speeds. Since the ejected particles move faster, fewer of them are required to achieve the same propulsive effect. This results in lower fuel consumption and higher payload.

To be competitive, plasma rockets must be lightweight and able to handle increasing levels of power in a relatively small package. In addition, given that they must be on for long periods of time, they must be reliable and have long-lived components. One way to meet these goals is to use electrodeless systems where the plasma is created and accelerated by the action of electromagnetic waves rather than by the presence of physical electrodes immersed in the flow. (The latter are severely limited by erosion and wear due to plasma bombardment.) A favored plasma generator for such applications is the helicon discharge developed in the 1970s for the plasma materials processing industry. Significant advances in our understanding of the physics and engineering of these devices has been driven by their application to space propulsion. Major efforts in the packaging of high-power electrical supplies are also under way in support of these technologies.

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[1] George W. Bush, speaking at NASA, "The United States Vision for Space Exploration," January 14, 2004.

Stochastic, Chaotic, and Collective Behavior

Quiescent, uniform plasmas are rarely found outside textbooks. Many low-temperature plasmas exhibit turbulent, chaotic, and stochastic behavior. Arc-generated plasmas used to spray coat turbine blades are usually turbulent. Streamers (filamentary plasmas similar to lightning) branch and wander in high-pressure gases and liquids in unpredictable ways. Even apparently quiescent glows may have striations and surprising collective motion (Figure 2.2.) *The scientific challenge is to understand the conditions that govern the transitions among the different regimes of behavior and to uncover mechanisms for controlling them.*

Plasma Interactions with Surfaces

Low-temperature plasmas are in contact with surfaces that profoundly affect the plasma properties. Even a simple chamber wall intended to be nothing more

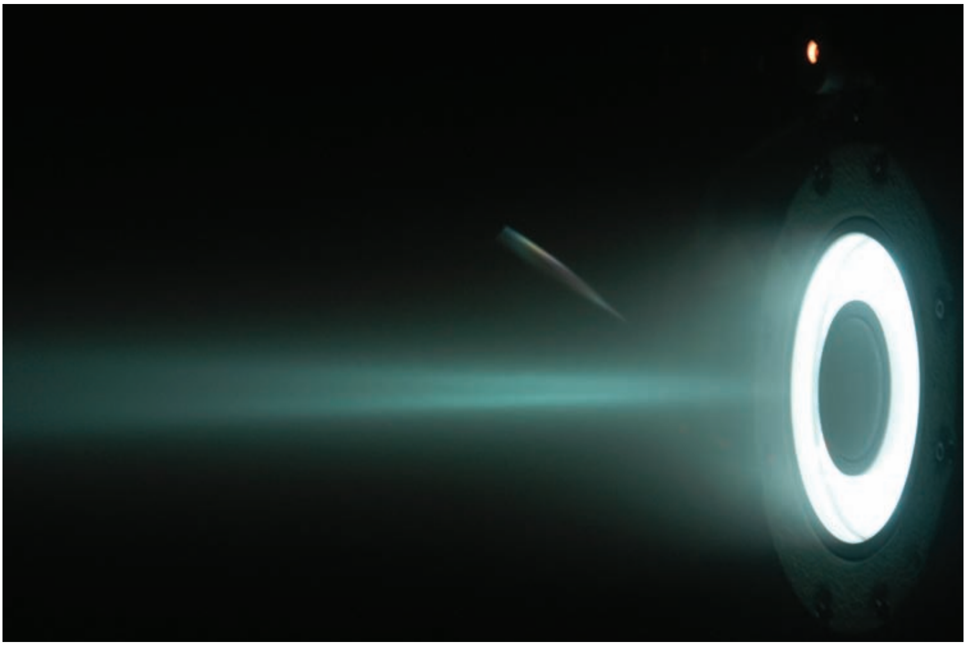

FIGURE 2.1.1 This Hall thruster is just one example of several plasma-based space propulsion technologies. Plasmas are uniquely able to convert electric input power into gas momentum with high efficiency. The technical challenges include the need for very high reliability and long life, which is addressed by managing the plasma–surface interactions within the thruster. Courtesy of NASA.

than an inactive part of the vacuum system can alter a plasma process by collecting or releasing material or by becoming electrically charged. In material processing plasmas, the basic purpose of the plasma is to alter the properties of a surface, depositing or removing material or chemically functionalizing the surface, and returning species to the plasma. Thus the surface is an integral part of the process and can be very complex, up to and including living tissue. *The scientific challenge is to quantify, characterize, and predict the interactions between reactive plasmas with complex surfaces.*

Plasmas in Dusty and Other Nonideal Media

Small clusters (tens of atoms), nanoparticles (a few to tens of nanometers), and larger particles (up to tens of microns) are present in many plasmas. Particles are sometimes a desirable product of a plasma process, as in the case of nanomaterial

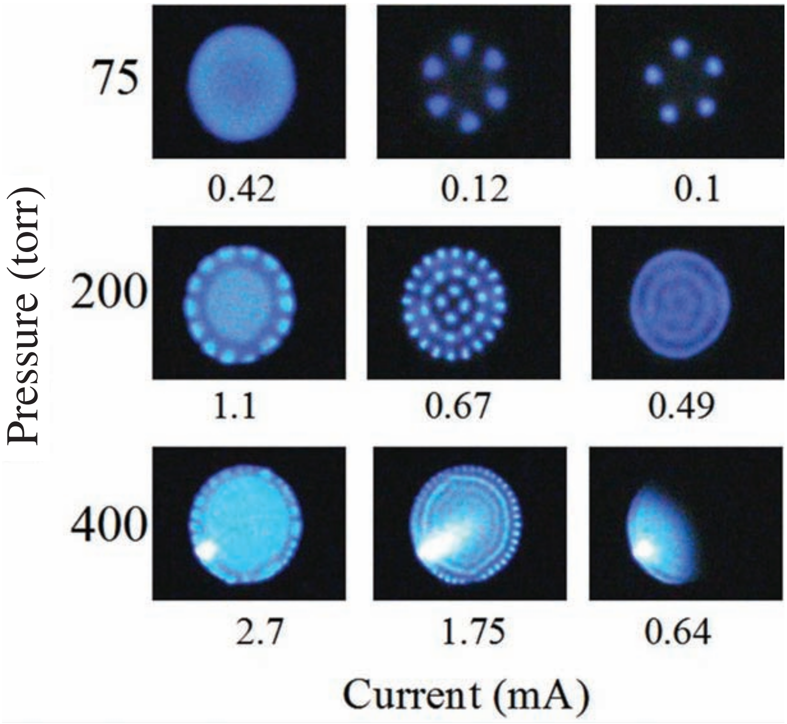

FIGURE 2.2 Plasma interactions with surfaces drive collective effects in near atmospheric-pressure microdischarges. These top-down views show the visible emission from a 750-micrometer-diameter low-temperature plasma in xenon. The patterns result from interactions of the plasma with its metallic and insulating boundaries. SOURCE: K.H. Schoenbach, M. Moselhy, and W. Shi, "Self-organization in cathode boundary layer microdischarges," *Plasma Sources Science and Technology* 13: 177 (2004); © IOP Publishing Limited.

synthesis or spray coating of jet engine components. Conversely, unwanted plasma-generated particles can cause killer defects during microelectronics fabrication. Dusty plasmas exhibit nucleation dynamics, crystal formation, and phase transitions that in many cases are found only in plasmas. *The scientific challenges include leveraging the unique plasma–particle interactions to create new structures and materials and to diagnose nonlinear phenomena.*

Diagnostics and Predictive Modeling

The ability to quantitatively predict the behavior of low-temperature plasmas is not only a test of our fundamental understanding but also has important economic implications because it can reduce the time, cost, and risk of developing new plasma applications. There has been tremendous progress in the development of

BOX 2.2
Making Nanoparticles with Plasmas

A new and exciting application of low-temperature plasmas is their use as controllable sources of nanometer-sized structures (e.g., nanowires, quantum dots, nanoparticles) that have novel physical and chemical properties. For example, low-temperature plasmas can be used to fabricate self-aligned carbon nanotubes, at both low and high pressure, and self-limiting nanowires on electronic materials. Plasma-engineered nanoparticles, often smaller than 10 nm, are being studied for their potential to enhance the properties of bulk materials for strength or ductility or to be used as building blocks for new photonic devices (Figure 2.2.1). Compared to other gas-phase methods for synthesizing such nanoparticles, plasmas have unique advantages. Among these are their ability to reduce particle agglomeration by charging all particles negatively and so have them be self-repulsive, their ability to anneal particles in situ in the plasma by unique plasma–particle interactions, and their ability to keep particles suspended in the synthesis reactor virtually indefinitely until they are used, thereby reducing possible contamination. Plasma-synthesized nanoparticles have already enabled development of new materials and devices, including mixed-phase nanocrystal/amorphous silicon films with improved optoelectronic properties, luminescent quantum dots, particles with improved magnetic properties, nanocrystal-based memory devices, single electron transistors, and cold electron emitters. Given the fast-paced growth of nanotechnology, it is expected that more such applications of "nanodusty plasmas"—plasmas containing nanoparticles—will rapidly emerge.

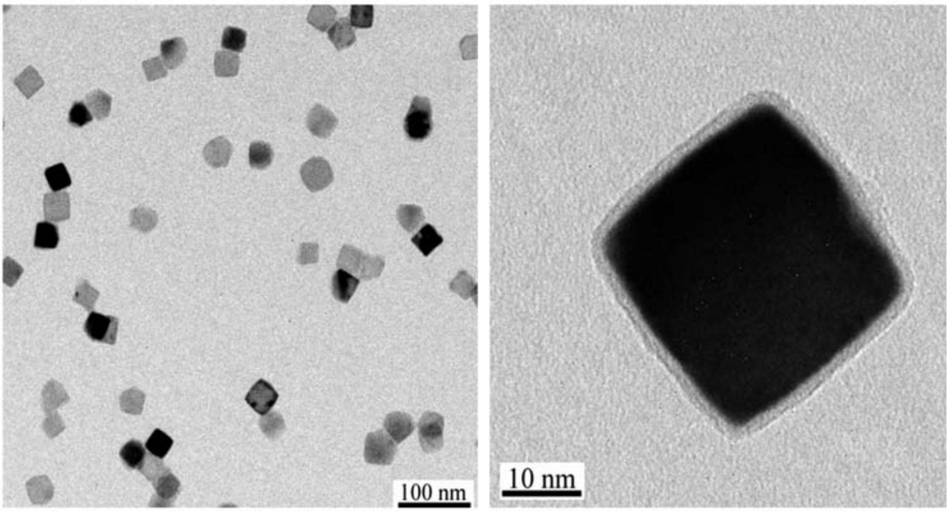

FIGURE 2.2.1 Laboratory plasmas can create an environment having conditions able to uniquely produce nanoparticles. In this example the pristine cleanliness of the plasma environment is needed to synthesize silicon nanocrystals with unique optoelectronic properties. SOURCE: A. Bapat et al., "Plasma synthesis of single-crystal silicon nanoparticles for novel electronic device applications," *Plasma Physics and Controlled Fusion* 46 (2004) B97; © IOP Publishling Limited.

BOX 2.3
Plasma Televisions and Displays

Ask the average person what is meant by a “plasma” and the answer will probably be “plasma television,” a big change from 10 years ago, when the answer would probably have been “blood.” Each pixel in a plasma television set is a self-contained fluorescent lamp capable of switching on and off rapidly enough to display moving images. A dielectric-barrier discharge in a mixture of rare gases produces ultraviolet radiation to excite phosphors and produce a red, green, or blue pixel. As cathode-ray tubes fall into disuse, many displays will soon be powered by plasmas in one form or another. Plasma televisions and computer displays form an image by filtering the light from fluorescent plasma lamps behind the screen, and computer data projectors are powered by very intense, high-pressure plasma lamps operating at internal pressures well above 100 atm and power densities above 100 W/mm^3. The success of plasmas in displays is a significant technological achievement and offers lessons for the future of low-temperature plasma science.

Applications Motivate Science That Impacts Daily Life

The challenges of tiny dimensions (100 µ) and transient operation (50 kHz) of plasma display panel pixels motivated a large effort to develop transient, three-dimensional models of pixel operation and corresponding diagnostics to measure their properties (Figure 2.3.1). The extreme conditions in a projector lamp have driven the need to quantitatively understand the lack of collisional equilibrium even at high pressures, where power transport is dominated by radiation. While it is true that commercial success depends on many factors, plasmas have emerged as a dominant display technology in large part because they are efficient, compact, and inexpensive. Understanding plasma transport is of scientific interest; but it is also required to design the product and meet the performance requirements.

The Large Potential for Economic Impact

The global market for displays is about $110 billion. Once the initial materials and electronics advances had been developed in laboratories in the United States, federal programs quickly ramped down support for continued research in the area. The Japanese and Korean governments, on the other hand, poured millions of dollars into the fundamental science of plasma displays in partnerships with industry. It was those government-led and -funded partnerships that produced the advances that enabled Japanese (and now Korean) manufacturing to take the lead. Because these firms achieved a dominant global market share, they are now able to dictate future trends in the industry. As a result, the United States has a small part of this global market. The absence of a distinctly supported low-temperature plasma science community (in contrast to engineering and application-development work supported by industry) may have contributed to this chain of events. It is beyond the committee’s scope to draw conclusions but within its scope to point out that there are lessons to be learned from this bit of recent history.

science-based, predictive models (Figure 2.3). Detailed diagnostic measurements and modeling can not only reveal the complex dynamics of a plasma but are also part of the work to develop and improve applications of plasmas such as plasma televisions. Nevertheless, modeling and simulation, diagnostics, and the allied

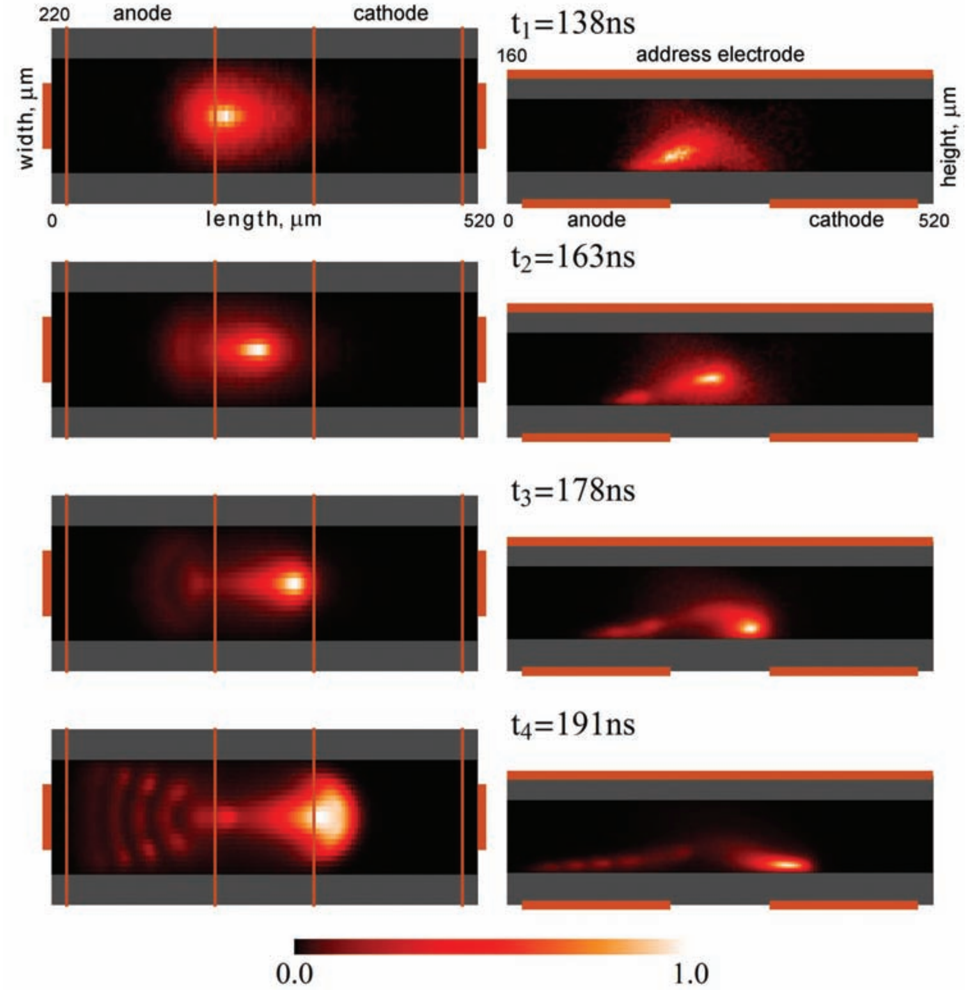

FIGURE 2.3.1 Each pixel of a plasma-display television has three electric discharges (red, blue, and green) having dimensions of a few hundred microns. During a single plasma pulse, complex phenomena occur as shown in this three-dimensional simulation of optical emission. Courtesy of Plasma Dynamics Corporation.

sciences face extreme challenges to develop comprehensive and validated theories, computer models, and material property databases (collision cross sections, reaction and transport coefficients, etc.) that place predictive capabilities in the hands of technologists. *Developing a predictive capability to quantify and advance*

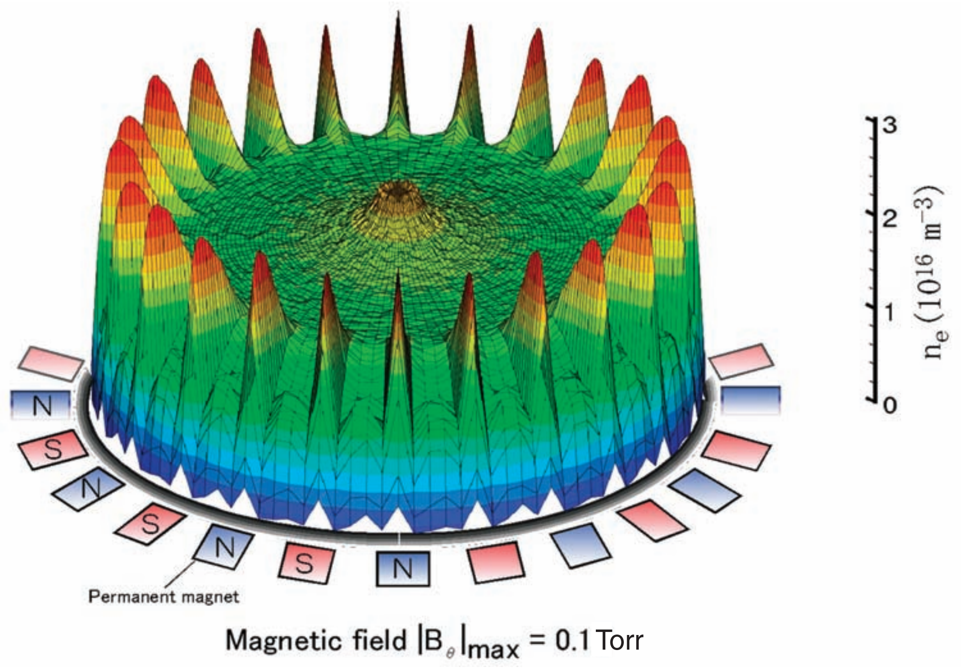

FIGURE 2.3 Advanced particle-in-cell simulation techniques provide a first-principles representation of advanced materials processing reactors such as this magnetron reactor. The electron density is shown as a function of position. This reactor may be used to etch nanometer-sized features or deposit only a few monolayers of metal on 300-mm wafers for fabrication of microelectronics. Courtesy of K. Nanbu, Institute for Fluid Science, Tohoku University.

our understanding of low-temperature plasmas and to leverage that understanding by speeding the development of technologies that benefit society represents the highest level of challenge and the highest potential return.

RECENT PROGRESS AND TRENDS

Low-temperature plasma science and engineering have long been driven by technological applications in disparate fields. For example, the jet turbine coating industry and the microelectronics industry both depend on plasmas, yet their researchers typically have few technical interactions. Advances in nonequilibrium electron transport that resulted from higher dimensional solutions of Boltzmann's equation benefited nearly the entire low-temperature discipline. However, when these advances were applied to investigating phenomena in different technology areas, the discipline fragmented.

The startling advances that result when scientific developments are leveraged across the entire field of plasma science are a model for rapid progress in the next decade. Achieving science advances that enable the development of technologies having great societal benefits often results from a convergence of areas within a field of research and related areas. The convergence between low-temperature plasma science and a related field is perhaps nowhere more evident than with the allied science areas of atomic, molecular, and chemical physics. Although important advances in the science of plasma turbulence can be made by studying plasmas in simple gases bounded by nonreactive surfaces, innovative new technologies will likely arise from research in complex molecular gases in contact with complex surfaces. The knowledge base of fundamental parameters, such as electron impact cross sections and reaction probabilities for ion collisions with inorganic and organic materials, is now inadequate to support those inquiries. The ability to quickly produce that knowledge, using experimental, computational, and theoretical methods, will become even more critical.

Scientific achievements in a diverse field like low-temperature plasmas are not ordinarily publicized in press releases, nor can they be individually characterized in terms of simply stated, high-level milestones like energy sufficiency for the United States. Instead, they emerge only after surveying progress across many disciplines and applications. A few specific examples are presented next, followed by observations about the field of low-temperature plasmas as a whole.

Generation, Stability, and Control of Very Small Area and Very Large Area Plasmas at Low and High Pressures

The generation, stability, and control of plasmas—particularly of large, high-pressure, nonthermal plasmas—face extreme science and technology challenges. Low-temperature plasmas are often used in environments requiring extreme reproducibility over large areas or volumes. One example is plasma deposition over many square meters of substrate area for photovoltaics or flat panel displays with uniformities of a fraction of a percent; another is the etching of a single atomic layer of material for a microelectronic component (Figure 2.4). The development of methods for controlling the stability of these plasmas is critical. Atmospheric-pressure plasmas stand out in this regard since the timescales for developing instabilities are inversely proportional to pressure and may last only a few nanoseconds at atmospheric pressure. Low-pressure plasmas have their own control challenges owing to their nonlocal nature and dependence on reactions that occur on surfaces and the conditions of those surfaces. Advances in the control of plasmas will require a convergence of modeling and simulation, diagnostics, generation of fundamental data, and plasma–surface interactions. The convergence of these areas has made atmospheric-pressure plasmas leading candidates for material processing, environmental, and medical applications at low cost.

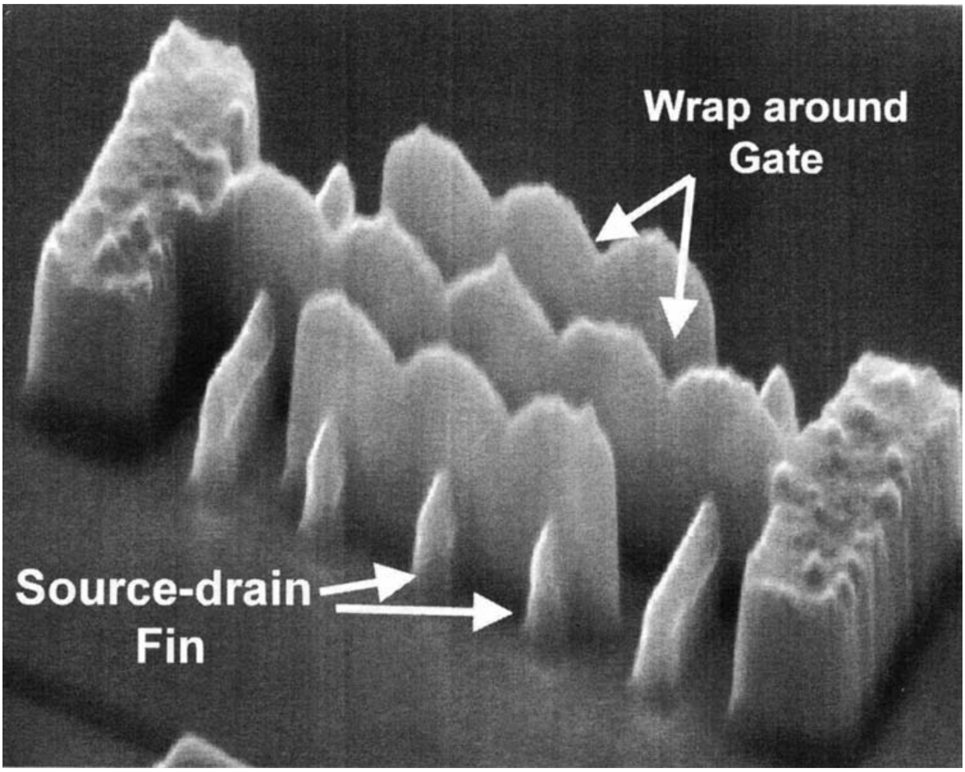

FIGURE 2.4 Future designs for microelectronics devices require fabrication of intricate structures such as this trigate transistor fabricated in silicon having dimensions of only tens of nanometers. Courtesy of R. Chau, Components Research, Technology and Manufacturing Group, Intel Corporation.

A fundamental scaling law of plasmas states that maintaining *pd* (pressure × diameter) and fractional ionization constant should result in similar behavior regardless of the separate values of pressure and diameter. These scaling laws have been leveraged to produce continuously operating plasmas whose dimensions can be measured in microns. Plasmas with continuous power deposition at levels approaching MW/cm^3 at pressures exceeding 1 atm are approaching the realm where quantum phenomena in plasmas may become important. Collective effects, transition to a liquid plasma state, and blurring of the boundary between gas- and condensed-phase plasmas hold unusual promise for discovering new phenomena (Figure 2.5). Extremely high-pressure, high-power, continuous-glow, dischargelike plasmas open the possibility of synthesizing new compounds and materials. It is impossible right now to maintain a conventional glow discharge at

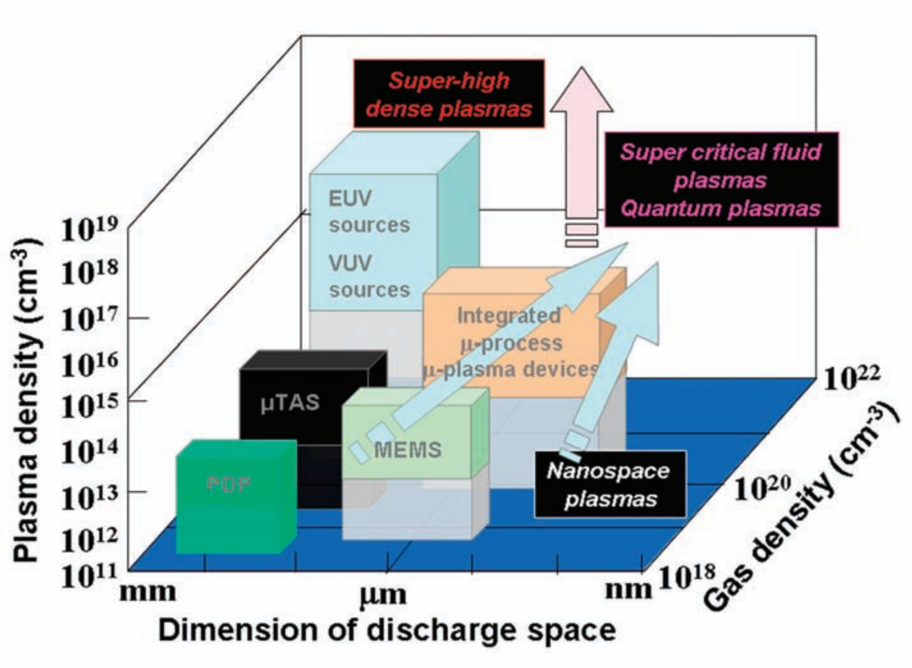

FIGURE 2.5 The scaling of plasmas to smaller size, higher gas pressure, and higher plasma density is leading to unique plasma sources for applications such as lab-on-a-chip and provides a miniature laboratory for the investigation of supercritical and quantum phenomena. Inspired by a diagram from K. Tachibana, Kyoto University. NOTE: EUV, extreme ultraviolet; VUV, vacuum ultraviolet; MEMS, microelectromechanical systems; PDP, plasma display panel; TAS, total analysis system.

low gas temperature in a steady state at power levels exceeding tens of kilowatts per cubic centimeter in a regime where three-body chemical reactions dominate. Thus new compounds, from inorganic to pharmaceutical, could be synthesized using microplasmas.

Very high-pressure projection lamp technology is one example of a microplasma. Projection systems require a compact, high-luminance light source. The current state-of-the-art light source is a mercury arc lamp whose pressure is more than 100 atm, with power dissipation exceeding an average of 100 W/cm^3 and approaching 1 MW/cm^3 based on arc volume. Fundamental science issues must be addressed for this class of photon sources to be advanced. Modeling is indispensable for such compact plasmas because of the cost of fabricating a large variety of geometries using different materials and because experimental diagnostics cannot easily resolve 1 mm^3 of arc. To perform a simple power balance, one must account for nonequilibrium (at 150-200 atm) near the electrodes. In fact, the electrode spot is molten during operation, and the plasma starts to exhibit liquid properties.

BOX 2.4
Pure Drinking Water

Most U.S. public water supplies are treated with chlorine, a generally safe and effective purification method despite persistent concerns about the formation of harmful chlorinated by-products. The use of nonchlorine alternatives has grown substantially in recent years, driven in part by the global scarcity of potable water and in part by concerns about the safety of chlorine storage tanks. Plasmas offer two proven alternatives to chlorine—ozone and ultraviolet treatment—where an improvement in plasma selectivity could have global impact.

Ozone, like chlorine, is a powerful oxidizer produced at the water treatment site by passing air or oxygen through a dielectric barrier discharge plasma. The ozone-enriched gas is then mixed with the water. Ozone leaves no residue in the water, so then there are no harmful by-products of the treatment; at the same time, however, it does not protect against downstream contamination. The fact that no chemical is required and that it can be switched on and off quickly makes it particularly good for systems at the point of water use.

Ultraviolet treatment works by moving water past special ultraviolet plasma lamps that emit radiation in the germicidal wavelength range around 260 nm. The treatment inactivates organisms, meaning that they are not necessarily destroyed but that they can no longer reproduce. The process is effective on most organisms because the absorption and inactivation occur at the basic DNA level. As is the case with ozone, there is no residual and no tank of chemicals, and the process can be powered up and down at will.

Both ozone and ultraviolet plasma water treatment systems are in commercial use in applications ranging from under-the-sink systems to municipal water treatment. New plasma-based methods are also being investigated, such as direct plasma treatment, where the discharge is physically sustained in the water. The total treatment cost is a consideration, particularly in municipal systems. It is a combination of the installation and operating costs, and it is the power density and efficiency of the plasma source that determines the size (initial cost) and electrical efficiency (operating cost) of the treatment plant. In both ozone and ultraviolet plasma sources there is a trade-off between power density and efficiency, so a scientific breakthrough to more selectively generate ozone or ultraviolet light in a more compact space could spread the use of these proven, nonchlorine treatment methods.

The supporting atomic physics must also advance beyond the current state of the art, requiring, for example, a detailed understanding of far-wing line broadening that occurs at extremely high pressure. In this example, interdisciplinary scientific investigation is driven by the need to enhance the performance of a consumer product.

Interaction of Plasmas with Very Complex Surfaces

As the surface being produced or modified becomes more complex, understanding the fundamentals of the interaction between the plasma and that surface becomes more important. It is rare that the surface in contact with a low-temperature plasma is atomically flat. It is often composed of multiple materials or, in some cases, of multiple condensed phases, liquid or solid. The ability to quantify and control plasmas that interact with geometrically complex surfaces having micro- and nanostructures and having different compositions, inorganic and organic, including living tissue, will be critical for advances in cutting-edge fields such as biotechnology and nanotechnology. For example, functionalizing the surface of a porous polymer for a tissue scaffolding to attract only desired cell types is a highly complex process from both topological and chemical perspectives. It was previously thought that plasma interactions with a silicon surface in semiconductor fabrication involved a distinct interface between the plasma and the semiconductor. Now we know that interface to be a highly complex intermixed layer in which plasma-generated particles can penetrate many layers down (Figure 2.6).

As different classes of plasmas are investigated and applied to surface modification, we find another example of a convergence of the field. Low-pressure plasmas are commonly used to modify the properties of high-value materials such as those used in microelectronics devices. High-pressure, filamentary plasmas are typically

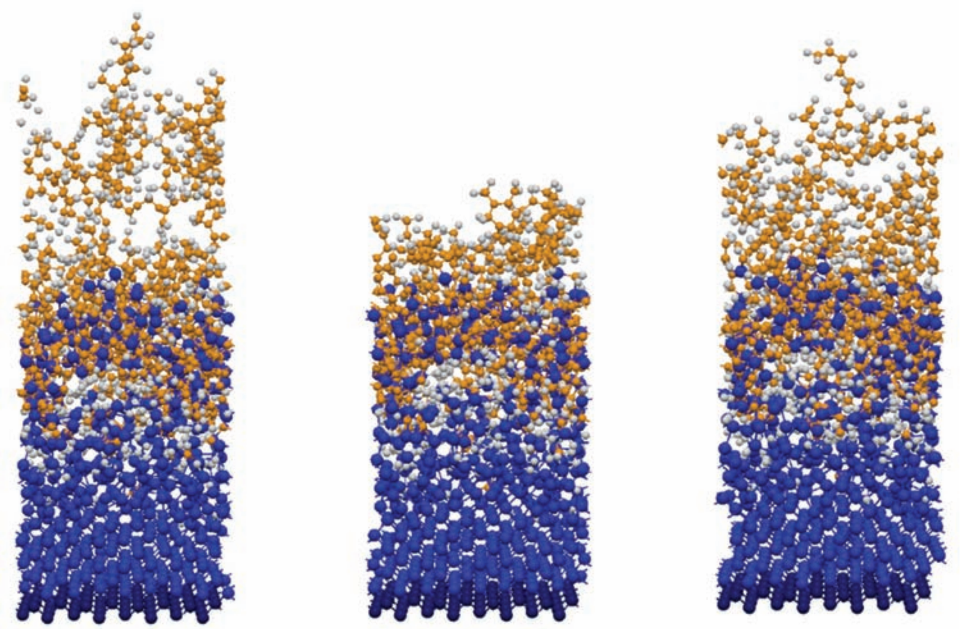

FIGURE 2.6 The profound coupling between plasmas and surfaces in low-temperature plasma science is illustrated by this molecular dynamics simulation of a semiconductor surface during plasma etching. The interaction of reactive plasma species (incident from the top of the figure) onto an initially crystalline surface (shown in dark blue at the bottom of the figure) produces complex intermixed layers that must be understood in detail to give the desired surface and to account for the reaction products that return to the plasma. Courtesy of D.B. Graves and J. Vegh, University of California at Berkeley.

BOX 2.5
Diffuse, Nonequilibrium Atmospheric-Pressure Plasmas

Overviews of low-temperature plasmas often place them in two classes: low-pressure nonequilibrium plasmas and thermal high-pressure plasmas. In the former, the electrons are much hotter than the ions (or neutrals). In the latter, a single temperature characterizes all particles. The two regimes are so different that each has its own set of practitioners who have not benefited from the other's work. Recently, a common middle ground has emerged—atmospheric-pressure, nonequilibrium plasmas (APPs)—that is scientifically rich and has great practical promise.

The advantage of low-pressure nonequilibrium plasmas is that they can be very selective in the excited species or surface reactions they induce, being able to etch a deep trench in silicon to make a transistor while leaving an adjacent nanometer of silicon dioxide untouched. This selectivity comes at the cost of low throughput, expensive vacuum systems, and no utility for biological material that cannot survive in a near vacuum. The great advantage of thermal high-pressure plasmas is that they can process material at a ferocious rate. Megawatts of power can be delivered at temperatures two to five times higher than any combustion process to cut metal or devitrify an entire landfill of hazardous waste. The problem is that their great processing power can be indiscriminate.

The promising middle ground, APPs, operate at high pressure, are nonequilibrium and stable and, in some cases, are diffuse uniform glows (Figure 2.5.1). At one extreme are corona discharges that, in spite of their plasmas being filamentary, on average uniformly process large volumes. At the other extreme are APPs that are truly uniform and diffuse plasmas. Unfortunately, the current parameter space for true glow discharge operation is limited, as is our scientific understanding of them. For example, do such plasmas depend on specific collision processes such as associative ionization?

Science advancements in APPs have already yielded tremendous benefits. Large-area plasma display televisions and functionalization of polymers are both outcomes of improved fundamental understanding of APPs. There is great additional practical promise for APPs, particularly glows. Think of large sheets of material—plastics, textiles, solar cells, organic electronics—being processed without costly vacuum systems. Think of converting garbage into hydrogen fuel and valuable metals. Think of performing surgery with a plasma instrument that can discriminate between individual cells. The full promise of APPs will be known only if they can be understood and managed based on fundamental scientific principles at two extremes—the nanoscopic kinetic level, where selective chemistry occurs, and the global stability level, likened to aerodynamics.

used to modify the properties of low-value materials, such as polymer sheets. As the value of materials increases and atmospheric pressure plasmas become more glowlike, the science, techniques, and application of low- and high-pressure plasmas interacting with nonideal surfaces converge.

Turbulent, Stochastic, and Chaotic Behavior of Complex Plasmas and Plasmas in Liquids

Diagnosing, predicting, and understanding the unique properties of plasmas sustained in liquids, supercritical fluids, and multiphase media such as aerosols (e.g., dusty plasmas) will reveal new and unexpected physical phenomena and will provide a knowledge base for new technologies. Nonideal plasmas dominated

FIGURE 2.5.1 The control of atmospheric pressure plasmas will provide the ability to economically treat complex surfaces, up to and including living tissue. Courtesy of R. Hicks, Surfx Technologies LLC.

by the collective effects of charged grains in dusty plasmas are challenging basic theories. Experiments are just emerging to determine the fundamental properties of plasmas sustained in conventional and supercritical fluids, which have charged transport dominated by interactions with clusters (Figure 2.7). The band bending that occurs at the surface of microplasma sources with electric fields of many hundreds of kilovolts per centimeter is sufficient to merge the continua of the solid and gas phases.

The ability to diagnose, predict, and manage the transition from deterministic behavior is critical to the development of new technologies. These challenges ultimately involve the convergence of time and length scales that vary over many orders of magnitude.

Control of fluid dynamic instabilities in high-pressure plasmas (shear layer

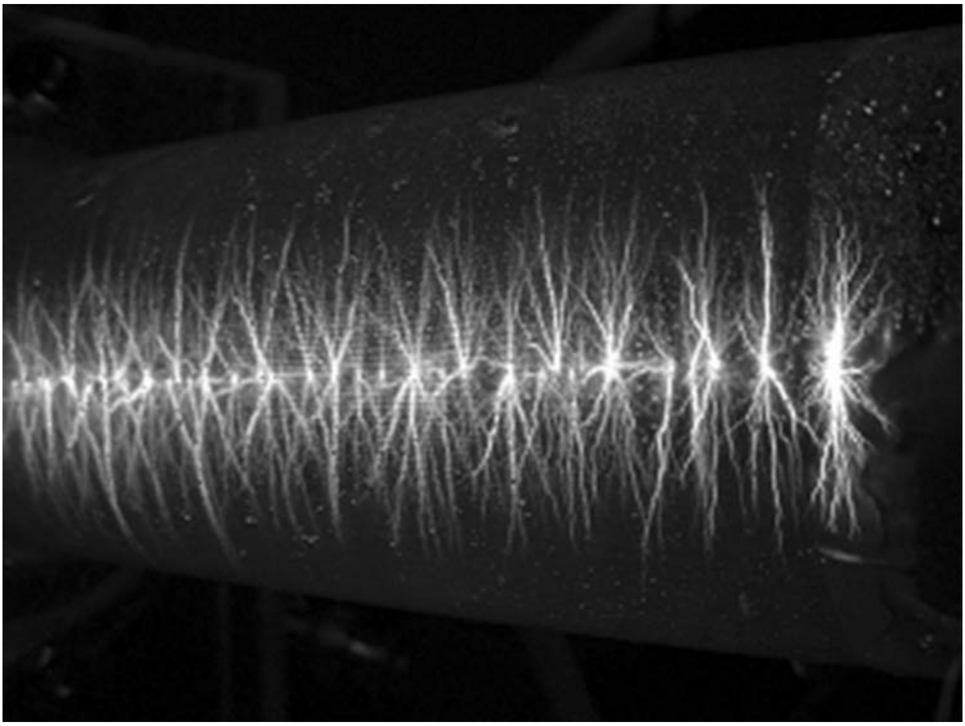

FIGURE 2.7 Electric discharge plasmas in liquids typically have complex streamerlike structures that produce gaseous radicals capable of remediating contaminants. Predictions of plasma behavior require a proper treatment of a hierarchy of temporal and spatial scales to capture the essential properties of chaotic processes such as these streamers and to predict the behavior of the whole plasma remediation process. © 2005 IEEE. SOURCE: A. Malik, Y. Minamitani, S. Xiao, J.F. Kolb, and K.H. Schoenbach, "Streamers in water filled wire-cylinder and packed-bed reactors," *IEEE Transactions on Plasma Science* 33: 490 (2005).

instability and turbulence) represents a fundamental challenge for technological applications such as plasma spraying. Spatial gradients can be so steep that a continuum description of heat and mass transfer may break down even at pressures of many atmospheres. The need to develop new modeling and diagnostic techniques that function at vastly different spatial scales having different physics at both low and high pressure reflects the convergence of the discipline.

In the case of dusty plasmas, the stochastic nature of particle charging leads to fluctuations in plasma–particle interactions. Models of particle charging by electron and ion collection usually assume that the particle surface is at the floating potential. However, due to its small capacitance and the discrete nature of its charge, a particle less than 10 nm in diameter (the most interesting size for many

BOX 2.6
Cleaner and More Efficient Use of Fossil Fuels

One of the keys to energy independence is the more efficient use of fossil fuels by methods that are also environment friendly. Common internal combustion engines in fact use a plasma (the spark plug) to initiate reactions in the cylinder to bring about combustion, which moves the piston. The manner in which this initiating plasma is created has important repercussions for the efficiency of the entire combustion process. One method now being investigated is to optimize the transient properties of the formative phase of the plasma—during the breakdown period, which lasts only tens of nanoseconds—to create precisely the radicals required to initiate efficient combustion. These transient plasmas have significantly higher fractions of energetic electrons (in excess of 10 eV) and, at atmospheric pressure, usually involve streamers. During the few nanoseconds of streamer propagation, electrons can efficiently produce radical species. The end result is that plasma-assisted combustion may allow extending ignition to leaner burning conditions, thereby reducing emissions or even enabling alternative fuels that are now not practical (Figure 2.6.1). At the other extreme, plasma-assisted combustion may facilitate the development of advanced propulsion concepts such as SCRAMjets or the use of plasma coatings on turbine blades in jet engines to shape the airflow and allow conventional propulsion systems to operate more efficiently.

Obtaining these benefits will require a truly interdisciplinary effort combining the expertise of plasma experts in investigating the fundamental properties of transient plasmas, pulsed-power experts to develop the electronics required to drive the transient plasmas and combustion and fluid dynamics experts with knowledge of fundamental combustion processes.

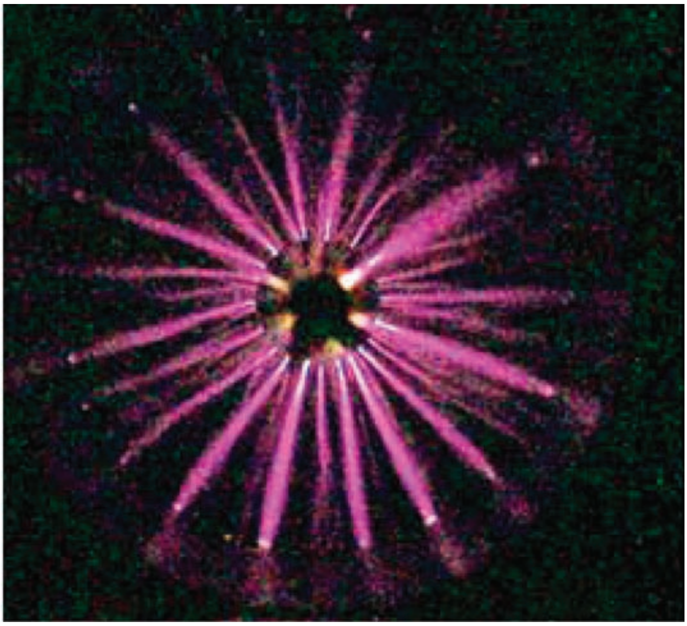

FIGURE 2.6.1 A short-pulse, high-voltage plasma sustained in a combustion chamber creates initiating radicals for the flame. This may produce both higher combustion efficiencies and use of alternative fuels. © 2005 IEEE. SOURCE: J. Liu, F. Wang, G. Li, A. Kuthi, E.J. Gutmark, P.D. Romney, and M.A. Gunderson, “Transient plasma ignition,” *IEEE Transactions on Plasma Science* 33: 326 (2005).

BOX 2.7
Energy-Efficient Lighting

Since the last decadal survey it has been reported that low-pressure metal halide discharge plasmas can produce ultraviolet radiation with efficiency comparable to the mercury plasma in fluorescent lamps. The plasma conditions are not dissimilar to those present in traditional fluorescent lamps, but instead of mercury the active component of the working gas is a metal compound such as indium iodide. This is the first time since the introduction of the mercury fluorescent lamp around 1940 that any low-pressure plasma light source has shown the potential to match the efficiency of the mercury fluorescent lamp.

If these new light sources become economically important, they will spawn a new interest in the science of plasmas in molecular gases. These are chemically complex plasmas far from Boltzmann or Saha equilibrium. Because only a tiny fraction of the data needed to understand their operation is available for metal halides from traditional measurement techniques, computational models have been built that make extensive use of ab initio and semiempirical methods to generate the required input data (electron-impact cross sections, and gas and surface reaction rate coefficients). The spectrum of radiation emitted from the plasma is that of the metal atom, indicating that nonradiative power loss mechanisms such as molecular dissociation and vibration can be managed, and also that the metal halide molecules can reform in a closed system with relatively cool surfaces.

Plasma light sources—fluorescent and several types of high-intensity-discharge lamps—produce four-fifths of all the light used in general lighting: stores, factories, offices, homes, parking lots, and roadways. The remainder is produced by incandescent lamps. Without energy-efficient plasma light sources there simply would not be large, brightly illuminated spaces, indoors or out, and the average office worker might still be working under a single incandescent lamp and wearing a green eyeshade. Even so, lighting accounts for a large portion of the national energy bill, 22 percent of all electricity produced in the United States, and contributes a proportionate amount to greenhouse gas emissions. Moreover, a substantial fraction of the electrical power expended for air conditioning goes to remove heat produced by inefficient lighting. Improved lamp efficiency and life come from improvements to plasma selectivity and management of plasma–surface interactions. Solid-state light sources are encroaching on plasmas, but in the absence of a breakthrough in either technology or price, recent projections are that they will account for less than 10 percent of the total lumens produced for general lighting in 2020.

technological applications) may not be at the floating potential for any of its charge states. This will require new theories of particle charging.

Reliable Quantitative Prediction of Plasma Behavior

The most popular use of low-temperature plasmas is to selectively activate atomic and molecular species to generate a product, such as photons for lighting or radicals for the deposition of films. Understanding the fundamental mechanisms that allow power to be efficiently channeled into preselected atomic and molecular states, resulting in, for example, predictable surface structures, is critical to generating these products in environmentally and economically friendly ways. An important example is the use of low-pressure plasmas to produce otherwise unattainable structures such as nanocrystals for quantum dots. These structures evolve in a narrow range of operating conditions where the precursor chemical species, the form of the activation energy, and the temperature are synergistic. The ability to plasma deposit biocompatible films that can tether desired molecules requires that the film have a precise composition, morphology, and, in some cases, molecular structure. The development of highly efficient plasma lighting sources that contain no mercury requires excitation of specific electronic states of the atoms or molecules. Selectively removing a toxic compound from exhaust or generating initiating radicals to speed the rate of combustion requires precise control of the energy pathways in the plasma.

The ability to produce specific atomic or molecular states or chemically active radicals in a particular sequence or location requires the energy distributions of charged and neutral particles to be precisely tailored through the manipulation of the electric and magnetic fields, in space, time, and frequency domains. This may, for example, require an electron distribution to be peaked in a narrow range of energies in a specified volume. Although these abilities exist, in principle, by intersecting electron and molecular beams, technologically important methods may require such selectivity over several square meters and so require less expensive and more easily scaled techniques. Scientific advances in chemically selective plasmas will make it practical to apply these unique conditions to large surfaces.

Emergence of Diffuse, High-Pressure Nonequilibrium Plasmas

The increasing focus of research and technology has resulted in the realization of large, diffuse, high-pressure plasmas that operate on a quasi-continuous basis. These plasmas are notable because they fall outside the limits of conventional plasma scaling and stability. They have great promise both for practical application, and also as a unifying platform for future low-temperature plasma science research.

FUTURE OPPORTUNITIES

Low-temperature plasma science and engineering differ from other areas of plasma science in the larger share of resources devoted to applications than to fundamental science. The total effort expended in applying plasmas to practical problems in industry is massive compared with the effort expended on any conceivable change in the resources allocated to low-temperature plasma science. It is therefore critical to identify and focus on scientific opportunities that are important to the field as a whole but are not addressed by industry. Many such high-impact areas do exist, not only for plasma science itself, but also for institutional, collaborative and funding arrangements. These opportunities were discussed in the preceding sections. Some specific challenges are presented here as examples.

Basic Interactions of Plasmas with Organic Materials and Living Tissue

A basic question for any use of plasmas for surface modification is, Which plasma species should be brought to the surface to achieve the desired result? And, when that has been done, Which species are returned to the plasma? Plasma scientists and technologists are beginning to be able to answer the first question, to conceive and arrange diffuse, high-pressure plasmas to deliver a specified flux of species to surfaces. However, at present it is unclear which species and conditions have beneficial effects on biological and biologically compatible materials, beyond the relatively nonselective use of plasmas to destroy pathogens. The starting point in deriving the full benefit of plasmas in biotechnology and healthcare is to understand the behavior of biologically compatible materials and living tissue in contact with plasmas, the species that must be generated in the plasma, and the species produced on the surface of (or inside) the tissue.

Lessons can be learned from the development of plasmas for semiconductor processing. Early work to understand the mechanisms of etching in idealized systems—in high vacuum, with carefully prepared surfaces and well-controlled fluxes of radicals—has been of enduring value for the field, despite the great variety and complexity of semiconductor processing chemistries. Semiconductor processing applications also taught plasma scientists the importance of the reaction products in the plasma, an example being the formation of particulates that in turn caused killer defects in the devices being fabricated. The identification of surrogate biological materials that can be used during the development of plasmas for important biomedical applications would be of great value for this emerging field.

Methods to Describe the Behavior of Plasmas That Contain Chaotic and Stochastic Processes

Low-temperature plasmas have always been considered as being “hierarchical,” “multiscale,” or “hybrid.” That is, the important plasma phenomena were categorized according to the spatial scale or the timescale and linkages made between those hierarchies. It has not to date been practical to integrate electron trajectories in a plasma torch or to consider the molecular dynamics of a surface exposed to incident radicals in a manner that is fully integrated with reactor-scale phenomena. Many of the most promising emerging applications of low-temperature plasmas are inherently stochastic in their basic nature, examples being the nucleation and charging of nanoparticles in plasmas, fluctuations in the anode arc attachment in plasma spray torches, the processing of irregular coal particles to reform hydrogen, atmospheric-pressure plasma streamers for plasma-aided combustion, and the generation of plasmas in liquid saline solutions for plasma-assisted surgery (Figure 2.8). This is an opportune time to develop general computational and

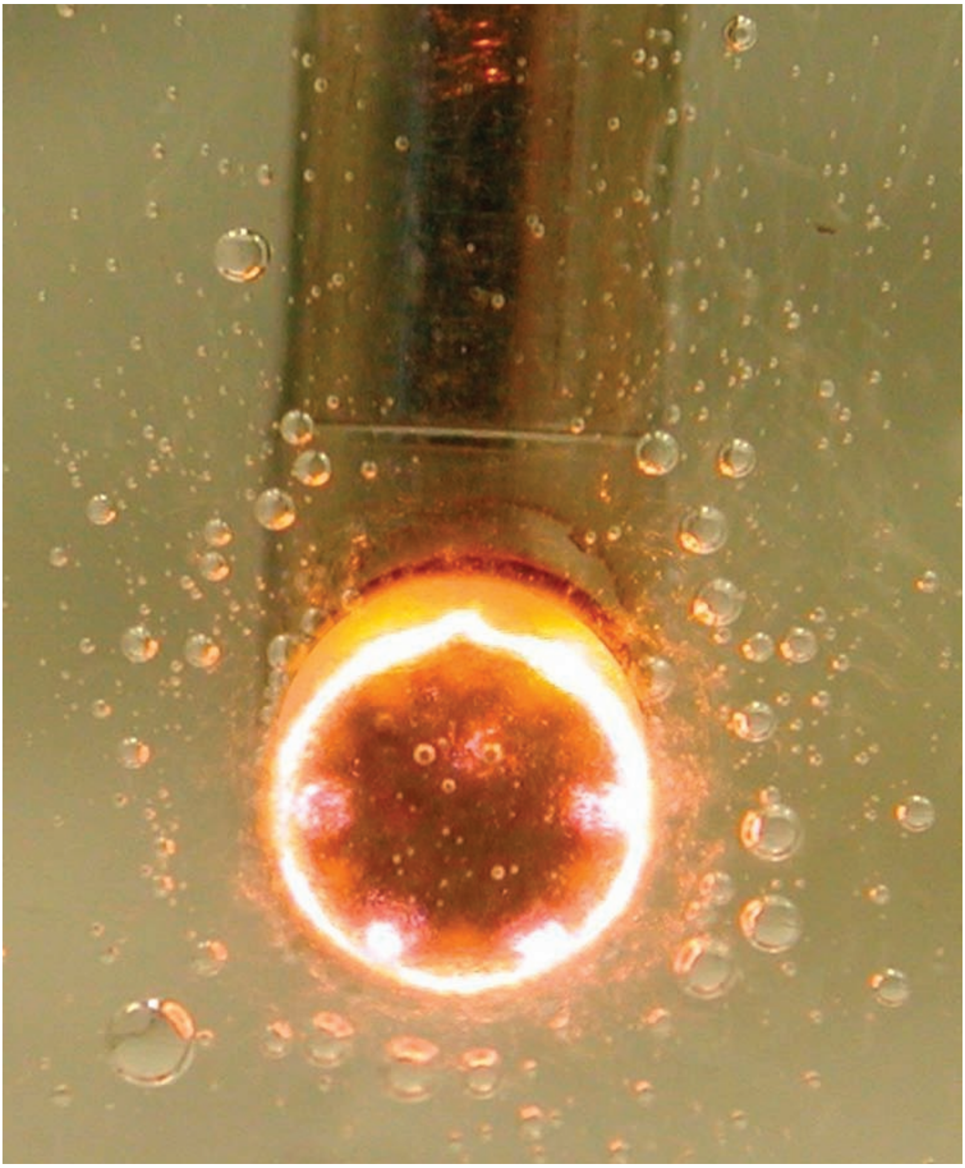

FIGURE 2.8 Plasma surgical instruments are in clinical use for cutting and cauterizing. The instrument shown here can sculpt tissue by producing reactive gaseous species under a liquid saline solution; the orange light is emitted by sodium atoms from the solution. Scientific advances on the interaction of plasma species with living tissue may lead to much more selective and beneficial use of plasmas in medicine, analogous to the fine control that is now exercised in semiconductor processing plasmas. Courtesy of K.R. Stalder, and ArthroCare Inc. SOURCE: K.R. Stalder and J. Woloszko, “Some physics and chemistry of electrosurgical plasma discharges,” *Contributions to Plasma Physics* 46 (1-2): 64-71 (2007). Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

diagnostic methods to treat these complex, stochastic, and multiscale processes. These methods should be integratable with more global hierarchical approaches.

Stability Criteria for Large-Area, Uniform, High-Pressure Plasmas

Atmospheric-pressure-glow plasmas hold great promise for advanced applications because they combine the selectivity of a low-pressure nonequilibrium plasma with the high power and throughput of high-pressure thermal plasmas. The basic stability criteria of these plasmas are only partly understood, yet it is these criteria that will ultimately determine the practical use and benefit of plasmas. For example, how might an atmospheric-pressure-glow discharge be sustained in a highly attaching gas mixture over many square meters of nonplanar surface with a uniformity of processing to within a few percent? It is important to develop a fundamental understanding of the instabilities that occur in these plasmas and to identify methods to manage them. These methods may be unique to low-temperature plasmas and to specific applications of these plasmas, but it is also the case that other areas of plasma science have made great strides in both passive and active instability control.

Interaction of High-Density Plasmas with Surfaces

Microplasmas, with their very high concentration of charged particles and dc operation, represent a new regime of operation and science for the field of low-temperature plasmas. A particular feature of microplasmas is that the plasma electrons may merge with the electrons in the materials that confine the plasma, and quantum effects can become important. There are many potential applications for these plasmas, ranging from extremely sensitive detectors to laboratories for studying nonideal plasma phenomena, and there is considerable enthusiasm for how their unique properties might be used. What is needed now is a basic understanding of the interaction of these high-density plasmas with surfaces, to lay the foundation for future applications.

Flexible, Noninvasive Diagnostics

As the complexity of plasma phenomena increases, the need for noninvasive diagnostics capable of extreme spatial and temporal resolution also increases. Important plasma phenomena are increasingly more transient, have shorter scale lengths, and may involve dust or liquids (Figure 2.9). The users are also becoming more diverse, as the field expands into new areas such as biotechnology. Current generations of diagnostics that have served the discipline well may not be suited

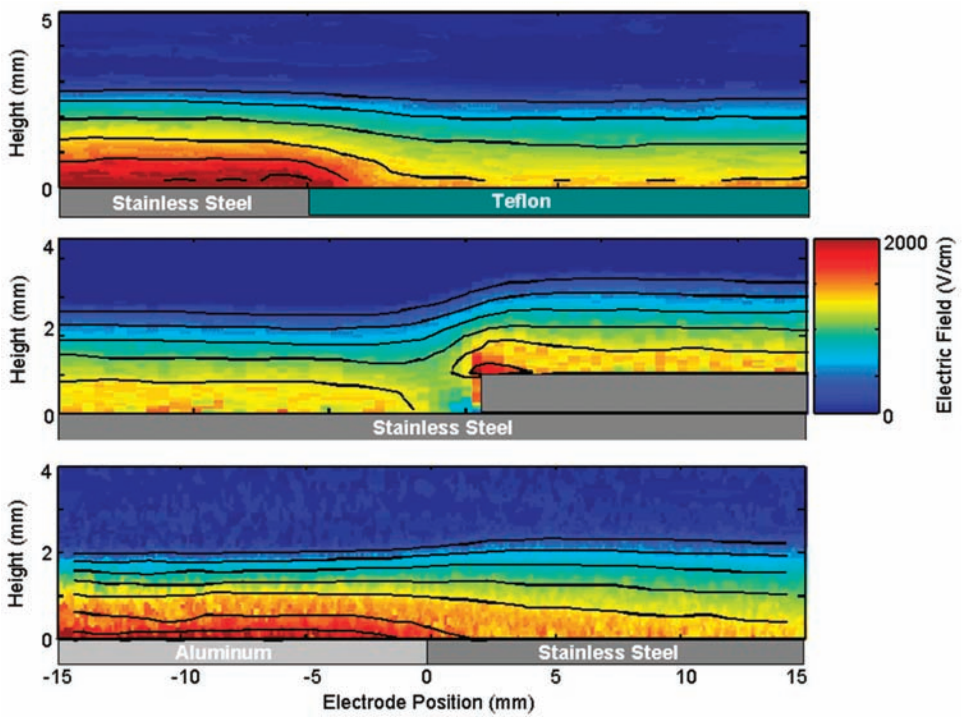

FIGURE 2.9 Noninvasive diagnostics provide insights into complex phenomena occurring in plasmas. Here electric fields above the electrodes of a semiconductor processing plasma are measured using laser-induced fluorescence. Courtesy of G. Hebner, Sandia National Laboratories.

for addressing the complexity described here. For example, conventional Langmuir probes may perturb the plasma; considerable effort must be expended to produce optical emissions that provide quantitative information; and absorption techniques, both optical and microwave, typically only provide two-dimensional information. The field is in need of new diagnostics that are general and can be used by nonspecialists as well as highly specialized diagnostics for specific purposes. For example, at one extreme are tomographic methods that provide nanosecond, three-dimensional resolution of the onset of instabilities at atmospheric pressure. At the other extreme are sub-Debye length, wireless-enabled sensors fabricated using microchip technologies that, dispersed in a plasma, radio back three-dimensional maps of plasma properties. Diagnostics are also required that address the critical plasma–surface interface, that assess the state of the surface, and that can be integrated into real-time-control strategies.

Fundamental Data

Predictive models and optical diagnostics in low-temperature plasmas rely on fundamental data such as material properties, cross sections, and reaction rate coefficients for both gas-phase and surface processes. Although plasma chemistry models for complex systems interacting with surfaces may have hundreds of reactions, the corresponding fundamental data are not available in the archival literature. The experience of the field throughout the development of semiconductor processing plasmas over the past two decades is that traditional laboratory measurements of these properties cannot keep pace with what is needed for the rapid development of the applications and changes and investigation of process chemistries.

In the past decade, the appetite for input data has motivated significant efforts to develop databases using a variety of techniques, ranging from ab initio to semiempirical methods and scaling laws. The multipronged approach has been successful in several applications, notably (1) metal deposition chemistries for semiconductor manufacturing and (2) lighting plasmas. The success of this approach rests on the recognition that it is more important to develop a data set or reaction mechanism that describes the plasma as a whole rather than a deep understanding of any given microscopic process. As such, a data set is a self-consistent list of reactions and corresponding data that can be used to predict plasma behavior with sufficient fidelity over a specified range of conditions. The best data sets are a careful trade-off between accuracy and generality on the one hand and the effort to develop them and the computational effort to make use of them on the other. Good data sets can even be used to identify critical processes where additional accuracy is justified.

The refinement of these data estimation methods so that they can be used with confidence by plasma scientists is an important activity. Even with robust data estimation methods, low-temperature plasma science will continue to support the atomic and molecular physics community, particularly the collision physics community, as a vital source of fundamental data without which progress in low-temperature plasmas would be much slower. Because the stewardship of this research has been almost entirely ad hoc, there are few guarantees for the future. Thus, in spite of its importance, the ability to make fundamental measurements—of, for example, electron impact cross sections—or the ability to compute such values is in danger of being lost in the United States unless the priorities change. Moreover, the lack of a clear federal commitment to this research makes such research unattractive to universities, and they are unlikely to hire new faculty with this expertise.

THE INTERNATIONAL PERSPECTIVE

The German Ministry for Education and Research (BMBF) has published several reports on low-temperature plasma research. *Evaluierung Plasmatechnik* stands out for its extensive use of surveys, data analysis, and economic assessment. *Plasma Technology: Process Diversity and Sustainability* is an English-language document that generally parallels and amplifies the applications and opportunities cited in the German-language report. From *Evaluierung Plasmatechnik* one learns that

- The United States is world-class in the development of low-temperature plasma devices and systems, along with Germany and Japan; France, the United Kingdom, Italy, and Russia are in the middle. China and Korea are investing heavily.
- In Japan some $30 million is devoted to research in low-temperature plasmas by various Japanese agencies. The focus areas are plasmas for transitioning microelectronics to nanoelectronics, solar cell production, carbon nanotube production, and catalysis.
- Cross-disciplinary programs and industrial group projects are important, and the German model uniquely brings academic research together with medium and large companies. Over the period 1996-2003, the BMBF invested €63.7 million (approximately $80 million) into 34 such cooperative projects.
- Some 350,000 German manufacturing jobs depend on plasma processes that are indispensable for the technology involved, representing $64 billion per year of economic activity. Sales of plasma sources and systems amount to $35 billion per year.
- In the United States there is no centralized organization to promote plasma technology development, and correspondingly no multiyear vision for the field.
- U.S. priorities are shaped by a long and complex process involving many people. U.S. organizations have no specific plasma emphasis. Indeed, a national initiative to support cross-disciplinary plasma research is lacking altogether in the United States.
- The emerging use of plasmas in life science is a U.S. strength not only because it necessitates interdisciplinary research but also because of U.S. strength in biotechnology.
- The United States is weak in the training of new plasma scientists, but it compensates by attracting scientists from all over the world.

Evaluierung Plasmatechnik notes a confusing divergence of opinion about the progress of the United States in low-temperature plasmas. The United States is rated as strong by most of the rest of the world but as weak by those working here. The committee proposes that this disparity occurs because external assessors base their observations on end products like computer chips. The United States is indeed a formidable competitor in this and other areas that involve plasma science, but for reasons that go far beyond the state of the science. Although this committee is not expert in global economic trend analysis, it believes that the entrepreneurial spirit, system of laws, and access to capital are also important for commercial success.

From another perspective, one can examine the level of U.S. participation in the professional and international low-temperature plasma community. Recent international benchmarking exercises have proposed looking at the proportion of papers presented by U.S. university researchers at scientific conferences. For instance, at the recent 2006 Gaseous Electronics Conference, the premier such conference in the United States, fewer than half of the papers came from U.S. authors. Fifteen years ago, this conference would have been dominated by papers from U.S. authors. Journals such as *Transactions on Plasma Science*, once dominated by U.S. authors in the subdisciplines of low-temperature plasmas, now are highly international. In turn, U.S. authors have low participation rates in foreign journals such as *Journal of Physics D* in the subdisciplines of low-temperature plasmas.

THE ACADEMIC PERSPECTIVE

There is currently no regular federal program dedicated to support the science of low-temperature plasmas at universities in the United States (see Appendix D for a brief survey of identifiable sources of public funding). Rather, the science is advanced within larger programs, both private and public, to develop specific technical applications that use plasmas. For example, the National Nanotechnology Initiative is a notable source of funding for developing nanotechnologies that use low-temperature plasmas. Much good plasma science is done within such programs. In fact most of the scientific highlights described earlier in this chapter came out of such applications-directed work. However, the amount of research on fundamental low-temperature plasmas attributable to areas such as materials processing and nanotechnology is tiny at best and the arrangement is ultimately unstable. Faculty appointments are based, in part, on the prospect for substantial, continued funding, leading to commensurate scientific breakthroughs and recognition in a science area. It is the committee's judgment that without a reliable source of funding for fundamental investigations in low-temperature plasmas, there will be soon be no faculty. Without faculty there can be no course development, textbooks, workshops, graduate theses, or scientists educated in the field entering the workforce. It is for this reason that the committee concludes that in the absence of clear action, low-temperature plasma science as an academic discipline will probably soon cease to exist in the United States. The loss of an academic basis for low-temperature plasma science would not only undermine the U.S. ability to train experts in this field but would also significantly reduce the capacity for U.S. innovation in the field.

In K-12 education, exposure to plasma science is essentially nonexistent. Plasmas are not a standard topic in introductory or required physics courses at the undergraduate level. At the graduate level, the highly interdisciplinary nature of low-temperature plasma science and engineering has caused plasma-related education to be fragmented across several academic disciplines. While physics departments are obvious homes for courses in plasma physics, the majority of scientists and engineers involved in low-temperature plasmas are trained not in physics departments but in any of several engineering disciplines (e.g., chemical, electrical, mechanical, aeronautical), chemistry, or materials science. Only a few universities in the United States offer graduate courses in low-temperature plasma physics, and in only a few academic universities does one find a critical mass (more than a single faculty member) of research activity in low-temperature plasmas. This situation stands in stark contrast to several relatively large research laboratories dedicated to low-temperature plasmas at academic institutions in Europe (Ireland, Italy, France, Germany, and the Netherlands) and in the Far East (Japan and Korea).

The U.S. funding situation deteriorated in stages since the last decadal survey. At that time, some low-temperature plasma science was supported by the Office of Naval Research, the Air Force Office of Scientific Research, the Office of Basic Energy Sciences at DOE, and the National Science Foundation (NSF). The NSF ERC for Plasma-Aided Manufacturing was still active at the University of Wisconsin and the University of Minnesota, and some research has been supported through Presidential Young Investigator grants. The NSF-DOE Partnership on Basic Plasma Science provided some funding during this time as well. Since the last decadal study, more than half of the funding sources for low-temperature plasma science have either disappeared or been dramatically reduced. As the committee prepares this decadal survey it can say that U.S. public funding is insufficient for young researchers to build and sustain a research program in the field. A result is that few if any openings for junior faculty exist in low-temperature plasma science, because academic departments are unlikely to seek faculty in areas that have such poor prospects for funding.

The interdisciplinary nature of low-temperature plasma science has impeded the kind of discipline-based evolution that enabled other fields to maintain large centers of research, education, and training at U.S. universities. At the same time, however, it provides exceptionally fertile ground for interdisciplinary education and training activities, provided that appropriate linkages can be built across academic departments, institutions, and private industry. This will require proactive and sustained support at the national level. For example, a new application of plasma science usually brings with it the need for a new, completely different skill set, such as a clinical researcher who is developing surgical plasma instruments. A highly effective approach, in view of the cross-disciplinary nature of the opportunities, is to have a balanced mix of investigators from very diverse disciplines. The fundamental plasma science is investigated in the context of an application, to optimize the relevancy of the science while speeding the development of the technology. It is difficult to imagine a more fertile environment for the education of young scientists and engineers.

THE INDUSTRIAL PERSPECTIVE

The true industrial viewpoint is the global perspective, in that companies operate in a globally competitive environment, and low-temperature plasma science transcends national boundaries. The U.S. perspective reflects a concern for the health of U.S. science, education, and industry within the global environment.

Industries that rely on low-temperature plasma technologies are no different than other industries that must globally compete. There is a constant need to innovate, to protect intellectual property, to focus on the highest value-added activities, to move quickly, and to manage risk. In short, it is an environment where time is money and where great value is placed on predictive capabilities that are accurate and reliable. The ability to understand and predict plasma behavior from a solid foundation of plasma science is the central theme of this report. A robust U.S. effort in low-temperature plasma science, reinforced by the competitive strength and entrepreneurial spirit of the United States, can convert the benefits of the applications not only into benefits for our nation but also into global benefits.

From the perspective of industry, education, training, and texts in low-temperature plasmas are scarce at all levels, from B.S. to Ph.D., pointing to a dearth of plasma science faculty to develop and teach such curricula. There is no core set of diagnostics, codes, and data to be nurtured, so that improvements and breakthroughs are not leveraged across the field. This points to a lack of coordination and stewardship of the field. There have been, and continue to be, cooperative arrangements between industry and academia—for example, the Semiconductor Research Corporation—but such arrangements are far more common outside the United States—for example, Germany's BMBF and Japan's MITI.[1]

Low-temperature plasmas already have global importance, and their impact is likely to grow. Companies of all sizes, from one-person start-ups to the world's largest industrial companies, contribute to and benefit from these growth areas. There is no lack of opportunity. The question for low-temperature plasma science and engineering as a discipline is whether the scientific progress will be led by open, public research or will be confined within companies that sometimes view the dissemination of knowledge as the loss of competitive advantage.

Immigration has been an important source of scientists for U.S. industry and for low-temperature plasma science in particular since the beginnings of industrial

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[1] The committee notes this pattern in passing; it certainly might be worthy of further study by a more qualified group to understand if it is more widespread and whether it arises from a structural difference in the U.S. university system.

research in the 19th century. Over the past 15 years the former Soviet Union has been a key source of scientific talent, and a current trend is the establishment of research facilities by U.S. industry in low-cost countries with abundant scientific talent, examples being India, China, and portions of Eastern Europe. The constant is that whatever the condition of U.S. academic plasma science, U.S. industry will draw on a global talent pool and, if expedient, will go where the talent is.

Will the United States prosper in this global environment? Here, as expressed in a recent NRC report, one has cause for concern.[2] Can the United States continue to rely on immigration as the primary source of scientific talent? Will subsidized industrial consortia in Europe and the Far East attract U.S. companies to operate there? Will U.S. companies continue to support U.S. graduate student research when it is less costly to hire an experienced Ph.D. in an overseas lab? The answers to these questions have impacts far beyond the health of low-temperature plasma science industries.

STEWARDSHIP OF THE FIELD

The fields of thermodynamics and aeronautics have historically benefited from the leadership and coordinating role of NASA through works such as the Joint Army Navy Air Force (JANAF) database. Genetic research moves forward faster and more effectively with the guidance and assistance of the National Institutes of Health (NIH); in fact, although DOE's Office of Biological and Environmental Research contributed significantly to the successful Human Genome Project, were it not for the home base of this research at NIH, it would have never moved forward so effectively. Low-temperature plasma science and engineering could be similarly propelled forward if there were a good steward for the field. However, it is not practical, and perhaps not even desirable, for a single agency or entity to become the steward for all of the science and applications given the diffuse nature of low-temperature plasma science, the diversity of the applications, and the advantage, in many cases, of involving private companies, from start-ups to conglomerates. Rather, some imaginative new paradigm may be required that captures the inter-disciplinary nature of the field: one that supports the fundamental science while integrating the applications-oriented research across constituency groups.

The commercial importance of low-temperature plasmas might lead one to assume that industry should pay for the research and that public funding should have no role. In addition to improving the fundamental knowledge base, public funding can have a large, positive impact because it can be targeted at common scientific issues that have a broad impact across the discipline and across the

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[2] See *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, Washington, D.C.: The National Academies Press, 2007.

industrial effort to apply plasmas for practical benefit. Public funding also has a role because companies tend to see basic research as a risky way to gain commercial advantage and its open publication as a loss of that advantage. Private funding of academic research and training is under extreme pressure because globalization has made it more costly for a company to fund a graduate student in the United States than hire an experienced staff member in other countries. U.S. policy makers and funding agencies represent the public's interest, which goes well beyond the competitive advantage of any one company. Public funding for low-temperature plasma science can ensure that research is conducted and disseminated in a way that promotes scientific progress, trains the next generation of scientists, and serves the national interest.

Unless concerted effort is applied, fundamental research and development in low-temperature plasmas for U.S. companies will continue to be progressively and perhaps irreversibly performed offshore, a trend that will probably also result in high technology manufacturing being performed offshore. As notably observed in the NRC report *Globalization of Materials R&D: Time for a National Strategy*,[3] the movement of high-technology manufacturing offshore is an inevitable response to free market forces and is not intrinsically problematic. However, the longer-term strategic concern is whether the United States will be able to maintain access to and competency in the latest scientific and technical developments if the bulk of the basic and applied research moves offshore. Active stewardship of low-temperature plasma science and engineering in the United States is required.

CONCLUSIONS AND RECOMMENDATIONS FOR THIS TOPIC

Low-temperature plasma science is an indispensable part of entire sectors of our high-technology economy. The unique, chemically active plasma environment can produce materials, fabricate structures, modify surfaces, propel vehicles, process gas streams, and make light in ways that are not otherwise possible. The practical contributions can be measured in real economic terms. The worldwide $250 billion semiconductor microelectronics industry is built on plasma technologies. The $2 trillion telecommunications industry, and all of the commerce, research, and technology enabled by microelectronics, would not exist in its present form in the absence of plasma etching and deposition. The entire state of worldwide technology would be dramatically different in the absence of plasma-assisted microelectronics manufacturing, perhaps stalling at a 1990 level. Let's consider some examples. Gene sequencing, which is enabling huge advances in health care, would not be possible if the researchers were forced to use 1990 computing technologies.

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[3] NRC, *Globalization of Materials R&D: Time for a National Strategy*, Washington, D.C.: The National Academies Press, 2005, pp. 3-5.

Lighting consumes 22 percent of all electric power produced in the United States; the power consumption would be would be three to five times higher in the absence of plasmas. The majority of turbine blades in state-of-the-art jet engines are coated using plasma spray techniques. Worldwide air-based commerce would not exist in its present form without plasmas. There would not be any two-engine, transoceanic commercial aircraft nor would there be high-performance fighters.

> **Conclusion: Low-temperature plasma science and engineering is an area that makes indispensable contributions to the nation's economic strength, is vital to national security, and is very much a part of everyday life. It is a highly interdisciplinary, intellectually diverse area with a rich set of scientific challenges.**

Low-temperature plasma science and engineering is a vital and continually evolving field. Within the last decade, startling new science developments have led to new applications such as hypersensitive optical detectors using microplasmas, plasma augmented combustion, plasma surgery, and plasma propulsion. The solutions to society changing problems (e.g., energy sufficiency, high-performance materials, sustainable manufacturing) can be partly found in the science and application of low-temperature plasmas.

Decadal surveys like this one often ask what opportunities will be lost if the United States does not support low-temperature plasma science and engineering. In this report, the more important question is about the consequences of failing to exploit the scientific challenges and opportunities outlined in this chapter. Moore's law for microelectronics and for developing the generations of microelectronics devices beyond current technologies can only be sustained with advances in low-temperature plasma science. Advanced materials for the entire realm of technologies that improve energy usage, from solar cells to fuel cells to high-efficiency combustion, will rely on advances in low-temperature plasma science. The next generation of biotechnology devices, from labs-on-a-chip to human implants, will require advances in low-temperature plasma science. There is a one-to-one mapping of these societal benefits with addressing and solving the science challenges described here.

Certainly, low-temperature plasma science and its many applications will continue to advance but at an ad hoc and unplanned rate. The question addressed in this decadal survey is whether or not the United States will propel the science and claim the benefits. Low-temperature plasma science and engineering are not recognized or funded as a scientific discipline in the United States. Progress in low-temperature plasma science occurs, for the most part, as a hidden part of programs whose emphasis is to develop applications that use low-temperature plasmas. Plasma science is now more often than not accomplished under the umbrella of a project funded to develop, for example, superhard refractory plasma deposited coatings, but not as a main thrust of the activity. As a result, the science lags the application and the plasma is viewed as a mysterious black box that is as likely to misbehave and ruin a promising application as it is to be the scientific cornerstone of an application with major societal impact.

> **Conclusion: The science and technology benefits from low-temperature plasma science and engineering, and the health of the field itself, depend on strong connections both with the applications—biology, environment, microelectronics, medicine, etc.—and with several closely allied sciences, notably atomic and molecular physics, chemistry, and materials science.**

The close coupling between science and application imparts a special vitality to the scientific work. When science and applications are in close contact, the science impacts the applications in positive ways that are readily understood by a wider audience. Low-temperature plasma science seeks to maintain this positive relationship. What is undesirable is the current imbalance, where effectively all scientific work occurs within mission- and objective-oriented programs whose fundamental purpose is something other than advancing plasma science. It is duplicative and wasteful because each application resolves the same science issue. It does not take the science to a point mature enough for general use that can translate the science across the entire field. It damages the credibility of plasma science and technology as a whole. That is, progress in low-temperature science is hindered by research programs that are perhaps too tightly coupled to applications. Conquering the intellectual challenges now facing the field requires a more coordinated, fundamental approach that advances the science in a manner that will also ultimately benefit applications.

Interagency collaborations such as the NNI have been effective in promoting and advocating intrinsically interdisciplinary fields of science. National consortia of companies, such as the Semiconductor Research Corporation, have successfully contributed to the vibrancy and health of a research sector that is critical to the economic well-being of the country.

> **Conclusion: Low-temperature plasma science and engineering share much intellectual space with other subfields of plasma science such as basic plasma science, magnetic fusion science, and space plasma science and will benefit from stewardship that is integrated with plasma science as a whole.**

Low-temperature plasmas share scientific challenges with other branches of plasma research. For instance, the principles underlying plasma heating, stability, and control in the low-temperature regime are the same as those that govern processes in magnetic fusion, just as the emergence of collective behavior is shared with many other areas of plasma science. Another crosscutting topic is plasma interactions with surfaces: These interactions are often the desired outcome of certain low-temperature engineering procedures, but in fusion, they must be controlled and minimized. Finally, basic plasma science studies of dusty plasmas have shed enormous light on the mechanism for controlling the rates and purities of plasma etching reactions. There is substantial overlap between the scientific objectives of low-temperature plasma research and the other branches of plasma science. The time is now to tap into this synergy.

> **Conclusion: There is no dedicated support within the federal government for research in low-temperature plasma science and engineering. The field has no steward because of its interdisciplinary nature and its connection to applications. As a result, the basic research, conducted primarily at U.S. universities, and the host of potential future applications underpinned by it are eroding and are at substantial risk of collapse. The field is in danger of becoming subcritical and disappearing as a research discipline in the United States.**

Low-temperature plasma science and engineering are recognized as a scientific discipline internationally and are nurtured and funded as such. It would be desirable to have a more data-centered discussion of this topic, but the fact is that no U.S. entity has taken up the role of steward for this field, even to the extent of collecting data. In the absence of data, the committee reverted to foreign assessments and anecdotal information.

> **Recommendation: To fully address the scientific opportunities and the intellectual challenges within low-temperature plasma science and engineering and to optimally meet economic and national security goals, one federal agency should assume lead responsibility for the health and vitality of this subfield by coordinating an explicitly funded, interagency effort. This coordinating office could appropriately reside within the Department of Energy's Office of Science.**

Low-temperature plasmas are pervasive and critical to the nation's economy and security; they pose intellectual challenges of the highest caliber that stand independent of their practical use. There is, however, no coordinated national stewardship of the field. That is, even if an initiative in federal support for low-temperature plasma research were to be undertaken, there is no entity within the government to oversee and lead it. (By contrast, NSF has clear stewardship over the NNI.)

Establishing a dedicated program within the Department of Energy's Office of Science would provide a science-based infrastructure for research in low-temperature plasmas. Support for the fundamental science would also appropriately reside in this lead agency. Because of the strong interdependence of low-temperature plasma science and its application, reflected in the ties between academia and industry, a low-temperature plasma science program would have to be well coordinated with related activities across the federal government.

Coordination of agency efforts is facilitated by the White House Office of

Science and Technology Policy; in some cases, such as the NNI, interagency coordination is also guided by a full-time director and coordination office. Just as the NNI effort is not a monolithic federal investment, neither would low-temperature plasma science and engineering be one. Instead, it would comprise a lead science effort with connections and collaborations in NSF, DOD, NIST, and even other parts of DOE. This new paradigm for low-temperature plasma research would also include U.S. industry. It should focus on scientific research topics, but in view of the many technical applications and the cross-disciplinary nature of the field, it should also

- Integrate across institutions (universities, national laboratories, and industry);
- Integrate across disciplines (from physics to engineering to medicine);
- Ensure that the research portfolio aligns with applications addressing national needs; and
- Develop the fundamental research component and clarify its connections to the diverse applications.

Seamlessly bringing together disciplines is difficult enough.[4] Seamlessly integrating institutions with very different purposes and legal structures (e.g., national laboratories and industry) is even more difficult. The committee emphasizes, however, that these difficulties are very real and must be overcome.

One such model might build on the success of the NNI by employing a full-time director for low-temperature plasmas. The director, assisted by a board of advisors from industry similar to the boards convened for the directorates of NSF and the DOD Offices of Scientific Research, would be responsible for maintaining and growing the initiative and setting priorities for funding. The director would also act as an advocate for the field with federal agencies in setting agency priorities, with the public, and with the popular media. This consortium might be unique among the federal agencies sponsoring research in having strong participation from industry as both advisory and funding partners. A model for coordinating the funding of basic research with applied research is the Semiconductor Research Corporation. The coordinating office and director could appropriately reside within the Office of Science at DOE.

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[4] The NRC report *Facilitating Interdisciplinary Research*, Washington, D.C.: The National Academies Press, 2004, explores some techniques for responding to these issues on campus.

3

Plasma Physics at High Energy Density

INTRODUCTION

High-energy-density (HED) plasma physics is the study of ionized matter at extremely high density and temperature. Quantitatively, HED physics is defined to begin when matter is heated or compressed (or both) to a point that the stored energy in the matter exceeds about 10^{10} J/m^3, the energy density of solid material at 10,000 K (~1 eV), which corresponds to a pressure of about 10^5 atmospheres or a light intensity 16 orders of magnitude greater than the Sun's intensity at Earth.

By this definition, matter under HED conditions does not retain its structural integrity and cannot be sustained or contained by ordinary matter or vessels.[1] Thus HED matter must be produced transiently in terrestrial laboratories, although it is common in high-energy astrophysics under both steady-state and rapidly changing conditions. For example, the center of the Sun, where fusion reactions have been converting hundreds of millions of metric tons of hydrogen into helium each second for billions of years, is estimated to have an energy density of 2×10^{16} J/m^3 (15 million K and 150 g/cm^3). Supernova explosions are obvious examples of transient HED astrophysical plasmas. Small-laboratory HED plasmas include the nanometer-sized clusters irradiated by very high intensity lasers, and the ~1 µm, 10 million K, near-solid-density plasmas produced when dense plasma columns

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[1] The committee has chosen 10^{10} J/m^3 as a reasonable lower limit of HED matter, even though it is an order of magnitude lower than the value chosen in the NRC report *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science* (Washington, D.C.: The National Academies Press, 2003), in order to include solid-density material at 1 eV.

carrying a high current implode unstably to form short-lived micropinches. By contrast, the magnetic confinement fusion plasmas discussed in Chapter 4 of the current report are limited to perhaps 10^6 J/m^3, which allows them to be confined by magnetic fields produced by steady-state electromagnets that are supported by common structural materials.

What Constitutes HED Plasma Physics?

The lowest temperature end of HED parameter space is condensed matter pushed beyond its limits, such as occurs when matter at room temperature is subjected to 1 million atm. At temperatures above a few thousand kelvin, any material becomes at least partially ionized, so HED physics is necessarily HED plasma physics. Such “warm dense matter” lies at the intersection of plasma science and condensed matter/materials science. At the opposite end of the parameter space are plasmas in which particles are at such high temperatures that relativistic effects must be considered, an exotic state of matter thought to exist in sources of extragalactic gamma-ray bursts as well as in the plasmas produced by lasers focused to very high intensity (more than 10^{20} W/cm^2) on solid surfaces. Some of these states are illustrated in Figure 3.1.

This report has been prepared on the heels of two related reports that conducted extensive scientific assessments of high-energy-density physics. The just mentioned NRC report *Frontiers of High Energy Density Physics: The X-Games of Contemporary Science* is an important background reference for this chapter. That report, hereinafter referred to as *The X-Games Report*, essentially laid the groundwork for defining the HED field and identified key research topics. In 2004, the National High Energy Density Physics Task Force delivered the report *Frontiers for Discovery in High Energy Density Physics* to the Physics of the Universe Interagency Working Group of the White House Office of Science and Technology Policy (hereinafter called *Frontiers for Discovery*). Together, these reports provide an elegant and comprehensive survey of the field. The areas covered in this chapter are illustrative and intended to highlight selected research opportunities in HED physics, not to provide a complete summary of all of the compelling research thrusts. Additional research topics, including quark-gluon plasmas and some aspects of laboratory astrophysics, are discussed in more detail in those reports.

Enabling Technologies and HED Science in Context

As was discussed in *The X-Games Report*, the portion of plasma parameter space accessible to the scientific community in the laboratory has been expanding to higher and higher energy density because of new technologies developed and facilities built to study matter under conditions that are reached in nuclear explo-

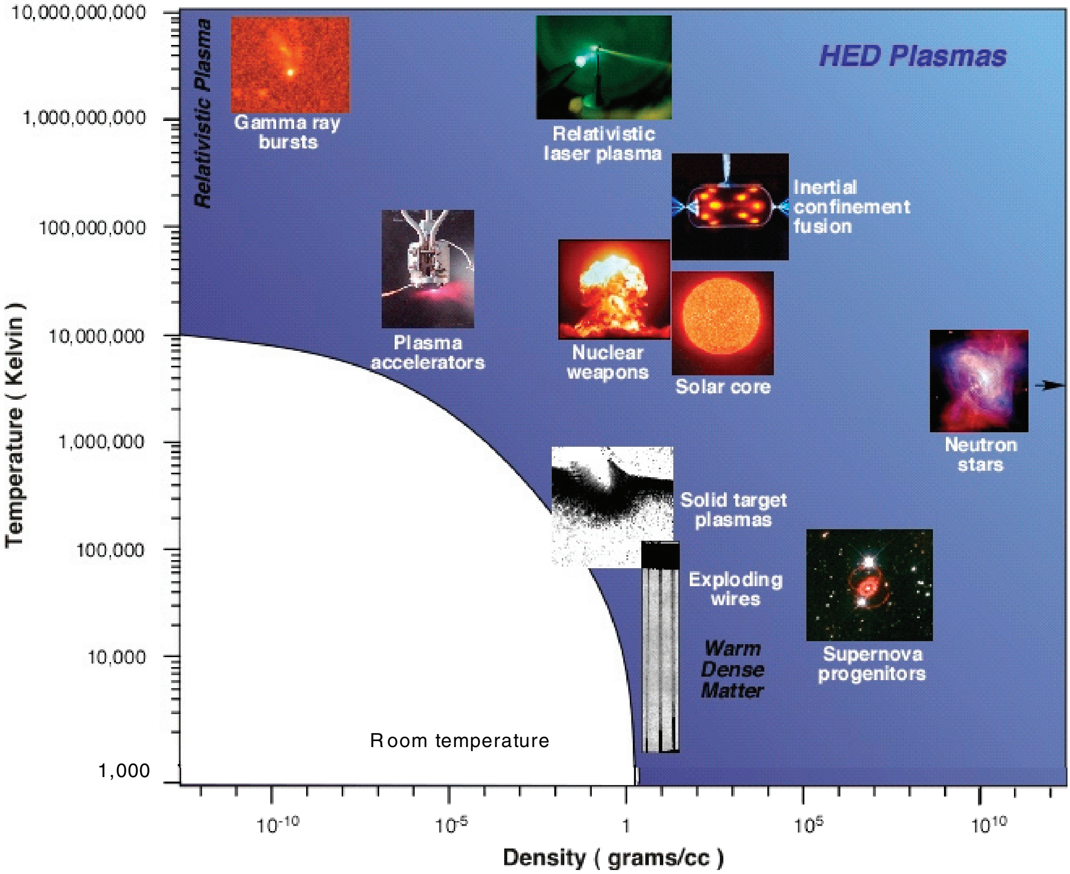

FIGURE 3.1 HED plasma space showing sample HED plasmas.

sions. Some of the highest power facilities used for HED experiments in the United States are listed in Table 3.1. The widespread laboratory study of HED plasmas enabled by these facilities exemplifies the point made in Chapter 1—namely, that new plasma regimes have become the subject of plasma physics research in the past decade. These facilities, including powerful lasers and pulsed power machines, are enabling plasma physicists, materials scientists, and atomic physicists to investigate states of matter that were not previously accessible for in-depth study in the laboratory. This trend will continue as facilities now under construction, also listed in Table 3.1, become operational during the next few years.

The development of high-power lasers and pulsed power technology was originally driven by the quest for inertial confinement fusion (ICF) in the first case and laboratory-scale nuclear weapon effects testing in the second. At present and

TABLE 3.1 Selected HED Facilities

Facility	Type of Machine	Energy Delivered	Peak Power/ Current	Energy Delivery	Repetition Rate	Location	Status
Large-scale							
National Ignition Facility	Laser	1.8 MJ	500 TW	Ultraviolet photons	~1 shot/ 3 hr	Lawrence Livermore National Laboratory	To be completed in 2009
ZR	Pulsed power	3.5 MJ	350 TW/ 26 MA; 4 Mbar	Electric current; magnetic pressure	~1 shot/ day	Sandia National Laboratories	To be completed in 2007
OMEGA/ OMEGA EP	Lasers	~30 kJ long pulse 3 kJ short pulse	30 TW/ EP 1 PW	IR/ ultraviolet photons	~1 shot/ 3 hr	Laboratory for Laser Energetics, Rochester	Operational/EP to be completed in 2008
Linac Coherent Light Source	X-ray free-electron laser	1 mJ	10 GW	X-ray photons	120 Hz	Stanford Linear Accelerator Center	To be completed in 2009
Mid-scale							
Titan	Laser	200 J	400 TW	Infrared photons	~1 shot/hr	Lawrence Livermore National Laboratory	Operational
Z-Beamlet/ Z-Petawatt	Laser	1 kJ + 500 J short pulse	1 TW/1 PW	Optical/IR photons	~1 shot/ 3 hr	Sandia National Laboratories	Operational/1 PW to be completed in 2007
Texas Petawatt	Laser	250 J	1 PW	Infrared photons	~1 shot/hr	University of Texas	To be completed in 2007
L'Oasis	Laser	4 J	100 TW	Infrared photons	~1 Hz	Lawrence Berkeley National Laboratory	Under upgrade
Hercules	Laser	20 J	800 TW	Infrared photons	~1 shot/ min	University of Michigan	To be completed in 2008
Cobra	Pulsed power	~100 kJ	1 TW/1 MA	Electric current	~3 shots/ day	Cornell University	Operational
Nevada Terawatt	Pulsed power and laser	100 kJ 35 J laser	2 TW/1 MA +100 TW laser	Electric current + IR photons	1 shot/day	University of Nevada	Operational; laser under construction

NOTE: Not included in this table are several important 10- to 100-TW lasers in use and under development at university and national laboratory facilities—for example, the 100-TW Diocles laser facility at the University of Nebraska at Lincoln. ZR, Z refurbishment; EP, extended pulse; IR, infrared.

for the last decade, the principal purpose of the research carried out at such facilities has been to help assure the safe and reliable operation of our nation's nuclear weapons stockpile in the absence of full-scale nuclear testing; this program of research is called the Stockpile Stewardship Program (SSP) and is sponsored by the National Nuclear Security Administration (NNSA). The vital connection between understanding HED states of matter and stockpile stewardship will be discussed in the next section.

Inevitably, the accessibility of a whole new range of conditions of matter means that new experiments will produce unanticipated results, some of which will have important implications for stockpile stewardship and many others of which will find applications in basic physics and in practical applications far removed from direct relevance to stockpile stewardship. It is the excitement of entering unknown regions of parameter space with these facilities that engender the committee's enthusiasm for HED plasma science, just as it did for the authors of *The X-Games Report*. Although that report is more comprehensive than this committee can be in its discussion of HED science opportunities, this committee will take advantage of the fact that this is a fast-moving field. Just since 2003, there has been great progress in several areas of HED plasma studies, including stockpile stewardship, ICF, and plasma wake field accelerators, as well as in basic HED science, some of which will be highlighted in this chapter.

In addition to depending on the aforementioned new facilities, the advances discussed depend on recent developments in large-scale computer simulation capability and the continuing development of diagnostic capabilities with exquisite temporal and spatial resolution. Although the state-of-the-art facilities and diagnostic systems at the NNSA-sponsored laboratories (Table 3.1) are largely used for mission-oriented research, there is movement toward making them more available to the broad community of scientists interested in HED research. One approach is to reserve a small fraction of facility time for non-mission-oriented experiments. Another is to encourage university–national laboratory collaborations leading to novel experiments that can benefit both a laboratory mission and basic-physics-oriented university scientists. For example, at the Stanford Linear Accelerator Center (SLAC), a laboratory of DOE's Office of Science, there are exciting new results on particle acceleration in laser- and particle-beam-driven, nonlinear wave–particle interaction experiments in HED plasmas. Continued progress on this front has the potential to shape future technology choices for the high-energy physics community. Such collaborations are potentially a good paradigm for NNSA to facilitate a broad range of HED science at its facilities.

University-scale pulsed-power machines and high-intensity lasers (also listed in Table 3.1), albeit considerably lower power than those at the NNSA laboratories, already play an important role in broadening the progress of research in the HED science program. They enable testing novel ideas and carrying out non-mission-oriented HED plasma research, as well as training the next generation of HED plasma physicists, without having to interrupt the schedule of the larger NNSA-sponsored facilities.

Both the larger facilities at the national laboratories and the smaller facilities at universities are providing a new window on nature by producing HED conditions that have not previously been studied, often leading to exciting, novel results. Quoting from *The X-Games Report* (p. x), ". . . research opportunities in this cross-cutting area of physics are of the highest intellectual caliber and are fully deserving of the consideration of support by the leading funding agencies of the physical sciences. . . . Such support . . . would greatly strengthen the ability of the nation's universities to have a significant impact on this exciting field of physics." Such support would also attract some of the brightest young scientists into the various subfields of HED plasma research and eventually to positions at the next generation of HED facilities that will soon be in operation.

IMPORTANCE OF THIS RESEARCH

HED plasma research in recent years has been largely driven by four applications that can be represented as Grand Challenges:

- *Inertial confinement fusion (ICF).* Can we achieve fusion ignition and, eventually, useful fusion energy from compressed and heated HED fusion plasma?
- *Stockpile stewardship.* Can we understand the properties of the materials in nuclear weapons under weapon-relevant conditions, together with the operative physical processes, well enough to ensure that the safety, security and reliability of the nuclear weapons stockpile of the United States can be maintained in the absence of nuclear testing?
- *Plasma accelerators.* Can we generate, using intense, short pulse lasers or electron beams interacting with plasmas, multigigavolt per centimeter electric fields in a configuration suitable for accelerating charged particles to energies far beyond the present limits of standard accelerators?
- *Laboratory plasma astrophysics.* Can we better understand some aspects of observed high-energy astrophysical phenomena, such as supernova explosions or galactic jets, by carrying out appropriately scaled experiments to study the underlying physical processes and thereby benchmark the computer codes used to simulate both?

Although these challenges will probably continue to be the main drivers for the research to be done in the coming decade, they have spawned many discoveries in several research areas in the last decade that provide additional research opportunities. These involve connections to a wide range of physics and technology areas, including plasma, condensed matter, nuclear and atomic physics, laser and particle beam-physics and technologies, materials science, fluid dynamics and magnetohydrodynamics, and astrophysics, all of which substantially enrich the intellectual content of HED plasma science.

Economic and Energy Security

The possibility of energy supplied by controlled fusion offers enormous potential economic security benefits through the energy-resource independence that would result for the United States and the rest of the world, as was discussed in Chapter 1. The ICF approach might offer a viable alternative to the international program in magnetic confinement fusion (see Chapter 4 and the discussion of ITER in Chapter 1).

Although the enabling technologies for HED plasma generation were driven initially by research oriented to ICF and military applications and are now driven by the Stockpile Stewardship Program, areas as diverse as medicine and industrial manufacturing have been impacted by these technologies. For example, the unique way an intense femtosecond laser ablates material is now used in eye surgery and for cleaning out clogged arteries. In the realm of industrial manufacturing, intense laser ablation will soon be used to machine precise holes in jet turbine blades, laser-based extreme-ultraviolet light sources drive the latest generation of integrated circuit lithography, and the intense bursts of x-rays from laser-generated HED plasmas are now being used to characterize aerospace components. As the capabilities of short-pulse lasers become better known, it is likely that many more practical uses will be developed.

National Security

The study of HED plasmas has been an important element of the research portfolios of the nuclear weapons laboratories for 40 years or more. Until perhaps 20 years ago, when high-power laser facilities became available, essential parts of that research had to be carried out using underground nuclear tests; there was no alternative method to address such physics issues as radiation transport and the physical properties of hot dense matter. In addition, an understanding of the effects of a nuclear explosion on nearby weapons and on both civilian and military electronics was achieved partially by testing components and subsystems of the weapons using high fluxes of x rays produced by pulsed power machines and partially by testing underground. The underground test moratorium 15 years ago was justified in part by the belief that rapidly advancing computer simulation capability, together with the anticipated new HED facilities, would make underground tests unnecessary for maintaining the safety, security, and reliability of our nuclear stockpile. NNSA's SSP is intended to turn this expectation into reality. Some of the HED science issues that have been addressed in recent years as part of SSP are discussed in the next section. In the coming decade, with the continued aging of the nation's nuclear stockpile and the continuing moratorium on testing them, HED science will play an even more important role in maintaining our national security.

Intellectual Importance

The coupling of HED plasma physics to several other subdisciplines of physics serves to broaden its intellectual impact well beyond its national security and ICF energy base. To summarize,

- Studying the properties of warm dense matter brings together plasma research and condensed matter and materials research.
- As temperatures increase, high atomic number HED plasmas bring plasma physicists together with atomic physicists to diagnose plasmas.
- The fluid instabilities and turbulence in plasmas (ionized fluids) are very similar to their counterparts in ordinary fluids.
- Nuclear physics contributes many diagnostic techniques to ICF, magnetic confinement fusion, and nuclear weapon studies.
- Nonlinear wave–particle interaction in HED plasmas could lead to the next generation of high energy accelerators, affecting, in turn, high energy physics.
- The principles of magnetohydrodynamics are central to understanding dense magnetized plasmas, such as wire-array z-pinches.
- HED plasmas provide fundamental data required by astrophysicists and may be able to contribute to the interpretation of high energy astrophysical observations.

The following paragraphs add more depth to these brief statements:[2]

- *Atomic physics.* HED drivers generate highly stripped, near-solid-density plasmas made of mid- and high-atomic-number atoms at temperatures of millions of degrees, with and without magnetic fields. Studying such plasmas contributes to our understanding of atomic processes and structure in complex ions subject to the strong electric and magnetic fields. Understanding dense radiating plasmas in the laboratory and in the interior of

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[2] For additional reading on the intersection of some of the frontiers of plasma science with those of atomic, molecular, and optical science, please consult the NRC report *Controlling the Quantum World: The Science of Atoms, Molecules, and Photons*, Washington, D.C.: The National Academies Press, 2007.

astrophysical objects often relies on our understanding of highly stripped atoms in extremely dense plasmas. HED plasmas enable theoretical predictions of atomic energy levels, rate coefficients, and so on, to be tested experimentally.

- *Condensed matter physics and materials science.* Studies of "warm dense matter" straddle the boundary between condensed matter and plasma physics. The kinds of equations of state and dynamic properties of materials questions being addressed by experiments on warm, dense, partially ionized matter at high pressure connect to the questions being addressed by materials science studies. Thus physicists and materials scientists interested in low-temperature matter at a pressure of 1 million atm do the same experiment on the same pulsed power machine to obtain relevant data as does the plasma physicist who is studying partially ionized matter at solid density and a few thousand degrees.
- *Nuclear physics.* A potentially important connection between HED plasma science and nuclear physics will materialize if and when ignition is achieved in ICF experiments on the National Ignition Facility (NIF). Between 10^{17} and 10^{18} energetic neutrons will be emitted from a submillimeter source in less than 1 ns, offering the possibility of neutron-induced reactions in nearby target nuclei that have already been excited by a previous neutron interaction.
- *Accelerator physics and high-energy physics.* The high cost and size associated with conventional radio-frequency accelerator technologies has for nearly three decades been the main driver of a new approach to accelerating charged particles. It has now been demonstrated that the interaction of powerful lasers and particle beams with plasmas can generate plasma waves with extremely large electric fields. Although the physics of plasmas and the physics of charged particle beams are distinct areas of research, there are important connections between the two disciplines in the areas of physical concepts, mathematical formulation, computational tools, applications, and terminology.
- *Pulsed x-ray sources for various applications.* Laser-driven plasmas and accelerators produce electron bunches of very short duration that can be converted to ultrashort pulses of x-ray radiation. These radiation bursts are so short that they can be used as a strobe light to freeze-frame the motion of complex systems, such as materials being compressed by shock waves or molecules undergoing chemical reactions. By enabling this diagnostic capability, HED technology impacts material science, chemistry, biology, and medical sciences.
- *Fluid dynamics.* There is close intellectual coupling between plasma physics and fluid dynamics through various hydrodynamic and magnetohydrody-

namic instabilities and turbulence. This certainly applies to the instabilities present in imploding inertial fusion fuel capsules.

- *Astrophysics.* Plasma and atomic physicists have collaborated for decades to make plasma spectroscopy a valuable tool for astrophysicists. HED plasmas are now being used to develop a database on equations of state, x-ray spectra, and radiation transport, all of which are also thought to be relevant to astrophysical observations. Whether HED plasmas can help to illuminate the dynamics in spatially distant cosmological events that take place on vastly different time and spatial scales is an open question.

Role of Education and Training

The national security of the United States requires the continuous presence of superior intellectual talent in all HED sciences at the DOE national laboratories. During the next 10 years or so, as the new facilities in Table 3.1 come into operation, it will be extremely important for HED university research programs to turn out bright, well-trained students to provide a pool of talent from which the national laboratories can draw. Although the changing character of the weapons complex will affect manpower needs, the age distribution of scientists at the weapon laboratories is such that retirements may also drive the need for new graduates.

At present, a few universities have multiterawatt laser facilities and 100-kJ pulsed-power systems (see Table 3.1) that can be used for HED plasma research. Support of some of the exciting science described in the following section can be expected to attract some of the best students to carry out thesis research on those facilities. Making national laboratory facilities available part of the time to university teams, including students, could help assure interest in working on such facilities.

RECENT PROGRESS AND FUTURE OPPORTUNITIES

This subsection begins with the main drivers of HED plasma physics research that were introduced in the last section. However, fundamental HED research is also driven by the access to new states of matter provided by pulsed-power machines and increasingly powerful short-pulse lasers. Opportunities to substantially expand fundamental HED research depend to a significant extent on the opening of the intermediate and large-scale facilities at the national laboratories to outside users part of the time. Some of the discoveries in HED science have already found practical uses, as noted in the subsection on national security. Others remain a scientific puzzle or a curiosity. Several topics in the category of curiosities are mentioned here. For a more comprehensive discussion, please refer to *The X-Games Report* or *Frontiers for Discovery*. One breakthrough that has opened an entirely new window on fundamental physics is highlighted in those two reports: the recent work with quark-gluon plasmas on the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. These novel quark-gluon phenomena are now thought to behave more like liquids than like plasmas per se. The committee hopes it is not missing too many of the ideas that will really blossom in the next decade, but then again, they would be welcome surprises.

Inertial Confinement Fusion

In the United States, ICF researchers have two goals: the use of laboratory-scale fusion explosions to acquire data for the U.S. nuclear weapons' SSP and the harnessing of these ICF explosions as a source of fusion energy. The vast majority of ICF research is funded by and directed at the former goal. However, it is the long-term opportunities associated with the second goal that motivate the enthusiasm for ICF of many of the researchers.

To produce laboratory-scale energy release for either application, fuel capsules containing the hydrogen isotopes deuterium and tritium (DT) must be compressed to at least 200 g/cm^3, hundreds of times the density of the solid, and heated to a high enough temperature, 100 million K, or about 10 keV, to induce a significant number of DT fusion reactions to occur before the fuel disassembles. This process is demonstrated at large scale by nuclear weapons and at astronomical scale by supernovas. By contrast, in magnetic confinement fusion, discussed in Chapter 4, strong magnetic fields confine the very hot plasma needed for a high fusion reaction rate in quasi-steady state.

There are two main approaches to compressing the fusion fuel to the densities required. The first, which has been the principal thrust of the SSP, is called indirect drive. In this approach, the energy provided by a very high power source (the "driver")—such as an intense laser, a high current particle beam, or a HED imploding plasma from a pulsed power machine—is converted into x rays inside an enclosure, called a hohlraum, to assure symmetric irradiation of the fuel capsule contained within the hohlraum. That x-ray bath then causes an ablation-driven spherically symmetric implosion of the fuel capsule. In the second approach, direct drive, the capsule implosion is caused by spherically symmetric direct irradiation of the surface of the capsule by the driver. These two approaches are illustrated schematically in Figure 3.2.

In both approaches to ICF, the energy absorbed by the fuel capsule surface layer, called the ablator, produces plasma that rapidly expands radially outward and acts like the exhaust of a rocket engine, driving the main mass of the fuel radially inward. The fuel is heated partway to the ignition temperature of 10 keV during the fuel compression by work done on the plasma to implode it. With conventional hot-spot ignition, the ignition temperature is reached in a central hot spot

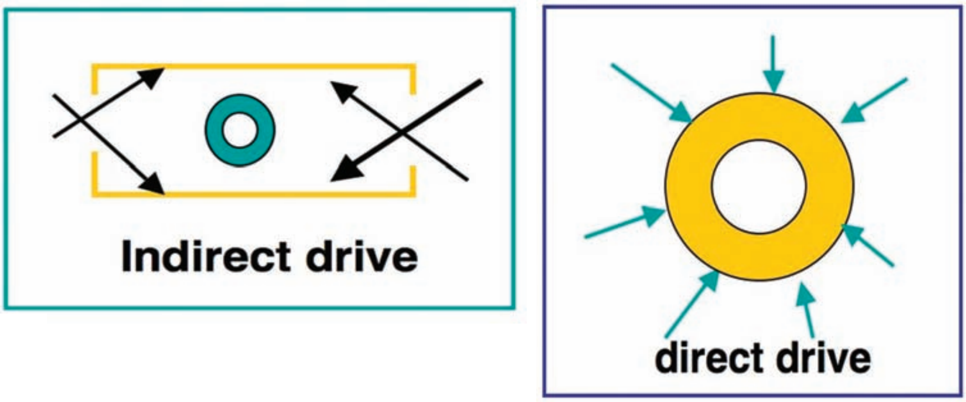


FIGURE 3.2 Schematic diagrams of the indirect drive and direct drive versions of inertial confinement fusion (ICF).

as rapidly converging fuel stagnates in the center just moments after the temperature is increased by converging shock waves. An alternative approach, called “fast ignition,” utilizes a second ultra-high-power, short-pulse external heating source impinging on the compressed fuel to locally increase the temperature to 10 keV. These alternatives are illustrated in Figure 3.3.

The first ignition experiments will be performed at the NIF, a laser that will deliver 1.8 MJ of ultraviolet light in 192 convergent laser beams. (See Table 3.1 for further information about the NIF and other HED facilities named in this section.) Completion of the NIF is scheduled for 2009, with initial fusion ignition experiments planned for the following year. Based on data obtained on the nova laser prior to its closure in the late 1990s, those first NIF experiments will utilize the most highly developed path to ICF, indirectly driven hot-spot ignition. Advances in the ability to carry out large-scale two- and three-dimensional computer simulations on ICF target designs, together with technology developments and high-quality experiments carried out using the largest available laser and pulsed power systems, OMEGA and Z, have all contributed to the forward momentum of the ICF effort during the last 10 years. The development of exquisite diagnostics enabling meaningful comparison of experiments with simulations has been key to this progress. As a result, the completion of the NIF in 2009 is generating great optimism that ignition in the laboratory will soon be within reach.

The main benefit of directly driven fuel implosions using lasers is reduced driver energy requirement if a sufficiently high level of capsule irradiation sym-

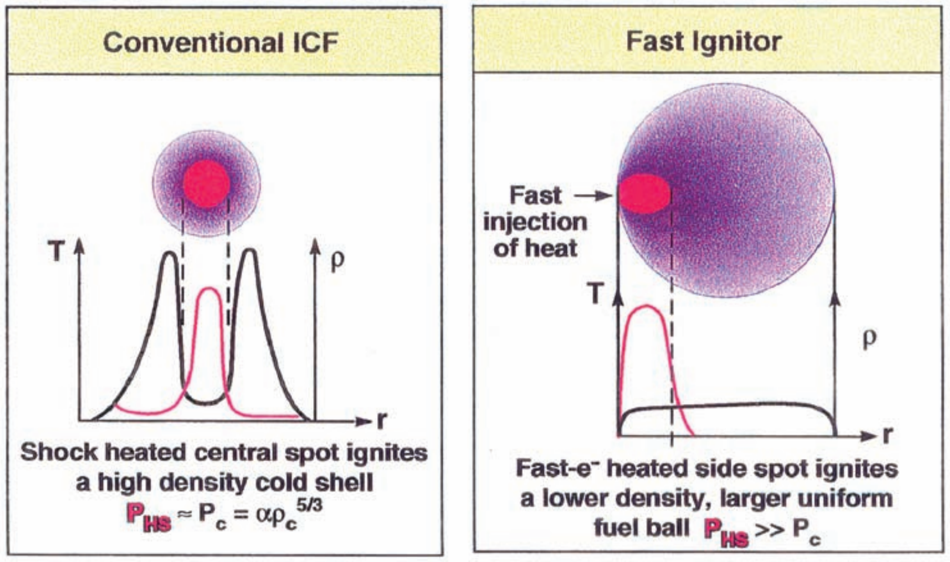


FIGURE 3.3 Hot-spot ignition vs. fast ignition of compressed deuterium-tritium fuel. Courtesy of Laboratory for Laser Energetics, University of Rochester.

metry and adequate hydrodynamic stability can be achieved during the implosion. The simplicity of the required target (only a fuel capsule is necessary) could be a substantial benefit for inertial fusion energy. Exquisitely diagnosed experiments utilizing the OMEGA and NIKE lasers, together with supporting computer simulations aimed at developing the direct drive approach, have generated optimism for this approach in recent years.

Research also continues on the possibility of using pulsed power to produce the x-ray source for indirect drive using imploding plasmas that start out as a cylindrical array of hundreds of very fine tungsten wires. The pulsed-power-based x-ray source, while less well developed than laser-based indirect-drive ICF, is an intriguing alternative because of the high efficiency (>10%) with which electric energy is converted to x rays. It offers the possibility of achieving high yield with a facility only a few times bigger than the soon-to-be-commissioned ZR machine. The presence of ultrahigh (megagauss) magnetic fields in an imploding plasma may suppress thermal transport across the field lines and thereby facilitate the creation of thermonuclear plasmas suitable for fusion-energy development.

There is also a parallel development path for indirect-drive ICF that makes use of pulses of charged particles. This driver option will be discussed in the context of the inertial fusion energy.

Challenges to the Achievement of ICF Ignition

There are many technical challenges to achieving ignition of fusion reactions in an ICF fuel capsule, and these will be important areas for HED plasma research in the next few years. The critical issues for fuel assembly and ignition are capsule implosion symmetry, which applies to all variants of ICF, and interaction of the laser beams with plasma in the hohlraum, which applies to the laser-driven, indirect-drive approach that will begin at the NIF in 2010. Thanks to modern computer simulation capabilities, many refinements have been developed for exactly how to best utilize the available laser power and how to avoid unacceptable growth of instabilities. For example, employing mixtures of elements on the inside of hohlraum walls instead of just elemental gold can improve the conversion efficiency from laser energy to low-energy x rays inside the hohlraum by 10-15 percent. Another example is the ability to design beryllium or plastic fuel capsule ablator shells with specific dopant profiles to mitigate hydrodynamic instabilities. Continuing to develop such refinements will be essential to the long-term success of ICF (and inertial fusion energy). State-of-the-art computer simulations of the latest hohlraum-plus-fuel-capsule designs imply that if the experiments go as predicted, as little as 50 percent of the NIF laser design energy will be needed to achieve ignition (ignition is defined as the ratio of fusion energy released to laser energy absorbed in the hohlraum).

Controlling the Implosion. A fundamental challenge to ICF is that the radius of a spherical shell of fuel surrounding a much lower-density deuterium/tritium-gas-filled sphere must be compressed by a factor of 30-40 for central hot-spot ignition. Furthermore, the fuel should be compressed nearly adiabatically, that is, with the least possible increase in thermal energy consistent with achieving a hydrodynamically stable implosion. This requires an incredibly uniform squeeze over the entire outside surface to assure a symmetric implosion that does not squirt much of the spherical shell of fuel into the low-density central region as a result of hydrodynamic instabilities. The necessary ingredients for implosion symmetry in indirect drive are that the laser irradiation of the hohlraum must be nearly uniform (this necessitates many beams) and that the radiation driving the ablation of the fuel capsule must be smoothed to near-perfect spherical symmetry by multiple absorptions and re-emissions of the radiation inside the hohlraum.

Increasing the central hot-spot temperature to 10 keV depends on the strength and timing of the shocks propagating through the target. Any energy delivered by photons or energetic electrons that heats the fuel before it is fully compressed is detrimental to capsule performance.

Laser–Plasma Interactions. Before the laser beams can be converted to x rays by striking the inside wall of the hohlraum, they must pass through substantial amounts of plasma that is coming off the hohlraum walls. The interactions of the laser light with these plasmas can drive waves in plasmas that could lead to a multitude of phenomena, many of them detrimental to the goal of creating smoothly distributed x rays in the hohlraum. As laser beams propagate through a high-temperature plasma they can (1) break into small filaments and spray out at an angle, (2) undergo significant energy transfer between crossing beams, (3) scatter back out of the hohlraum, and/or (4) generate high-energy electrons via a variety of instabilities involving either electron plasma waves (the stimulated Raman instability and the two-plasmon decay instability) or ion-acoustic waves (the stimulated Brillouin instability). These phenomena could be disastrous—for example, energetic electrons could preheat the cold fuel or the waves could scatter a significant fraction of the laser energy back out of the hohlraum. Considerable progress toward understanding and controlling these phenomena has been made in recent years. For example, computer simulations and experiments suggest that the effect of some of these instabilities can be reduced by using mixtures of gases filling the hohlraum to damp the waves and by smoothing the laser beams' energy profile. However, substantial uncertainties still remain, so that understanding laser–plasma interaction will be the subject of many near-future experiments and computer simulations.

Fast Ignition

The alternative and less-well-developed fast ignition approach to heating the compressed fuel would be applicable, in principle, to any method by which the fuel might be compressed. The basic principle of fast ignition is that a small portion of unstructured, fully compressed fuel is heated to the ignition temperature by a short-pulse laser in 10-30 psec. As a result, hydrodynamic mixing cannot quench the burn, and the fuel is far from pressure equilibrium. This allows the main fuel to be less dense than for hot-spot ignition. Recent experimental and computational research on coupling ultra-high-power laser energy into compressed fuel suggests dramatically favorable driver energy consequences for the fast ignition approach. More fuel is predicted to undergo fusion reactions for a given driver energy, and the total laser energy that must be delivered to a fuel capsule to achieve the high gain needed for inertial fusion energy is predicted to be an order of magnitude less for fast ignition than for hot-spot ignition.

The coupling of laser energy into the compressed fuel depends on the generation and control of extremely large currents (~10^9 A) of electrons or subsequently produced ion beams. These flows, together with the incident laser fields, generate enormous electric and magnetic fields. Magnetic fields, for example, can exceed 1,000 T. These extreme conditions lead to very rich physics that needs to be understood, implying fertile areas for research during the next 10 years if experimental facilities are available. For example, ideas have been put forward to shorten the distance between (1) the point beyond which light cannot propagate in the target plasma and (2) the compressed fuel that is to be heated by the fast ignition pulse energy. One possibility investigated experimentally on a facility in Japan is the use of an evacuated cone in the capsule to open a path for the short pulse laser. Simulations of implosions with this geometry are in good agreement with experimental implosions (Figure 3.4).

Much more work is needed to determine the viability of fast ignition but is being seriously hampered by the lack of domestic facilities at the necessary laser power and energy. As a result, fast ignition experiments at the petawatt power level (e.g., 1 kJ in 1 psec), as well as other experiments requiring similar power levels, must be carried out abroad using the Vulcan laser (Rutherford Laboratory, U.K.) or the Gekko petawatt laser (Institute of Laser Engineering, Osaka, Japan) until U.S. facilities come on line (see Table 3.1).

Inertial Fusion Energy

Achieving fusion ignition in a single fuel capsule at the NIF is both the first step for SSP applications and the proof-of-principle step for the development of ICF as a practical path to the inexhaustible energy source that many believe fusion

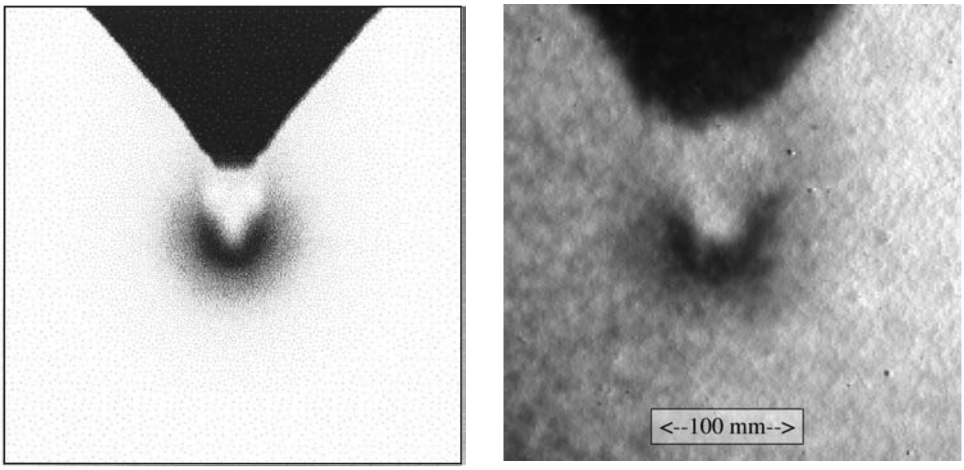


FIGURE 3.4 Comparison of a computer simulation and an experiment addressing fast ignition. Reprinted with permission from R. Stephens, S. Hatchett, M. Tabak, C. Stoeckl, H. Shiraga, S. Fujioka, M. Bonino, A. Nikroo, R. Petrasso, T. Sangster, J. Smith, and K. Tanaka, "Implosion hydrodynamics of fast ignition targets," *Physics of Plasmas* 12: 7 (2005). © 2005, American Institute of Physics.

will eventually be. Achieving ignition will demonstrate a practical understanding of a broad variety of HED physical processes, such as laser–plasma interaction, hydrodynamic instabilities, and radiation transport, in tandem. This intellectual milestone will then have to be followed by major developments in high-repetition-rate drivers, large-scale fuel capsule manufacturing, and other technologies that are required for practical fusion energy based on ICF. Issues such as developing materials that can tolerate the high neutron flux of a fusion reactor and tritium handling are common to both ICF and magnetic confinement fusion.

Laser development paths for inertial fusion energy (IFE) have already been staked out for diode-pumped solid-state lasers and krypton fluoride gas lasers. Both approaches have been exploited to demonstrate 5- to 10-Hz lasers delivering between 50 and 100 J per pulse over extended periods of time. These systems still require extensive development to reach the ~10 kJ per beam level needed for a reactor laser system. However, it is noteworthy that even a small additional step forward—for example, a 100- to 1,000-J laser system that could produce pulses as rapidly as a researcher could use them (i.e., as rapidly as gas puffs or new targets can be put in position)—could provide the opportunity to revolutionize the way some classes of data are collected, for example, in laser-wake field accelerator studies or x-ray spectroscopy research on highly stripped high-atomic-number materials.

Pulsed-power-driven IFE is now projected to involve 0.1-Hz “recyclable transmission line” repetitive pulse systems, which are still at the stages of conceptual design and technology development.

The heavy-ion-driver approach to IFE benefits from the fact that high current heavy-ion-beam technology is being developed with the high repetition rate capability that is common for high-energy accelerators. At present, the capability of heavy-ion beams to deliver a power pulse to a target is many orders of magnitude away from a proof-of-principle demonstration. However, recent experiments on space-charge-neutralized beam transport using a preionized plasma have enabled a potassium beam with a head-to-tail velocity ramp imposed on it to be longitudinally compressed by a factor of 50 (in peak current) to a few nanoseconds in duration. Radial focusing by a factor of 200 in intensity was also achieved in a plasma. Both results were in good agreement with the results of particle-in-cell computer simulations. Although these beams are still at the level of a few amperes and a few hundred keV, at present intensities they can already be used for studies of warm dense matter that take advantage of the fact that energetic ions deposit their energy deep within a target.

Stockpile Stewardship

The goal of the SSP is to assure the safety, security, and reliability of the U.S. nuclear weapons stockpile without carrying out full-scale nuclear weapons tests.

The task includes assessing the weapons for safety and reliability as they age and modifying them as necessary to extend their lives. HED plasma science is a critical component of the SSP for testing materials, for validating computer codes, and so on. The complexity of these weapons and the wide range of physical processes and extreme states of matter involved when one is detonated make stockpile stewardship an exceedingly challenging task. To achieve the goals of the SSP requires a fundamental understanding of many different materials under conditions ranging from room temperature to millions of degrees, with both ends of this range well within the HED range.

The SSP experimental component must provide accurate fundamental materials data for many different materials over the wide range of densities and temperatures that occur in nuclear weapon explosions. For example, data on equations of state, materials strength, and radiative properties are essential for accurate calculations by nuclear weapon codes. Thus stockpile stewardship is the driver for much of the HED materials research described below. The experimental program also must include well-diagnosed dynamic HED plasma experiments that will be able to validate computer simulations of how a specific configuration of materials will respond if it is rapidly heated from room temperature to the weapons-relevant regime. Finally, the experimental program must carry out complex experiments that involve several, if not all, of the physical processes that are important in a nuclear weapon explosion, albeit not with all the same materials and not necessarily at the same temperatures, in order to illuminate their interaction. This class of experiments includes, for example, radiation transport in a multimaterial ICF capsule ablation layer in the presence of shock waves and hydrodynamic instability growth. Understanding the results of such experiments and validating the computer codes used to predict their outcome obviously go hand in hand.

Stockpile stewardship clearly also requires the ability to carry out large-scale computer simulations of very complex processes in HED matter in three dimensions. For example, three-dimensional computer codes are being developed that include models of material microphysics, intermediate-scale turbulence, radiation transport, and the like. To be credible, the computer codes must be validated and extensively benchmarked by analytic theory and laboratory experiments as just discussed. (These codes can be benchmarked against the underground test database as well as against laboratory experiments.)

ICF is a key element of the SSP for several reasons. First, with the heavy reliance of ICF target design on computer simulation capability, the achievement of fusion ignition in an ICF fuel capsule will be a major integrated test of the predictive capability of multidimensional computer simulation codes that model self-consistently the many physical processes relevant to nuclear weapon explosions. In addition, achieving ignition of an ICF fuel capsule will greatly extend the range of temperatures, densities, shock strengths, etc. over which weapons-relevant materials and certain aspects of a weapon detonation can be studied. Finally, the exciting scientific challenge of achieving the near-term goal of fusion ignition in the laboratory, followed by the equally exciting and even more challenging goal of developing practical inertial fusion energy, will draw some of the brightest young minds into the HED plasma field, talent needed to maintain a robust SSP in the future.

An alternative approach to carrying out HED experiments relevant to stockpile stewardship is provided by the generation of intense x-ray bursts using wire-array z-pinches driven by pulsed-power machines. This approach involves delivering millions of amperes of current to a cylindrical array of fine wires. The current-carrying plasmas that form around each wire are all attracted to the cylindrical axis by the total magnetic field, where they form a hot, dense plasma radiation source. Such plasmas were used to produce many kilojoules of soft x rays starting in the 1970s, but the last decade has seen a dramatic advance in the x-ray power that can be produced by these machines. The breakthrough that enabled z-pinches to achieve extremely high peak power (over 200 TW) and energy (nearly 2 MJ) x-ray pulses was the use of hundreds of wires in a cylindrical array instead of the small number of wires used in earlier, lower current experiments. Such high x-ray yields have led to the Z-machine's being used for important stockpile stewardship experiments related to the aging of stockpile weapons.

The achievement of such high x-ray powers and energies has also led to the serious consideration of using z-pinches for indirect-drive ICF. Exciting proof-of-principle experiments with a deuterium-containing fuel capsule have yielded over 10^{13} fusion neutrons (eclipsing the best fusion yield ever produced on the Nova laser). A major effort is under way to understand the physical processes that underlie the behavior of wire-array z-pinches in order to enable the optimum design of experiments on the refurbished Z-machine, called ZR. ZR will be capable of delivering 26 MA into wire-array z-pinch loads. Materials and radiation flow experiments important to stockpile stewardship are planned, including experiments relevant to hot-spot-ignition-based and fast-ignition-based ICF.

Although basic science is not a mission of NNSA, the need for a pool of talented young HED scientists to staff its new facilities and the need to promote innovation has motivated NNSA to establish the Stewardship Sciences Academic Alliances program, followed by the Stewardship Sciences Graduate Fellowship Program (see http://www.krellinst.org/ssgf/). Both programs are important for the health and development of the HED plasma science field.

Properties of Warm Dense Matter and Hot Dense Matter

An important aspect of HED plasma research is the study of the fundamental properties of dense matter subject to extremes of pressure and temperature. How compressible is it? How much does the plasma radiate, and how opaque to radiation is it? What is its electrical conductivity? How viscous is it? These properties, which are well understood for material normally encountered at room temperature or for hot plasmas that are tenuous, are not well understood for many HED plasmas. Indeed, much of the underlying physics that defines such quantities as compressibility and opacity cannot be simply described using well-developed physical theories. For example, when a solid material is heated to 10,000 K, the electrons and ions cannot be treated as if they were constrained in a lattice structure, as they are in a room temperature solid, but neither are they are governed by Debye shielding, as are most low-density plasmas. Such plasmas, described as "strongly coupled," are characterized by the fact that the electrostatic (coulomb) potential energy between neighboring charged particles exceeds the mean kinetic energy, and the electrons are at least partially degenerate. Some of the studies of fundamental aspects of strong coupling are discussed in Chapter 6.

The atomic physics of dense plasmas is similarly complicated. As the temperature at solid density is driven up to perhaps 10 million K, the matter becomes fully singly ionized or even multiply ionized if it is a high atomic number material. The electrostatic potential energy between particles remains high, assuring complicated atomic physics if there are still bound electrons on the atoms. Now that we can make the HED plasmas routinely using lasers and pulsed-power machines, we are beginning to understand them. Figure 3.5 illustrates the density-temperature regimes of particular interest here. At the lower temperatures, the physics of these warm dense matter states join with the physics of dense low-temperature plasmas that are finding many new applications (see Chapter 2).

In the past decade, many advances have been made toward understanding the properties of warm and hot dense matter, examples of which follow:

- *Equation of state (EOS).* An EOS attempts to describe the relationship between temperature, pressure, density, and internal energy for a given substance or mixture of substances. In experiments starting with dense, room-temperature materials, ultra-high-power lasers can drive shock waves or can heat the matter so fast that no expansion can take place during the heating pulse (this is known as isochoric heating). The Z-pulsed power machine has been used for isentropic compression experiments. An example of results from an isochoric heating experiment is shown in Figure 3.6. The data from such experiments can help differentiate among complicated EOS models. As another example, experiments were carried out on the Nova laser to determine the EOS for shock-compressed deuterium. A small but important disagreement between the experiments and theoretical calculations was found over a parameter range of importance to ICF. Later experiments on the Z-machine and then on OMEGA obtained experimental EOS results that differed significantly from the Nova results and are closer to the calculated EOS.

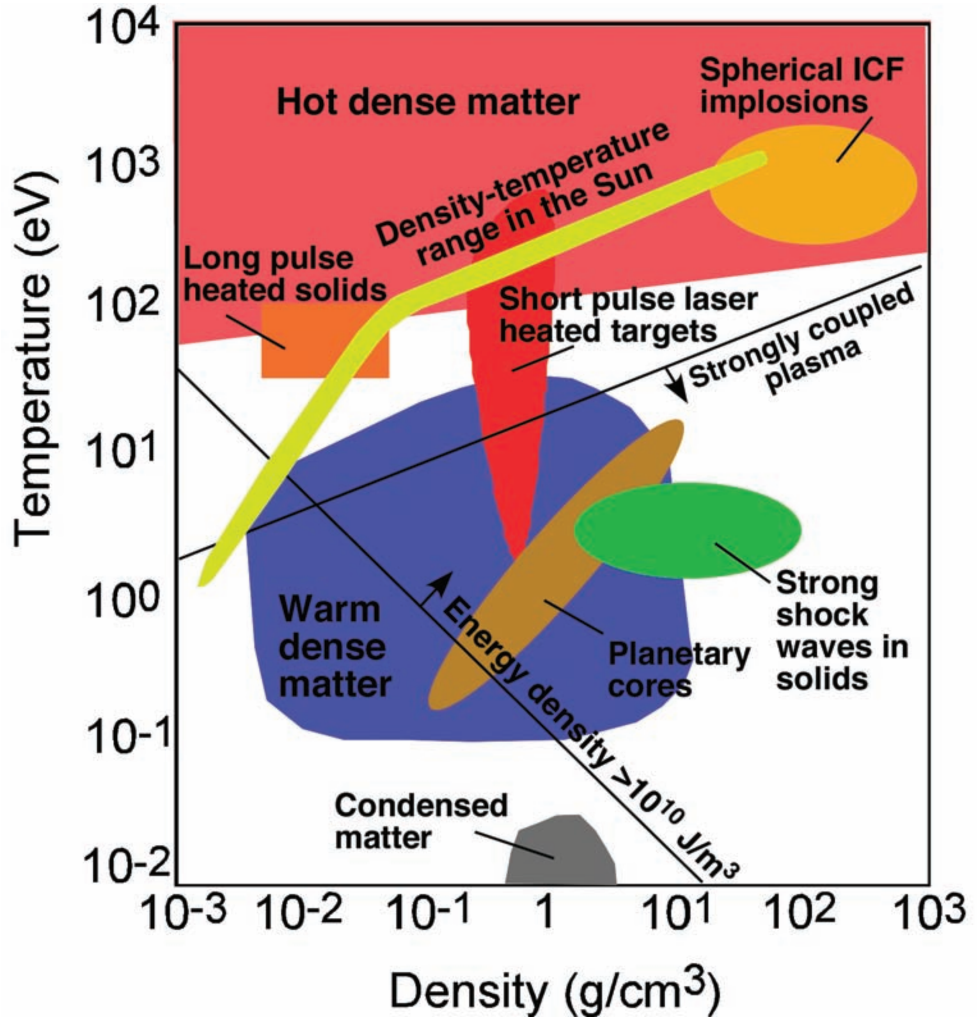


FIGURE 3.5 Phase diagram illustrating the regimes of warm and hot dense matter. Note that this diagram expands beyond the HED range of parameters.

- *Radiative properties.* Much progress has been made in computational methods for determining the radiative and opacity properties of dense plasmas. Experiments have been important in validating these calculations, as was illustrated in a pioneering Z-machine experiment on the opacity of iron, which is important for understanding the structure of the Sun. Agreement between theoretical modeling and experiments implies we are beginning to understand the properties of ions, electrons, atoms, and even molecules in dense plasmas.

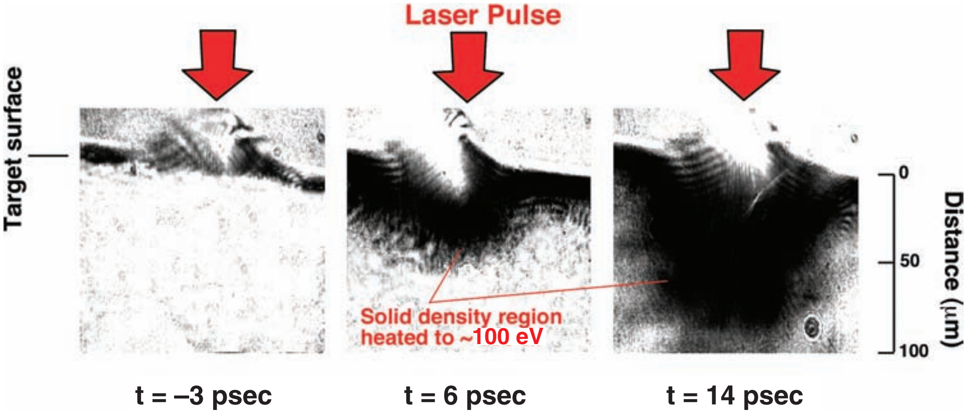


FIGURE 3.6 Time-resolved image of a short pulse laser isochorically heating a fused silica target. The transparent target was heated by a picosecond infrared laser pulse from the top. A radiative heat wave travels in over the course of ~10 psec and heats the solid density material to a temperature approaching 10^6 K. The images were taken by probing the target edge with a second picosecond pulse and imaging the shadow that the opaque heated material makes. These data were taken at Imperial College. Reprinted with permission from T. Ditmire, E.T. Gumbrell, R.A. Smith, L. Mountford, and M.H.R. Hutchinson, "Supersonic ionization wave driven by radiation transport in a short pulse laser produced plasma," *Physical Review Letters* 77: 498 (1996). © 1996 by the American Physical Society.

- *Electrical properties.* In the past decade, it was learned that for matter with temperatures below a few eV, both electrical and thermal conductivities depend markedly on plasma density. This behavior has important ramifications for the initiation of wire-array z-pinch implosions. Major advances in theoretical understanding of electrical properties have been achieved through the medium of molecular dynamics calculations. Short-pulse laser experiments have been particularly effective in deriving conductivity data on solidlike-density plasma heated on a femtosecond timescale.
- *Dynamic properties.* The properties discussed above are usually defined for materials in equilibrium. However, in some practical situations, the time scale required to reach equilibrium is incommensurate with the dynamics of the system under investigation. This leads to an added level of complexity. Many recent shock physics simulations have begun to address these issues. Time-resolved experiments such as the recent use of short bursts of x-ray from intense lasers to image shocks propagating in solid density materials have begun to yield dynamic information on rapidly heated plasmas.

The committee foresees several exciting research opportunities for the next decade, including the topics discussed below.

Warm Dense Matter

Warm dense matter (WDM) is a particularly intriguing subset of the HED regime, as it refers to a regime of heated dense matter that is neither solid, fluid, nor traditional plasma. On the one hand, it refers to states from near-solid density to much greater densities with temperatures comparable to the Fermi energy. It also refers to those plasmalike states of matter that are too dense and/or too cold to admit to standard solutions used in plasma physics, the strongly coupled regime referred to earlier, in which theories based on only two particles interacting by coulomb interaction forces at a time fail. WDM, therefore, refers to a region between condensed matter and plasmas. The accessibility of WDM has grown dramatically in recent years thanks to high-intensity, short-pulse lasers and pulsed-power machines, but studies have only just begun. There will be many intellectually exciting opportunities for research in this regime in the coming decade. One profound fundamental question that needs to be answered is whether matter can be transformed into new phases at high density and pressure or if it undergoes a metal-insulator transition. The answer to a question like this can impact our understanding of the cores of the giant planets as well as many areas of applied science: ICF implosions, exploding wires, detonators, z-pinch wire-array dynamics, x-ray laser sources, laser machining and fabrication, and high-velocity impacts.

Making WDM does not require the largest, most energetic drivers. Ion-beam accelerators, university-scale pulsed-power machines, and subpicosecond, 100-TW lasers that are small enough to be described as tabletop size can also generate interesting WDM. However, while the intermediate-scale facilities at the NNSA laboratories are needed for many of the most interesting experiments, a strong outside users' program exists only on the OMEGA laser system. Rapid progress in this research area would benefit substantially from a significant level of user access to some of the other NNSA facilities. A particularly exciting opportunity will exist at the Linac Coherent Light Source (LCLS), to be built at SLAC, where rapid energy deposition with deposition lengths long compared to target thicknesses will produce uniformly heated, uniform-density samples that can then be probed rapidly with LCLS x-ray pulses.

The application of ion-beam drivers to WDM, discussed at some length in *Frontiers for Discovery*, benefits from the uniform energy deposition rate of energetic ions in matter near the Bragg peak. Thus studies of the strongly coupled plasma physics of warm dense matter between 0.1 and 1 eV can be carried out even with relatively low energy beams that are made available in the inertial fusion energy program by uniformly heating thin foil targets. The experimental advances strongly suggest that interesting WDM plasmas can be studied with ion-beam drivers in the next few years. Longitudinal beam compression by factors of 50 or more to ~2 nsec was achieved by applying a voltage ramp to the beam. Beam radial focusing in a space-charge-neutralizing plasma was also demonstrated. Both results confirmed computer simulations, underscoring the importance of the increases in predictive capabilities.

Radiative Properties in Extreme Magnetic Fields

While great progress has been made in the study of the radiative properties of dense plasmas without embedded magnetic fields, much less is known about hot dense matter with very strong magnetic fields. Such information would help us to understand some astrophysical phenomena, laser–target interaction experiments, and z-pinch implosions. For example, observations show that white dwarf stars can have surface magnetic field strengths up to 100,000 T. Magnetic fields in laser-target plasmas and pulsed-power experiments can easily exceed 1,000 T, with one recent short-pulse laser experiment reaching 5×10^4 T. Such fields can significantly modify radiative properties in these HED plasmas. The motion of atoms or ions that are not fully stripped in a strong magnetic field affects their atomic structure to the point where radiative transitions become very broad, causing substantial changes in opacity of the matter and eliminating standard features in emission spectra. Opportunities for curiosity-driven experimental and theoretical research abound in this area.

Hot Dense Matter

Hot dense matter refers to the regime of high temperatures and densities (e.g., 10^7 K and 100 g/cm^3) similar to those found at the center of the Sun and in the cores of ICF implosion experiments. Even for the relatively simple situation of the Sun's core, our ability to simulate the radiation outflow that leads to the solar radiation we observe is enormously challenging. Conditions that approach this regime are produced when certain wire-array z-pinch configurations called X pinches implode unstably to form near-solid-density, 10 million K metal plasmas. Understanding the plasma dynamics and atomic physics properties of 20 to 40 times ionized high-atomic-number atoms in a solid density plasma with magnetic fields of perhaps 10,000 T is a challenging undertaking, again providing inspiration for curiosity-driven research.

Plasma-Based Electron Accelerators

The latter half of the 20th century witnessed remarkable advances in our understanding of the elementary constituents of matter thanks to the development of ever more powerful and ingenious particle accelerators. As we enter the new century, continued progress in unraveling the most fundamental questions of our time is threatened because accelerators at the energy frontier have become too big and expensive for any one nation to build. As was discussed in Chapter 1, new physical mechanisms that enable extremely large electric fields must be invented and developed for these accelerators. Plasma-based accelerators might enable the next giant leap forward, because the magnitude of the electric field in a plasma is not limited by the electrical breakdown strength of any solid material, eliminating the major limitations on the electric field at the position of an accelerating particle bunch.

Because the mechanism of plasma wake field accelerators was discussed in Chapter 1, here we simply summarize. An ultra-high-intensity laser or electron beam propagating through a plasma creates a high-gradient, large-amplitude plasma wave that moves with the speed of light in the wake of the beam. This wake field, in turn, can be used to trap and accelerate a trailing bunch of charged particles to relativistic energies (Figure 1.5). The accelerating fields in the plasma wave structures can, in principle, reach gradients that are many orders of magnitude greater than present radio frequency (RF) accelerator technology.

Highlights

Based on research carried out since the late 1970s and spurred on by recent developments in laser technology and multidimensional computer simulation capability, laser-based wake field accelerator experiments in 2004 by three independent groups achieved accelerated beams of electrons at the ~100 MeV energy level. Accelerating gradients of ~50 GeV/m were achieved, three orders of magnitude greater than were achieved with conventional RF accelerator technologies. Beam characteristics were a transverse emittance of less than 2 mm-mrad, an energy spread of 2 or 3 percent, and pulse length of less than 50 fsec (see Figure 3.7). The charge per pulse was about 0.3 nC. These performance characteristics are comparable to the performance of state-of-the-art photocathode RF guns. The results were chosen as one of the top 10 discoveries of the year by *Nature*. More recently, a high-quality electron beam with 1 GeV energy was produced by channeling a 40-TW peak power laser pulse in a 3.3-cm-long, gas-filled capillary discharge waveguide.

Electron-beam-driven plasma wake field accelerator research has its roots even further in the past, with the theory having been worked out in the 1960s by Veksler and Budker in the former Soviet Union. At SLAC in 2005, a self-ionized, beam-driven plasma wake field accelerator accelerated particles by >2.7 GeV in a 10-cm-long plasma module. A 28.5-GeV electron beam with 1.8×10^{10} electrons was compressed to 20 μm longitudinally and focused to a transverse spot size of 10 μm at the entrance of a 10-cm-long column of lithium vapor with a density of 2.8×10^{17} atoms/cm^3. The electron bunch fully ionized the lithium vapor to create a plasma and then expelled the plasma electrons. These electrons returned one-half

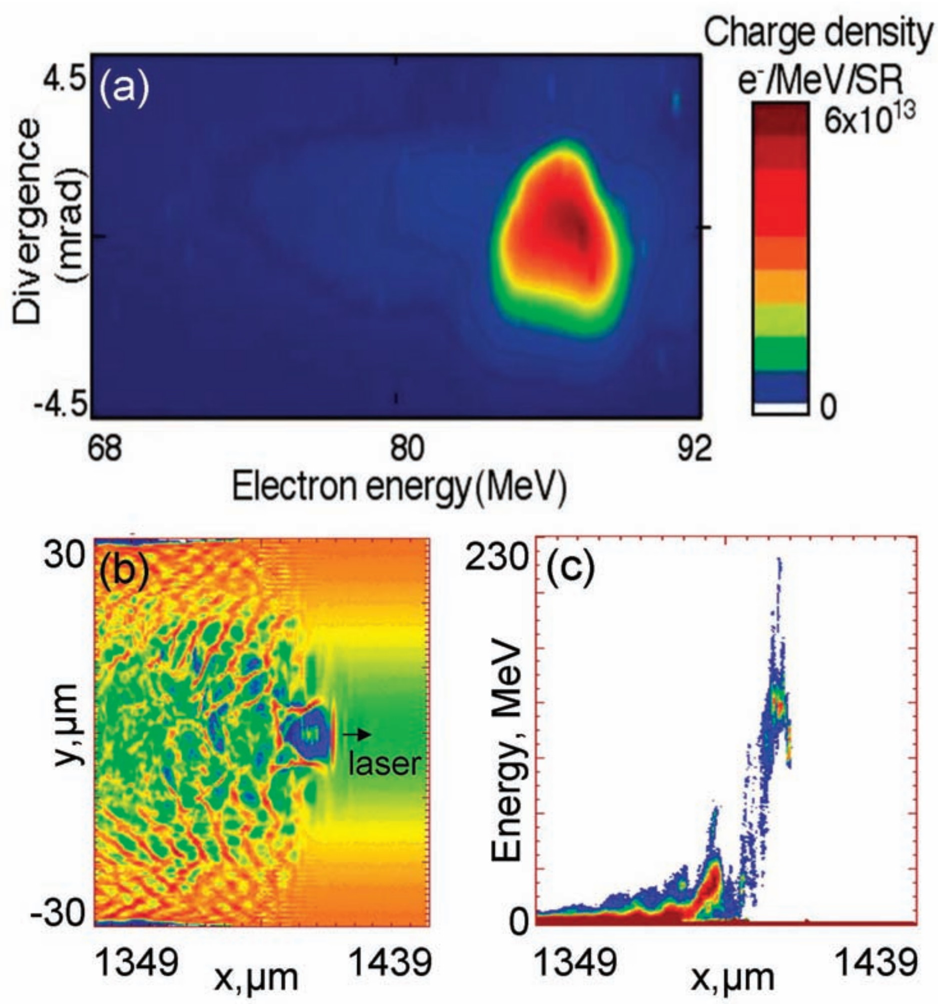


FIGURE 3.7 *(a)* Laser wake field accelerator experiments demonstrated production of low-energy spread electron beams using plasma channels to extend the interaction distance beyond the diffraction distance. Beams up to 150 MeV were observed using a 9-TW laser. *(b)* Particle simulations show that the important physics is trapping in the first wake period behind the laser, with termination of trapping due to wake loading. *(c)* Concentration of the particles in energy at the dephasing point when they outrun the wake. The predicted final energy is near the experimental observation. Courtesy of W.P. Leemans, Lawrence Berkeley National Laboratory (LBNL). SOURCE: C.G.R. Geddes et al., *Physics of Plasmas* 12: 056709 (2005). © 2005 American Institute of Physics.

plasma period later, driving a large-amplitude plasma wake that in turn accelerated particles in the back of the bunch by more than 2.7 GeV. In February 2006, after fabrication of 1-m-long plasma source and beamline modifications, the same collaboration demonstrated doubling of the energy of some of the 30-GeV electrons in a plasma accelerator, a significant advance in demonstrating the potential of plasma accelerators.

The research opportunities for this field over the next decade will clearly focus on answering the question asked in the second section of this chapter: Can we generate, using intense, short-pulse lasers or electron beams interacting with plasmas, multigigavolt per centimeter electric fields in a configuration suitable for accelerating charged particles to energies far beyond the present limits of standard accelerators?

Additional research and development steps must be taken. For example, the plasma through which the laser or particle beam propagates must be tailored so as to maximize the peak electric field and length over which acceleration takes place. It will also be necessary to optimize the laser or electron beam pulse intensity profile and the plasma profile so as to minimize the emittance and energy spread of the accelerated beam for the beam to be as useful as possible for particle physics experiments.

Laser wake field accelerator issues associated with long-distance propagation and acceleration include optical guiding, instabilities, electron dephasing, and group velocity dispersion, all of which can limit the acceleration process. As an example, the scale length for laser beam diffraction is too short to allow reaching GeV electron energies, so optical guiding mechanisms like relativistic focusing and ponderomotive channeling, as well as preformed plasma channels, are necessary to increase the acceleration distance. Recent high-intensity experiments have demonstrated guidance over 10 diffraction lengths by a plasma channel. Combining such guiding techniques with an injector geometry that allows controlled acceleration of monoenergetic beams will be a key step in the development of laser wake field accelerators.

Understanding the interplay among the nonlinear physical processes in plasma wake field accelerators requires numerical simulations. Particle-based models, such as fully explicit particle-in-cell (PIC) algorithms, which allow the self-consistent treatment of particle trajectories in their electromagnetic fields, are essential. Recent advances in algorithms and high-performance computing have enabled the development of highly efficient, fully parallelized, fully relativistic, three-dimensional PIC models that are used for the self-consistent modeling of full-scale wake field experiments, giving results such as that shown in Figure 1.5.

Experiments are under way to demonstrate the production of GeV-class femtosecond electron beams in distances of a few centimeters. Such a device could serve as the first building block in future high-energy physics accelerators, but it might also lead to significant advances in accelerator-based light sources as well. A key challenge will be the development of high repetition, femtosecond laser systems with high (multi-kilowatt) average power.

Plasma-based accelerators have clear connections to many fields of science. Laser-driven accelerators produce electron bunches of very short duration that can be converted to ultrashort radiation pulses. Therefore, in addition to impacting high-energy physics, significant impact is expected in materials science, nuclear science, chemistry, biology, and medical sciences through the use of intense radiation produced from the femtosecond electron bunches covering a wide range of the electromagnetic spectrum, from the terahertz regime to gamma rays, or directly from the electron beams.

It is important to point out that these results are built on nearly 30 years of university research on plasma wakefield accelerators that was consistently sponsored over the years by the NSF and the DOE's Office of High Energy Physics. As described in Chapter 6, important progress on these research questions is often made in smaller-scale experiments, especially with the development of short-pulse lasers (see the section on laser-produced and high-energy-density plasmas in Chapter 6 for details). The value of continuous support for high-risk but promising ideas over decades until definitive results are obtained is clear.

Laboratory Simulation of Astrophysical Phenomena

The universe has become the subject of much more probing studies in recent years because of new telescopes that cover the entire electromagnetic spectrum. They have permitted phenomenally high-energy events to be observed but not understood. Can we possibly do HED experiments in the laboratory that can illuminate these dramatic but spatially and temporally distant events? How can we test hypotheses concerning the physics of an observation that took place millions or even billions of light years away? The NRC report *Connecting Quarks with the Cosmos* says that the goal of laboratory plasma astrophysics is to discern the physical principles that govern extreme astrophysical environments through the laboratory study of HED physics. The challenge here is to develop physically credible scaling relationships that enable, through the intermediary of a computer code, laboratory experiments on the scale of centimeters or meters to illuminate physical processes taking in a distant part of the universe over enormous length scales (see, for example, Figure 1.14).

There is general agreement that laboratory experiments can and do provide atomic physics, equations of state, and other data on HED states of matter similar to those hypothesized to exist in distant objects. Laboratory plasma physicists, atomic physicists, and astrophysicists have, in fact, collaborated for many decades to make plasma spectroscopy a valuable tool for astrophysicists. The fresh twist is that laboratory experiments now allow experimentalists to investigate macroscopic volumes of HED plasma in states that are thought to be relevant to astrophysics and to determine equations of state, x-ray spectra, and radiation transport coefficients.

The use of HED laboratory experiments to investigate physical processes thought to be operative in astrophysical phenomena is a relatively new and controversial endeavor. It is generally believed that laboratory experiments cannot directly simulate an astrophysical situation even if some of the relevant dimensionless parameters are on the same side of some critical value, whatever that might be, in both the laboratory and the cosmos. However, the new generation of laboratory HED facilities can investigate matter under conditions that enable some of the physical processes that are thought to underlie observed phenomena to be studied. Examples of processes and issues that can be experimentally addressed in the laboratory under conditions that may be relevant to a range of astrophysical phenomena are compressible hydrodynamic mixing, strong-shock phenomena, magnetically collimated jets, radiative shocks, radiation flow, complex opacities, photoionized plasmas, equations of state of highly compressed matter, and relativistic plasmas. The laboratory experiments can, therefore, be used to validate the computer codes that are being used by astrophysicists to try to understand the observations, assuming that the scaling laws imply that the experimental regime scales in some reasonable way to the astrophysical phenomenon. Thus, although the growing capacity of experimental studies has potentially opened new windows on cosmic plasmas and their behavior, it is not yet clear that these experiments will one day become standard tools for addressing issues of astrophysical plasmas.

Many complex large-scale structures observable in the universe result from the nonlinear evolution of flows emanating from compact objects. Astrophysical plasma jets are a prime example of this class of phenomena and are also a good example of how laboratory experiments might contribute to an understanding of astrophysical observations. These collimated flows range over size scales from the 0.1 parsec associated with planetary nebulae and young stellar objects to the kiloparsec jets driven by active galactic nuclei. The most pressing questions concerning these flows center on the processes responsible for their formation and collimation as well as their interaction with ambient media. In particular, the effects of radiative cooling, magnetic fields, and intrinsic pulsing on jet structures have received much attention in the literature. In addition to the examples cited, during the last stages of a massive star's evolution, jets arising during gravitational collapse may play an important role in the explosion of some types of supernovas.

Experiments designed to be relevant to these astrophysical phenomena are performed using high intensity lasers and conical wire arrays on pulsed-power facilities. The laboratory jets are formed hydrodynamically in these experiments, in some cases through converging conical flows that were either shock-driven or ablatively driven. In some of these experiments, radiative cooling has been achieved in the jets, allowing issues such as collimation to be studied. In other cases, the propagation of a jet through an ambient medium has been studied. Jet bending via the ram pressure of a crosswind has also been explored. Issues such as stability, collimation, and shock physics associated with jets might be addressed, but their relevance to astrophysical observations requires similarity of the physical situation, as determined by dimensionless parameters, and evidence that the scaling laws adequately connect the two hugely disparate situations. Morphological similarity between a laboratory plasma and an observation is not a particularly useful indication of relevance.

Fundamental HED Research

While the Grand Challenge applications of HED science discussed above have driven much of HED research in the past 10 years, the blossoming of this science outside the national laboratories has led to a series of exciting new research areas outside the scope of those applications. Much basic and applied HED research is being pursued in universities as well as in government laboratories and promises interesting opportunities in the coming decade. Research in many of these areas is of importance not only for intellectual reasons but also because the projects train students who ultimately become the leaders in the large projects that address national priorities.

Advanced Computer Simulation of HED Plasmas

Advances in predictive capability made possible by computer simulations are revolutionizing all areas of HED plasma research. Advanced computing has also been used to build complex physical models to yield detailed results that can be compared with experimental results. One such model involves the density functional theory calculations of the hydrogen equation of state. The challenge in the next decade for computational HED science will be in studies of plasma phenomena in which relevant physics occurs on very wide spatial and temporal scales. For example, the dramatic advances in PIC simulation capabilities that are being applied to understanding a host of laser–plasma interaction problems are still limited to the submillimeter scale. The coming decade will see novel extensions of these codes using hybrid approaches spanning large spatial scales.

HED Shock, Jet, and Ablation Hydrodynamics

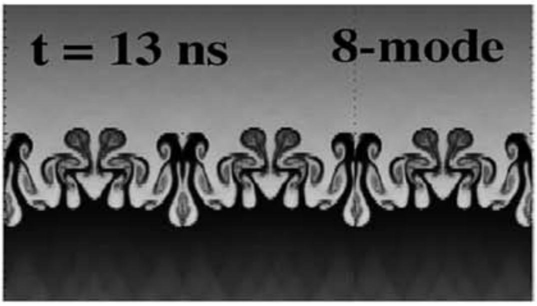
The past 10 years have seen quite remarkable progress in our ability to study in the laboratory various HED hydrodynamic phenomena, such as very high Mach number shock experiments. For example, high-power lasers have been used to study Rayleigh-Taylor and other instabilities in shock waves at pressures well over 1 Mbar in solid density material. An example is shown in Figure 3.8. These experiments can now be performed at sufficiently high Reynolds number, Peclet number, and Mach number that the equations describing these shocks are similar to those that describe supernova dynamics. What's more, our understanding of the hydrodynamics at the front of radiation-driven ablation has improved dramatically in the past decade. When a radiation field, such as from a laser, heats a plasma, material is ablated and the pressure exerted by this ablating material can drive instabilities. While achieving an understanding of ablation front hydrodynamics is critical to continued progress in ICF, this research also holds out hope of shedding light on ablation front instabilities found in such astrophysical situations as radiatively driven molecular clouds.

Radiation Hydrodynamics

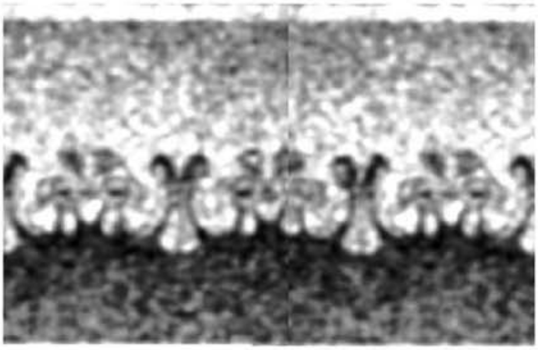
Experiments in which radiation strongly affects the evolution of the plasma structure is also an area of active research. Most extensively studied are radiative shock waves in which the radiative fluxes exceed the material energy fluxes at the shock front and in which radiative losses are an important element of the dynamics. These experiments, which have been performed on facilities such as the OMEGA, JANUS, and Z-Beamlet lasers, have been useful in studying hydrodynamic instabilities and evolution in the radiative regime. There have also been some very exciting demonstrations of high Mach number plasma jets driven both by high-energy lasers and by z-pinches. Radiative dynamics often plays an important role in astrophysical jets, and the laboratory jet experiments are beginning to reach into this radiative regime.

Atomic and Radiation Physics in HED Plasmas

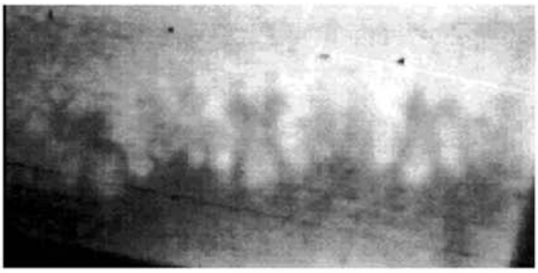
Atomic emission and absorption properties in hot dense plasmas are complex and are an active area of research. The past decade has seen the development of atomic structure and scattering codes that can compute details of the atomic quantum-level structure and kinetics, including ionization balance and level populations in high atomic number plasmas. Experimentally, there have been important developments in spectroscopic diagnostic instrumentation in the past 10 years. Such diagnostic capability enables a comparison of theory and experiment that is sufficiently detailed to reveal plasma conditions as a function of space and time through comparison of observed and calculated spectra. The measurement accuracy is sufficient to check code calculations of spectral line energies. These new diagnostics coupled with a detailed understanding of atomic physics in dense plasmas will lead to new ways of measuring and studying HED plasmas in the coming decade, including igniting ICF cores.



(a) **Numerical radiograph**



(b) **Simulated radiograph**



(c) **Experimental radiograph**

FIGURE 3.8 Comparison of numerical simulations and experiment on multimode Rayleigh-Taylor instabilities. *(a)* A numerical radiograph from simulations. *(b)* Same as *a*, except with experimental noise added into the simulated output. *(c)* Experimental radiograph on strong shock-driven experiments done at the OMEGA laser. Courtesy of Laboratory for Laser Energetics (LLE), University of Rochester. SOURCE: A.R. Miles, D.G. Braun, M.J. Edwards, H.F. Robey, R.P. Drake, and D.R. Leibrandt, "Numerical simulation of supernova-relevant laser-driven hydro experiments on OMEGA," *Physics of Plasmas* 11: 3631 (2004). © 2004 American Institute of Physics.

Ultraintense Laser Generation of Bright Radiation Sources with HED Plasmas

When an intense laser irradiates a solid target, energetic electrons are accelerated into the target and the electrons then generate x rays by various mechanisms. The past 10 years have seen the exploitation of this physics for the development of x-ray sources that are very bright and ultrafast (with pulse widths well under 1 psec). These ultrashort x-ray bursts driven by high-repetition-rate, multiterawatt lasers have found applications in a range of time-resolved x-ray spectroscopy experiments and dynamic probing experiments, such as those for the study of femtosecond condensed-matter dynamics, including melting and phonon propagation in laser-excited crystalline materials. Other time-resolved x-ray spectroscopy techniques, such as x-ray absorption spectroscopy or x-ray scattering, are now being implemented. These sources may soon be bright enough to probe the dynamics of chemical and biochemical reactions. At the petawatt level, isochoric heating experiments devoted to equation-of-state studies will be possible.

Intense Femtosecond Laser Channeling in Air Over Long Distances

Recent experiments have shown that an intense femtosecond laser of a few millijoules to a joule in energy can self-channel in a gas, producing plasma filaments as long as a few kilometers. This allows laser spots of a few tenths of a millimeter to be delivered at great distances from the laser sources. It has also been observed that these plasma filaments are accompanied by strong terahertz emission. This self-channeling may lead to unique lidar systems that can detect atmospheric pollution or weaponized chemical and biological agents.

Nonlinear and Relativistic Laser–Plasma Interactions

Recent fundamental laser–plasma interaction research has concentrated in part on understanding such phenomena as the nonlinear saturation of the stimulated Raman scattering instability in a single hot spot and the use of optical mixing techniques to disrupt parametric instabilities, thereby providing some means of controlling these instabilities. In the coming decade, nonlinear effects such as so-called KEEN waves will be studied experimentally. What is more, with the recent development of laser technology capable of focused intensities over 10^{19} W/cm^2, a wide range of relativistic laser–plasma phenomena, including novel nonlinear optical interactions and the creation of matter-antimatter plasmas, have become possible. Nonlinear optical phenomena attributable to the relativistic mass change of the electrons in the laser field lead to self-focusing and -channeling of the laser, or the generation of high-order harmonics in the laser field. The physics of how laser pulses interact with underdense plasma is critical in ICF and wake field accelerator research.

University-Scale, Pulsed-Power-Driven HED Plasmas

Kilovolt, near-solid-density plasmas can be produced routinely in the laboratory by pulsed-power machines capable of as little as 50-100 kA with ~50- to 200-nsec pulse durations. In the last 10 years, such plasmas have been used to develop many x-ray diagnostics that are also useful on large-scale pulsed-power machines at the national laboratories using a variant of the exploding wire z-pinch called an x-pinch. This plasma yields x-ray sources as small as 1 μm that can be used for x-ray point-projection radiography with extremely high temporal and spatial resolution. At the 1 MA level, university machines have been used to generate plasma configurations that some believe are relevant to understanding astrophysical observations. As is the case with university-scale laser facilities, university-based pulsed-power systems offer opportunities to probe hot dense plasma in preparation for experiments on large-scale facilities, to benchmark computer codes, and to train students in the skills needed by the national laboratories. For example, wire-array z-pinch experiments at 1 MA university-scale machines (Figure 3.9) can test hypotheses about the origin of the instabilities observed in the wire-array z-pinches on the Z-machine.

Rod-Pinch Development for Radiography

Intense electron beams have been used to produce large amounts of 0.1-10 MeV radiation from 1-15 MV pulsed-power machines for simulating the effects of nuclear weapons since the 1960s. However, the ability to focus a high current (~100 kA), multi-MeV beam to a ~1 mm spot for radiography has only recently been achieved. A sharp-pointed tungsten rod anode on an axis that extends through the hole of an annular cathode of a few megavolts pulsed-power machine has solved that problem. The cylindrical electron beam emitted from the cathode pinches down toward the rod and then propagates along the rod in such a way as to deposit its energy predominantly near the ~1 mm diameter tip. As a result, extremely fast hydrodynamics experiments, such as the subcritical plutonium materials science experiments being carried out as part of the SSP, can be performed with radiography having a resolution of a few millimeters using pulsed-power machines of modest size that produce only a few megawatts.

ADDRESSING THE CHALLENGES

NNSA facilities are (legitimately) largely reserved for mission-oriented research. However, there are synergies between mission-oriented SSP science and fundamental HED science, and there are benefits to the cross-fertilization that occurs when university–national laboratory collaborations are developed. The

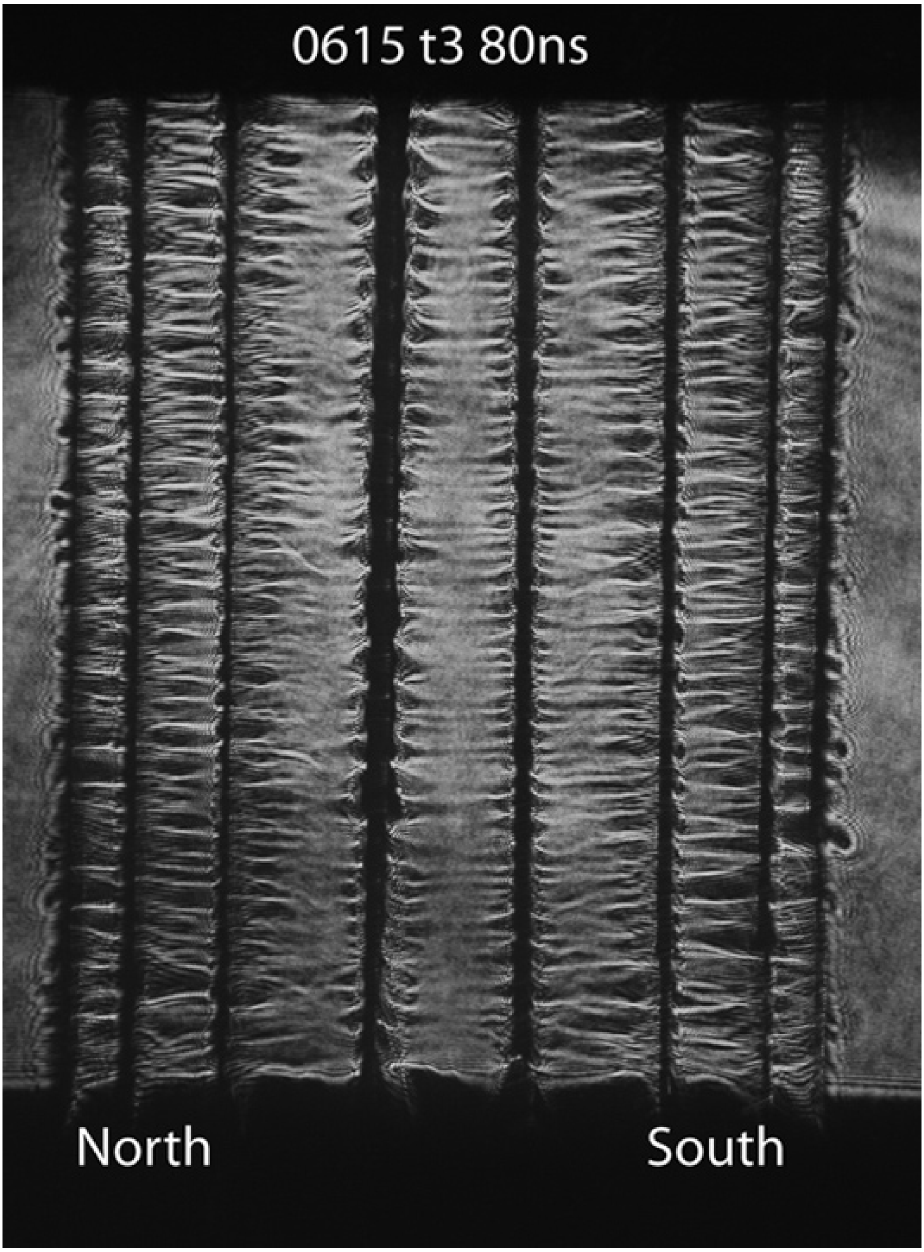


FIGURE 3.9 Laser shadowgraph image of an exploding wire z-pinch on the 1 MA COBRA generator at Cornell that started out with a cylindrical array of eight 12.7-μm Al wires at a radius of 8 mm. The anode (cathode) of the array is at the top (bottom). Notice the short wavelength structure in the plasmas around each exploding wire. Also, note that there is a plasma forming on the array axis. Courtesy of the Laboratory of Plasma Studies, Cornell University.

committee therefore applauds the NNSA Stewardship Sciences Academic Alliances program, which supports a broad range of HED science at universities and small businesses, as well as the new Stewardship Sciences Graduate Fellowship program. These will enable the research community to take advantage of more of the research opportunities offered by the HED field. Nascent efforts to develop user programs at NNSA's intermediate- and large-scale facilities at the national laboratories are another step in this direction. Investigator-driven science can be facilitated by encouraging two kinds of collaboration:

- Dual-purpose (unclassified) experiments that involve collaborations between university and national laboratory scientists, in which both parties benefit, the former by acquiring publishable data together and the latter by advancing stockpile stewardship science, and
- Outside user programs on all major NNSA facilities, similar to the program at the National Laser User Facility (the OMEGA laser) at the University of Rochester, which sets aside perhaps 10-15 percent of the run time for investigator-driven research.

A facility that is particularly in demand for investigator-driven research could increase its availability for a relatively small incremental cost by adding a shift each week, avoiding a reduction in the number of pulses available for mission-oriented research. As demand for intermediate-scale facility time increases, the HED research community and its sponsors should determine if HED research progress is significantly hampered by a lack of facilities dedicated to investigator-driven, peer-reviewed research. If that is happening, a case should be developed for the design, construction, and operation of a professionally managed, open-access, user-oriented facility similar to the synchrotron light sources operated for the materials science community by the DOE's Office of Basic Energy Sciences.

Finally, the committee observes that while a high-repetition-rate, 100-J laser for HED science experiments is not fully developed, both diode-pumped solid-state lasers and krypton fluoride lasers are approaching that level of capability. Several HED research areas could benefit from a shot-on-demand capability if at least one high-repetition-rate, 100-J laser is completed and the system turned into a user facility. Two such possibilities were mentioned at the end of the section on ICF, earlier in this chapter.

CONCLUSIONS AND RECOMMENDATIONS FOR THIS TOPIC

Conclusion: The remarkable progress in high-energy-density plasma science and the explosion of opportunities for further growth have been stimu-

lated by the extraordinary laboratory facilities that are now operating or soon will be completed.

The laser and pulsed-power facilities that are now available, both very large and small enough to be called tabletop, enable the production and in-depth investigation of matter in parameter regimes that were previously considered beyond reach. The applications of HED plasma science and the issues surrounding it that can be addressed by these facilities range from Grand Challenges of applied science to basic atomic, plasma, and materials physics. Connections to many other areas of the physical sciences, including condensed matter, nuclear, high energy and atomic physics, accelerators and beams, materials science, fluid dynamics, magnetohydrodynamics, and astrophysics substantially broaden the intellectual impact of HED plasma research. As in all areas of plasma science, progress in HED research has benefited tremendously from advances in large-scale computer simulation capability and from newly developed diagnostic systems that have remarkable spatial and temporal resolution.

The outcome of HED plasma research activities in the next decade will impact the SSP, our ability to interpret observed high-energy astrophysical phenomena, and our basic understanding of the properties of matter under extremes of density and temperature. In the longer term, the research highlighted here could lead to radically different particle accelerators with ultrahigh energies. It could also demonstrate the feasibility of inertial confinement fusion as a practical, inexhaustible energy source.

Conclusion: The exciting research opportunities in high energy density (HED) plasma science extend far beyond the inertial confinement fusion, stockpile stewardship, and advanced accelerator missions of the National Nuclear Security Administration and the Department of Energy's Office of High Energy Physics. The broad field of HED plasma science could exploit the opportunities for investigator-driven, peer-reviewed HED plasma research better if it were supported and managed together with research encompassing all of plasma science.

The NNSA provides by far the largest amount of research funding in the HED plasma area. The Stewardship Sciences Academic Alliances Program is a good start toward a healthy HED plasma research infrastructure outside the national laboratories. The Department of Energy's Office of High Energy Physics (OHEP) and Office of Fusion Energy Sciences (OFES) provide additional support for some areas of HED plasma research. However, progress in many other areas of HED plasma science, such as warm dense matter, laboratory plasma astrophysics, and atomic physics in hot dense matter, is limited by the relatively narrow missions of the NNSA, the OHEP, and the OFES. Advances in investigator-driven, peer-reviewed

HED research outside the scope of the mission-oriented agencies might develop much more rapidly if HED plasma research were integrated with the rest of plasma science in an organization whose mission included basic science. The announcement of a joint NNSA and OFES program in HED laboratory plasma physics is an important step forward.[3]

Conclusion: The cross-fertilization between the national laboratory programs of the National Nuclear Security Administration (NNSA) and university research could be improved by increased cooperation between university and national laboratory scientists, facilitated by NNSA.

User programs on the major NNSA facilities at the national laboratories that provide a significant amount of facility time for investigator-driven research are lacking. Intermediate-scale, user-oriented facilities, such as a petawatt laser facility comparable to the Rutherford Laboratory in the United Kingdom, are also lacking. The NNSA is beginning to foster user programs at its major facilities as well as collaborative experiments between university and national laboratory scientists, but such opportunities are not yet available to the broader scientific community. Successful examples are the National Laser Users Facility at the University of Rochester and, in magnetic confinement fusion research, the use of DIII-D at General Atomics. There are many other examples of this growing trend throughout the physical sciences.

Conclusion: If the United States is to realize the opportunities for future energy applications that may come from the achievement of inertial fusion ignition, a strategic plan is required for the development of the related science and technology toward the energy goal. Currently no such plan exists at the Department of Energy. Perhaps more important, there are no criteria to guide the determination of when such a plan should be developed.

The U.S. fusion program includes inertial fusion energy as a potential alternative path to practical fusion energy in parallel with the magnetic confinement fusion approach. However, favorable results from ICF ignition experiments could change the landscape of and significantly impact DOE's planning for the deployment of fusion as an alternative energy resource for the United States. The large-scale introduction of commercial fusion reactors based on either magnetic or

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[3] This program was announced in February 2007 in the FY2008 presidential budget request. It includes individual investigators, research center activities, and user programs at national laser facilities. The programmatic and scientific future of the program will be discussed in greater detail in the forthcoming report from the OSTP Task Force on High Energy Density Physics, a panel of the Physics of the Universe Interagency Working Group.

inertial confinement just a decade sooner will pay huge dividends to the United States economy and national security in the long term.

> **Conclusion: Pursuit of some of the most compelling scientific opportunities in HED physics requires facilities of an intermediate scale. The ability to propose, construct, and operate such facilities or to be granted access to existing facilities is quite constrained because the emerging scientific community is supported primarily through NNSA and is constrained by the overarching NNSA mission.**

The emergence of HED physics as an intellectual discipline organized around compelling research topics was well articulated in *The X-Games Report.* As declared in that report and in the current report, the field is developing rapidly. In particular, science topics such as laser–plasma interactions and warm dense matter could be explored at intermediate-scale facilities. Still largely embedded within NNSA, the scientists working on these topics do not have a mechanism for identifying, prioritizing, and managing a portfolio of small and intermediate-scale facilities. The committee notes that one symptom of this situation is the absence of competition among proposals for different facilities or even a discussion about them in the community.

> **Recommendation: Existing intermediate-scale, professionally supported, state-of-the-art, high-energy-density (HED) science facilities at the national laboratories should have strong outside-user programs with a goal of supporting discovery-driven research in addition to mission-oriented research. To encourage investigator-driven research and realize the full potential of HED science, the research community and its sponsors should develop a rationale for open-access, intermediate-scale facilities and should then design, construct, and operate them.**

Intermediate-scale facilities may be sited at universities or national laboratories; there are advantages to both. Intermediate-scale facilities have the flexibility and accessibilty to exploit opportunities that do not require the largest facilities (NIF, OMEGA-EP, and ZR), whose allocations of shots will be influenced by mission-oriented science. As such, existing intermediate-scale facilities could and should be shared by basic and programmatic science users. Provided operating costs can be funded, a broad user program at the existing facilities can enable new science while avoiding the capital costs of new construction.

Small-scale facilities at universities complement intermediate- and large-scale facilities by testing novel ideas, developing diagnostic techniques, serving as staging grounds for experiments intended to be run on larger facilities, and providing critical hands-on training for the next generation of HED experimentalists. Assuming the community clearly identifies the need, intermediate-scale user facilities should be built for HED science on the same basis as the DOE Office of Basic Energy Sciences provides user facilities for materials research.

Finally, the committee notes that additional resources will be required to construct and operate any such new facilities. The DOE Office of Science should provide a framework for plasma science as a whole and play a role in managing a robust user program for broader science experiments at NNSA's largest facilities.

4

The Plasma Science of Magnetic Fusion

INTRODUCTION

A New Era in Magnetic Fusion Research

The worldwide magnetic fusion research effort to develop a virtually unlimited, environment-friendly energy source is entering a new era. The first experiments to explore magnetically confined fusion burning plasmas will begin in the international fusion device ITER[1] late in the next decade. This is of enormous scientific importance. Indeed, it will provide the first opportunity to study the rich and possibly unexpected physics of burning plasmas. Understanding and controlling burning plasmas is an essential step in developing fusion as a source of electricity. In addition to its scientific importance, ITER is expected to be the first magnetic fusion device to generate substantial levels (as much as 500 MW) of thermal fusion power for hundreds of seconds—a very significant step for future energy security. This chapter outlines the recent scientific progress that has brought magnetic fusion to this historic juncture. It also highlights the outstanding plasma science issues. These issues inform two key strategic questions facing the magnetic fusion community:

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[1] The evolution of the worldwide fusion research program to the ITER project and key characteristics of the ITER device are summarized in Appendix B.

- What plasma science must be developed to maximize the scientific output of ITER?
- What science and enabling technology must be developed to move beyond ITER to fusion-generated electricity?

The nonplasma fusion sciences and enabling technologies needed to develop an electricity-producing fusion power system are beyond the scope of this report; they are discussed in the report of the Burning Plasma Assessment Committee.[2]

Magnetic Fusion: A Brief Description

The design and proposed operation of ITER illustrates the key principles, physical processes, and terminology involved in magnetic fusion. To introduce these basic ideas and give a context for recent developments, we will refer to the ITER design. The plasma is contained in a toroidal (doughnut-shaped) steel vacuum vessel of major radius 6.2 m and minor radius 2 m (Figure. 4.1). Wrapped around the vessel are superconducting coils that produce a toroidal magnetic field of 5.3 T (the coils are dark orange). The plasma (pink) consists of electrons, deuterium ions, and tritium ions. These charged particles carry an electrical current that creates part of the magnetic field. They travel along and spiral around the magnetic field lines—see, for instance, Figure 4.2. The radii of the ion spirals, the ion Larmor radii, are typically a couple of millimeters (in ITER conditions)—a thousandth of the 2-m minor radius. The plasma is collisionless in the sense that a typical charged particle will circumnavigate the torus hundreds of times in a characteristic collision length. In the middle of the plasma the particles have temperatures of greater than 100 million degrees (10 kV) and densities of 10^{20} particles per cubic meter; these values decrease approaching the vacuum vessel wall.

Deuterium and tritium ions fuse to form a helium nucleus (alpha particle) with 3.5 MV of energy and a neutron with 14.1 MV of energy. The fusion happens predominantly in the center of the plasma, where the ions have enough energy (over 10 kV) to overcome their mutual electrostatic repulsion. Most important to the burning plasma regime is the confinement of the energetic alpha particles, since collisional heating from the alphas is used to maintain the high plasma temperature. The neutron produced in the fusion reactions crosses the magnetic field and deposits four-fifths of the fusion energy in the external structure. In a future fusion reactor the neutrons will strike lithium nuclei in a blanket surrounding the plasma, splitting the lithium into helium nuclei and new tritium nuclei for fueling the plasma. Heat to power turbines and generate electricity will also be extracted

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[2] NRC, *Burning Plasma: Bringing a Star to Earth*, Washington, D.C.: The National Academies Press, 2004. Hereinafter referred to as *Burning Plasma*.

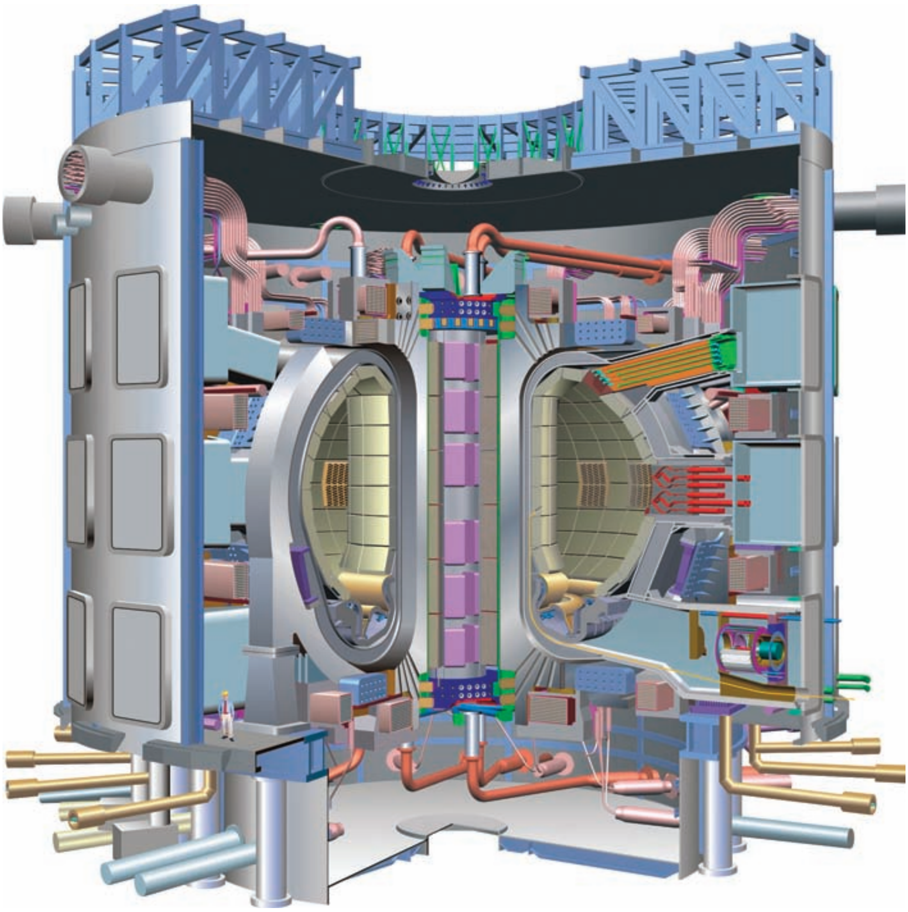

FIGURE 4.1 Cutaway drawing of the International Thermonuclear Experimental Reactor (ITER), to be built over the next decade in Cadarache, France. For the size scale, note the small blue standard person shown in the lower left portion of the figure. The hot plasma is enclosed in a magnetic doughnut, whose dominant magnetic field coils encircle the plasma. Detailed characteristics of the ITER device can be obtained from http://www.iter.org. Published with permission of ITER.

from this blanket. Blanket prototypes will be tested to only a limited extent in ITER, and ITER will not produce electricity.

The power balance of the plasma is the key issue for ITER. The plasma will be heated by up to 80 MW of fusion alpha particle heating, and up to about 100 MW of external heating can be added using injected neutral particle beams and externally excited plasma waves. To achieve the ITER design goal of $Q \geq 10$, where Q is the ratio of total fusion power (500 MW at ITER) to external heating power, only 40-50 MW of external heating is expected to be needed. Heat is lost from the

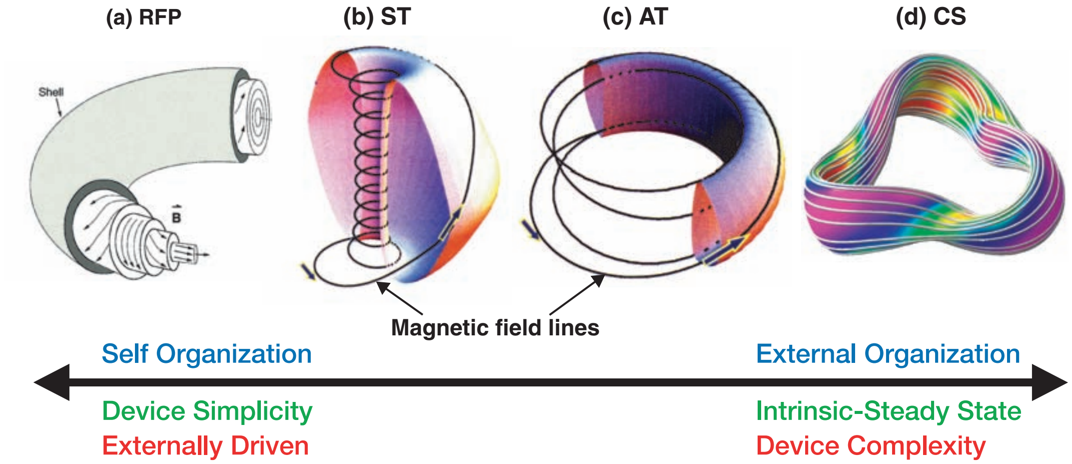

FIGURE 4.2 The magnetic topology of the main U.S. magnetic fusion concept improvement experiments in decreasing order of plasma self-organization. *(a)* Reversed-field pinch (RFP), a high β (pressure) device where the fields are created mainly by plasma currents and rearranged by a self-organizing dynamo. *(b)* Spherical torus (ST), also very high β, which has seen rapid development in the last decade (see Figure 4.3). *(c)* Advanced tokamak (AT), with research in the last decade having shown that with certain current profiles and plasma shapes the tokamak can have considerably enhanced β, transport barriers (regions where turbulence is suppressed), and self-generated bootstrap currents driven by the pressure gradient; these achievements should be exploited in advanced scenarios on ITER. *(d)* Compact stellarator (CS). Two features of stellarators—inherent steady-state operation of stellarators and the recent findings that high-β instabilities may be more benign than in tokamaks—are clear potential advantages that may outweigh the added complexity of three-dimensional field configurations. The field is mainly produced by external coils. Courtesy of D.A. Spong, Oak Ridge National Laboratory.

plasma in several ways but predominantly via small-scale plasma turbulence in the hot core. The typical time for energy to be lost, the energy confinement time, is more than 3 sec. ITER is projected to be firmly in the burning plasma regime, where the fusion self-heating exceeds the external heating. Ignition, where the self-heating is sufficient to supply all the energy to sustain the plasma and Q becomes infinite, may be approached but it is not an ITER goal.

ITER has been designed by extrapolation from existing experiments. Key processes limit the performance, and these can be roughly split into four interrelated areas of research:

- *Macroscopic stability and dynamics.* The fusion power increases roughly with the square of the plasma pressure. It is therefore desirable, in ITER and future fusion reactors, to maximize the plasma pressure. However, when the plasma pressure exceeds a critical value proportional to the magnetic pressure, macroscropic instabilities degrade or destroy the plasma. Some instabilities develop in hundreds of microseconds and smash the plasma against the wall. Others that grow on a longer timescale change the magnetic topology into one where the field lines wander across some or all of the plasma. The loss of heat along the wandering field lines caused by the slower instabilities leads to undesirable cooling of the plasma. In large devices the faster instabilities damage the external structure. Research is focused on (1) trying to raise the critical pressure to attain better fusion performance, (2) understanding the limits so that they can be avoided, and (3) developing methods to control the slower instabilities.

- *Cross-field transport from microscopic processes.* The free energy available from the large pressure and temperature gradients can drive a wide variety of small-scale microinstabilities and microturbulence in the plasma. The electric fields of this turbulence cause particle orbits to cross the magnetic field and transport heat and particles from the hot core to the colder edge much faster than the plasma transport induced by particle collisions. Reducing the plasma turbulence would decrease heat loss and allow for smaller burning plasmas. Research is focused on (1) understanding and predicting the turbulence, (2) elucidating the transport mechanisms for heat, particles, and momentum, and (3) finding regimes of low heat loss from the combination of collisional and turbulent processes.
- *Boundary physics.* The edge of the plasma is a very complex region where the plasma transitions from the hot plasma core to a colder partially ionized plasma. Heat and particles are transported through the edge to the surrounding chamber walls or specialized high-heat-flux surfaces via various collisional, intermittent (bursty), and turbulent processes. To control the outflow, the outer shells of field lines are steered onto the specialized high-heat-flux surfaces. This is called the “divertor.” The power onto the material surfaces in ITER is near the limit materials can stand without rapid erosion. Research is focused on (1) understanding the edge turbulence and transport, (2) controlling instabilities in the edge, and (3) spreading the heat loads over larger areas of material surfaces.
- *Wave–particle interactions.* Plasma waves carrying energy and momentum can propagate through magnetically confined plasmas. Ions or electrons moving at roughly the speed of the wave exchange energy and momentum with it. Radio frequency waves are launched into fusion plasmas to heat and drive currents by this wave–particle interaction mechanism. Energetic particles, particularly alpha particles from fusion reactions in ITER, can impart energy to waves and destabilize them inside the plasma. Such instabilities may then eject the alpha particles from the plasma before they slow down and deposit their fusion energy in the plasma. Research is focused on (1) perfecting techniques to deliver heat and current to precise positions in the plasma with externally launched waves and (2) understanding and preventing the energetic particle instabilities.

In a fusion burning plasma, all the processes described above are closely interrelated: macroscopic instabilities change the magnetic configuration in which the cross-field transport, boundary, and wave–particle effects take place; the cross-field transport, boundary, and wave–particle heating effects (from both external sources and fusion-produced alpha particles) determine the internal pressure and magnetic field profiles; and so on. The scientific challenge in ITER will be to explore the exothermic fusion burning plasma regime in which plasma self-heating dominates the plasma dynamics. This highly nonlinear regime will probably lead to many new and exciting discoveries. Research on fusion burning plasmas will be focused on (1) determining how the large alpha particle component and heating changes the plasma behavior, (2) exploring plasma transport at the larger plasma scale relative to microturbulence eddy scales, and (3) controlling the highly nonlinear and interconnected burning plasma regime.

The success of the ITER burning plasma experiment depends on continuing to improve understanding and predictive capability. Such improvements would build on the scientific advances outlined in the section on recent progress and future opportunities, later in this chapter. The required progress in these key areas will not be possible without a significant expansion of our plasma diagnostic capabilities. Quite simply, we cannot understand what we cannot measure. Existing theoretical models are not yet sufficient to accurately predict many aspects of burning plasma regimes. National initiatives focused on enhancing analytic theory, improving computational algorithms, and making dramatic improvements in the diagnostics deployed at existing facilities would make possible further breakthroughs in our understanding of the key burning plasma physics issues. Such initiatives would allow the United States to retain its leading role in plasma science within the international magnetic fusion program. ITER needs a deeper understanding of these key plasma physics issues; the party that comes to the ITER table with this expertise will have a strong position in the international magnetic fusion program for at least 15 years.

Concept Improvement Is Important for ITER and Beyond

At this time the tokamak is the logical choice of configuration in which to study burning plasmas—an essential step on the road to fusion power (see *Burning Plasma* for more details). The tokamak configuration has achieved the best overall fusion performance thus far and has been used in the design of ITER. However, it is clear that devices with considerably better performance are possible even though they have not yet been fully explored or perhaps even identified. The integrity and the insulating quality of the confining magnetic field may be improved by changing the configuration to a modified (“advanced tokamak”) configuration or from a tokamak to something else. Principal among the alternatives are the tokamak variants—spherical torus, stellarator, and reversed-field pinch (Figure 4.2 and

Table 4.1). The list also includes many other less-developed concept exploration ideas.

These concept improvements must develop further during the ITER era and provide a basis for going beyond ITER to commercial fusion power. The goal is to be in a position to define an optimal fusion energy system for the post-ITER phase of magnetic fusion energy development—a demonstration electricity-producing power plant. Thus a key component of the U.S. fusion program, the importance of which this committee reaffirms, is the study of plasma confinement in tokamak variants and nontokamak magnetic confinement devices.

While the fusion potential of a given concept is a complicated question, two

TABLE 4.1 Characteristics of Major Magnetic Confinement Experimental Devices Around the World

Device Name	Location	Year of First Plasma	Minor Radius (m)	Magnetic Field (T)	Type of Device
United States					
DIII-D	San Diego, Calif.	1986	0.67	2.4	Comprehensive tokamak
MST	Madison, Wisc.	1988	0.52	0.5	Reversed-field pinch
C-Mod	Cambridge, Mass.	1991	0.22	8.0	High-magnetic-field tokamak
NSTX	Princeton, N.J.	1999	0.65	0.5	Spherical torus
Foreign					
T-10	Russia	1975	0.35	3	Comprehensive tokamak
JET	U.K.	1983	1.25	3.4	Comprehensive tokamak
FTU	Italy	1989	0.30	8.0	High-magnetic-field tokamak
JT-60U	Japan	1990	1.00	4.0	Comprehensive tokamak
ASDEX-U	Germany	1991	0.50	3.9	Comprehensive tokamak
Tore Supra	France	1997	0.70	4.5	Superconducting tokamak
MAST	England	1998	0.65	0.6	Spherical torus
LHD	Japan	1998	0.60	3.0	Superconducting stellarator
RFX-mod	Italy	2004	0.47	0.7	Reversed-field pinch
EAST	China	2006	0.40	3.5	Superconducting tokamak
Being built					
KSTAR	South Korea	2008	0.50	3.5	Superconducting tokamak
SST-1	India	2008	0.20	3.0	Superconducting tokamak
NCSX	Princeton, N.J.	2009	0.30	1.7	Compact stellarator
JT-60SA	Japan	2011	1.10	2.7	Superconducting tokamak
W-7X	Germany	2012	0.35	3.0	Superconducting stellarator
World project					
ITER	France	2016	2	5.3	Superconducting fusion burning tokamak

NOTE: Plasma minor radius is half the width of the plasma in the horizontal midplane. Magnetic field strength is in tesla. Since fusion power is proportional to the fusion reaction rate integrated over the volume, the fusion potential is given approximately by the product of the square of plasma pressure β ($\beta = nT/(B^2/2\mu_0)$), the fourth power of the magnetic field B (in tesla), and the plasma volume (in cubic meters). Detailed parameters of these facilities and many other smaller devices are available from the following Web sites:

- U.S. facilities, at http://www.science.doe.gov/ofes/majorfacilities.shtml
- European facilities, at http://www.edfa.org/eu_fusion_programme/r-experimental_facilities.htm
- World Survey of Activities in Controlled Fusion Research, at http://nds121.iaea.org/physics/
- http://www.fusion.org.uk/links/

simple considerations point to the direction of improvement. Raising the pressure limit for a given magnetic field and increasing the plasma volume increases the fusion power for a given cost of magnet coils (the parameter β, the ratio of plasma pressure to magnetic pressure quantifies this). It is also desirable to reduce the turbulence so that the same confinement could be reached in a smaller device or with weaker field. Progress in demonstrating these advantages has been achieved over the past decade (Figure 4.3). Many magnetic confinement concepts are being pursued in the United States and worldwide (Table 4.1). At the present time, however, the four concepts shown in Figure 4.2 are thought to offer the most significant potential advantages over the conventional tokamak.

However, concept improvement has two other important roles. First, it generates new ideas and regimes to be explored on ITER. Second, it enhances the understanding of plasmas by broadening available plasma conditions and challenging the predictive models. Like all the areas discussed in this chapter, concept improvement would benefit greatly from a program to develop a new generation of diagnostic tools and predictive models.

The critical long-term goal of the concept improvement program is to identify and develop a more efficient magnetic configuration for the post-ITER phase of magnetic fusion research. But, the burning plasma and concept improvement parts of the fusion program are not, of course, separate in a scientific sense. Indeed, over the past decade, U.S. leadership in a number of scientific areas has contributed significantly to making ITER smaller, more efficient, and less expensive. This was done by helping redefine ITER's scientific goals, advocating significant science-driven changes in the engineering design, and by developing and pushing several modes of advanced tokamak operation pioneered in U.S. fusion experiments. The path beyond ITER to an optimal reactor is clearly predicated on understanding the basic plasma processes and thereby improving the science-based predictive capability. The concept improvement program plays an important role in improving this capability both for specific concepts and for magnetic confinement in general. One reason for this is that innovative concepts explore a broader range of plasma conditions. Also, some basic plasma processes are best studied in a particular configuration, yet the knowledge gained has application in all. A good example is the reversed-field pinch, where three-dimensional magnetic reconnection and magnetic turbulence are prevalent and therefore easier to study.

The United States is well positioned to continue to lead in scientific understanding and innovation in magnetic fusion research. A balanced, forward-looking plan that focuses on further improving our predictive capability for the plasma physics processes that limit fusion reactor performance would naturally emphasize improved diagnostics, continued exploration of tokamak-variant and nontokamak configurations, and a healthy theory program. An innovation-focused plan would also make allowance for new discovery. Because the United States will not have to

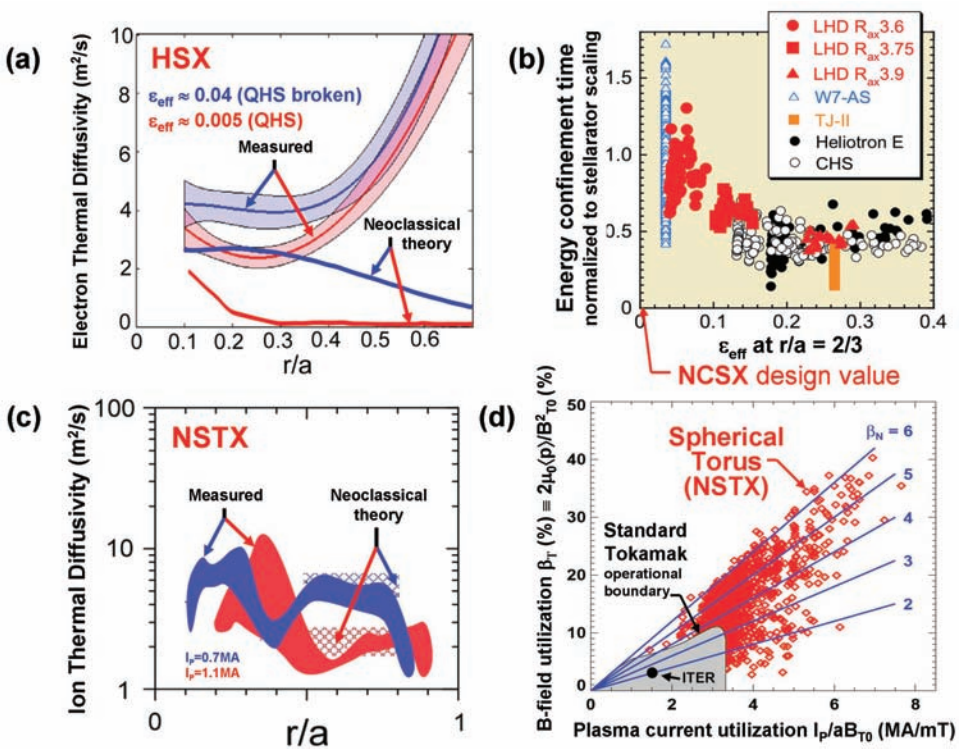

FIGURE 4.3 Building a better magnetic bottle: examples of recent progress. In stellarators (three-dimensional magnetic configurations), large particle drifts across the magnetic field can cause significant heat and particle loss. Over the last 20 years, theoreticians have discovered three-dimensional configurations with effective symmetries in the magnetic field strength. These have low drift losses. The deviation from symmetry is measured by the parameter ε_{eff}. Recent results from the Helically Symmetric Experiment (HSX) demonstrating the expected reduction in the electron diffusion in the low ε_{eff} quasi-helically symmetric (QHS) configuration are shown in diagram *(a)*. SOURCE: Adapted from J.M. Canik and D.T. Anderson, *Physical Review Letters* 98: 085002 (2007). © 2007 by the American Physical Society. Diagram *(b)* displays results from many stellarator experiments showing increased confinement with smaller ε_{eff}. Also shown is the design value for the National Compact Stellarator Experiment (NCSX), which is under construction. SOURCE: Adapted from H. Yamada, J.H. Harris, A. Dinklage, E. Ascasibar, F. Sano, S. Okamura, J. Talmadge, U. Stroth, A. Kus, S. Murakami, M. Yokoyama, C.D. Beidler, V. Tribaldos, K.Y. Watanabe, and Y. Suzuki, "Characterization of energy confinement in net-current free plasmas using the extended International Stellarator Database," *Nuclear Fusion* 45: 1684-1693 (2005). Diagram *(c)* presents data from the National Spherical Torus Experiment (NSTX) showing ion transport at the collisional levels (marked "neoclassical") in discharges where turbulence is suppressed by sheared flows. SOURCE: Adapted from S.M. Kaye, R.E. Bell, D. Gates, B.P. LeBlanc, F.M. Levinton, J.E. Menard, D. Mueller, G. Rewoldt, S.A. Sabbagh, W. Wang, and H. Yuh, "Scaling of electron and ion transport in the high-power spherical torus NSTX," *Physical Review Letters* 98: 175002 (2007). © 2007 by the American Physical Society. Diagram *(d)* shows that, as predicted by theory, NSTX achieves large values of current and pressure for given magnetic field strengths at the center of the plasma—over 10 times the ratios expected in ITER. SOURCE: Adapted from S.M. Kaye et al., "Progress towards high performance plasmas in the National Spherical Torus Experiment (NSTX)," *Nuclear Fusion* 45: S168-S180 (2005).

shoulder a major fraction of the ITER cost, the country will be well positioned to lead the exploration of new plasma confinement and fusion science ideas that come to the fore over the next two decades.

Examining Table 4.1 again, however, one observes that many other countries are developing a new generation of facilities, often employing scientific developments that stem from older U.S. research. The United States played a more dominant role in magnetic fusion research when there were fewer players. It is clear, however, that with its present set of aging domestic facilities the United States is not well-positioned to lead in the many aspects of the science and technology that require either large powerful devices or the long pulses that superconducting magnets enable.

IMPORTANCE OF THIS RESEARCH

Magnetic fusion research has one primary goal: to develop a virtually unlimited, noncarbon, environment-friendly source of energy for the production of electricity. The potential of fusion is enormous—see the first section in Chapter 1. Reactor system studies indicate that magnetic fusion could produce electricity at a cost (about 6 to 8 cents per kilowatt hour) commensurate with the likely cost of other baseload electricity-producing systems in the middle of the 21st century.[3] Thus magnetic fusion could become a critically important contributor to the energy security of the United States by the end of the 21st century.

The primary goal of magnetic fusion research is important enough that it would be pursued even if it produced no other scientific benefit. However, magnetic fusion research does contribute to the national scientific enterprise in three ways that are not directly part of the primary goal:

- *Plasma physics: Magnetic fusion relies upon and drives plasma science.* The most critical science for fusion is plasma physics. Thus the fusion research program has been the primary driver for development and support of plasma physics, a new discipline of physics, over the past 50 years. For example, in just the past decade fusion research has produced studies of laboratory magnetic reconnection; plasma and fluid dynamos; and microturbulence. These processes have great importance in space and astrophysical plasmas (see Chapter 5), and insight gained in the magnetic fusion program continues to be fruitful. The relatively large investment in developing computational methods for fusion is benefiting many areas of plasma research. This includes the direct use of fusion computer codes in other areas of plasma science. Similarly, new diagnostics developed in

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[3] See http://aries.ucsd.edu/ARIES/DOCS for more information.

magnetic fusion have found application in areas such as low-temperature plasma science.

- *Science: Fusion contributes to other sciences.* Fusion research continues to make important contributions to broader scientific pursuits. These include very significant contributions to the theoretical understanding of complex nonlinear systems. For example, fusion research has made fundamental contributions to the understanding of the onset of stochasticity, chaos, and nonlinear dynamics. These insights have important application in, for instance, meteorology and planetary science. Fusion research has also advanced atomic physics in two ways: by investigating and measuring the atomic processes in the low-temperature, partially ionized plasmas at the edge of fusion experiments and by providing a hot plasma environment to measure the properties of highly stripped atoms of relevance to astrophysical plasmas.
- *Workforce: The fusion program has trained many plasma scientists.* The challenge and importance of fusion research has always been very attractive to students. It can be expected to have an even stronger draw over the next decade for both the United States and the rest of the world, as carbon-free energy becomes an increasingly important societal goal and ITER is being built. The fusion research program continues to train many young scientists who then move into other areas of plasma science such as space plasma physics, stockpile stewardship, inertial confinement fusion, and plasma processing of microprocessors.

The NRC report *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program* (2001) examines in more detail the linkage between fusion science and other areas of science. It identified a need to enhance those connections and reduce the perceived isolation of the fusion community. In response to a recommendation in the report, two university-based fusion science centers have been established to form new links with the general physics community. NSF's Physics Frontier Center at the University of Wisconsin, the Center for Magnetic Self-Organization, is also making explicit connections between fusion science, basic plasma science, and space and astrophysical plasma science. In the era of ITER, it will be increasingly important to enhance these connections so as to exploit the expertise of the wider scientific community for the benefit of fusion and to disseminate the insights and understandings gained in fusion.

RECENT PROGRESS AND FUTURE OPPORTUNITIES

Since the achievement of significant deuterium-tritium fusion power in the mid-1990s (see Chapter 1), the magnetic fusion program has become focused on solving key science issues and developing predictive capability. Significant progress has been made in a number of scientific areas, as described in the remainder of this section. Two factors have been instrumental in this progress: Plasma diagnostics has improved so that plasma properties at multiple spatial points and times are readily available and new theoretical models have been developed and implemented in computer codes. Examples of progress and opportunities in four areas will be discussed: (1) macroscopic stability and dynamics; (2) microinstabilities, turbulence, and transport; (3) plasma boundary properties and control; and (4) wave–particle interactions in fusion plasmas.

Macroscopic Stability and Dynamics

The first issue in magnetic confinement is to control the macroscopic stability of the plasma. The plasma is confined with strong magnetic fields that are generated both by powerful magnets and by large currents flowing in the plasma itself (see Figure 4.1). The pressure expansion force of the plasma (typical pressures are a few atmospheres) is balanced by the magnetic forces. Small distortions from equilibrium grow when either the pressure or the current exceed stability limits. These distortions can grow on timescales as fast as tens of microseconds or as slow as seconds. Defects (distortions, aneurysms, and islands) form in the magnetic fields, bringing hot plasma into contact with relatively cool material surfaces and/or diluting the hot central plasma with cool plasma from closer to the edges of the device. Boxes 4.1 and 4.2 describe two important examples of success in understanding, calculating, and suppressing important macroscopic instabilities.

Advances in theory and computation have yielded an improved understanding of the stability boundaries in most situations. These theories are largely based on magnetohydrodynamics—a fluid approximation to the plasma behavior. These calculations now incorporate the full geometric complexity of the plasma equilibrium. Although some kinetic and dissipative effects are being considered, more research is needed to improve the theoretical models. Thus precise quantitative theoretical predictions of stability boundaries are not yet possible. Nonetheless, by feeding the understanding into empirical models and fitting the data, ITER's stability can be fairly precisely predicted.

Opportunities in Macroscopic Stability and Dynamics

Two goals motivate macroscopic instability research: to develop a precise quantitative predictive capability and to find regimes where the plasma parameters exceed the normal limits set by instability thresholds and the plasma is controlled without deleterious effects. Recent progress suggests that these goals will largely be achievable in the next decade if advances in the theoretical models and their computational implementation are forthcoming. Despite steady increases in computer power, simulating the fundamental kinetic plasma equations is very challenging, and rapid progress can often be made only through "reduced" models, typically hybrids of fluid and kinetic descriptions. In principle, such models average over short time and space scales to deduce tractable macroscopic equations. Two aspects of the physics require development. The first is reduced hybrid magnetohydrodynamic (MHD) modeling, in which very low collisionality kinetic effects are included. Such modeling must include the nonlocal effect of long collision lengths of particles communicating plasma conditions long distances along magnetic field lines. The second physical effect that must be included in models is the interaction of the microinstabilities and turbulence with the macroinstabilities. This multiscale interaction will require interfacing fast-timescale microturbulence codes with macroinstability codes.

Because it is relatively easy to identify growing instabilities, experimental stability boundaries are well known. However, our understanding of the nonlinear evolution of instabilities is relatively primitive. For instance, in many cases it is not known when instabilities will grow explosively and when they will saturate at small amplitudes. Neither is it known when (nontearing) instability leads to nonlinear magnetic reconnection. Recent advances in diagnostic imaging make it possible to see details of the nonlinear structure. A comprehensive understanding of macroinstability physics is possible in the next decade if both the models and the diagnostics are improved. In many cases better understanding is likely to result in development of new control methods.

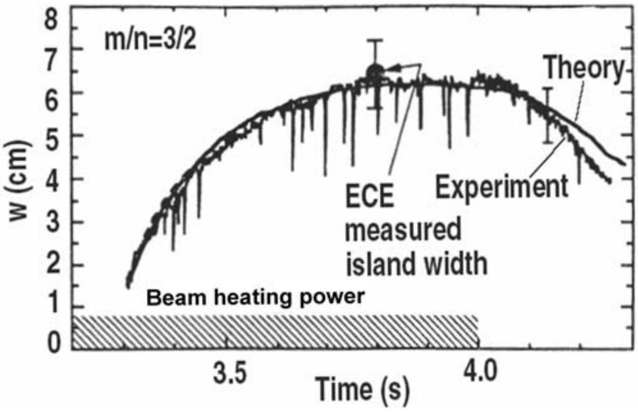
Microinstabilities, Turbulence, and Transport

The second major challenge for magnetic confinement is to improve the thermal insulation provided by the magnetic field. If energy diffused from the hot, central tokamak plasma to the relatively cool periphery via particle collisions alone, then the projected energy confinement time in ITER plasma would be hundreds of seconds, not three. However, this is not expected since at fusion temperatures energy diffusion across the magnetic field in a nearly collisionless magnetized plasma is dominated by small-scale microturbulence. This turbulence is driven by the strong gradients in plasma temperature, pressure, etc. Because the turbulent eddies are small (typically a centimeter or two in size), the random walk of particles and heat across the plasma is not catastrophic—but it is problematic nonetheless. Details of the rate of energy transport vary, but larger magnetic fields result in smaller eddies and therefore smaller energy losses. If one could eliminate energy diffusion due to microturbulence, the payoff would be substantial. Energy transport via collisions alone would yield a burning plasma in a device whose linear dimensions are less than half the size of ITER. Controlling and perhaps reducing

BOX 4.1
Slowly Growing Magnetic Islands

Magnetic islands are large-scale structures that break equilibrium symmetry so that magnetic field lines connect hot plasma regions to colder ones, degrading plasma energy confinement. These islands are created by a class of "tearing" instabilities that grow on timescales of a few tenths of a second and connect the normally distinct magnetic surfaces. This is slow magnetic reconnection. In high-pressure plasmas, the saturated island width is measured via electron cyclotron emission (ECE) to be proportional to the plasma pressure. This scaling can impose an effective limit on the maximum pressure achievable in a tokamak since large islands can result in complete loss of plasma confinement. *(a)* Image of magnetic islands calculated in simulations. Field lines wrap around the green island surface as the surface itself wraps around the torus. *(b)* Comparison of theoretical predictions and the experimental measured island width—the good agreement is representative of the progress in understanding. SOURCE: Z. Chang, J.D. Callen, E.D. Fredrickson, R.V. Budny, C.C. Hegna, K.M. McGuire, M.C. Zarnstorff, and TFTR group, "Observation of nonlinear neoclassical pressure-gradient-driven tearing modes in TFTR," *Physical Review Letters* 74: 4663 (1995). *(c)* Diagram of wave ray trajectories (red line) of high-power microwaves that are launched toward an absorption layer controlled in real time to be inside the island. *(d)* Data showing the shrinkage of the island width when microwaves are applied. Current driven by the waves replaces missing current and shrinks the island until it self-heals. This effective island healing has been demonstrated in several existing devices, and near-term experiments will determine how to properly scale the physics of this technique to ITER plasmas. SOURCE: Adapted from R.J. LaHaye, "Neoclassical tearing modes and their control," *Physics of Plasmas* 13: 055501 (2006).

(a)



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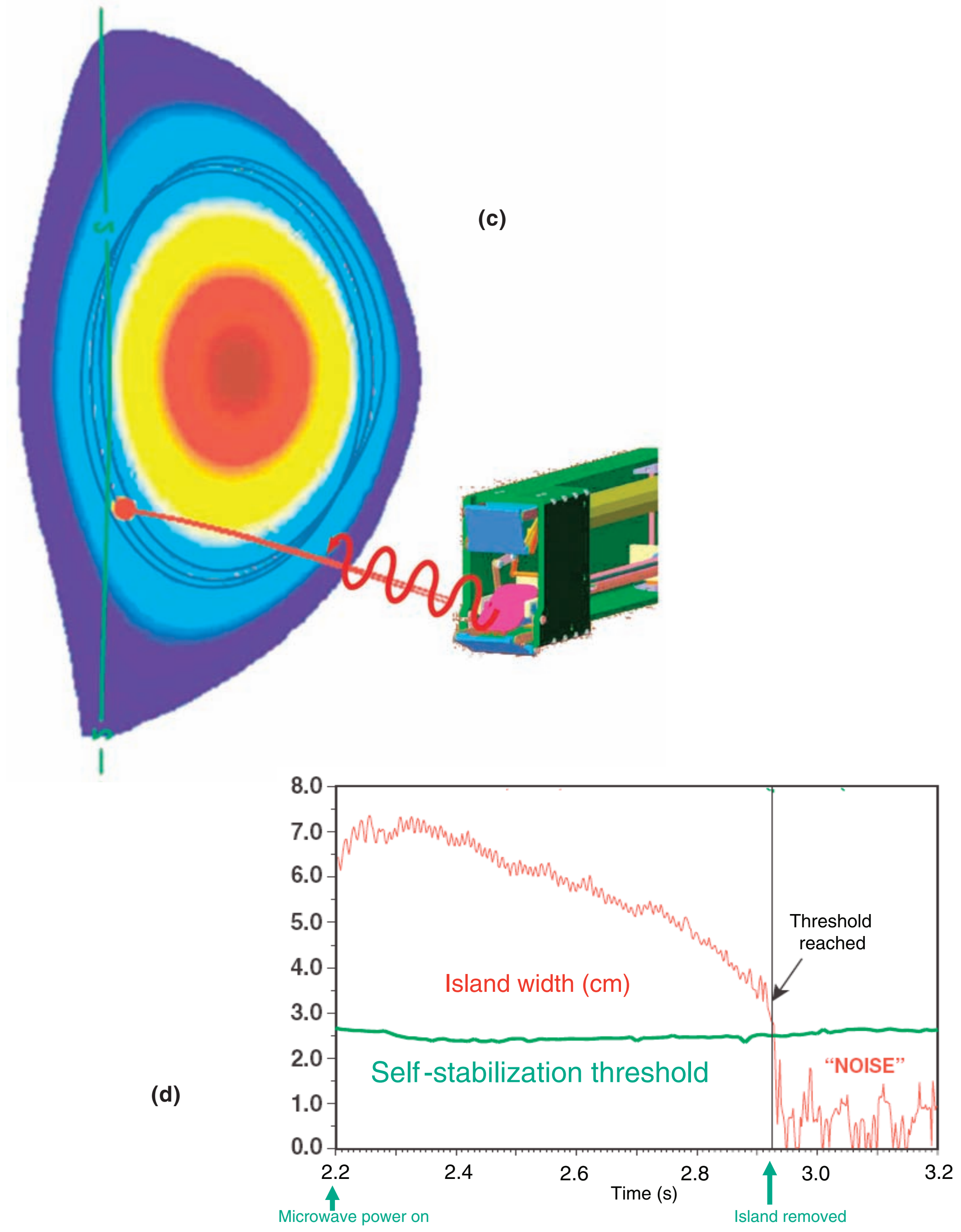
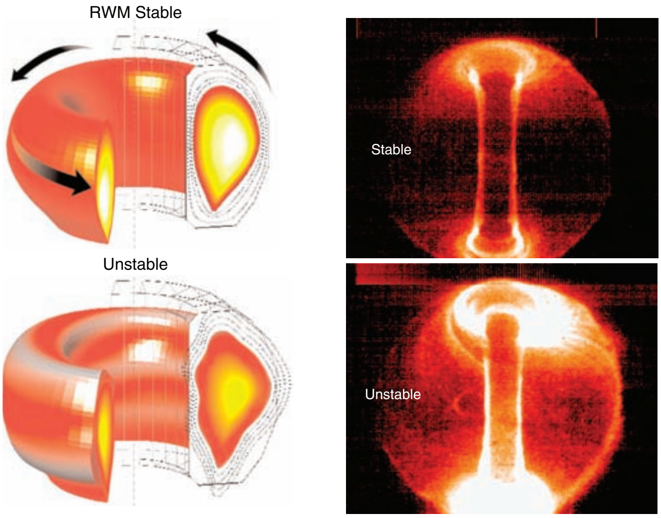

(c)
(d)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Threshold reached
Island width (cm)
Self-stabilization threshold
"NOISE"
2.2
2.4
2.6
2.8
3.0
3.2
Time (s)
Microwave power on
Island removed

BOX 4.2
Resistive Wall Modes

At high plasma pressures, tokamak and spherical torus plasmas can develop instabilities that cause large-scale helical deformations of the equilibrium magnetic field. Close-fitting electrical conductors can slow the growth of such modes to the timescale of magnetic field penetration of the resistive wall—hence the name resistive wall mode (RWM). These modes grow sufficiently slowly that they can be controlled and suppressed. In tokamaks and spherical tori, spinning the plasma sufficiently fast past the conducting wall, combined with plasma dissipation, can completely stabilize the mode. *(a)* Calculations and data showing stability with flow and instability without flow. Courtesy of General Atomics and Princeton Plasma Physics Laboratory. *(b)* Fast camera image revealing the global helical deformation of the plasma during an RWM. These are in good agreement with reconstructions



(a)

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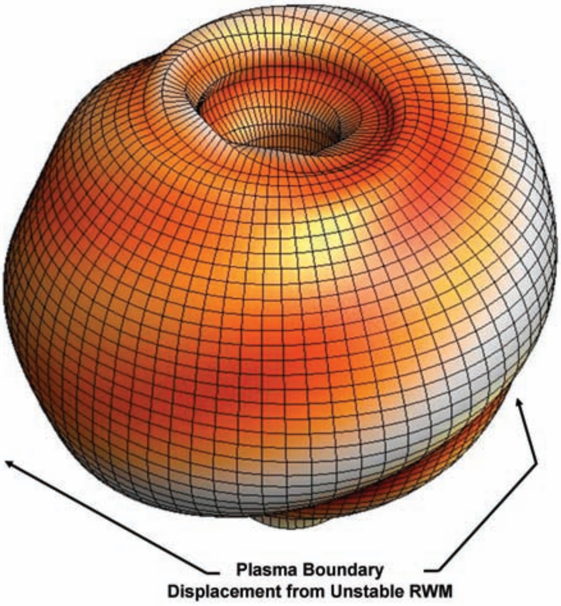
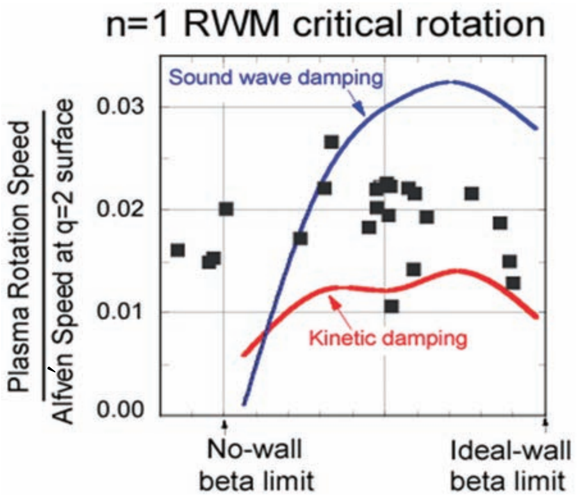


of the plasma boundary from magnetic field measurements and calculated RWM eigenfunctions. SOURCE: S.A. Sabbagh, C. Sontag, J.M. Bialek, D.A. Gates, A.H. Glasser, J.E. Menard, W. Zhu, M.G. Bell, R.E. Bell, A. Bondeson, C.E. Bush, J.D. Callen, M.S. Chu, C.C. Hegna, S.M. Kaye, L.L. Lao, B.P. LeBlanc, Y.Q. Liu, R. Maingi, D. Mueller, K.C. Shaing, D. Stutman, K. Tritz, and C. Zhang, "Resistive wall stabilized operation in rotating high beta NSTX plasmas, " *Nuclear Fusion* 46: 635 (2006). *(c)* Comparison of critical rotation speed for RWM stabilization and the measured critical value versus the plasma β (pressure). There is reasonable agreement with theoretical models, but the underlying plasma dissipation mechanisms are still under investigation. Additional understanding in critical rotation has been obtained using balanced beams at DIII-D. SOURCE: R.J. LaHaye, A. Bondeson, M.S. Chu, A.M. Garofalo, Y.Q. Liu, G.A. Navratil, M. Okabayashi, H. Reimerdes, and E.J. Strait, "Scaling of the critical plasma rotation for stabilization of the n = 1 resistive wall mode (ideal kink) in the DIII-D tokamak," *Nuclear Fusion* 44: 1197 (2004). RWMs change the magnetic geometry of the plasma equilibrium and generate a torque that slows the plasma rotation. *(d)* Comparison of the measured torque and theory. SOURCE: W. Zhu, S.A. Sabbagh, R.E. Bell, J.M. Bialek, M.G. Bell, B.P. LeBlanc, S.M. Kaye, F.M. Levinton, J.E. Menard, K.C. Shaing, A.C. Sontag, and H.Yuh, "Observation of plasma toroidal-momentum dissipation by neoclassical toroidal viscosity," *Physical Review Letters* 96: 225002 (2006). The stabilization of the RWM allows operation at much higher pressure and fusion power than is otherwise achievable. For the low plasma rotation values expected on ITER, RWM stabilization may require active magnetic feedback control and is presently being prototyped on several devices. SOURCE: S.A. Sabbagh, R.E. Bell, J.E. Menard, D.A. Gates, A.C. Sontag, J.M. Bialek, B.P. LeBlanc, F.M. Levinton, K. Tritz, and H. Yuh, "Active stabilization of the resistive-wall mode in high-beta, low-rotation plasmas," *Physical Review Letters* 97: 045004 (2006).



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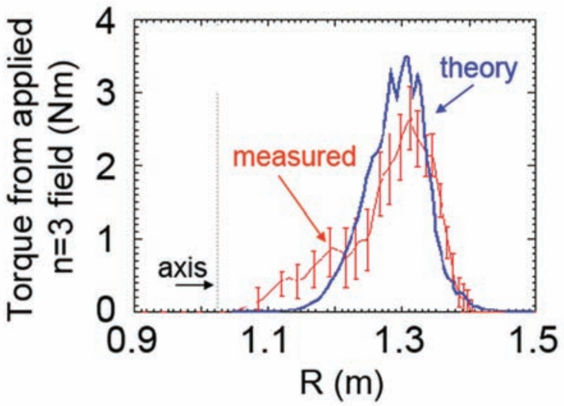


(d)

microturbulence in the new burning plasma regime of ITER will be central to the success of the project.

Over the last decade, experiments and theory have shown that the small-scale turbulence that limits tokamak energy confinement (in most present conditions) is excited when the gradient of the logarithm of the ion temperature exceeds a specific threshold. The threshold depends in a complicated way on many local parameters: the geometry of the magnetic field, the gradients of density and velocity, and so forth. In most conditions, these quantities can be measured and the threshold can be numerically calculated. Indeed, a significant triumph of the last decade is the development of codes that can accurately solve the nonlinear, five-dimensional phase space (three-dimensional space and two-dimensional velocity) system of equations that describe electrostatic turbulence: the gyrokinetic equations. Further, unlike a decade ago, codes designed for this purpose are now in use at every large tokamak facility. For the high temperatures of interest, the turbulence-induced transport that occurs when the threshold is crossed is strong enough to force the local plasma temperature to remain close to the threshold. The overall energy confinement that results is well predicted by large-scale numerical turbulence simulations (Box 4.3).

It is now clear that the limits imposed by the threshold model are at least partially surmountable. Under certain circumstances (particularly hollow current distributions and strong flow shear), regions of reduced turbulence called transport barriers develop spontaneously inside or at the edge of the plasma. In these regions the thermal insulation is very good, perhaps limited only by collisional processes, and the temperature gradients greatly exceed the usual threshold values. It has been shown experimentally that these regions of enhanced thermal insulation are associated with strong layers of flow shear and reduced turbulent fluctuations. In parallel with the work on transport barriers, it has become clear that weaker shear layers are generated by the turbulence itself, greatly reducing the energy losses that would occur in their absence (Box 4.4). This insight grew out of experimental, theoretical, and computational efforts and was a major success of the last decade of plasma science research in magnetic confinement fusion.

Microturbulence in concept improvement devices can be quite different from the phenomenon in the tokamak. Fluctuations in the reversed-field pinch, for example, perturb the magnetic field significantly (Box 4.5). The perturbed magnetic field lines no longer isolate the plasma from the boundary, and charged particles traveling along the field lines can wander out of the device. The fundamental physics of this type of transport has been studied effectively in the reversed-field pinch, where ways to reduce its effects have been developed. Theory predicts that as many concepts improve and push to higher pressure (β), transport along chaotic magnetic field lines will play a larger role.

Opportunities in Microinstabilities, Turbulence, and Transport

While progress in microinstability research has been strong over the last decade, maintaining the pace of this research in the next decade would likely require a refocused effort with clearer short-term objectives and even greater focus on comparisons of theory predictions (analytic and computational) with experimental data. Three scientific goals frame opportunities in this area. The first is to develop more accurate predictive models of the turbulence and transport, especially the electron dynamics, including the irreducible levels when mircoturbulence is absent. The second is to find, perhaps through a better understanding of transport barrier physics, regimes where turbulence and transport are reduced. The third goal is to advance the science of low-collisionality plasma turbulence—turbulence with multiple scales in all dimensions of phase space. The computer codes for studying these problems are rapidly maturing. The principal needs for the next decade are in the areas of theory (to understand the nonlinear results) and diagnostics (to enable experiment/theory comparisons).

All thrusts of magnetic confinement research, from ITER to innovative concepts, will benefit from improving the predictive understanding of microturbulence. Predictive models must include the ability to model four different spatiotemporal scales simultaneously: fast electron dynamics; slower ion dynamics; longer wavelength, mesoscale plasma dynamics; and the slow evolution of bulk plasma (thermodynamic) properties that occurs on the transport timescale. This will require the development of new reduced theoretical models of plasma behavior. Our understanding of the turbulence will be enormously enhanced when diagnostics capable of distinguishing fine levels of detail and measuring several plasma parameters simultaneously can image the full cross section of the plasma. Such full-body diagnostics will reveal the global structure and the mesoscale correlations.

Boundary Plasma Properties and Control

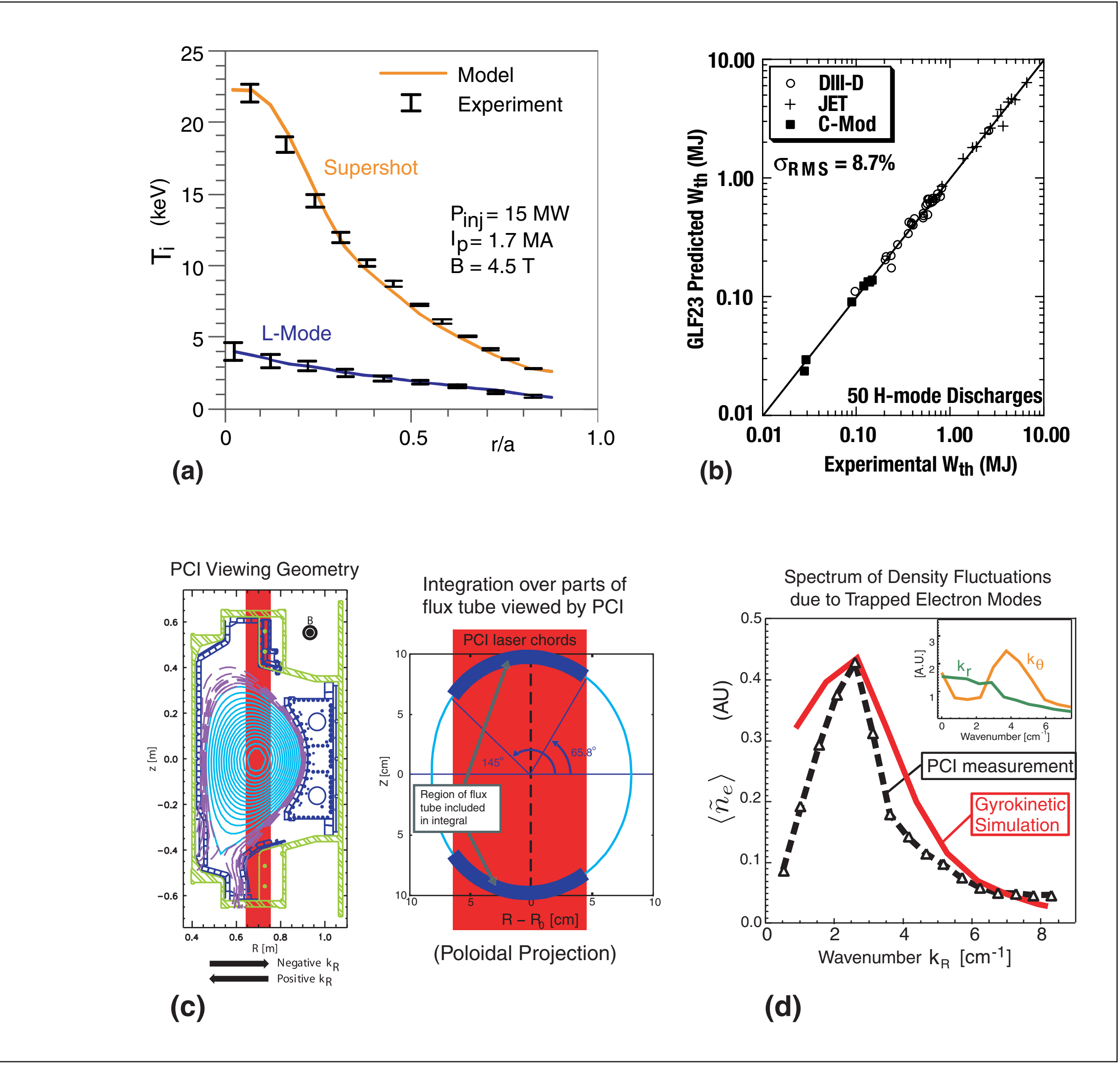
In a magnetic confinement device, the bulk of the plasma is kept away from material structures for two distinct reasons. First, material structures act as a heat sink and cool the edge of the plasma. Hot charged particles exit the plasma and cold charged or neutral particles (some dislodged from the wall) enter the plasma. Second, hot plasma that comes into contact with material structures can melt, erode, or otherwise degrade these structures. Larger devices are generally more susceptible to this problem of material heating because the power per unit area increases with device size. The risks to plasma facing components also increase when the power is exhausted in short bursts and over small areas rather than continuously and smoothly over the entire plasma surface (Box 4.6). Because of its size, ITER will explore a new regime of boundary plasma physics in which the competing needs of

BOX 4.3
Science-Based Confinement Models

Progress in the understanding of plasma turbulence has been substantial over the last decade. *(a)* In the mid-1990s, simulation-based transport models with no empirical parameters successfully predicted large differences in ion temperature, which empirical scaling laws cannot distinguish. The sharp difference in the gradient in the central plasma was shown to be a consequence of the higher temperature at the plasma edge. This breakthrough focused attention on the plasma edge. Courtesy of D. Ernst, MIT. *(b)* Models of ion temperature gradient (ITG) turbulence were subsequently shown to be consistent with data from several experiments and configurations. Courtesy of J. Kinsey, General Atomics. *(c)* Recently, attention has shifted to direct comparisons of the fluctuations observed in experiment and simulations. Actual diagnostic views *(left panel)* are synthesized in numerical simulations *(right panel)*. Courtesy of D. Ernst, MIT. *(d)* The predicted spectrum's shape is in excellent agreement with the experimentally measured density fluctuations. The final panel also shows the broadening of the early focus on ITG turbulence to include trapped electron mode (TEM) turbulence. Courtesy of D. Ernst, MIT. NOTE: PCI, phase contrast imaging; AU, atomic units.

the plasma and the plasma facing components come into conflict as never before. Indeed, ITER will press up against the material limits.

In many devices (including ITER) the plasma in an edge layer, called the scrape–off layer, is steered along field lines into a cool region called the divertor. The field lines in the divertor direct the exhaust into solid plates that take some of



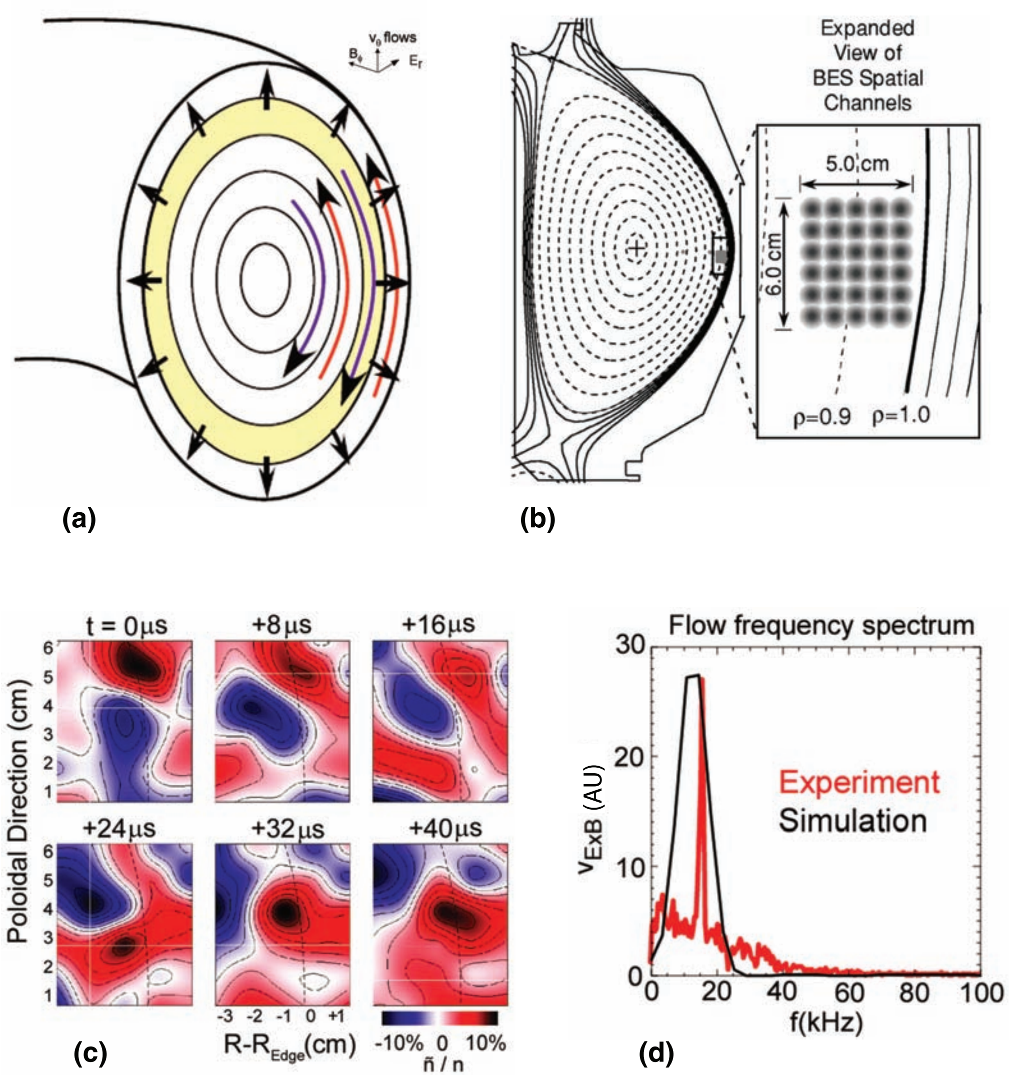
the power exiting the plasma. Atoms in the edge and the divertor radiate the rest of the power.

It is desirable to maximize the radiation (without introducing too many neutrals) and the effective area of the divertor plates. Much of the research in the last decade has been to design divertor configurations that accomplish this. One radical

BOX 4.4
Turbulence and Shear-Flow Generation

An important element of understanding plasma turbulence is how it regulates itself and thereby saturates in amplitude. Turbulence in tokamaks can drive sheared flows that saturate or even suppress the turbulence, a kind of turbulent self-regulation. *(a)* Cartoon of poloidally symmetric flows found to be present and important in nonlinear simulations of tokamak turbulence. Several mechanisms for their generation have been identified theoretically. Radial oscillations of these poloidal flows, illustrated by the red and blue/purple opposing arrows, are predicted to help regulate the turbulence and determine the transport levels. *(b)* Configuration of the two-dimensional array of points imaged by the beam emission spectroscopy (BES) diagnostic developed in the last decade. This diagnostic has revealed the detailed structure and dynamics of plasma turbulent density fluctuations in a small region near the plasma boundary. SOURCE: G.R. McKee, McKee, R.J. Fonck, M. Jakubowski, K.H. Burrell, K. Hallatschek, R.A. Moyer, D.L. Rudakov, W. Nevins, G.D. Porter, and P. Schoch, “Experimental characterization of coherent, radially-sheared zonal flows in the DIII-D tokamak,” *Physics of Plasmas* 10: 1712 (2003). *(c)* Images of the fluctuations that are used to determine the amplitude, eddy size, correlation, and characteristic flow speeds of the density fluctuations. *(d)* Initial comparisons of the experimentally measured flow velocity fluctuation frequency spectrum show good agreement with predictions from simulation and theory. A focus of current research is to understand the conditions under which these shear layers form, the processes that limit their extent, and the lower limits on transport that can be achieved. In the next decade enhanced diagnostics could provide images and data from a larger fraction of the plasma to investigate spreading of turbulence from one region to another. SOURCES: X.Q. Xu, W.M. Nevins, R.H. Cohen, J.R. Myra, and P.B. Snyder, “Dynamical simulations of boundary plasma turbulence in divertor geometry,” *New Journal of Physics* 4: 53 (2002) and K. Hallatschek and D. Biskamp, “Transport control by coherent zonal flows in the core/edge transitional regime,” *Physical Review Letters* 86: 1223 (2001).

solution, flowing liquid lithium as a plasma facing component, is currently being explored on a small scale. Such a liquid wall may act like a sponge soaking up particles exiting from the plasma without returning any cold particles. This raises the possibility of hotter plasma edges and vastly improved plasma performance. In addition, the liquid lithium could allow self-healing of the plasma facing components after large transient heat-flux events.



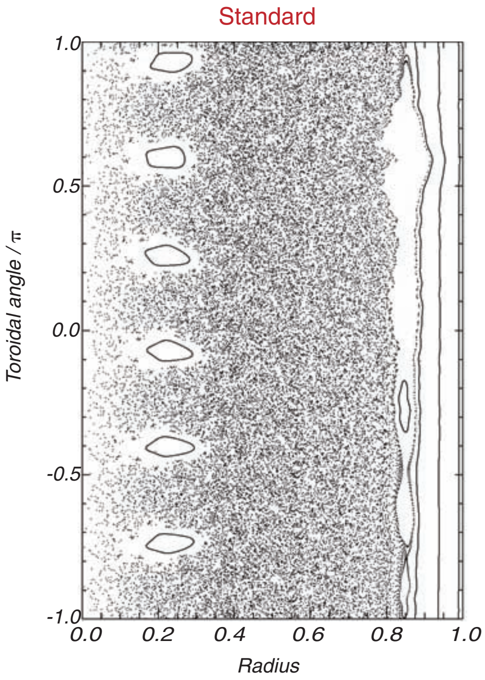
Opportunities in Boundary Plasma Properties and Control

The chief goal of research in boundary plasma properties is to find a stable regime where plasma and heat can be removed from the plasma and collected without damage by material surfaces. It is also important that in such a regime the temperature at or near the edge be substantial. Progress toward this goal has been

BOX 4.5
Controlled Chaos

Fluctuations in a plasma-confining magnetic field can cause magnetic field lines to wander chaotically through the plasma. Charged particles that follow the field lines will then also wander chaotically. Such magnetic chaos occurs in a toroidal laboratory plasma, the reversed-field pinch, as illustrated in the field line puncture plot *(a)* inferred from scaled computer modeling of the experiment. Each dot denotes a puncture of a field line with the plane, as lines wander in the radial direction (the horizontal axis) as they progress toroidally (the vertical axis). Recently, experimenters developed methods to decrease the drive for the chaos. Chaos is then largely eliminated *(b)* and magnetic islands become visible. Chaos develops when magnetic islands overlap. The extent of the overlap is measured by a parameter (inferred from experiment) shown in *(c)* that exceeds unity when nearby islands overlap. When chaos is controlled in the experiment (the blue curve), islands are mostly separated (or absent) over much of the plasma. The effect of chaos on transport of energy through the plasma is large. When chaos is present, energy transport in experiment (the thermal diffusivity) in *(d)* is large and in agreement with theory based on the chaos of *(a)*. When chaos is suppressed, transport is greatly reduced, with a 10-fold enhancement in the confinement of energy in the plasma. Images courtesy of S.C. Prager, University of Wisconsin at Madison.

(a)



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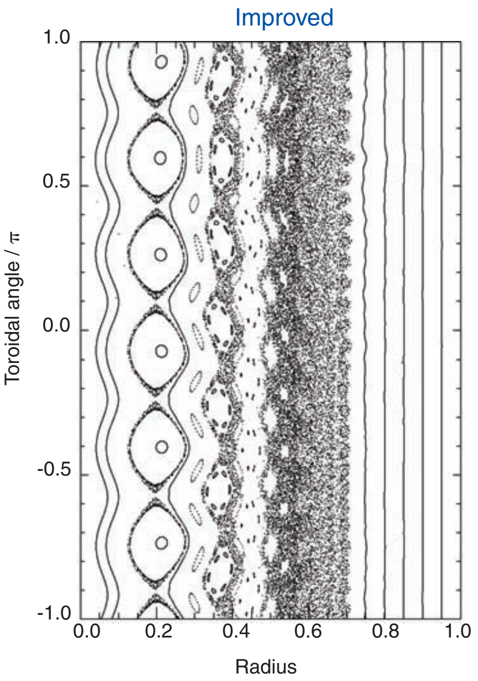
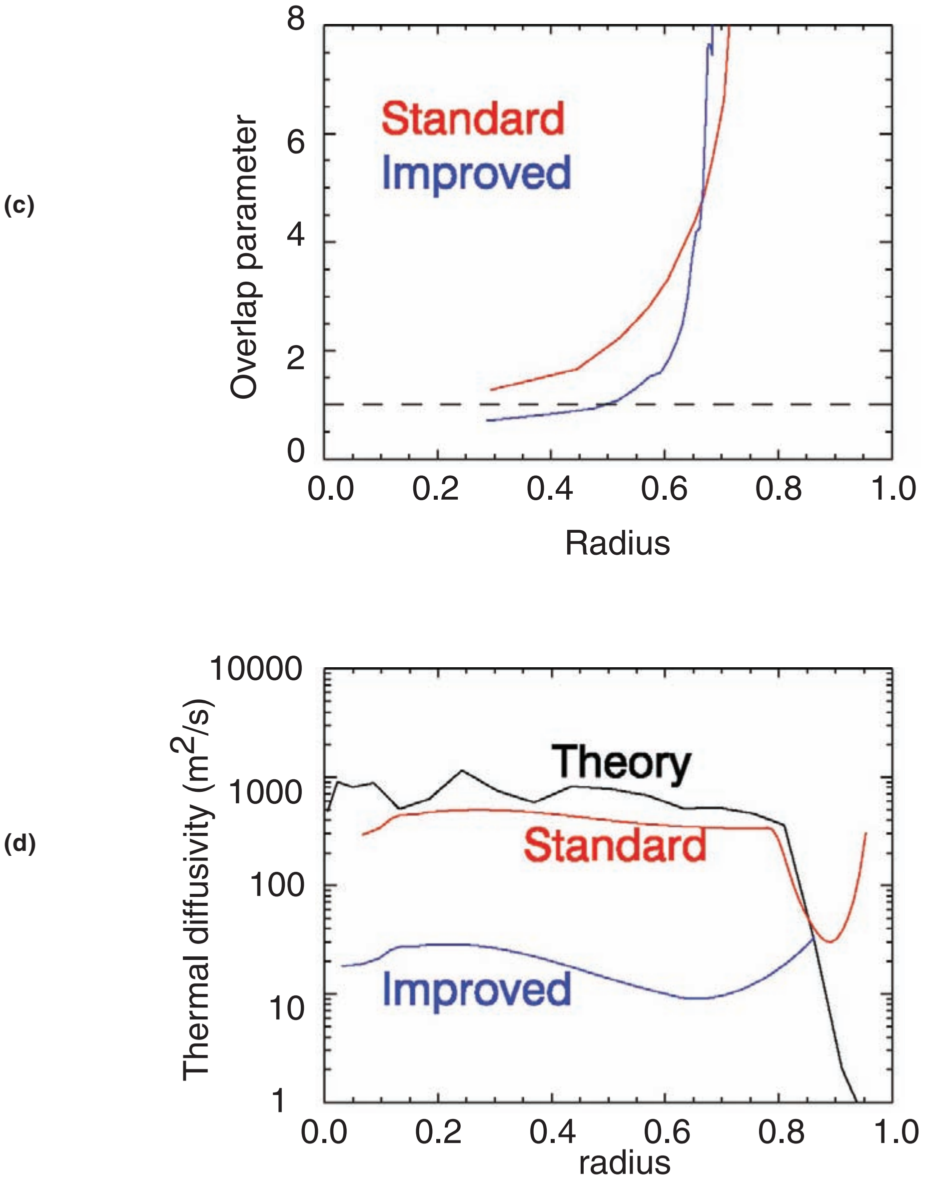
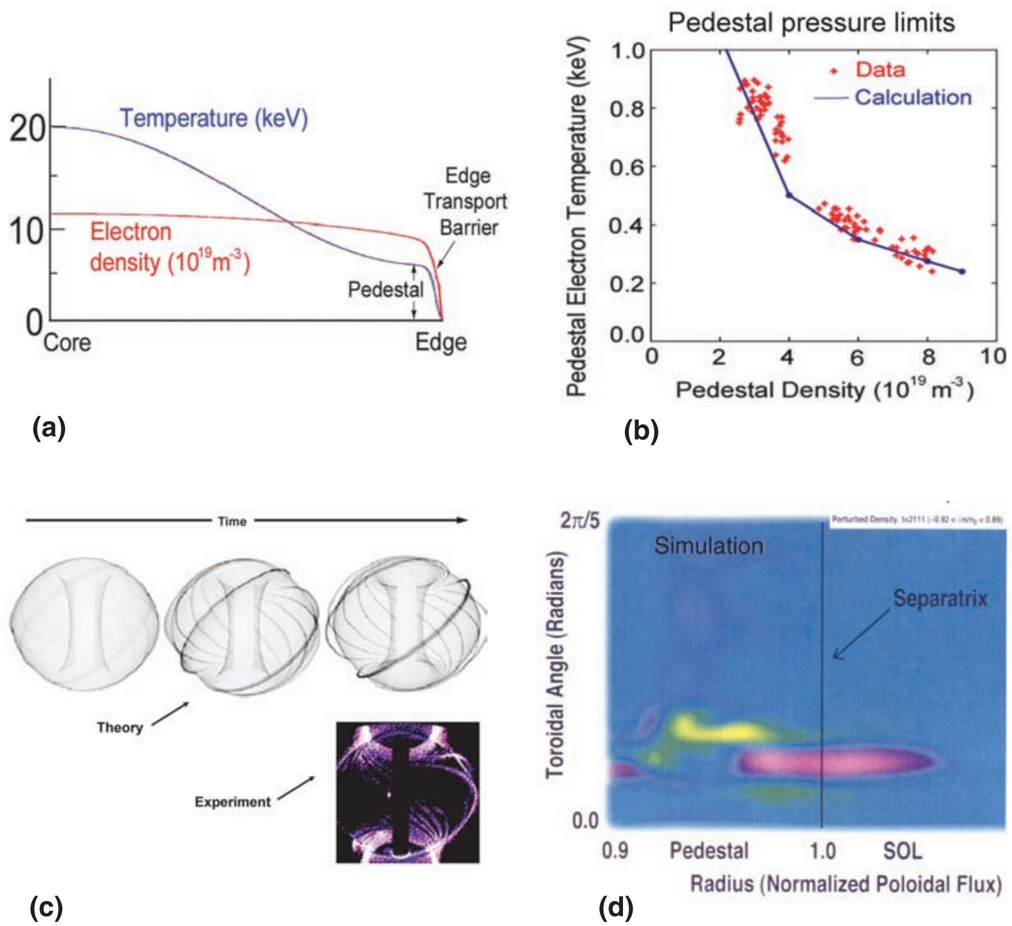



(c)
8
6
4
2
0
Overlap parameter
Standard
Improved
0.0
0.2
0.4
0.6
0.8
1.0
Radius
(d)
10000
1000
100
10
1
Thermal diffusivity (m^2/s)
Theory
Standard
Improved
0.0
0.2
0.4
0.6
0.8
1.0
radius

BOX 4.6
Edge Pedestal and Stability

Since turbulent energy transport limits the temperature gradient over most of the temperature profile, obtaining a transport barrier with high confinement near the plasma edge is crucial for ITER to reach burning conditions in the plasma center. While the edge barrier can be obtained, it is unstable above a critical pressure gradient. These instabilities, called edge localized modes (ELMs), deposit some fraction of the pedestal energy into the divertor or onto the wall in less than one thousandth of a second. *(a)* The desired ITER plasma temperature and density profiles with edge transport barrier. The key parameter for fusion performance is the temperature pedestal height—here it is about 5 kV. *(b)* Pressure limits in the pedestal. Instability occurs above the red line. Theory of the instability boundary is in reasonable agreement with the observations. SOURCE: P.B. Snyder, H.R. Wilson, J.R. Ferron, L.L. Lao, A.W. Leonard, D. Mossessian, M. Murakami, T.H. Osborne, A.D. Turnbull, and X.Q. Xu, "ELMs and constraints on the H-mode pedestal: Peeling–ballooning stability calculation and comparison with experiment," *Nuclear Fusion* 44: 320 (2004). *(c)* Photograph and theoretical model of an unstable edge mode that has coalesced into singular plasma filaments aligned along and carrying a magnetic field line. The filaments erupt from the plasma carrying heat and particles. Such filaments have been observed in numerous experiments and some of their characteristics are in agreement with theory. SOURCES: A. Kirk, H.R. Wilson, G.F. Counsell, R. Akers, E. Arends, S.C. Cowley, J. Dowling, B. Lloyd, M. Price, and M. Walsh, "Spatial and temporal structure of edge-localized modes," *Physical Review Letters* 92: 245002 (2004); R. Maingi, C.E. Bush, E.D. Fredrickson, D.A. Gates, S.M. Kaye, B.P. LeBlanc, J.E. Menard, H. Meyer, D. Mueller, N. Nishino, A.L. Roquemore, S.A. Sabbagh, K. Tritz, S.J. Zweben, M.G. Bell, R.E. Bell, T. Biewer, J.A. Boedo, D.W. Johnson, R. Kaita, H.W. Kugel, R.J. Maqueda, T. Munsat, R. Raman, V.A. Soukhanovskii, T. Stevenson, and D. Stutman, "H-mode pedestal, ELM and power threshold studies in NSTX," *Nuclear Fusion* 45: 1066 (2005); M.E. Fenstermacher, T.H. Osborne, A.W. Leonard, P.B. Snyder, D.M. Thomas, J.A. Boedo, T.A. Casper, R.J. Groebner, M. Groth, M.A.H. Kempenaars, A. Loarte, G.R. McKee, W.M. Meyer, G. Saibene, M.A. VanZeeland, X.Q. Xu, L. Zeng, and the DIII-D Team, "Structure, stability and ELM dynamics of the H-mode pedestal in DIII-D," *Nuclear Fusion* 45: 1493 (2005). *(d)* Nonlinear simulations of edge instability dynamics confirm the filamentation process, and such simulations are being used to better understand heat and particle transport in the nonlinear phase of the edge pressure collapse. If edge instabilities become too violent, large amounts of plasma energy are released rapidly, potentially damaging reactor components. Present experiments and modeling are exploring ways to reduce or eliminate these instabilities while still retaining high confinement near the plasma edge. Extrapolating these techniques to ITER is an active area of research. SOURCE: P.B. Snyder, H.R. Wilson, and X.Q. Xu, "Progress in the peeling-ballooning model of edge localized modes: Numerical studies of nonlinear dynamics," *Physics of Plasmas* 12: 056115 (2005).

largely, though not entirely, empirical. The development from first principles of a reduced physics model capable of describing the full range of plasma boundary phenomena is an area of active research. This effort will also benefit (as do other areas) from diagnostic improvements. A new experiment, intermediate in scale between current U.S. facilities and ITER, could study boundary plasma science issues in conjunction with enabling fusion technology research (high-heat-flux components, development of materials that are resistant to damage from 14-MeV neutrons, and so on). Such an experiment would not focus on the science of burning plasmas, but it could nonetheless accelerate progress toward an economically attractive fusion reactor.

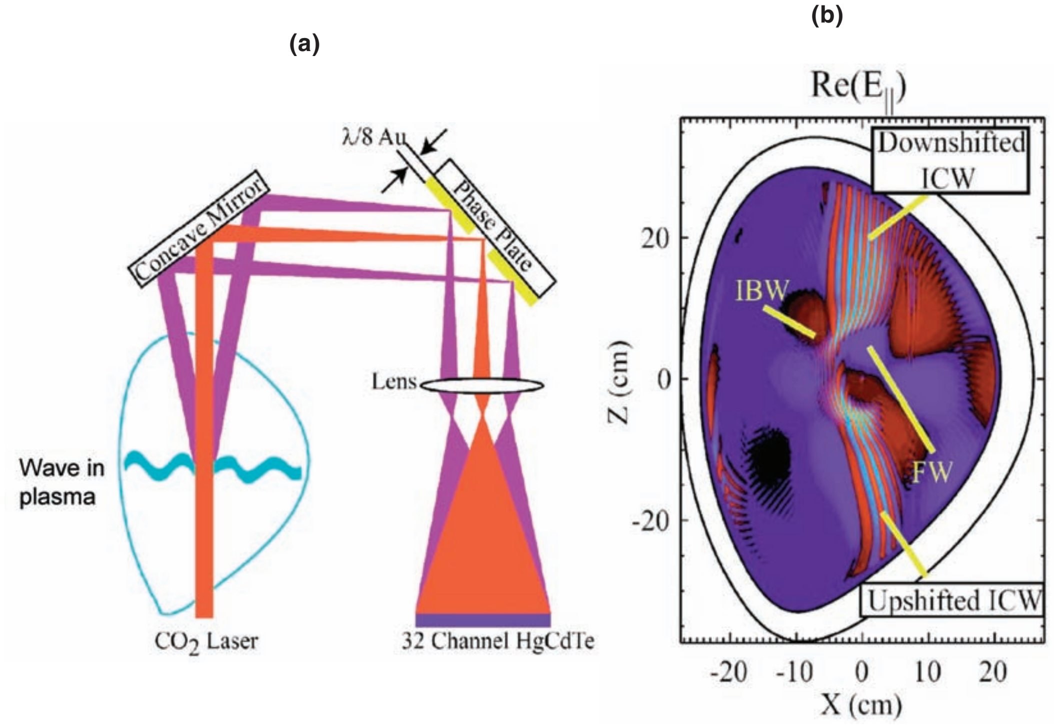


Wave–Particle Interactions in Fusion Plasmas

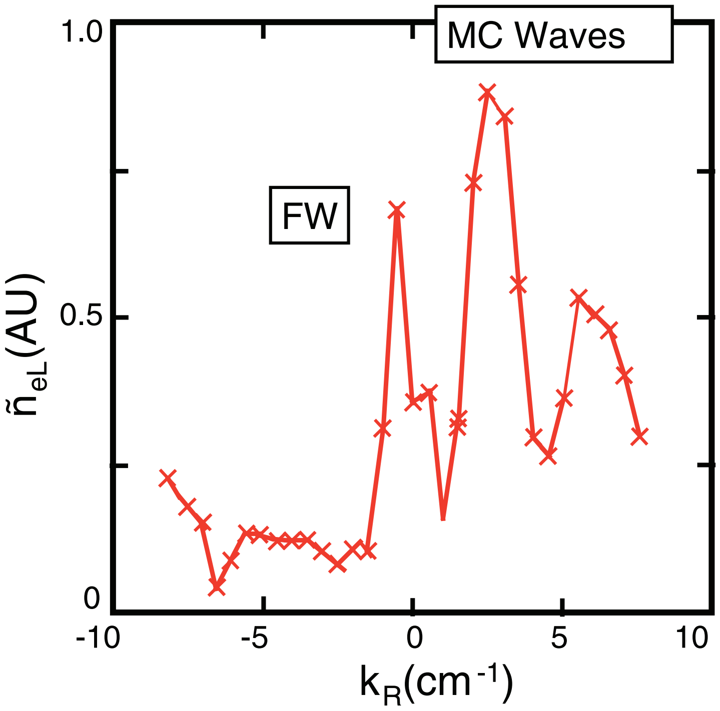
Hot magnetized plasma supports a huge variety of waves that can exchange energy and momentum with the plasma particles. The resonant particles, those moving almost at the speed of the wave, interact strongly with the wave. Stable waves launched from the edge of the plasma are used to heat the plasma and to drive current in the plasma. This is a well-developed technique and can be modeled with high accuracy—an example of the state of the art is given in Box 4.7. Resonant particles can cause waves to become unstable—Box 4.8 shows an example of such instability that can be driven by energetic particles.

BOX 4.7
Fast-Wave Heating

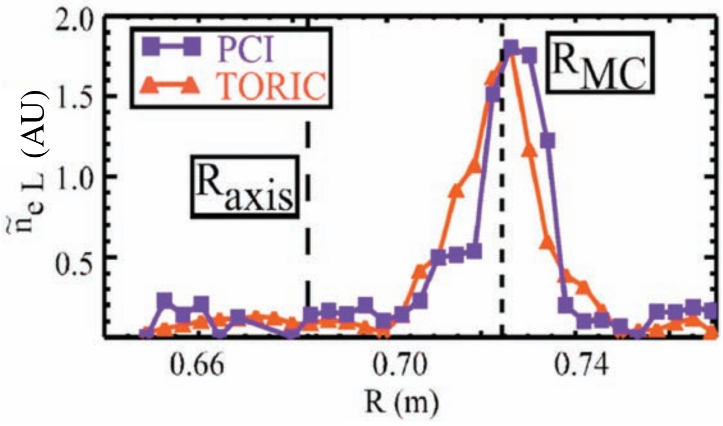
High-power electromagnetic waves of tens of megahertz are commonly launched into fusion plasmas to heat the plasma and drive plasma current. *(a)* Diagram of a multichord phase contrast imaging technique developed in the last decade that measures the wave number of the wave-induced density fluctuations. *(b)* Numerical simulation of a high phase velocity wave, the fast wave (FW), that is launched from the right into a tokamak plasma. Simulations have become powerful enough to resolve the transformation of waves from one mode into another, a process known as mode conversion. Here the FW is predicted to mode-convert into two other waves with much shorter wavelength perpendicular to the confining magnetic field (IBW, ion Bernstein wave; ICW, ion cyclotron wave); shown is the real part of the parallel electric field ($\mathrm{Re}(E_{||})$). *(c)* Data from the imaging technique that measures the expected launched ($k_R < 0$) and reflected ($k_R > 0$) low-k fast wave and the higher-k mode-converted (MC) waves. *(d)* Comparison of the experimental and theoretical profiles of the line-integrated density fluctuations showing agreement. High-k MC waves are predicted to be capable of generating sheared plasma flows and could ultimately provide a powerful tool for efficiently controlling plasma microturbulence and therefore the fusion gain in burning plasmas. SOURCE: S.J. Wukitch, Y. Lin, A. Parisot, J.C. Wright, P.T. Bonoli, M. Porkolab, N. Basse, E. Edlund, A. Hubbard, L. Lin, A. Lynn, E. Marmar, D. Mossessian, P. Phillips, and G. Schilling, "Ion cyclotron range of frequency mode conversion physics in Alcator C-Mod: Experimental measurements and modeling," *Physics Plasmas* 12: 056104 (2005). NOTE: PCI, phase contrast imaging; R, radius.



(c)


MC Waves
FW
1.0
0.5
0
ñ$_{eL}$(AU)
-10
-5
0
5
10
k$_R$(cm^{-1})

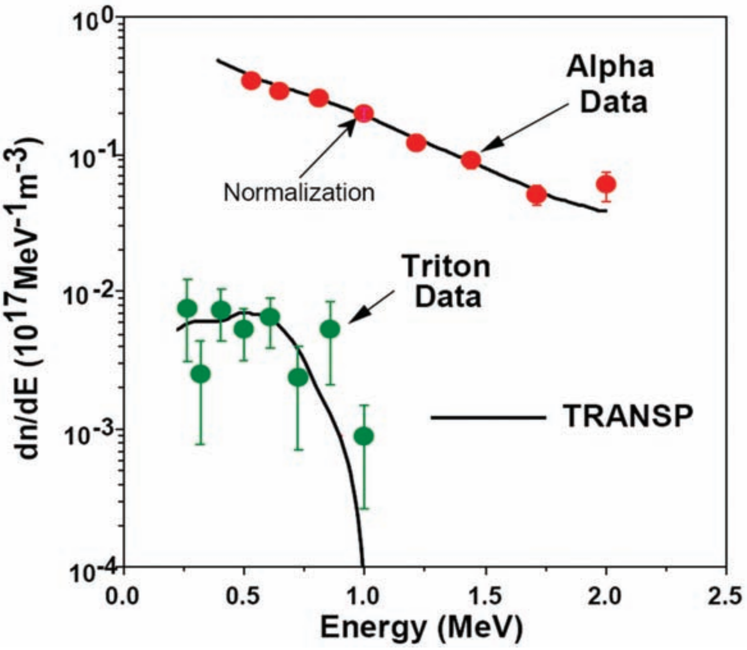
(d)

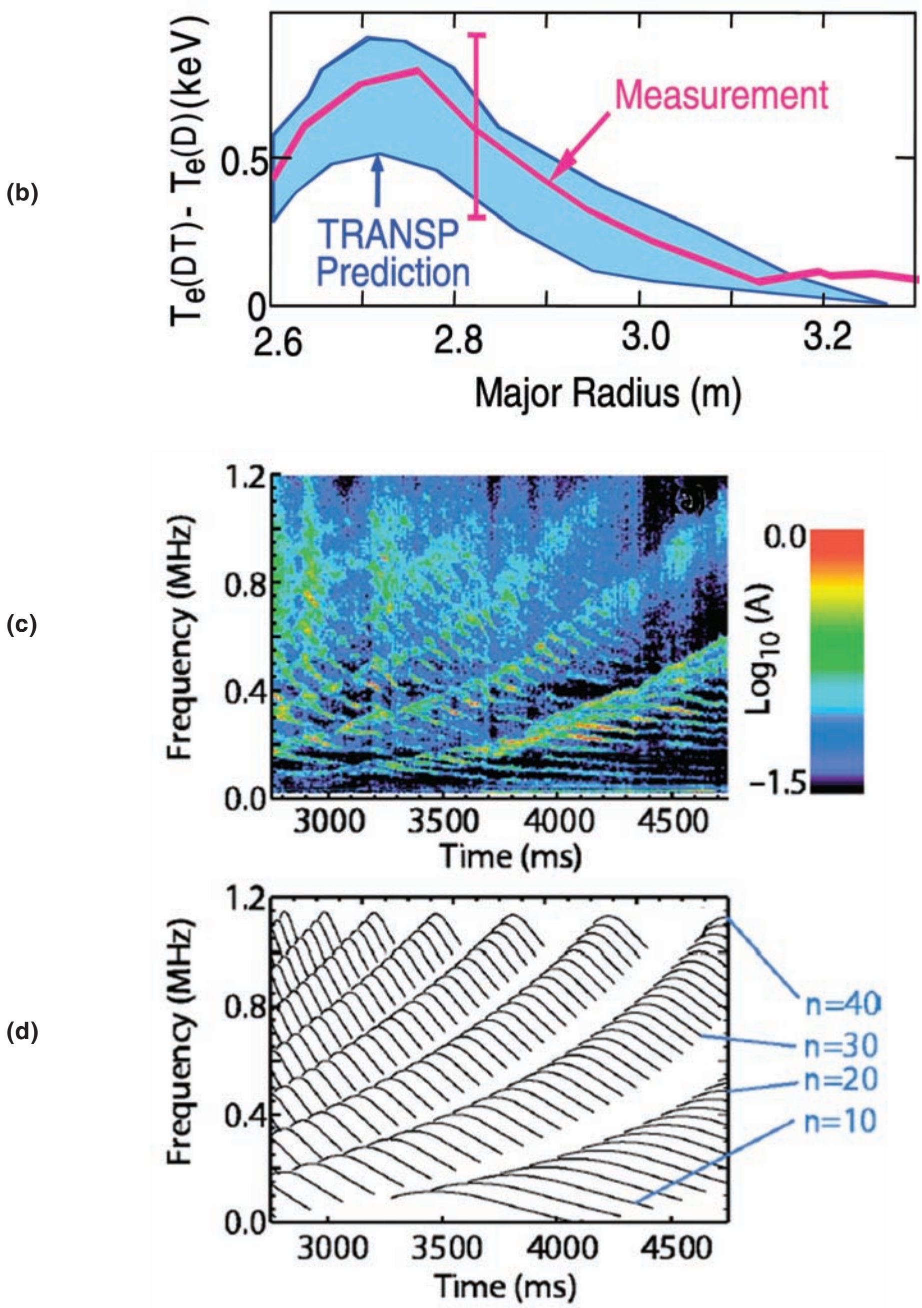

2.0
1.5
1.0
0.5
ñ$_e$ L (AU)
PCI
TORIC
R$_{axis}$
R$_{MC}$
0.66
0.70
0.74
R (m)

BOX 4.8
Alpha-Particle-Driven Instabilities

The 3.5-MeV alpha particles from deuterium-tritium fusion reactions are born with velocities just above the fastest characteristic macroscopic (Alfvén) wave speed of the plasma and are therefore capable of giving energy to the Alfvén waves, creating instabilities. These instabilities can threaten the reactor and the fusion burn by transporting alpha particles to reactor walls before they can heat the background plasma. *(a)* Triton (tritium nuclei) and alpha particle energy distribution functions were found to be consistent with theoretical expectation (from collisions, without instabilities). Courtesy of IOP Publishing Limited; S.S. Medley, R.V. Budny, D.K. Mansfield, M.H. Redi, A.L. Roquemore, R.K. Fisher, H.H. Duong, J.M. McChesney, P.B. Parks, M.P. Petrov, and N.N. Gorelenkov, *Plasma Physics and Controlled Fusion* 38: 1779 (1996); and R.K. Fisher, J.M. McChesney, P.B. Parks, H.H. Duong, S.S. Medley, A.L. Roquemore, D.K. Mansfield, R.V. Budny, M.P. Petrov, and R.E. Olson, "Measurements of fast confined alphas on TFTR," *Physical Review Letters* 75: 846 (1995). *(b)* The measured and predicted plasma electron heating through collisions with alphas. Reprinted with permission from G. Taylor, J.D. Strachan, R.V. Budny, and D.R. Ernst, "Fusion heating in a deuterium-tritium tokamak plasma," *Physical Review Letters* 76: 2722 (1996). Copyright 1996 by the American Physical Society. *(c)* Frequency versus time data from new density fluctuation diagnostics revealing a multitude of destabilized Alfvén wave eigenmodes that are not detectable by magnetic sensors outside the plasma. *(d)* Theoretical Alfvén eigenmode spectrum showing excellent agreement with data. Such waves could redistribute the alpha particles in advanced operating modes proposed for ITER. *(c)* and *(d)* Reprinted with permission from R. Nazikian, H.L. Berk, R.V. Budny, K.H. Burrell, E.J. Doyle, R.J. Fonck, N.N. Gorelenkov, C. Holcomb, G.J. Kramer, R.J. Jayakumar, R.J. LaHaye, G.R. McKee, M.A. Makowski, W.A. Peebles, T.L. Rhodes, W.M. Solomon, E.J. Strait, M.A. VanZeeland, and L. Zeng, "Multitude of core-localized shear Alfvén waves in a high-temperature fusion plasma," *Physical Review Letters* 96: 105006 (2006). © 2006 by the American Physical Society.

(a)




(b)
$T_e(DT) - T_e(D)$ (keV)
0
0.5
2.6
2.8
3.0
3.2
Major Radius (m)
Measurement
TRANSP Prediction
(c)
Frequency (MHz)
0.0
0.4
0.8
1.2
3000
3500
4000
4500
Time (ms)
(a)
0.0
−1.5
Log_{10} (A)
(d)
Frequency (MHz)
0.0
0.4
0.8
1.2
3000
3500
4000
4500
Time (ms)
n=40
n=30
n=20
n=10

Opportunities in Wave–Particle Interactions

The goals of wave–particle research in the next decade are twofold: first, to extend the modeling of launched wave excitation and propagation to three dimensions and, second, to explore possible energetic-particle-driven instabilities in ITER. Calculations of the linear properties of the instabilities are rapidly becoming routine. The challenge now is to understand the nonlinear evolution and interaction of multiple unstable modes and their effect on fast-particle confinement. In particular, it is not clear whether the instabilities will benignly (perhaps beneficially) redistribute alpha particles or eject them to the reactor walls, potentially damaging the plasma facing components. Improved understanding of wave heating and fast-ion transport is needed to confidently predict the characteristics of the dominant heating sources in ITER burning plasmas.

CONCLUSIONS AND RECOMMENDATIONS FOR THIS TOPIC

The U.S. decision to rejoin ITER is recent, and the magnetic fusion program is beginning to evolve into the burning plasma era. The present U.S. program was shaped in 1996 when a science-focused mission with three goals was adopted: (1) advance plasma science in pursuit of national science and technology goals; (2) develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program; and (3) pursue burning fusion energy science and technology as a partner in the international effort. These goals remain entirely pertinent since the central strategic questions that frame the future program are the following:

- What plasma science must be developed to maximize the scientific output of ITER?
- What science and enabling technology must be developed to move beyond ITER to fusion-generated electricity?

The specific plasma science issues were discussed in the preceding section.

> **Conclusion: The scientific opportunities in magnetic fusion science are compelling, intellectually challenging, and a direct product of the scientific focus of the U.S. magnetic fusion program over the past decade. Realizing the promise of these opportunities and addressing new challenges will hinge on maintaining the focus on achieving three goals: (1) advancing plasma science, (2) ensuring concept improvement through innovation, and (3) pursuing burning plasma science.**

The science focus resulted in the growth of predictive capability, which now provides much of the direction for the program. This increasing capability to predict and control the behavior of magnetically confined plasmas has begun to replace sometimes costly and time-consuming empirical approaches. For example, it has yielded a cheaper and more promising design for ITER. Organizing and structuring the program around key science issues requires a prioritization that is beyond this committee's mandate (this issue is addressed later in this section). However, the science dictates some opportunities and directions that should be part of the program.

The key to recent and future progress on all three goals lies in better measurements and better models that will allow addressing and resolving new scientific challenges and opportunities as they arise.

> **Recommendation: DOE should undertake two broad initiatives that are essential for advancing all areas of magnetic fusion research:**
>
> **(1) A diagnostic initiative to develop and implement new diagnostics in magnetic fusion experiments.**
> **(2) A theory initiative to reinvigorate theory and develop the next generation of models.**

Both initiatives require additional resources in their respective areas.

Recent advances inside and outside the magnetic fusion program have made possible diagnostics that can measure multiple physical quantities at many points inside the plasma simultaneously. A diagnostic initiative would lead to a new generation of diagnostics that would test the veracity of present predictive models (e.g., tractable reduced models such as hybrid fluid-kinetic models of macroscopic instabilities and the five-dimensional gyrokinetic models of microturbulence) and stimulate the growth of better models through a complementary theory initiative. Specifically, a major new diagnostics initiative like that proposed by the community's Transport Task Force in its white paper[4] is needed. The cost and scale of these diagnostics may exceed present levels, but so will the value of the information derived from the measurements. Taking advantage of this opportunity to significantly advance plasma measurements should be a key priority of the magnetic fusion program.

Most of the advances in modeling plasmas originated from the development of tractable reduced models, helped by the astonishing increase in computational power. Addressing the fusion plasma science challenges will require new theory and models to extract further scientific gains from the next generation of computational modeling. The theory program needs to be reinvigorated, paying special attention to the support of theorists who are willing and able to engage with the experimental

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[4] The white paper of the fusion community's Transport Task Force on the type of diagnostic initiative that is needed for microturbulence and anomalous transport is available at http://psfcwww2.psfc.mit.edu/ttf/transp_init_wht_paper_2003.pdf.

and simulation communities. The fusion program's ability to evaluate new ideas for magnetic confinement depends critically on advancing predictive capability. It is the broad analytic aspects of theory that are the weakest in fusion plasma science today. Filling this critical void in the theory program should be a very high priority for the next decade. Theory has not only a direct impact but also plays a role in enabling the next generation of advances in computational simulation and modeling. The recent growth of large-scale computation in fusion research through the Scientific Discovery through Advanced Computing (SciDAC) initiatives in concert with the DOE Office of Advanced Scientific Computing Research (OASCR) has been laudable. In FY06, for instance, the DOE Office of Fusion Energy Sciences (OFES) theory program was supported at about $25 million; the OFES contribution of $4 million to SciDAC was highly leveraged by OASCR to amount to a total investment of more than $10 million. Without these essential theory and diagnostic initiatives, large-scale computation would have only a limited impact on the magnetic fusion program. Moreover, the impact of computation would be greatly enhanced by stronger coupling to the theoretical and experimental components of the magnetic fusion program. It is the committee's opinion that new and continued investments in large-scale computation for fusion will achieve far better leverage if they are accompanied by investments to improve the underlying basis of analytic theory.

> **Conclusion: Participation in ITER remains the most effective path for accomplishing the U.S. objective of studying a fusion burning plasma. Maximizing the return on the U.S. investment in ITER will require the United States to maintain leadership in advancing key areas of plasma science and in ensuring concept improvement through increased scientific understanding. Without continuing leadership in these areas, the success of the ITER burning plasma experiments will be at some risk.**

The next large step in magnetic fusion research is to measure and explore the properties of burning plasmas. This step has been greatly facilitated by the U.S. decision to participate in ITER, which was recommended by the NRC Burning Plasma Assessment Committee.[5] Significant research must continue in order to maximize ITER's engineering and scientific success and to optimize its ultimate performance. Over the past decade, U.S. leadership in a number of scientific areas has contributed significantly to making ITER smaller, more efficient, and less expensive. This was achieved by redefining ITER's scientific goals, advocating major changes in the engineering design, and by developing and pushing several advanced modes of tokamak operation. Many of these contributions to ITER came not from burning plasma research but from research formally classified as part of

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[5] National Research Council, *Burning Plasma: Bringing a Star to Earth*, Washington, D.C.: The National Academies Press, 2004.

the pursuit of the program's plasma science or concept improvement goals. The United States is projected to contribute \$1.122 billion for its participation in the ITER construction project. To obtain an appropriate scientific benefit from this very substantial investment and to ensure ITER's success, the United States would be wise to retain, and preferably grow, a strong domestic fusion science research program. Such a program is necessary to develop the understanding and predictive capability that is needed to extract critical information from ITER and to project beyond ITER to fusion power.

Conclusion: To ensure that the magnetic fusion program can progress beyond ITER to electricity-producing fusion power, it is essential that research in concept improvement and innovation continue.

To hasten fusion energy development, a demonstration reactor must follow the completion of the burning plasma research mission on ITER. This will require the definition and development of high-performance reactor configurations operating at high plasma pressure (β) with controlled macroscopic instabilities, minimal microturbulence, and tolerable edge conditions. Research in concept improvement has shown that several configurations promise to yield improved predictive understanding, new plasma regimes, and potentially superior reactor designs. Without continuing U.S. leadership in this area it is unlikely that improved configurations will be ready in time, and the era of fusion power will be delayed.

Conclusion: The U.S. fusion program lacks a clear vision for the next decade and has been slow to react to and evolve toward the developing burning-plasma, ITER era.

While the scientific opportunities, the promising methodologies, and the program elements are clear, the detailed program structure is not. Although the ITER site was decided on only in mid-2005, the recent establishment of the U.S. Burning Plasma Organization is a positive step. However, the U.S. fusion program does not have a strategy for its evolution over time periods longer than the yearly budget cycles. In particular, it has not responded adequately to a program recommendation of the Burning Plasma Assessment Committee: "A strategically balanced U.S. fusion program should be developed that includes U.S. participation in ITER, a strong domestic fusion science and technology portfolio, an integrated theory and simulation program, and support for plasma science. As the ITER project develops, a substantial augmentation in fusion science program funding will be required in addition to the direct financial commitment to ITER construction."[6] This recommendation has not yet been adequately addressed beyond participation in ITER. Also, the Energy Policy Act of 2005 calls for a plan for evolution into the burning plasma, ITER era and calls for its review by the National Research Council. The

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[6] From the report *Burning Plasma*, p. 6.

U.S. community has taken positive steps to organize itself for the burning-plasma era, most notably with the formation of the U.S. Burning Plasma Organization, a grassroots technical organization that is coordinating U.S. research activities in preparation for ITER.

Although the scientific isolation of the magnetic fusion community—both from the rest of the physical sciences and from the rest of the plasma science community[7]—is decreasing, it is limiting progress and hindering the spread of knowledge and expertise developed in magnetic fusion to other areas. Including the community within a broader framework in the DOE Office of Science would have substantial intellectual benefits for the plasma science of magnetic fusion.

The committee notes that the U.S. magnetic fusion science community has made several efforts to develop plans for the future, most recently in two reports of the Fusion Energy Science Advisory Committee: *Scientific Challenges, Opportunities, and Priorities for the U.S. Fusion Energy Sciences Program* (2005) and *A Plan for the Development of Fusion Energy* (2003). More work is needed.

Recommendation: The United States should develop, and periodically update, a strategy for moving aggressively into the fusion burning plasma era over the next 15 years. The strategy should lay out the main scientific issues to be addressed and provide guidance for the evolution of the national suite of facilities and other resources needed to address these issues. Such strategic planning should include 10 considerations.

- The critical strategic and scientific issues that need to be addressed over the next 15 years by the magnetic fusion community: (1) the plasma science needed to maximize the scientific output of ITER and (2) the science and enabling technology for going beyond ITER—to guide the development of a strategy.
- The importance of focusing on fewer scientific issues in greater depth—to compete effectively internationally.
- Development of fusion plasma science and, accordingly, predictive capability through initiatives in diagnostics and theory, with greater coupling to the continuing development and utilization of large-scale computations—to maintain leadership in key scientific areas.
- Participation of the U.S. scientific community in setting the ITER scientific agenda and planning for U.S. involvement in ITER experiments—to ensure a strong scientific focus for ITER and significant involvement of U.S. scientists.

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[7] Please see the following report for a comprehensive discussion of this issue: NRC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, Washington, D.C.: National Academy Press, 2001. This report is also described in Appendix E of the current report.

- Transformation of the present portfolio of aging U.S. facilities into a new portfolio designed to expeditiously address key fusion scientific issues, including a schedule for retiring some devices to make room for innovative new experimental facilities and resources needed—to rejuvenate the portfolio of U.S. experimental facilities.
- The desired degree of participation and timing of evolution toward fusion research program based on international collaboration—to take advantage of some overseas facilities that are more capable than present U.S.-sited facilities and to prepare for leading some key scientific experiments on ITER.
- The balance between the burning plasma program and the development of innovative regimes and devices that look beyond ITER—to be prepared for the fusion demonstration era that will follow ITER.
- Possible change in the structure of the fusion program from a focus on particular experimental facilities, to a focus on science-oriented campaigns—to better align the program with its scientific objectives.
- Rejuvenation of the U.S. fusion workforce—to address the impending demographic challenge and the need for a new generation of fusion scientists for the burning plasma era.
- Feasible budgetary scenarios for implementing this strategic plan over the next 10 to 15 years—to indicate how the fusion program should evolve to address its scientific goals over that period.

There is a significant opportunity and an urgent need for the U.S. fusion program to develop a comprehensive, 15-year strategic plan. The plan would include 10 years of preparations for ITER construction, initial operation and scientific experiments, and the first 5 years (approximately) of ITER experimentation.

While current fusion budget projections by DOE provide fully for U.S. participation in the ITER construction project, in the most optimistic budget scenarios the domestic fusion research program (the program beyond that needed for ITER construction) is projected to grow only with inflation and the current partial (less than 50 percent) utilization of the major magnetic fusion research facilities is expected to continue. These projections make it difficult for the United States to close the growing gap between newer, more capable intermediate-scale facilities being built abroad and the aging U.S. facilities (Table 4.1).

Until the strategic planning has been completed, it is not possible to predict how facilities may evolve or to determine appropriate budget levels. It is, however, clear from the earlier discussion in this section that the domestic fusion program must remain strong for ITER to be successful and for the eventual development of fusion power. This will require a robust level of support for the domestic fusion program.

5

Space and Astrophysical Plasmas

INTRODUCTION

Most of the observable universe is in a plasma state. Plasma regimes range from the dense cores of stars to the relativistic electron-positron plasmas around pulsars and include the vast, diffuse plasmas that fill the spaces between galaxies. Furthermore, many of the fundamental questions in space and astrophysics require plasma physics for their answers. These questions have been identified by NASA, NSF, and other organizations as among the central science questions of our time. How does the universe begin? (As a plasma, according to the popular big bang model that has been so successful for the past decade.) How are the planets such as Earth formed? (In disks of plasma around stars, according to one theory.) What is the nature of our own solar system and its planetary plasma environment? And what is the nature of the extreme plasma environment around black holes?

In addition to serving a purely intellectual purpose—enabling an understanding of the universe in which we live—plasma physics has important practical implications for the interaction of satellites and humans with the space environment. Astronaut safety and spacecraft health issues require analysis of the plasma physics of radiation environments and payload charging. Accelerating the commercial use of space requires detailed knowledge of space weather. Although the science behind space weather has begun to move from the research community to the commercial and operations communities, it is still a formidable challenge to model the near-Earth space environment to the required level of quantitative prediction.

The popular appeal of space and astrophysics—both the science itself and programs such as NASA's Space Camp, the Hubble Space Telescope, and the Apollo program—helps maintain the national awareness of intellectual, scientific, and engineering endeavors. Space science and astrophysics thus play an important role in motivating future generations of scientists, engineers, and—specifically—plasma scientists.

Our current understanding of many space and astrophysical observations is rooted in plasma physics, and continued progress requires a better understanding of fundamental plasma processes. Indeed, conceptual advances in all of the six key processes discussed in Chapter 1 are essential. But while plasma physics can be considered a tool for space physics and astrophysics, the relationship is increasingly a two-way street. Space and astrophysical observations uncover dramatic and exotic new plasma physics regimes for study and provide detailed data to illuminate fundamental plasma processes. The diversity of plasma regimes encourages broad-based data analysis and innovative theory. In many cases, it also enables a search for new basic plasma processes that can be extracted from the specific parameter regimes and explored on a more fundamental basis.

The space plasma and astrophysical plasma physics communities are at a critical juncture. Instead of leaning on the laboratory plasma experience for guidance, they are pioneers in investigating new plasma physics regimes. How can the best progress be made in this new environment? Clearly, the goals of space physics and astrophysics are to understand the universe broadly, not to understand the specific details of plasma science. It is not obvious, however, where to find the most effective balance between fundamental plasma understanding on the one hand and the application of existing knowledge to particular objects on the other. Both are needed for progress on the broad goals of space physics and astrophysics. It is important to recognize and exploit the intimate links between plasma science in the laboratory and plasma science in space and astrophysics. Such cross-fertilization requires close communication and coordination between communities to enhance the flow of information in all directions.

The next section highlights progress and prospects for three research topics in space and astrophysical plasma physics: the origin and evolution of structure in a magnetized plasma universe; particle acceleration throughout the universe; and the interaction of plasmas with nonplasmas. The chapter concludes with a summary of challenges for the next decade and recommendations for meeting these challenges.

RECENT PROGRESS AND FUTURE OPPORTUNITIES

Space and astrophysical plasma physics includes systems ranging from the Earth's mesosphere through the solar wind and heliosphere (Figure 5.1) and out through plasmas on the scale of the universe as a whole. The physical conditions

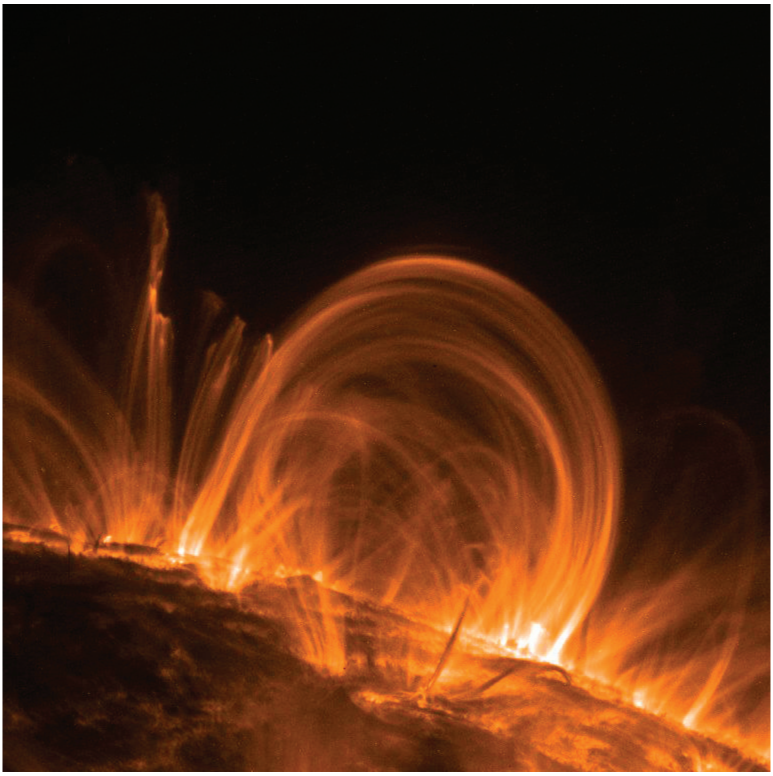

FIGURE 5.1 TRACE image of the solar corona, illustrating some of the science questions presented in this chapter: structured plasmas protruding from the surface of the Sun with particle acceleration during solar flares, and interaction between the collisionless solar corona and the collisional points near the photosphere of the Sun. Courtesy of Transition Region and Coronal Explorer (TRACE), a mission of the Stanford-Lockheed Institute for Space Research and part of the NASA Small Explorer program.

in space and astrophysical plasmas vary enormously, both in terms of the absolute densities and temperatures and in terms of the dynamical importance of processes such as collisions between particles. Consider a few examples of the relevant physical conditions. In Earth's atmosphere, temperature and gas density range from approximately 270 K and 3×10^{19} particles per cubic centimeter at the surface of Earth (where matter is neutral and not a plasma) to 180 K and 1,000 electrons per cubic centimeter in the partially ionized collisional mesosphere. From the center of the Sun to the solar wind at Earth, the temperature decreases from ~5 million K to $\sim 10^5$ K and the density decreases from $\sim 10^{26}$ particles per cubic centimeter to ~1 particle per cubic centimeter.

On astrophysical scales, the range of physical conditions is even more extreme, with temperatures reaching $\sim 10^9$ K around some black holes and neutron stars and gas densities as small as $\sim 10^{-4}$ particles per cubic centimeter in the space between galaxies (roughly a billion times more rarified than the best vacuums created in laboratories on Earth). Magnetic field strengths range from ~10^{15} G for the most strongly magnetized neutron stars (a billion times greater than the largest sustained laboratory magnetic fields), to ~1 G for Earth, to ~10^{-6} G in galaxies like our own. Although the latter magnetic field strength may sound weak in absolute terms, the magnetic force on the gas in galaxies is as important as the vertical gravity in the disc of a galaxy.

Studying plasmas over such a range of parameter space is greatly helped by the fact that the underlying plasma physics is often indifferent to the absolute temperature and density of the plasma but instead depends only on key dimensionless ratios. For example, the dynamics of a plasma is typically much more sensitive to the ratio of the magnetic energy density to the thermal energy density of the plasma than it is to the absolute value of either energy density alone. Thus the strongly magnetized coronas of a star and a galaxy have much in common even though the galaxy's magnetic field is at least six orders of magnitude smaller. In addition to the similarities in key dimensionless ratios, similar physical processes are also at work in a wide range of space and astrophysical environments. One of the goals of this chapter is to highlight three technical questions that cut across a wide range of problems: (1) To what extent is plasma science independent of the regime? (2) When is the coupling between small and large scales important? (3) How does nonideal plasma behavior influence dynamics? With such a diverse range of plasma regimes to study, an exhaustive account of the progress and challenges in space physics and astrophysics is impossible. Instead, examples of efforts at the intersection of space and astrophysics with plasma physics are presented.

In developing its analysis, the committee relied heavily on the excellent work of two previous NRC committees. In addition to hearing testimony from participants in those studies, this committee paid close attention to three earlier reports, *Plasma Physics of the Local Cosmos* (2004), *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (2003), and *Astronomy and Astrophysics in the New Millennium* (2001). Readers interested in a more comprehensive discussion are strongly encouraged to consult these references. Finally, this report highlights only the most compelling research themes; discussion of specific opportunities in HED astrophysical science can be found in NRC report *Frontiers of High Energy Density Physics: The X-Games of Contemporary Science* (2003) and *Frontiers for Discovery in High Energy Density Physics* (2004), a report from the White House's Office of Science and Technology Policy.

What Are the Origins and the Evolution of Plasma Structure Throughout the Magnetized Universe?

The observable matter in the universe is predominantly in the form of magnetized plasma. The largest volumes of such plasmas are in the intergalactic medium (e.g., galaxy clusters) and the smallest such surround planetary moons. The origin of magnetic fields in such objects (galaxies and moons) is one of the central puzzles in plasma astrophysics and space physics. Equally important is the question of how the magnetized plasma influences the structure, both spatial and temporal, and evolution of the object under consideration. Clearly these questions are ultimately related to the process of magnetic self organization, one of the six key plasma processes highlighted in Chapter 1. Here the current understanding of magnetic field generation and its impact on the evolution of structure in the universe is reviewed, highlighting recent progress and suggesting directions for future research. The discussion starts with the largest scales of the universe as a whole and proceeds to smaller and smaller scale objects such as galaxies, stars, accretion disks, and the planets in our solar system.

Plasmas and Magnetic Fields on Cosmological Scales

It is not known when and how the universe first became magnetized. Although there are various theoretical arguments that small fields could have been generated primordially in the early universe (while it was entirely a plasma), there are currently very few observational constraints on these processes. Aside from primordial theories, the leading idea for the origin of magnetic fields is that they are amplified and shaped from weak seed fields by the turbulent motions involved in structure formation. Weak seed fields can be produced by many mechanisms, including thermoelectric-driven currents. This mechanism is called dynamo action. Because the electrical conductivity of astrophysical plasmas is so large, the field remains nearly frozen in the plasma; the field lines move like threads stuck into the plasma, as they would in a superconductor. The field is thus stretched and amplified by the turbulent motions of the plasma.

Although it is generally believed that dynamo action is responsible for the origin of magnetic fields in smaller gravitationally bound objects (e.g., stars, galaxies, planets), its application to the largest structures in the universe is less clear. Smaller objects have the significant advantage that they amplify fields much more rapidly since they have shorter dynamical times and rotate faster. Fields amplified in energetic small objects such as accretion disks around black holes can be subsequently ejected via outflows into the surrounding space. For example, observations of clusters of galaxies directly show magnetized outflows (“jets”) from the central black hole extending out into the intergalactic medium (see Figure 5.2, showing an x ray and radio image of Abell 400). However, such fields weaken when they are ejected into a larger volume, and it is not yet clear whether they can magnetize the vast volumes of intergalactic space.

To understand the formation of large-scale structure, astrophysicists have employed large-scale numerical simulations to model the collapse and clumping of

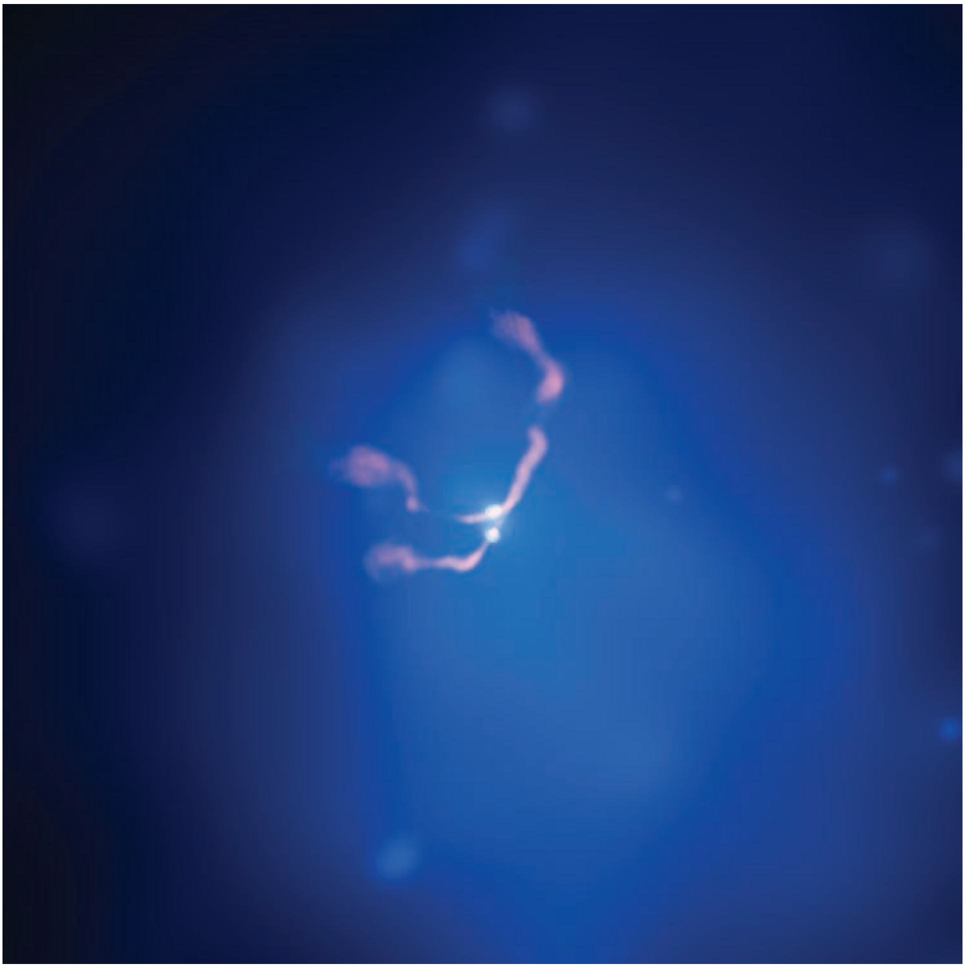

FIGURE 5.2 This composite x-ray (blue) and radio (pink) image of the galaxy cluster Abell 400 shows two radio jets immersed in a vast cloud of multimillion-degree x-ray-emitting gas that pervades the cluster. The jets emanate from the vicinity of two supermassive black holes (bright spots in the image). The image is approximately 1 million light-years on a side. Courtesy of NASA/CXC/AIfA/D. Hudson and T. Reiprich and NRAO/VLA/NRL; based on data in D.S. Hudson, T.H. Reiprich, T.E. Clarke, and C.L. Sarazin, *Astronomy and Astrophysics* 453: 433-446 (2006).

dark matter and gas. Given the complexities of this problem, most research to date has ignored the magnetic field and the fact that most of the matter in the universe is an ionized plasma. If, however, the field was formed early in the evolution of the universe (either primordially or by the first generation of stars and black holes), the magnetic forces may play a significant role in the subsequent evolution of structure in the universe. In addition, much of the plasma in the universe is relatively low density and hot (between 1 and 10 keV). The mean free paths of electrons and ions are thus quite large, and the transport of heat and momentum by the low collisionality plasma can have a significant influence on the behavior of plasma during structure formation. It is therefore expected that the plasma physics of structure formation will be a significant topic for research in the coming decade.

Plasmas and Magnetic Fields on Galactic Scales

As the universe expands and cools, galaxies form as plasma flows in toward the center of gravitational-potential wells established by dark matter. Magnetic fields in intergalactic space will be dragged in with the plasma, providing the initial seed field for the magnetized plasma now observed to fill the space between stars in galaxies—the interstellar medium (ISM). The initial seed magnetic field is subsequently amplified and shaped by the complex physical processes occurring in galaxies. Outflows from stars (like the solar wind) and explosions of stars (supernovas) can churn up the plasma in galaxies and also twist and amplify the magnetic field; similarly, the rotation of gas in a galaxy amplifies the galactic magnetic field. Through these dynamo processes, magnetic fields in galaxies are believed to acquire both a large-scale coherence such as that seen in Figure 5.3 and small-scale turbulent structure. Plasma and magnetic fields can also be ejected from the galaxy to form a galactic corona, analogous to the solar corona.

Dense magnetized clouds of weakly ionized plasma in the ISM are often the sites of intense star formation, as clumps of gas collapse under their own gravitational pull. Understanding the physics of the ISM in detail is thus a key to understanding how stars like the Sun form. Observations reveal that the ISM in galaxies is highly turbulent, with the random velocities often greatly exceeding the speed of sound. The energy source that maintains these motions is poorly understood and is one of the central problems to be addressed in the coming decade as numerical simulations improve and can be quantitatively compared to observations.

Because of its enormous size, the gas (plasma) in galaxies is a useful environment for studying some aspects of basic plasma physics. A particularly important example of this is that the spectrum of density fluctuations in the ISM of our galaxy is a $k^{-5/3}$ power law over nine orders of magnitude in length scale. This is identical to the power law predicted and observed for unmagnetized (Kolmogorov) turbulence and yet the ISM is strongly magnetized. Recent attempts to understand this puzzle have led to significant advances in the understanding of the nature of plasma turbulence (a key process highlighted in Chapter 1). The resulting Goldreich-Sridhar theory, which has been confirmed in some respects by simulation, is an important breakthrough in the understanding of plasma turbulence and has a wide variety of applications to space and astrophysical plasmas.

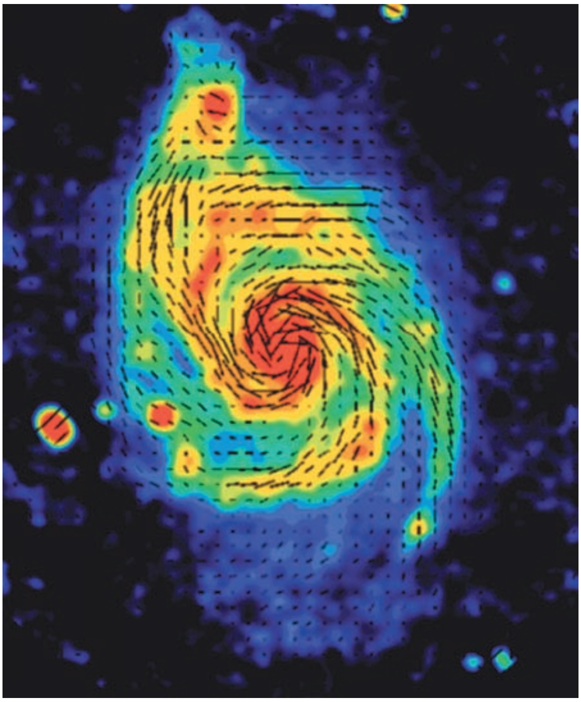

FIGURE 5.3 Galactic magnetism. Radio image of nearby galaxy M51, the "whirlpool galaxy." Colors show the intensity of plasma emission and black lines show the direction of the magnetic field inferred from the polarization of the emission (the length of the black lines is proportional to the degree of polarization). Courtesy of NRAO/AUI/NSF.

Plasmas and Magnetic Fields in Accretion Disks

The inflow (accretion) of matter toward a central gravitating object is one of the most ubiquitous processes in astrophysics and is responsible for forming much of the structure in the universe. During the accretion process, the gravitational potential energy of the inflowing matter is released in the form of radiation and outflows. When the central object is a black hole or neutron star, this liberation of energy is one of the most efficient ways of converting matter into radiation known in the universe. It is up to 50 times more efficient than nuclear fusion in stars. An understanding of the plasma physics of accretion is essential for solving a wide variety of problems—from the formation of stars and planets to achieving the long-sought goal of using observations of black holes and neutron stars to test general relativity's predictions for the structure of space-time in the most extreme environments. In the next decade, observational techniques will enable direct imaging of plasma in the vicinity of the event horizon of massive black holes in several nearby galaxies. There are exciting prospects for seeing general relativistic effects in such observations, provided that the dynamics of the plasma around the black hole is sufficiently well understood.

In the past decade, understanding of the plasma physics of the accretion process has advanced enormously. It was shown that a differentially rotating plasma is unstable to generating dynamically strong magnetic fields, which redistribute angular momentum and allow plasma to flow inward. Experiments are being developed to study this magnetorotational instability and its nonlinear evolution in liquid metal experiments; indeed, it may already have been detected in a recent experiment.

Numerical simulations have begun to study the time-dependent dynamics of disks, significantly improving on previous steady-state theories. In the context of accretion onto black holes, simulations have been carried out in full general relativistic MHD (see Figure 5.4 for a snapshot of the flow structure from such a simulation). Rapid progress is likely to continue over the next decade as the simulations incorporate more realistic physics and can be compared more closely to observations.

Under certain conditions, the plasma flowing onto a black hole or a neutron star can be so hot and tenuous that the collisional mean free path greatly exceeds the size of the system, much like the solar wind. Initial progress has been made on

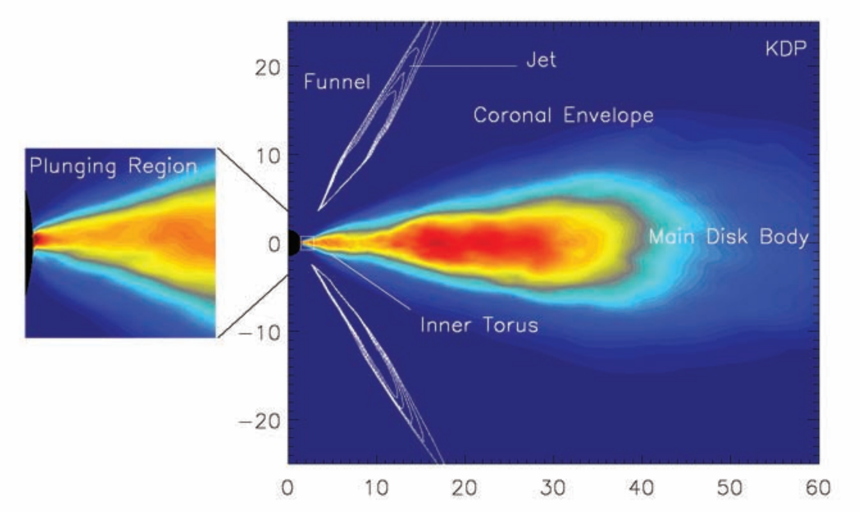

FIGURE 5.4 The inner regions of an accretion disk around a black hole, as calculated in a general relativistic MHD numerical simulation. The black hole is at coordinates (0,0) with an event horizon of radius unity. The accretion disk rotates around the vertical direction (the axis of the nearly empty funnel region). Its density distribution is shown in cross section, with red representing the highest density and dark blue the lowest. Above the disk is a tenuous hot magnetized corona, and between the corona and the funnel is a region where there is ejection of mildly relativistic plasma that may be related to the formation of the jets seen in the earlier figure. Image based on work appearing in deVilliers et al. (2003), © American Astronomical Society.

understanding how such a magnetized collisionless plasma accretes, but more work is needed on the dynamics of such low-collisionality accretion flows.

In addition to providing a key observational window into black holes and neutron stars, accretion disks are also the sites of star and planet formation, as discussed later in the section on nonideal (dusty) plasmas.

Plasmas and Magnetic Fields in Stars

Most stars are sufficiently hot and ionized to behave as plasmas throughout most of their volume. Surrounding the star is a magnetized plasma environment—for example, the Sun has a hot plasma corona and farther out the solar wind. Loops of magnetic field emerge from the Sun's surface (Figure 5.1). Periodic flares and eruptions of plasma release significant amounts of magnetic field energy in the form of heat, radiation (largely x rays), and accelerated particles. It is thought that the release of magnetic energy is a result of magnetic reconnection and is the dominant source of energy for the solar corona. (Magnetic reconnection is discussed in more detail in the next subsection.) In addition to this flaring near the surface of the Sun there is also extended heating out to distances of a few solar radii along open magnetic field lines. This heating is believed to drive away some of the coronal plasma leading to the solar wind. In the past decade observations with the SOHO satellite have provided direct constraints on the physical origin of this heating, implicating heating by very high frequency plasma fluctuations (near the cyclotron frequency). However, a detailed understanding of the origin of these fluctuations remains elusive.

The Sun's magnetic field, which is responsible for much of the activity in the corona and solar wind, is believed to arise by means of a dynamo driven by solar convection and rotation. The rotation profile of the solar interior inferred from observations of sound waves on the surface of the Sun (helioseismology) has provided strong constraints on the dynamo process. Large-scale numerical simulations have made significant progress in understanding solar convection and its effect on the solar magnetic field, but many features of the solar dynamo and solar structure (e.g., the magnetic field reversals of the Sun and the rotation profile in the solar convection zone) remain to be understood as the computations become increasingly realistic.

An extreme analogue of solar flares is observed from a class of astrophysical objects that occasionally produce large flares of gamma-ray radiation. It has now been confirmed that these flares arise from "magnetars," neutron stars with the strongest magnetic fields of any known stellar object (roughly 10^{14} to 10^{15} G, compared to about 10^{12} G for more typical neutron stars and about 1 G for the Sun). Theoretical arguments suggest that such magnetic fields may arise in a dynamo during the first 30 sec in the life of a rapidly rotating neutron star after it is formed from the collapse (and explosion) of a massive star. Magnetars appear to make up about 10 percent of the neutron star population, suggesting that for a reasonable fraction of the time, the formation of compact objects involves dynamically important magnetic fields. Another class of astrophysical gamma-ray transients—long-duration gamma-ray bursts—has also been definitively linked to the explosions of massive stars (supernovas). These observations strongly motivate studies of supernovas, including the effects of magnetic fields. Such studies have just begun in detail, and significant progress is likely in the coming decade.

Plasmas and Magnetic Fields on Planetary Scales

The planets in our solar system are buffeted by the solar wind plasma that streams out of the Sun past the planets. This solar wind plasma demarcates the heliosphere. The interaction of the solar wind with the atmospheres and magnetic fields of the planets creates magnetospheres, plasmas that are trapped on the magnetic field lines emanating from the planets themselves. In the local cosmos, the structure and evolution of the heliosphere of our Sun and the magnetosphere of the Earth are controlled and ordered by magnetic fields. They are a primary parameter of space weather, which has important consequences for satellites and humans in space. Thus understanding how magnetic fields are generated, transported, and dissipated is a fundamental problem in basic plasma science and of great importance for describing magnetospheres. Three questions dominate current research: magnetic reconnection at boundaries, Alfvénic coupling and transport across magnetospheric regions, and planetary dynamos.

Magnetic Reconnection. The breaking and reconnection of magnetic field lines is an important part of magnetic self-organization, which has significance for laboratory, fusion, and space plasmas. The basic process and the outstanding issues are described in the first section of Chapter 1. The prevalence of this research topic is a symptom not of repetition or redundancy in plasma science but of the underlying unity of the intellectual endeavor. As a physical process, magnetic reconnection plays a role in magnetic fusion, space and astrophysical plasmas, and in laboratory experiments. That is, investigations in these different contexts have converged on this common scientific question. If this multipronged attack continues, progress in this area will have a dramatic and broad impact on plasma science.

At planetary scales, reconnection shapes and organizes the magnetic field of the planet and the solar wind. Significant reconnection occurs between field lines in distinct regions of the solar wind; field lines in the solar wind and the magnetosphere at the magnetopause (on the Sun side of the planet); and in the magnetotail (on the side of the planet away from the Sun). Reconnection in Earth's magnetotail releases magnetic energy explosively and initiates substorms—the excitations of the magnetosphere and ionosphere that are visible as the aurora borealis. Reconnection also enhances the transfer of particles between the solar wind and the magnetosphere. Clearly, understanding the reconnection processes is critical to developing a predictive model of Earth's plasma environment.

Recent progress in understanding reconnection highlights the effectiveness of abstracting a plasma process and studying it in several environments. It has been studied in fusion experiments (Chapter 4), basic laboratory experiments (Chapter 6), with theory and computations, and with spacecraft. Observing reconnection in space has the great disadvantage of having undergone very few probes, at most a few spacecraft for any given event; it has the great advantage, however, of allowing a huge range of scales for the in situ observation. Figure 5.5 shows two examples of recent observations.

Observations like these, with minimal diagnostics and numbers of probes, are complemented by laboratory experiments with many probes but smaller dynamic range and by theory and computational modeling. Results of recent experimental work are shown in a figure in Chapter 6. However, present experiments are limited by the inability to measure the fine-scale structure in the dissipation region, relatively low repetition rates, and constraints imposed by the reconnection geometry. The development and deployment of a new class of microprobes would significantly enhance existing experiments.

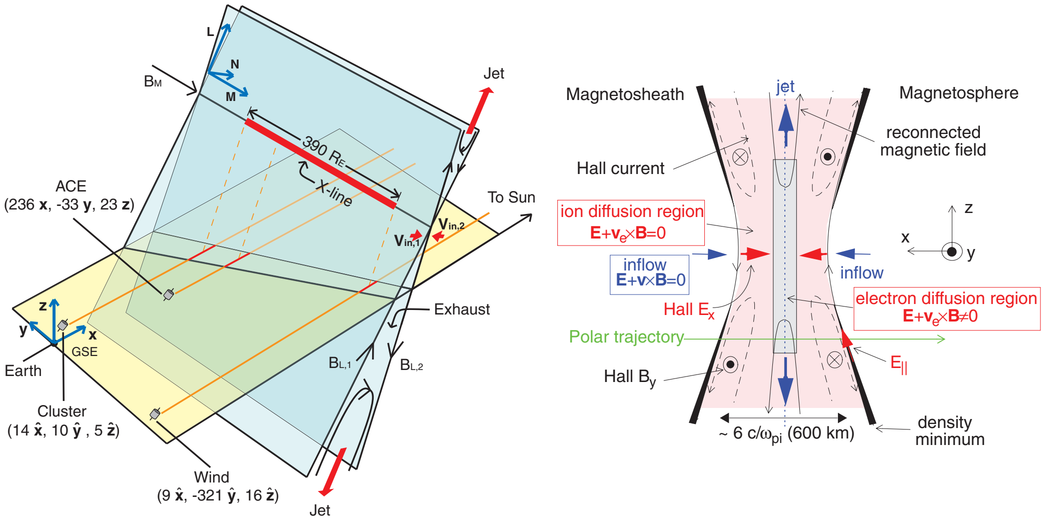

FIGURE 5.5 Studying magnetic reconnection with spacecraft. Observations of reconnection on extremely large (2×10^6 km) and extremely small (600 km) scales. Left panel shows configuration of three spacecraft observing the passage of the same x-line over 2 hours. Right panel shows details of the diffusion region as interpreted from Polar spacecraft observations. Courtesy of T. Phan, University of California at Berkeley.

Satellite measurements in space, dedicated laboratory reconnection experiments, and the emergence of a new generation of computational models have led to significant advances in our understanding of the physics of fast reconnection in nature. However, important questions remain:

- What sets the near explosive rate of reconnection, and how does it scale with plasma conditions?
- How do the field lines break? Does turbulent drag between electrons and ions play a role?
- How is reconnection triggered? Why does it sometimes wait while energy builds up in the field?
- What is the role of the three-dimensional field structure?

There are a number of impediments to bringing the reconnection problem to closure. In Earth's magnetosphere, there is no easy way to arrange a satellite at the right place and time to study the onset of reconnection. In fusion experiments, there is a lack of diagnostic capability to measure the structure of the high-temperature-core plasmas, and the present generation of dedicated laboratory reconnection experiments do not have a sufficient separation of microscopic and macroscopic spatial scales to explore the buildup-and-release cycle. Nonetheless, recent results have driven a sense of optimism that, with the necessary resources, the magnetic reconnection problem is soluble. NASA and its international partners are continuing major investments in the exploration of magnetic reconnection through satellite measurements. Laboratory reconnection experiments funded by DOE and NSF are making significant contributions. Further experimental progress will require larger devices and significant investment in diagnostics. Without continuing cooperation between laboratory and space plasma scientists it is doubtful that this problem can be solved.

Alfvénic Coupling and Transport. Magnetic field lines emanating from Earth's core pass through the neutral atmosphere to the ionosphere (a partially ionized plasma layer) and on to the magnetosphere. A central issue in ionospheric physics is the nature of magnetosphere-ionosphere coupling and the role of the magnetic field in this coupling. How mass, momentum, and energy are transported between the ionosphere and magnetosphere, and how disturbances in the magnetosphere are transmitted to the lower ionosphere, are questions rich in plasma physics. The answers to these questions are critical for developing a predictive capability for space weather.

Magnetospheric disturbances and reconfigurations are propagated to and from the ionospheric boundary via Alfvén waves along the field lines. The resulting coupling is a complex problem involving the boundary conditions set up by the state of the dynamic ionosphere. Reflection patterns at each end of the field line generate very fine-scale structure in the ionosphere, particularly in the auroral regions. The problem is inherently multiscale and inhomogeneous. Recent efforts involve attempts to quantify the significance of these small-scale structures for large-scale dynamics and aurora generation. How much microphysics must be resolved in order to have accurate predictions of macroscopic dynamics? Similar physics arises where coronal field lines meet the Sun's surface (Figure 5.6) and in jovian studies.

To understand the coupling, scientists have employed a huge variety of observational approaches: high-resolution radars; multipoint spacecraft (e.g., the Cluster mission); modeling; and ground-based information, including magnetometer chains, camera chains, and the THEMIS spacecraft ground array.

Observations and theory and modeling tools are complemented by extremely high-resolution laboratory data that study the fundamental plasma science. The example shown in Figure 5.6 illustrates in great detail the microphysics of one such Alfvénic wave–particle interaction. This image shows a lab experiment relevant to coronal heating, where Alfvén waves propagate up field lines away from the Sun and run into a magnetic beach, heating electrons in the process. The experiment may be of relevance in the ionosphere, where the geometry is backward for incom-

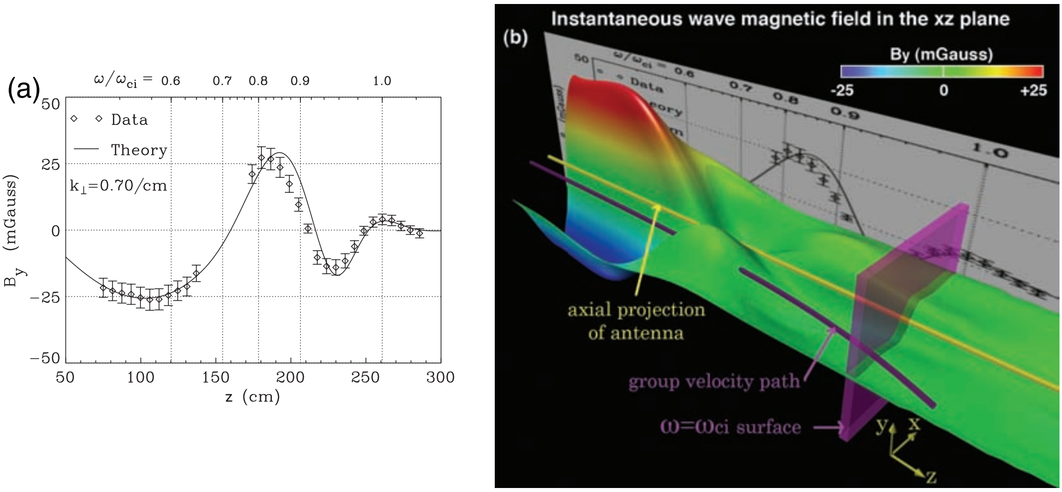

FIGURE 5.6 Alfvén waves hit a beach. *(a)* Measured instantaneous shear Alfvén wave magnetic field pattern (colored surface) together with *(b)* a comparison to a theoretical model. The waves are generated using a modulated field-aligned current in a parallel background magnetic field gradient. Waves propagate into the low field "beach," where they damp near the ion-cyclotron resonance layer (shown in magenta). Courtesy of S. Vincena, Large Area Plasma Device (LAPD) Plasma Laboratory, University of California at Los Angeles.

ing waves. The data were obtained at over 2,500 spatial locations using a single three-axis inductive probe over the course of several days. The highly reproducible background plasma, generated at 1 Hz, allows the single probe to nonperturbatively measure the plasma volume. The measured decay of Alfvén wave energy was successfully modeled using ion-cyclotron and electron Landau damping. These interactions are responsible for accelerating electrons along Earth's auroral field lines, a key aspect of magnetosphere-ionosphere coupling (see the next section).

Planetary Dynamos. In Earth's dynamo, the field is amplified and regenerated in the conducting liquid core. These dynamos have a resemblance to the plasma dynamos of clusters, galaxies, accretion discs, and stars, though planet cores are not very good electrical conductors and their fields are smoothed by resistive diffusion. Observations and theory of planetary dynamos are much more complete. Indeed, modeling of Earth's dynamo is one of the most successful uses of high-performance computers in science. Computational models have reproduced the approximate structure of the observed field and the reversals of the magnetic poles (Figure 5.7). A number of laboratory experiments to study dynamos under earthlike conditions have been carried out (see Chapter 6).

It is not known how much these results can be applied to plasma dynamos, where the fields are much more tangled and the microscopic processes involve electron and ion dynamics. However, there is considerable optimism that the advances in computer modeling will also benefit plasma dynamos.

More generally, however, there is an obvious connection between magnetohydrodynamics (which often involves conducting fluids that are not plasmas) and plasma physics proper. In the minds of many practitioners, there is hardly any distance between these subjects. For instance, virtually all lab experiments testing ideas on (plasma) accretion disks are based on the use of liquid metals; dynamo experiments probing dynamo theories (for solar and stellar dynamos, for instance, which all take place in plasmas) are without exception also based on the use of liquid metals; and so forth. As discussed elsewhere, the exploration of where magnetohydrodynamic modeling of plasma phenomena breaks down is a leading research topic.

How Are Particles Accelerated Throughout the Universe?

It is a remarkable observational fact that most astrophysical and space plasmas contain a significant population of highly energetic particles (particles with energies well above the typical thermal energy of the system). Such particles are detected both directly when they reach us here on Earth and indirectly, via the radiation they produce (i.e., synchrotron radiation from relativistic electrons).

Cosmic rays impinging on Earth were first discovered in 1912 and continue

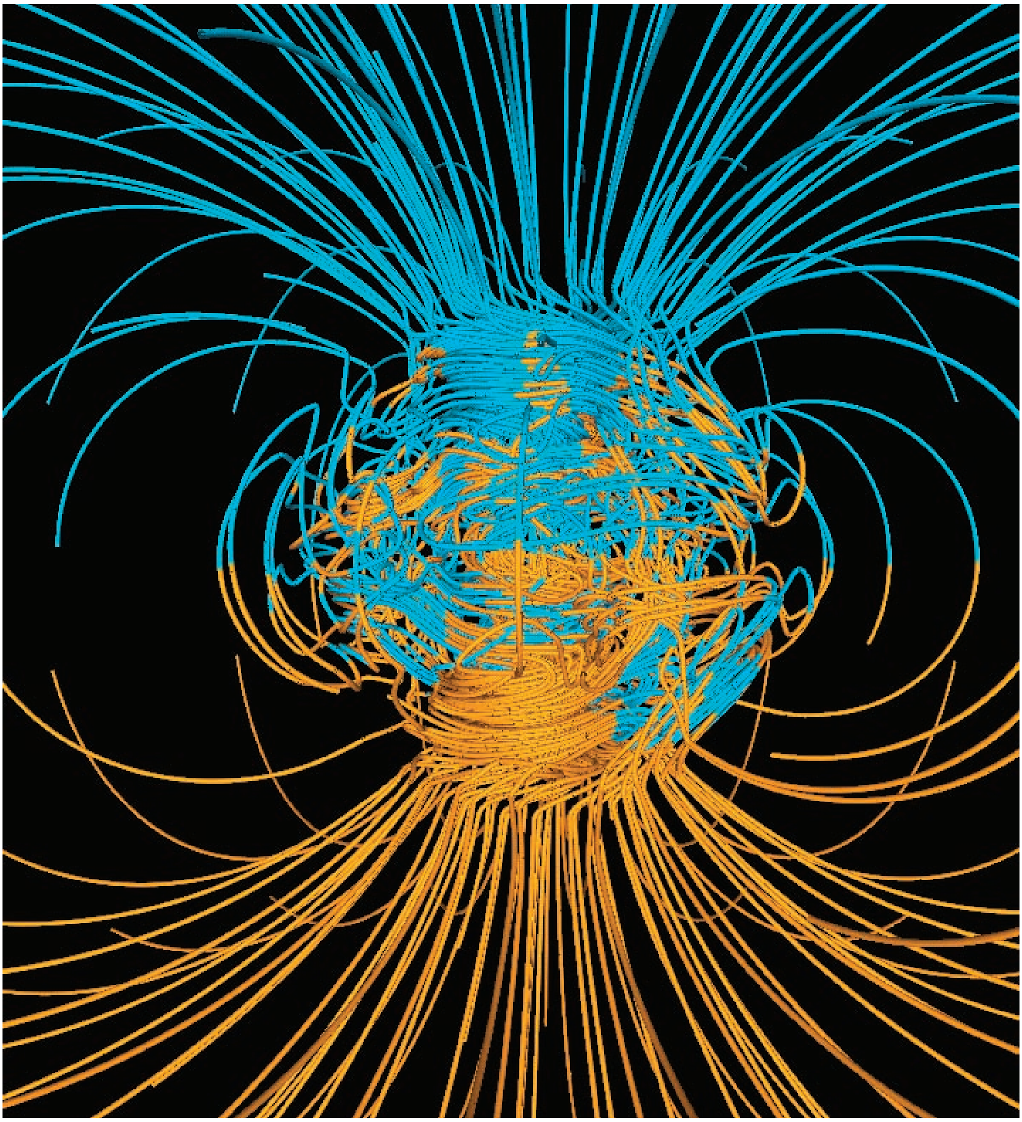

FIGURE 5.7 A computer simulation of Earth's magnetic field. A snapshot from a three-dimensional geodynamo simulation by G. Glatzmaier, University of California at Santa Cruz, and P. Roberts, University of California at Los Angeles. Magnetic field lines are blue where the field is directed inward and yellow where directed outward. The rotation axis of the model Earth is vertical and through the center. The field lines are drawn out to two Earth radii. Simulations such as this one have successfully produced spontaneous reversals of a dipole magnetic field similar to those inferred from Earth's paleomagnetic record.

to provide an extraordinarily rich arena for studies of both plasma physics and particle physics. As Figure 5.8 shows, they are observed to have energies ranging from <1 GeV to nearly 10^{20} eV. The latter particles, dubbed ultra-high-energy cosmic rays, have energies similar to that of a baseball and thus pack quite a punch!

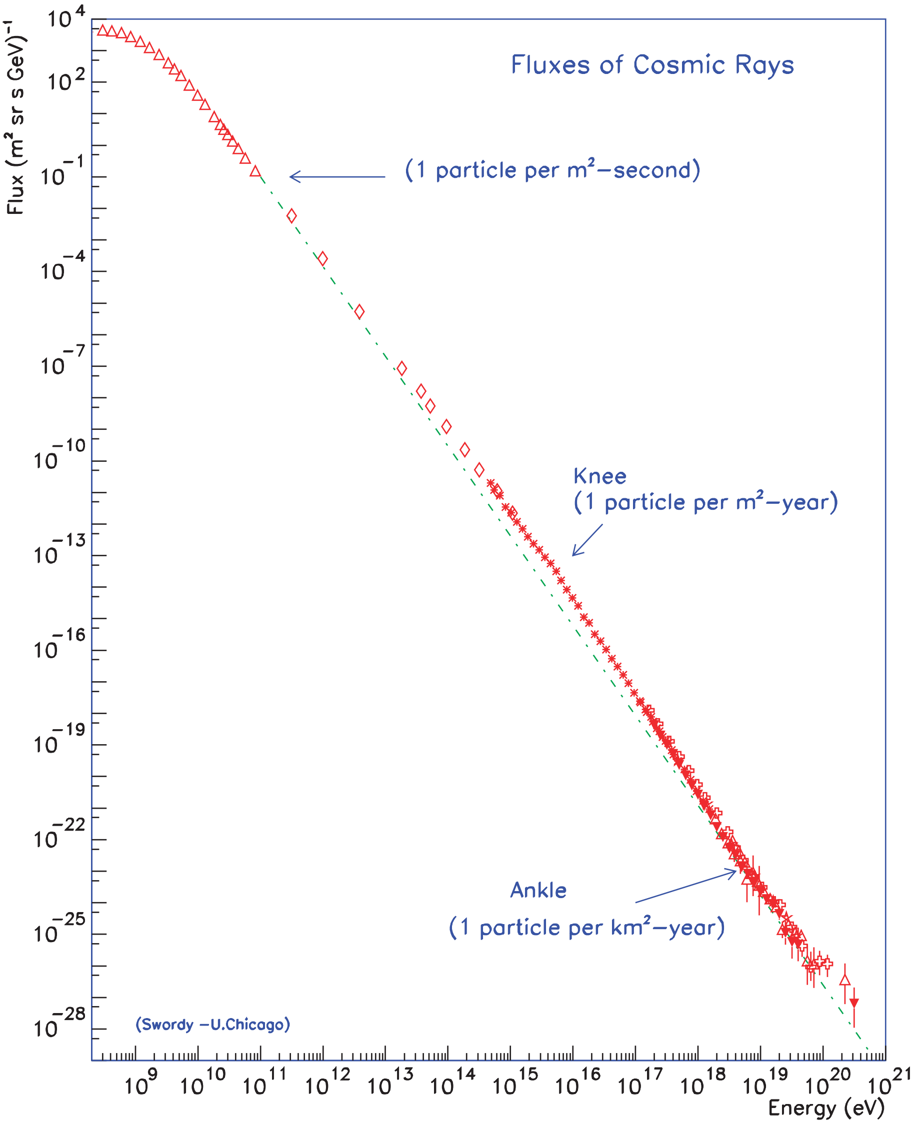

FIGURE 5.8 The spectrum of cosmic rays as detected on Earth (number of cosmic rays of a given energy reaching Earth as a function of energy). Most of the cosmic rays are believed to be produced by supernovas (stellar explosions) in our own galaxy. However, the most energetic particles (>10^{18} GeV) probably have an extragalactic source. Courtesy of S. Swordy, University of Chicago.

Particles with these energies cannot be confined to the galaxy and must originate in extragalactic sources (the motion of such particles through the universe depends sensitively on the uncertain strength and geometry of the magnetic field on cosmological scales). Very few astrophysical objects have characteristics consistent with allowing the acceleration of such particles. The most promising candidates are gamma-ray bursts and massive black holes, but more observations are required to determine which (if either) of these hypothesized sources is correct.

The total energy contained in cosmic rays in our galaxy is similar to the energy stored in the magnetic field. Together, these constituents contain enough energy to keep the gas in the galaxy from the gravitational pull of the stars. Rather than being mere curiosities, the energetic particles are thus crucial constituents of the interstellar medium. A similar conclusion is reached in a wide variety of space and astrophysical environments. For example, observations of solar flares imply that a significant fraction of the magnetic energy is released as highly energetic particles.

The acceleration of cosmic rays, and of high-energy particles more generally, is one of the long-standing problems in plasma astrophysics. What follows highlights several examples of recent progress on understanding particle acceleration and key areas in which research on particle acceleration is likely to have a major impact over the next 10 years. The study of particle acceleration has deep connections to other areas of physics, notably particle physics. These connections will strengthen in the coming years, when results from the Gamma-Ray Large Area Space Telescope (GLAST), among other facilities, become available, and with the development of large-area neutrino telescopes.

Fermi Acceleration

In 1949, Fermi proposed that particles can be efficiently accelerated by scattering them off moving inhomogeneities in a plasma. A useful analogy is to imagine balls bouncing off moving walls: each time a ball hits a wall moving toward it, the ball gains energy at the expense of the wall. This idea is at the heart of two of the primary models for particle acceleration in space and astrophysical plasmas: diffusive shock acceleration and acceleration by plasma turbulence.

It is generally believed that galactic cosmic rays between 10^{16} and 10^{18} eV originate in supernova shocks in the ISM. In canonical diffusive shock acceleration theory, particles are accelerated at shocks as they are reflected back and forth across the shock by turbulence. Recent observations of TeV gamma rays from ground-based telescopes such as the High Energy Stereoscopic System (HESS) have detected roughly a dozen galactic sources, many of which have plausible associations with supernovas. The majority of these sources have power-law TeV spectra consistent with the expected energy spectra of shock-accelerated particles. Analogous evidence in the form of synchrotron spectra in accord with expectations has existed for decades, but the new TeV observations probe much higher energy particles. In addition to the observational progress, numerical simulations of nonrelativistic collisionless shocks directly reveal the acceleration of protons to high energies. Much still remains to be understood, however, in particular the detailed structure of collisionless shocks and the connection between simulations of shock acceleration and canonical diffusive shock acceleration theory.

On December 16, 2004, Voyager 1 made its highly anticipated crossing of the termination shock of the solar wind, where the solar wind slows down and begins to join the ambient ISM. It had long been predicted that the anomalous cosmic rays—a population of ~10-MeV cosmic rays with unusual (anomalous) composition—were accelerated at the termination shock, which would provide an accessible example of shock acceleration of energetic particles. Although Voyager detected the abrupt acceleration of lower energy ions, there was no significant change in the intensity or spectrum of anomalous cosmic rays crossing the termination shock. The implications of these important observations for shock acceleration theory remain unclear and will be an active area of research in the coming years. Voyager 2, which carries additional plasma detectors, will pass through the shock in 2009 or 2010 and will provide additional observational input.

Acceleration of particles by plasma turbulence is favored by many as the dominant acceleration mechanism in solar flares, as it appears to account most readily for the preferential heating of different ion species (the turbulence itself may be generated by the reconnection that drives the flare). Cosmic rays initially accelerated at supernova shocks may be further reaccelerated by plasma turbulence in the ISM of our galaxy. Progress in the theoretical understanding of MHD turbulence in the past decade has been dramatic and is crucial for a predictive theory of particle acceleration by turbulence. Continued progress on this front, together with models of the dissipation of turbulence in collisionless plasmas, should provide major advances in the understanding of particle acceleration by turbulence.

Particle Acceleration by Reconnection

As discussed in Chapter 1, magnetic reconnection converts magnetic energy at large spatial scales to fast plasma flows and energetic electrons and ions. Satellite measurements during solar flares have provided a wealth of evidence that a substantial fraction of the released energy is channeled into energetic electrons and ions. Satellite measurements in the magnetosphere suggest that the energetic electrons are produced in the vicinity of the magnetic x-line. Simple models, however, fail to explain these observations. Strong ion heating during reconnection events has been measured in fusion and dedicated laboratory reconnection experiments. However, our understanding of these observations, particularly why so much energy appears as energetic electrons, remains incomplete. Numerical simulations are beginning to probe the acceleration of particles during reconnection (see, for example, Figure 5.9). While good progress can be expected in the next 10 years, it will not be possible to model the whole process—for example, in solar flares the microphysics of reconnection and particle acceleration cannot be simulated simultaneously with the three-dimensional evolution of the magnetic

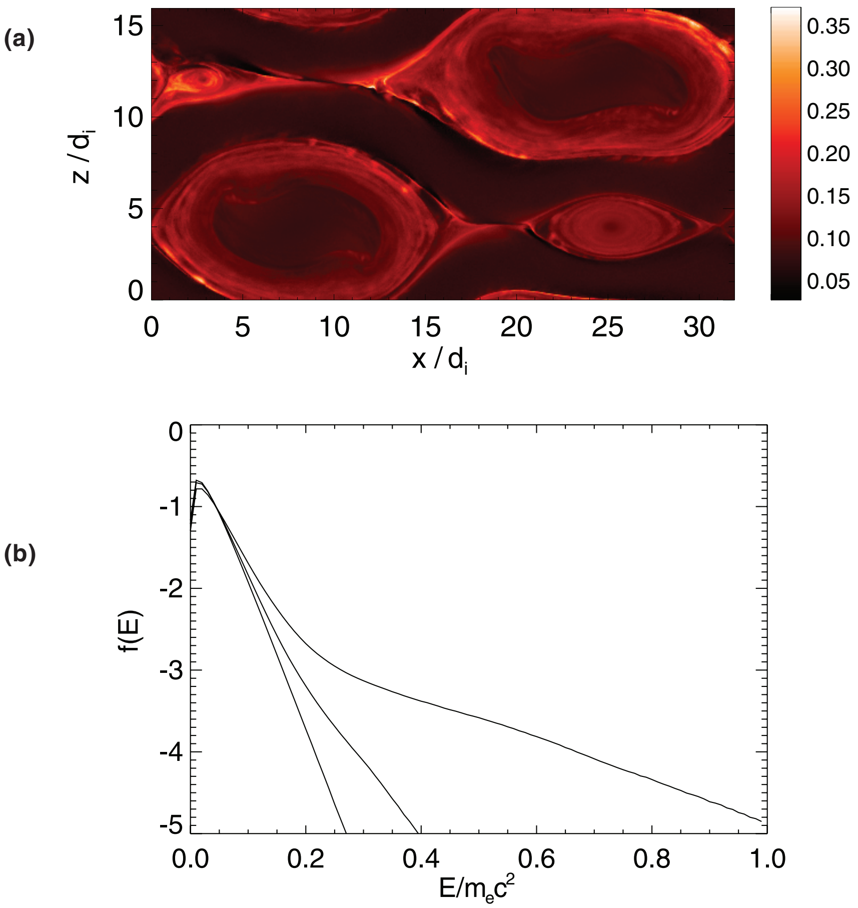

FIGURE 5.9 Electron acceleration in reconnection. Particle-in-cell simulations exploring the production of energetic electrons during magnetic reconnection. *(a)* Electron temperature during magnetic reconnection in a configuration with two adjacent current layers and an initial ambient out-of-plane magnetic field. Intense particle heating is seen along the separatrices that connect to the magnetic x-lines. In *(b)*, the electron energy distribution is shown at three times during the simulation. A fraction of the electrons reach relativistic energies. This is a computationally challenging problem because of the large range of spatial scales involved. Courtesy of J. Drake, University of Maryland at College Park from work published in J.F. Drake, M.A. Shay, W. Thongthai, and M. Swisdak, *Physical Review Letters* 94: 095001 (2005).

field, even with expected increases in computer power. Thus it is critical that the basic plasma physics of reconnection and acceleration be developed to the point that a model can be developed of their macroscopic consequences for use in larger-scale calculations.

Auroral Acceleration

Earth's aurora provides a nearby natural plasma physics laboratory for the study of parallel electric field formation, with applications to other magnetized planets such as Jupiter or to any object with strongly convergent magnetic fields, such as pulsar magnetospheres or astrophysical jets from active galactic nuclei. The plasma processes responsible for and caused by these parallel electric fields proceed on microscopic scales far below the mean free path and many orders of magnitude below any resolvable astronomical scales. They are not accessible other than by analogy with the processes taking place in the aurora. Field-aligned current requirements in magnetic-mirror geometries that have anisotropic particle distributions can generate many microscopic parallel potential drops—resulting in beams of electrons, auroral kilometric radiation (AKR), or other coherent emission of radiation. The question of how potential drops distribute themselves along magnetic fields is an open one of general interest in plasma physics, and much effort is now going into understanding these potential drops in both upward and downward regions of auroral current. In the downward-current region, though, it is a "stiff" dynamic range problem, with no clear resolution.

Laboratory experiments, space and astrophysical observations, and modeling are all providing useful insights into auroral acceleration processes. The FAST spacecraft's study of the generation of AKR from auroral particle distributions through a maser process (see Figure 5.10) is a recent example of progress. This radiation is of wide interest as it is one of the few electromagnetic signatures that can leave a magnetized planet and can thus be used as a remote sensor of magnetic fields. It is also implicated in radiation from stars and the Sun.

Particle Acceleration in Relativistic Plasmas

All of the above advances apply to fundamentally nonrelativistic plasmas permeated by relativistic constituents that are small in number. However, a wide variety of astrophysical objects, including pulsars, jets from active galactic nuclei, and gamma-ray bursts, contain fully relativistic plasmas and relativistically strong magnetic fields. Such environments require understanding shock acceleration at relativistic speeds, magnetic dissipation in relativistic plasmas, and acceleration by turbulence in the extreme relativistic limit. It is unclear which of these mechanisms

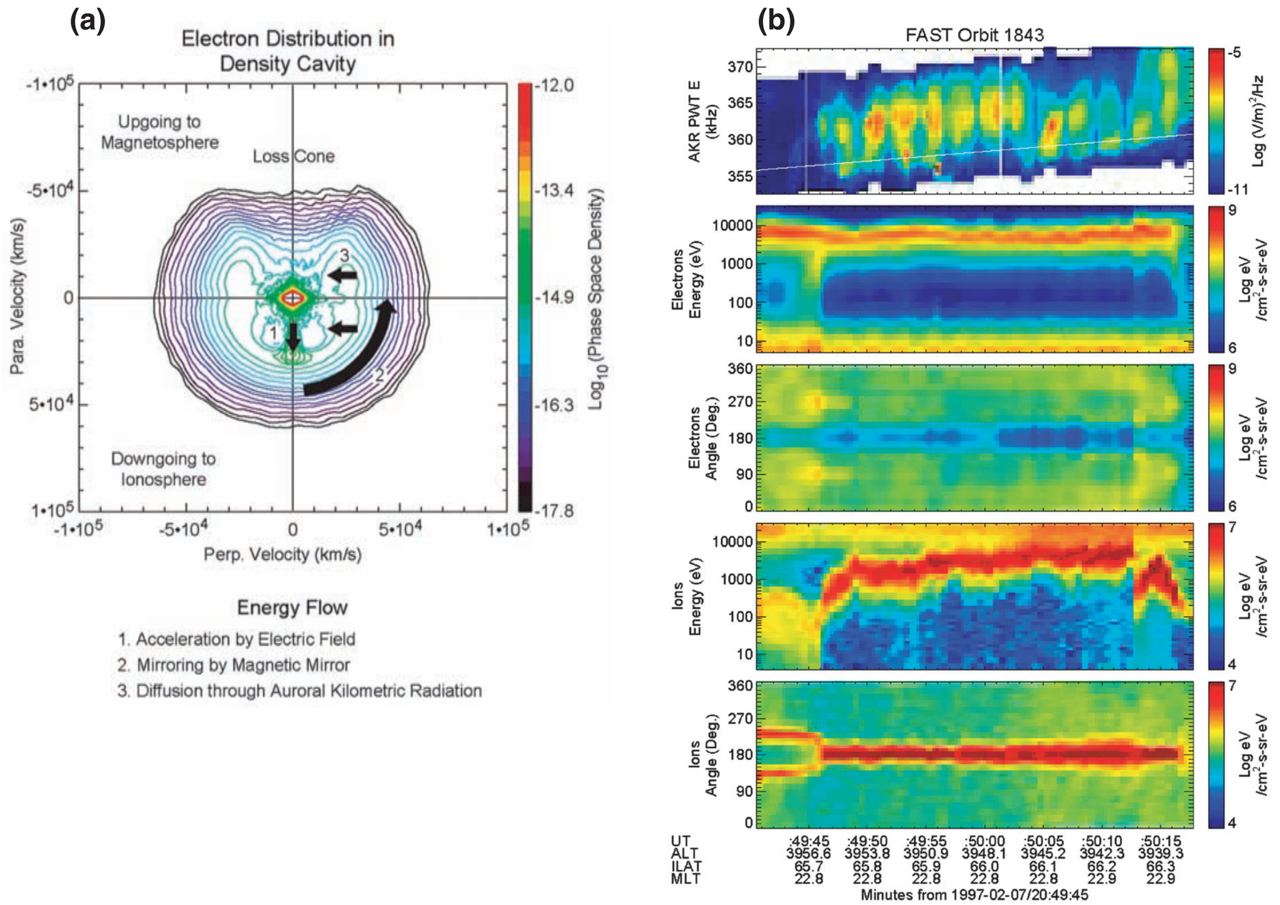

FIGURE 5.10 Auroral kilometric radiation (AKR) maser instability. *(a)* Energetic electron distribution function contours perpendicular and parallel to the magnetic field from FAST. This distribution is unstable to relativistic electron-cyclotron waves that are observed as AKR. Arrows indicate energy flow in the instability. *(b)* The frequency spectrum of the emitted radiation, electron energy distribution, electron angular distribution, ion energy distribution, and ion angular distribution versus time as seen by FAST. Courtesy of R.E. Ergun, University of Colorado, Laboratory for Space and Atmospheric Physics.

is the dominant mechanism for particle acceleration in relativistic astrophysical plasmas.

The understanding of magnetic reconnection in a relativistic environment has just begun; the development of such understanding, through theory and kinetic simulation, as well as the incorporation of that understanding into macroscopic models, is a crucial requirement for advancing the modeling of relativistic environments.

Significant effort has gone into extending the diffusive shock acceleration mechanism to the relativistic environment. Calculations have shown that large amplitude magnetic turbulence is required to provide sufficient scattering in the vicinity of the shock. In the last decade, direct simulation techniques have been applied to the relativistic shock problem, for shocks both with and without upstream magnetic fields (see, for example, Figure 5.11). To date, relativistic shock simulations have yet to show solid evidence for significant particle acceleration, including no evidence for the high turbulence levels required in the phenomenological models. Deeper resolution of these issues awaits the rapidly improving ability to do three-dimensional simulations.

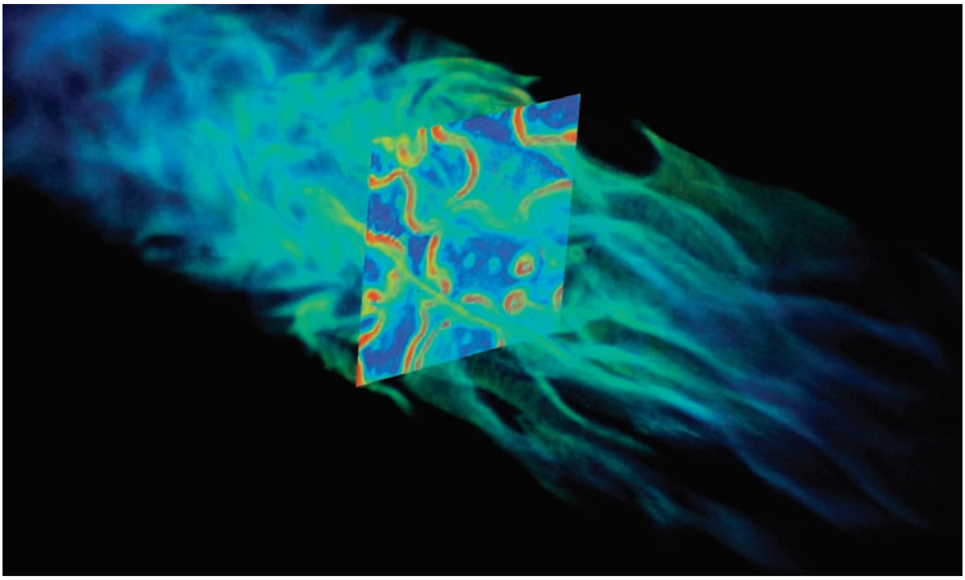

FIGURE 5.11 Magnetic energy density in a relativistic collisionless shock, viewed toward the upstream direction; the shock propagates toward the lower right corner. The filamentary structure is due to the instabilities that generate the shock. Courtesy of A. Spitkovsky, Princeton University.

How Do Plasmas Interact with Nonplasmas?

The interactions of plasmas with neutrals, particulates, and boundaries is a field of study well illustrated by space observations. Many of the scientific issues in this area have parallels in low-temperature laboratory plasma physics. For example, spacecraft charging in plasmas is a complex technological problem with roots in laboratory and theoretical studies of sheaths (Box 1.1). Interactions of plasmas with neutral gases are important both at atmospheric boundaries and in the far heliosphere. Dusty plasmas appear throughout this entire report, with connections to fusion, low temperature, and basic plasma physics (see Chapter 6). Dusty plasmas in space are a significant part of this field of study. In the heliosphere, dust from meteors, comets, and planetary rings provides a rich natural basis for the study of dusty plasmas. On even larger scales, the small admixture of plasma and charged dust in galaxies like the Milky Way strongly influences how stars and planets form. Recent progress in the basic physics of dusty plasmas is addressed in the same section.

There are many fundamental open questions about plasma–nonplasma interactions. Is the mesosphere an active or passive part of atmospheric and climate change? What are charging and accumulation processes for particulates (charged dust)? How does ionospheric plasma physics mesh with atmospheric chemistry? What are the physics of mass loaded plasmas, partially ionized plasmas, and neutral atom–plasma interactions? How does the plasma physics change if the plasma is just one of many species present and is weakly (or strongly) interacting with them? What is the plasma physics (probe physics) of sheaths around charged spacecraft? Questions like these provide the opportunity to study nature but also promise insight into technological problems in fusion, industrial plasmas, and probe physics.

Astrophysical Examples of Plasma–Nonplasma Interactions

In many astrophysical environments, the interaction between plasmas and nonplasmas plays a crucial dynamical role. This is particularly true of the dense, relatively cold gas out of which stars and planets form. The majority of this cold gas is neutral atomic or molecular material that only indirectly feels the effects of the ambient electric and magnetic fields, via collisions with the comparatively rare ionized matter. One specific context in which these plasma physics issues have been extensively studied is the accretion disks present in sites of star and planet formation. The same general issues that arise in this context also arise throughout the ISM of galaxies more generally and in the dense nuclei of galaxies where massive black holes form and grow.

Planets, including Earth, form as gas and rocks collect together in the disk of dust and gas surrounding a newly formed star. The past decade has seen a revolution in our understanding of planetary systems, with the discovery of over 200 extrasolar gas giant planets (like Jupiter). Many of these planets are on rather elongated (eccentric) orbits close to their parent stars, in contrast to the massive planets of our solar system, which reside at large distances from the Sun on nearly circular orbits. The most plausible explanation for this difference is that the planets were formed at large distances but some slowly moved inward through interactions with their host accretion disk. The accretion disks out of which planets form are believed to be only weakly ionized (Figure 5.12). The plasma physics issues for this problem thus naturally evoke two general questions:

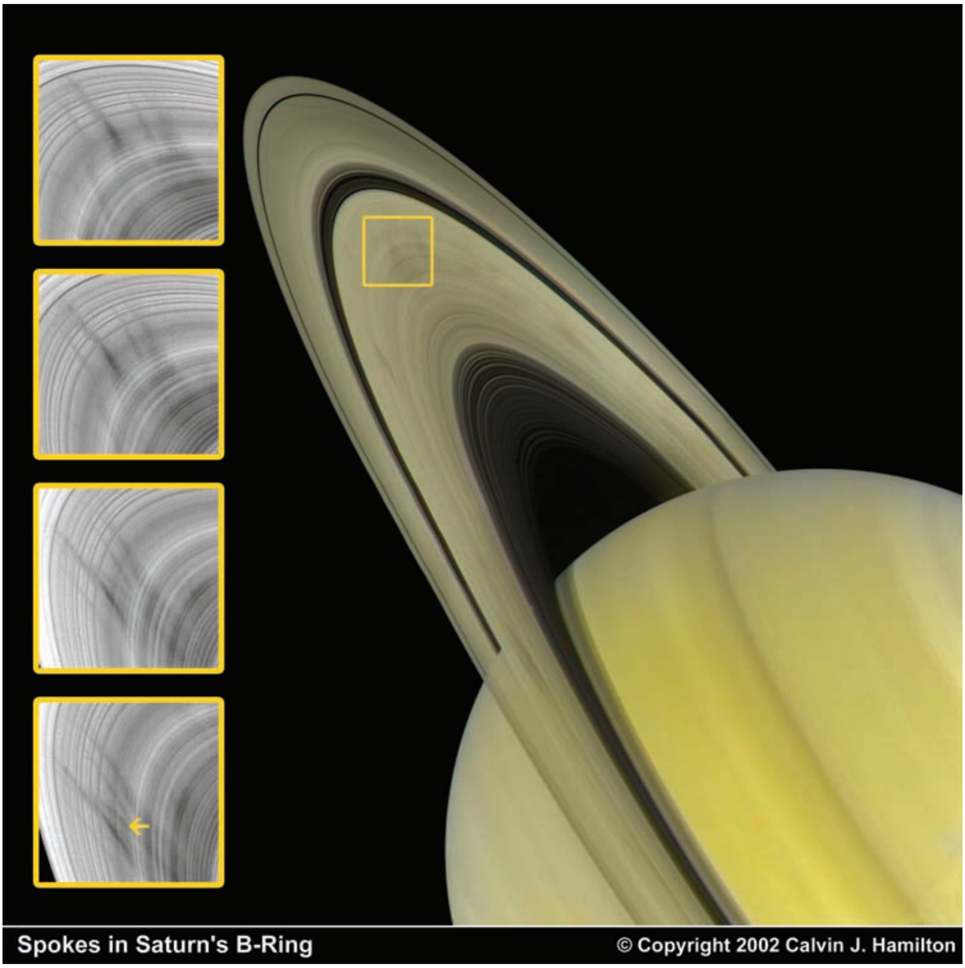

FIGURE 5.12 The Voyager 2 spacecraft discovered the spoke structure on Saturn's rings. These may be charged dust elevated above the larger ring bodies. Courtesy of Calvin J. Hamilton.

- What is the actual degree of ionization in disks around young stars, and how is the coupling between the gas and the magnetic field maintained (if indeed it is)?
- How does the accretion process proceed under low-ionization conditions, and what are the implications of the low degree of ionization for the mechanisms of star and planet formation and planetary migration?

Heliospheric Dust and Neutral Interactions with Plasmas

Progress in clarifying dusty plasmas will have a big impact on heliospheric physics. Both the heliosphere and the ISM are full of dust of all relevant sizes. Interstellar dust grains are present at all ecliptic latitudes throughout the plasma-laden heliosphere and in adjacent interstellar space, where they form about 1 percent of the ISM. Grains with an interplanetary origin are found in the ecliptic plane and isolated cometary streams. In studying the interaction between charged interstellar dust grains and the heliosphere, the goal is to understand the time-dependent and size-dependent filtration of interstellar dust grains in different heliospheric regions.

During the first Jupiter flyby that deflected the Ulysses satellite into a circumpolar orbit, onboard dust detectors separated out two dust populations—small particles of jovian origin and grains with retrograde orbits, as expected for interstellar dust grains coupled to the interstellar gas flowing at about 26 km/sec through the heliosphere. Subsequent observations by Ulysses, Galileo, and Cassini found interstellar dust at all ecliptic latitudes. The plasma wave detectors on board the Voyager 1 and 2 satellites have detected micron-sized grains out to 85 AU in the outer heliosphere. Grain fluxes in the outer heliosphere are an order of magnitude higher than in the inner heliosphere.

Some of the unsolved problems regarding the interaction between interstellar dust and the heliosphere are the following:

- Understand the charging, filtration, and deflection of small charged grains as the grains cross the bow shock in the outer heliosheath regions and enter the heliosphere.
- Understand the effect of merged interaction regions (turbulent regions in the heliosphere) on small-grain dynamics in the outer heliosphere, including grain charging and deflection.
- Model the diffusion or streaming of grains with an ecliptic (planetary) origin toward higher latitudes, for all radial distances in the heliosphere.
- Understand the differences seen between interstellar dust fluxes at Voyager 1 in the outer heliosphere and those measured in the inner heliosphere and at high latitude by Ulysses and other spacecraft.

Timely answers to these questions will help us to understand the size and mass distributions of small interstellar and interplanetary dust grains that have been returned to Earth by STARDUST, which brought dust samples from the comet Wild 2 back to Earth, as well as the expected grain fluxes from future dust observatories in space.

Mesospheric Dust and Collisional Plasmas

Earth's mesosphere starts about 40 km above Earth's surface, where the atmosphere is neutral, and ends 80 km above the surface, where the gas is partially ionized (Figure 5.13). This region provides an excellent laboratory to study fundamental low-temperature plasma physics issues. These issues are of great importance in understanding possible changes in our atmosphere. Indeed, predictive modeling of the mesosphere requires a better understanding of the plasma science. Here the focus is on two interrelated plasma issues that are being studied:

FIGURE 5.13 Noctilucent clouds. These beautiful highflying clouds form at heights of 80 kilometers above sea level or more and are thought to be made of ice forming around mesospheric dust. Because these clouds reflect light very weakly, they are only visible just after nightfall as in this photo where the noctilucent clouds are easily spotted because they are the only clouds high enough to reflect light from the setting sun. Courtesy of Pekka Parviainen, © 2004.

- The transition from a collisional to a collisionless plasma environment as a function of altitude and
- The interaction of the mesospheric gas and plasmas with dust and aerosols.

Mesospheric chemistry is highly dependent on the plasma/gas conditions; however, this chemistry is outside the committee's purview.

The density of the electrons is expected to decrease if and when aerosols charge negatively. Thus aerosol charging may be responsible for large drops in electron density observed by ground-based radars, However, contrary to expectations, in situ rocket measurements often find positively charged aerosols. It is clear, therefore, that aerosol charging mechanisms are not yet understood. Charging models are needed that include the effects of collisions between neutrals, electrons, and ions, as well as possible effects related to high aerosol densities. The continuous nucleation and evaporation of the aerosols, their wind-driven transport, and the subsequent buildup of electric fields due to possible charge separation must also be investigated. Clearly, this region offers a rich set of basic physical phenomena that at the moment escape our full understanding. Progress requires a combination of in situ and laboratory experiments, as well as the development of theoretical models.

In weakly ionized plasmas such as the mesosphere, ion-neutral collisions cannot be neglected. The interpretation of Langmuir probe measurements, our most basic plasma diagnostics tool, remains difficult in this environment due to the absence of detailed theoretical models. A rocket transitions from a collisional regime at low altitude, where fluid formalism can be used, to a regime where the collisional mean free path becomes larger than a rocket (at around 80 km in altitude) and the physics is best described using a kinetic approach. Models that connect these regimes smoothly do not yet exist.

Plasmas can also interact with radiation fields such as in stellar atmospheres. While understanding of radiative transfer in dynamic gaseous media is relatively well developed, the importance of the interactions between electromagnetic radiation and matter in the plasma state has only recently been recognized. Understanding these interactions can provide insights into radiation-plasma coupling in the other astrophysical systems.

CONCLUSIONS AND RECOMMENDATIONS FOR THIS TOPIC

It is clear from the examples presented in the preceding section that progress on the broad goal of understanding the universe and on many of the central questions in space physics and astrophysics is dependent on a better understanding of plasma phenomena. As an indication of the importance of plasma science to space and astrophysics, note that many of the highly recommended ground-based and

TABLE 5.1 Astrophysics and Space-Physics Projects Illustrating the Overlap Between NASA Missions and Plasma Physics

Initiative	Plasma Interest
Astrophysics	
Advanced Solar Telescope (AST)	Magnetic fields, solar flares, dynamos
Constellation-X Observatory (Con-X)	Black holes, x-ray clusters
Gamma-ray Large Area Space Telescope (GLAST)	Particle acceleration, compact objects
Very Energetic Radiation Imaging Telescope Array System (VERITAS)	Cosmic rays, particle acceleration
Solar Dynamics Observatory (SDO)	Solar magnetic field, space weather
Square Kilometer Array (SKA)	Early universe, compact objects
Energetic X-ray Imaging Survey (EXIST) Telescope	Black holes, the transient x-ray sky
Frequency Agile Solar Radio Telescope (FASR)	Solar corona, solar flares, space weather
Advanced Radio Interferometry Between Space and Earth (ARISE)	Acceleration and collimation of jets
James Webb Space Telesope (JWST)	Star and planet formation, neutral-plasma interactions
Combined Array for Research in Millimeter-wave Astronomy (CARMA)	ISM, neutral-plasma interactions
Space	
Advanced Composition Explorer (ACE)	Solar wind monitor
Cluster	Multipoint studies of plasma boundaries
Reuven Ramaty High Energy Solar Spectroscopy Imager (RHESSI)	Advanced imaging of solar plasma processes
Fast Auroral Snapshot Explorer (FAST)	Auroral plasma processes
Wind satellite	Solar wind plasmas
Rockets/balloons	Ionosphere and mesospheric studies
Solar Terrestrial Relations Observatory (STEREO)	Stereo imaging of solar processes
Solar-B, Hinode	Solar imaging
Time History of Events and Macroscale Interactions during Substorms (THEMIS)	Global reconfiguration of Earth's magnetosphere; study of the magnetism and instabilities of the Sun
Solar Dynamics Observatory	Solar magnetic fields, dynamo, variability
Interstellar Boundary Explorer (IBEX)	Exploring boundary with ISM
Magnetospheric Multiscale (MMS)	Multiple-point plasma processes
Polar	Auroral processes
Radiation Belt Storm Probe (RBSP)	Radiation belt studies
Juno	Jupiter's magnetosphere and aurora

NOTE: The first half of the table shows some astrophysical missions recommended in *Astronomy and Astrophysics in the New Millennium* and their connection to plasma physics. The second half of the table shows some space physics missions recommended in *The Sun to the Earth—and Beyond* as well as some currently operating missions and their connections to plasma physics.

space-based initiatives of the National Research Council's 2001 decadal survey of astronomy and astrophysics[1] are intimately related to the plasma science contained in this report. Table 5.1 lists these major and moderate-scale initiatives along with

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[1] NRC, *Astronomy and Astrophysics in the New Millennium*, Washington, D.C.: National Academy Press, 2001.

the plasma physics that is addressed by each. Interpreting observations from many of the new frontiers in experimental astrophysics—such as large-area neutrino telescopes (e.g., IceCube) and perhaps even gravitational-wave observatories (e.g., LIGO and LISA)—will require understanding the plasma physics of the underlying astrophysical sources. Table 5.1 also lists ongoing and upcoming space, solar, and heliospheric missions that are reliant on plasma physics to address both their underlying science goals and their exploration mission objectives; the list of initiatives is largely based on the National Research Council's 2003 decadal survey of solar and space physics.[2]

Conclusion: Plasma physics is increasingly important for research in space physics and astrophysics. Also, space physics and astrophysics are providing critical insights that illuminate fundamental aspects of plasmas. Indeed, some compelling research questions in plasmas physics will be best answered by research in space and astrophysical contexts.

This chapter presents examples of where space and astrophysical observations have led to new a understanding of basic plasma physics processes, including fast reconnection, dusty plasma interactions, and high-energy particle acceleration. The corollary to using plasma physics to explore space is that space and astrophysical plasma physics are opening up many new regimes of plasma physics (e.g., general relativistic plasmas) that have not been and cannot be studied in laboratory settings. Many frontiers remain to be explored, such as plasma physics on cosmological scales. New missions and telescopes will continue to add to the plasma physics that can be studied. Deployment of new measurement techniques, such as using networks of sensors to develop near-real-time multipoint measurements of macroscopic plasma phenomena, also promises to offer a watershed opportunity.

Conclusion: Given the growing role of plasma physics in space science and astrophysics, it is essential that undergraduate and graduate physics and astronomy curricula include some fluid mechanics, magnetohydrodynamics, and plasma physics as a basic requirement.

It is uncommon for undergraduate physics and astronomy curricula to include any fluid mechanics, MHD, or plasma physics. These subjects are also missing from many graduate astronomy curricula. Thus many Ph.D. candidates in space and astrophysics are poorly prepared to meet the many challenges and opportunities in plasma-related space physics and astrophysics.

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[2] NRC, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, Washington, D.C.: The National Academies Press, 2003.

Conclusion: Progress in understanding the fundamental plasma processes in many space and astrophysical phenomena is greatly leveraged by close communication among space, astrophysical, and laboratory plasma scientists.

The diversity of regimes studied in space physics and astrophysics makes it important to highlight the connections between the different plasma regimes studied in space and astrophysics and the related fields of laboratory plasma physics described in this report. There are many examples of such connections in addition to those discussed in the text. For example, laboratory studies of the equations of state and opacity of dense matter are a crucial ingredient used in models of dense astrophysical plasmas. As another example, electromagnetic wave–plasma interactions and related phenomena in the upper atmosphere have close analogies to terrestrial technologies. Dusty plasmas, which were first observed and studied in space, have been the topic of intense study in laboratory experiments. In addition, the physics of dusty plasmas is crucial for understanding the plasma nucleation of nanocrystals for photonics and for preventing particle contamination of silicon wafers during plasma processing for microelectronics fabrication. The fundamental plasma–particle interactions occurring in Earth's mesosphere are directly analogous to those occurring in laboratory plasmas.

In a number of research areas, the collaboration between the laboratory, space, and astrophysical communities has led to significant scientific progress.[3] Studies of common plasma processes—rather than the large-scale morphology of observed systems—provide the most promising linkages for the different plasma physics communities. The six key plasma processes and questions discussed in Chapter 1 define the linking processes in a broader sense. To isolate a process it is critical to ask one of the three pervasive technical questions in this chapter. To what extent is the plasma science independent of the regime? Where the science is regime-independent, collaboration can effectively leverage individual community efforts. Maintaining and strengthening the linkages between communities is therefore highly desirable.

Recommendation: Agency coordination mechanisms such as the Physics of the Universe Interagency Working Group and the Astronomy and Astrophysics Advisory Committee should explicitly include plasma physics when they coordinate research in laboratory, space, and astrophysical plasma science. Such coordination would be greatly facilitated by improved stewardship of laboratory plasma science by DOE's Office of Science.

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[3] For more information on the connections between laboratory HED experiments and astrophysics, please see *The X-Games Report.*

NASA and NSF support most of the studies of plasmas phenomena in space and astrophysics. Studies of fundamental plasma processes in laboratory plasma science are supported by DOE (in NNSA and OFES) and, to a lesser extent, by NSF. For instance, readers will note that research on magnetic reconnection is taking place under NASA's auspices as part of space plasma physics, under NSF and DOE's auspices with basic laboratory experiments, and even under the auspices of DOE's magnetic fusion research program as it studies self-organization in toroidal plasmas. The separation of funding sources could impede effective strategies to attack key plasma problems simultaneously from several angles. Such a multipronged attack cannot be achieved without close collaboration between scientists and agencies of the federal government in all communities. On the other hand it would not be desirable to separate space physics and astrophysics plasma research from their broader context in space and astrophysics.

Although the committee was not charged with conducting a comprehensive review of the federal solar and space physics research portfolio, it is important to note that the above recommendation has significant overlap with the recommendations of NRC's Solar and Space Physics Survey Committee for its 2003 report *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics.*[4] In other words, the traditional space and astrophysics communities and the traditional plasma science community have identified enhanced federal coordination as a key action item.

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[4] NRC, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, Washington, D.C.: The National Academies Press, 2003, p. 12.

6

Basic Plasma Science

INTRODUCTION

In the preceding chapters, the committee described studies of many fundamental plasma phenomena as they relate to research in a particular topical area. In this chapter, it describes complementary plasma studies, where the primary goal is to isolate and study in detail fundamental plasma phenomena. These studies echoes principal themes of the report, focusing on the discovery and exploration of new plasma regimes and testing our understanding of the underlying principles of plasma science. The phenomena of interest span a vast range. Of particular interest, for example, are the six fundamental processes highlighted in Chapter 1: multiphase effects in plasmas; explosive instabilities; particle acceleration mechanisms; turbulence and turbulent transport, magnetic reconnection and magnetic self-organization; and the effects of strong particle correlations in plasmas. These and many other important plasma effects manifest themselves in a wide range of situations, from dusty plasmas to HED plasmas.

While the primary goal is to explore these and other important phenomena in detail, there is a close connection to the broad range of other investigations in this report, from fusion, to space and astrophysics, to HED and low-temperature plasmas. These advances in our fundamental understanding are crucial for innovating technologies that use plasmas. Just as developing and validating fundamental theories of the band structure of semiconductors necessarily preceded transistors, developing and validating fundamental theories of the basic behavior of plasmas necessarily precedes exploiting plasma technologies fully for energy, national security, and economic competitiveness.

Such scientific inquiry frequently leads to the discovery of qualitatively new phenomena and new plasma regimes. Recent examples include states of true thermal equilibrium in single-component plasmas, the creation of a wide range of HED and ultracold plasmas, and creation of the first stable neutral antimatter (antihydrogen). In each case, new physical situations and phenomena have been discovered that allow us, in turn, to test and expand our fundamental understanding in new ways. This research provides strong intellectual ties to other areas of science and engineering, including fluid dynamics, atomic physics, nonlinear dynamics, soft condensed matter physics, and solid-state plasmas.

The research is typically done on the smallest scale the problem admits, so that there is the flexibility to make changes quickly and economically as the science unfolds. The complementary roles of theory and computation are critical. This is particularly true in plasma science, where nonlinear and nonequilibrium phenomena in many-body systems are of central importance.

These research activities serve a critical function in educating and training scientific and technical personnel. Typical research efforts are small, university-scale activities. As such, they provide excellent opportunities to train students in a variety of disciplines and techniques that are critical not only to plasma science but also to many other areas of modern science and technology. Such projects allow young researchers to participate in all facets of the research, from planning, to conducting experiments and calculations, to disseminating research results. These small-scale research projects produce a very significant fraction of the U.S. Ph.D.'s in plasma science.

RECENT PROGRESS AND FUTURE OPPORTUNITIES

As our knowledge of plasma science has grown over the past decade, so has our appreciation of the vast range of plasma phenomena. Plasmas of interest span enormous ranges of parameters—more than 22 orders of magnitude in density (i.e., 10^{22}), 15 orders of magnitude in temperature, and 19 orders of magnitude in magnetic field. Plasmas at the extremes include the tenuous ISM, laser-cooled plasmas, relativistic laser-driven plasmas, stellar interiors, and the magnetospheres of pulsars. Understanding the fundamentals of plasma behavior over such enormous ranges of parameters presents huge challenges.

Here the committee discusses progress and future opportunities in eight topics:

- Nonneutral and single-component plasmas,
- Ultracold plasmas,
- Dusty plasmas,
- Laser-produced and HED plasmas,

- Microplasmas,
- Turbulence and turbulent transport,
- Magnetic fields in plasmas, and
- Plasma waves, structures, and flows.

The first five topics are unique *or* special physical situations in which research is yielding a wealth of scientific progress and new opportunities (Box 6.1). An analogy can be drawn with condensed matter physics, where different materials exhibit vastly different phenomena, from quantum dots to carbon nanotubes to high-temperature superconductors; study of each physical system is yielding important new science. Access to these new regimes of plasma science has been made possible by developments in other fields as well as by improved techniques within basic plasma science itself. For example, techniques developed in atomic, molecular, and optical science for cooling, trapping, and working with ultracold atoms and molecules have contributed to basic plasma science studies. Similarly, the development of ultra-short-pulse, high-power lasers (as described in Chapter 3) has opened a window on fundamental physics studies of HED plasmas in the laboratory.

The final three topics—turbulence, magnetic fields, and plasma waves, structures, and flows—are three of the six key science themes highlighted in Chapter 1. The science benefits greatly from the many synergies between these themes. Studies of ordering in pure ion plasmas are relevant to dusty plasmas and HED plasmas. Understanding turbulence and its consequences is furthered by experiments in nonneutral as well as neutral plasmas. Studies of structure and self-organization benefit from a range of experimental and theoretical efforts. Progress in one area can often be validated quickly and used in another. This complementary approach—perhaps more than ever before—is central to rapid and efficient progress.

Two crosscutting physics concepts further unify the research—the concept of strong and weak coupling and the concept of plasma self-organization (Box 6.2). Whether a plasma is strongly or weakly coupled is determined by the ratio,

BOX 6.1
The Dynamic Forefront of Research—New Opportunities

Many of the current forefront areas in basic plasma research (dusty plasmas, HED plasmas, microplasmas, and ultracold plasmas) were virtually below the scientific radar screen at the time of the last decadal study. Recent studies have extended by orders of magnitude the range of plasma parameters amenable to study, identified new phenomena, motivated new theory, and led to new understandings of plasma behavior, providing a wealth of exciting new research opportunities.

BOX 6.2
Strong and Weak Coupling and Quantum Effects

One important crosscutting theme in plasma science is the commonality of phenomena in weakly coupled plasmas and strongly coupled plasmas. The defining quantity is the Coulomb coupling parameter, Γ, which is the ratio of the average interparticle Coulomb potential energy divided by the kinetic energy of a plasma particle, namely $\Gamma \equiv e^2/ak_BT$, where $a = [(3/4\pi n)]^{1/3}$ is the average interparticle spacing, n is the plasma density, T is the plasma temperature, and k_B is the Boltzmann constant.

Weakly coupled plasmas correspond to $\Gamma < 1$; they typically exhibit waves and nonlinear phenomena, instabilities, turbulence, and a lack of spatial ordering (as in a gas). Weak coupling effects dominate in space plasmas and magnetic confinement fusion plasmas, such as those in tokamaks.

Strongly coupled plasmas are characterized by $\Gamma > 1$, where $\Gamma \sim 1$ corresponds to a liquid and $\Gamma \geq 200$ corresponds to crystalline ordering. In the solid phase, the crystalline structure can dominate physical properties, and transport typically occurs via the diffusion of defects. Examples in which strongly coupled plasma phenomena are important and frequently dominant include pure ion plasmas, ultracold plasmas, dusty plasmas, and laser-produced HED plasmas.

A further distinction is the regime in which quantum mechanical effects are important. Quantum effects in the particle energy distributions are important at high densities and low temperatures when the Fermi energy is greater than the plasma temperature, namely $n > (3\pi^2)^{-1}(2mk_BT/\hbar^2)^{3/2}$, where $\hbar$ is Planck's constant. Quantum effects are important for waves and oscillations when $\hbar\omega \geq k_BT$, where ω is the oscillation frequency. The boundaries between strongly and weakly coupled plasma phenomena and those in which quantum effects are important were shown schematically in Figure 1.2.

Γ, of the Coulomb potential energy to the plasma temperature. Strongly coupled plasmas ($\Gamma >> 1$) are characterized by very strong Coulomb correlation effects that ultimately lead to crystalline order. Examples include dusty plasmas, ions in electromagnetic traps, and neutron stars. Weakly coupled plasmas ($\Gamma < 1$) include most laboratory plasmas and fusion plasmas. These plasmas are much more likely to exhibit nonlinear wave phenomena and turbulence.

The second crosscutting theme is self-organization, which can dominate plasma behavior. While the spatial ordering discussed above is analogous to ordering in ordinary liquids and solids, weakly coupled plasmas in a magnetic field, for example, undergo much more extensive topological changes as a result of the reconnection and rearrangement of the field. This, in turn, can produce qualitative changes in the shape of the plasma, the nature of particle orbits, and other plasma properties. Such self-organization phenomena are important, for example, in magnetic confinement fusion and in space and astrophysical plasmas, where they can create a range of behaviors, including explosive events, shocks, and large-scale flows.

Nonneutral and Single-Component Plasmas

Typical plasmas discussed in this report are approximately electrically neutral and have roughly equal densities of positive and negative charges. However, there is an important special class of plasmas for which this is not the case, so-called nonneutral plasmas, the extreme case being a plasma of a single sign of charge, a so-called single-component plasma. In this case, a uniform magnetic field can be used to restrict the plasma radially, and electrostatic voltages used to confine particle motion along the magnetic field. While these plasmas exhibit phenomena similar to electrically neutral electron-ion plasmas, single-component plasmas can be confined indefinitely. This permits studies of a wide range of plasma phenomena with high precision, including critical plasma processes that are not understood (described in Chapter 1), such as strong correlation and turbulence.

Single-component plasmas have remarkable properties. Examples include pure ion, electron, positron, and antiproton plasmas. They can evolve to true states of thermal equilibrium uncommon in other plasmas. Magnetized electron plasmas behave as ideal, two-dimensional fluids, with electron density playing the role of fluid vorticity. This has enabled new studies of vortex turbulence and led to the discovery of novel vortex crystal states, illustrated in Figure 6.1, which motivated a new theory of the turbulence.

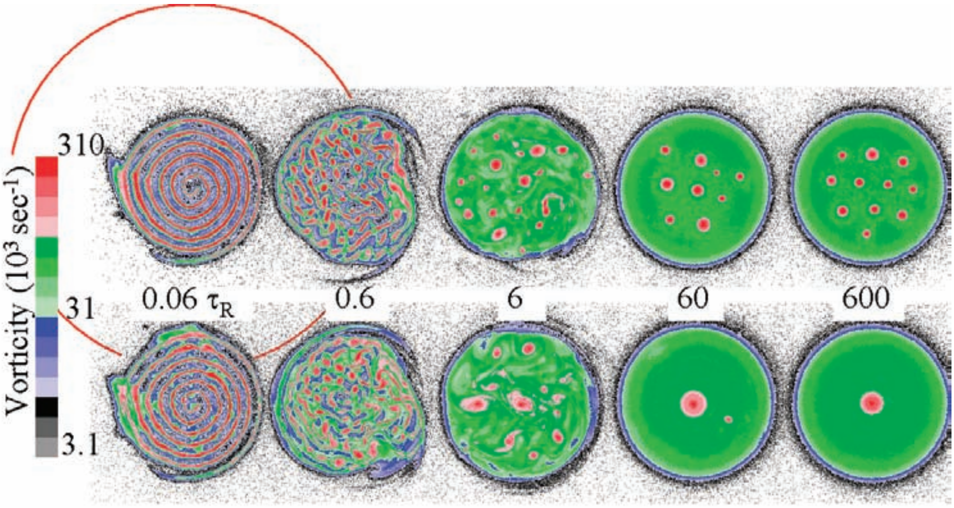

FIGURE 6.1 Evolution of vortex turbulence in a pure electron plasma. These magnetically confined plasmas flow across the magnetic field in direct analogy to the flow of an incompressible fluid with an unusually small viscosity. Recently, these plasmas were used for tests of theories of the behavior of two-dimensional flows in ideal fluids not possible in other physical systems. The experiments demonstrated surprising new phenomena. Electron density, which is the exact analogue of vorticity in an ordinary fluid, can relax (above) to a vortex crystal or (below) to one large-scale vortex. Courtesy of C.F. Driscoll, University of California at San Diego.

Crystal formation in pure ion plasmas has a long and distinguished history that began in the 1980s with work on ion plasmas in Penning and radio-frequency traps carried out in parallel with complementary work on cold ion plasmas in storage rings. Recent investigations of nonneutral and single-component plasmas have explored with precision the details of such crystal formation. It had long been predicted that an infinite homogeneous Coulomb crystal would have a body-centered cubic structure, and this has now been confirmed experimentally—the ultimate result of strong correlation when $\Gamma \geq 200$. Recent theory for relatively thin plasmas with only a few crystal planes predicted a series of structural phase transitions due to an intricate interplay between surface and bulk free energy. The spectacularly successful test of this theory is shown in Figure 6.2 for a cold ion plasma at a temperature ~3 mK and $\Gamma > 500$. Other important recent results include the creation of antiproton and positron antimatter plasmas, studies of energy transport through long-range collisions, and studies of the intrinsic thermodynamics of these systems. One long-term goal is study of relativistic electron-positron plasmas, which are of astrophysical interest, for example, in the magnetospheres of pulsars.

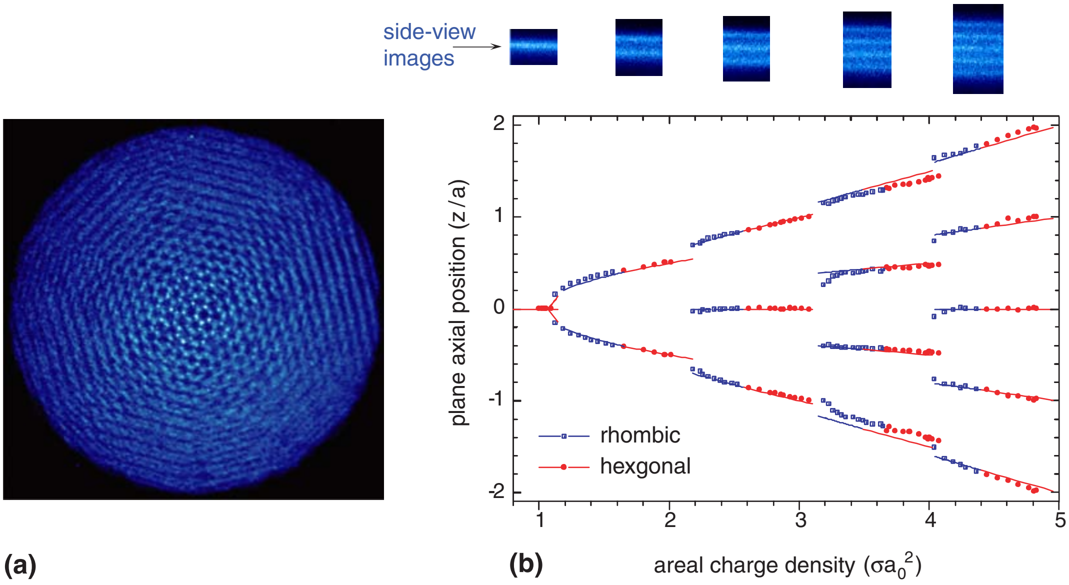

FIGURE 6.2 Spatial ordering in pancake-shaped strongly correlated plasmas with a small number of crystal planes ($\Gamma > 500$). *Left:* top-view, in-plane image of a hexagonal crystal. *Right, above:* side-view images of the crystal planes. *Right, below:* the phase diagram as a function of in-plane charge density, showing the phase changes and introduction of new crystal planes. Lines are the theoretical predictions, illustrating superb agreement. Courtesy of J.J. Bollinger, National Institute of Standards and Technology.

Recently, a method was discovered to compress nonneutral plasmas radially across the confining magnetic field (the so-called rotating-wall technique, which employs a rotating electric field). Now a standard tool around the world, it enables plasma confinement for essentially infinite times and the plasma density to be precisely controlled and varied over orders of magnitude. Potential applications include long-term storage of antimatter, particle-antiparticle traps, and commercial positron beam sources for materials analysis. Application of this technique to antimatter plasmas was critical to the recent success, described below, in creating the first cold antihydrogen atoms.

Owing to the unique confinement properties of single-component plasmas and the fact that they can reach thermal equilibrium, plasma transport processes can be studied in them with a precision not possible in other situations. This is done by making controlled departures from equilibrium and observing the relaxation of the plasma back to the equilibrium state. While the simplest nonneutral plasmas are cylindrically symmetric with no regions of localized particle trapping, the effects of asymmetries have been observed but are not yet understood. This offers the opportunity to bridge the gap between our understanding of nonneutral plasmas and conventional electron-ion plasmas. For example, plasma rotation, which is a zeroth-order effect in single-component plasmas owing due to their space charge, is known to play an important role in confinement in tokamak plasmas.

Ultracold Neutral Plasmas

Ultracold plasmas provide qualitatively new opportunities for plasma science, ranging from the study of spatial ordering in new plasma regimes, to the study of novel atomic physics processes, to the development of techniques to produce and study antihydrogen. Research in this area resides at the boundary between atomic physics and plasma physics. These novel plasmas provide the opportunity to push plasma physics into new regimes in parameter space. Aided by the powerful tools of laser cooling and laser manipulation and imaging of the plasma ions (techniques similar to those used to form Bose condensed gases of alkali atoms), studies of ultracold plasmas provide new tests of our understanding of plasma phenomena and new scientific opportunities. For example, ultracold plasmas can be used to study regimes where correlation effects are important and situations in which the electron and ion temperatures are vastly different.

Typical ultracold plasmas are formed from cold gases of atoms at ~10 μK, photoionized to produce electrons with energies of a few kelvin. The resulting ultracold, unmagnetized plasma expands freely into vacuum, driven by the pressure of the electron gas. In these unusually cold plasmas, the dominant collisional mechanism is three-body recombination forming highly excited (Rydberg) atoms. Recombination rates increase rapidly as the temperature is lowered and can be exceedingly large, with as much as 30 percent of the plasma converting to Rydberg atoms. When the laser frequency is tuned below the ionization limit, a gas of ultracold Rydberg atoms is formed that, in turn, quickly forms an ultracold plasma through atom-atom collisions.

These ultracold plasmas serve as laboratories for studies of the statistical mechanics and thermodynamics of elementary plasma systems. For instance, the electrons gain almost all the energy from ionization. They rapidly come to thermal equilibrium at a higher temperature than the ions. The random positions of the electrons and ions following ionization induces disorder heating. As the plasma expands, there is competition between expansion cooling, in which the electrons transfer their energy to ion expansion, and recombination-induced heating, in which excess energy is carried away by the free electrons. The electrons are weakly correlated, while correlation of the ions is important ($\Gamma \sim 4$). Temporal oscillations of the kinetic energy are observed that provide a clear signature for the importance of these correlations. One outstanding issue is how the approach to (quasi-) equilibrium proceeds in a system in which the density and, possibly, the temperature change by many orders of magnitude.

One popular topic in ultracold plasma research is the creation and study of the stable, neutral antiatom antihydrogen, which is the bound state of a positron and an antiproton. There is keen interest in making precise comparisons between the properties of such antimatter and those of matter to test fundamental symmetries of nature. Examples include tests of invariance with respect to charge conjugation, parity, and time reversal (the so-called CPT theorem) and precise tests of the gravitational attraction of matter to antimatter. Recently, two groups at the antiproton decelerator at CERN in Geneva produced the first neutral, low-energy antimatter (weakly bound antihydrogen atoms) by mixing cryogenic positron and antiproton plasmas. Data from one of these experiments are shown in Figure 6.3.

A quantitative understanding of the plasma processes involved in antihydrogen formation will be required to raise production and trapping efficiency. The current technique requires overlapping of the positron and antiproton charge clouds. Understanding how to improve the production efficiency as well as how to trap the antihydrogen without instabilities is an important subject for research. Other outstanding problems include developing a method to trap the neutral antihydrogen atoms in shallow magnetic-gradient traps and to drive the highly excited (Rydberg-state) atoms to the ground state so that their properties can be studied with precision.

Dusty Plasmas

Dusty plasmas are ionized gases containing small (i.e., micron-size) particles of solid material. The “dust” can be virtually any material, dielectric or conducting,

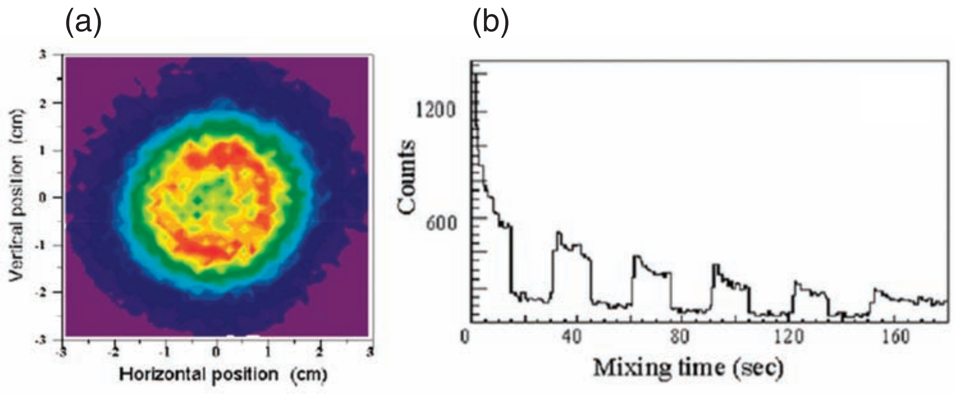

FIGURE 6.3 Antihydrogen in the laboratory: *(a)* image of antiproton decays as neutral antihydrogen atoms are formed in an antiproton-positron plasma and hit the plasma-confining electrodes and *(b)* modulation of the antihydrogen production rate by varying the positron plasma temperature. Such production in the laboratory of the first stable, neutral antimatter depends critically upon creating and manipulating cold, antimatter plasmas. Courtesy of the Athena Collaboration, via J. Hangst, University of Aarhus, Denmark.

from precision microspheres introduced deliberately into the plasma to dust particles grown in situ by aggregating atoms from the ambient neutral gas. A particularly important feature of dusty plasmas is that the dust particles become highly charged. A 10-micron particle can have a charge of ~10^4 electrons. As a result, particles can be levitated against the force of gravity by electric fields that occur naturally in the plasma. Because the dust particles repel one another, they often become strongly coupled with values of $\Gamma >> 1$. This produces strong spatial correlations of the dust particles, so that they often exhibit liquid- or solidlike behavior. They scatter light efficiently, so it is possible to track particle motion in real time using video imaging, which allows comparison of experiment and theory with a precision not possible in other plasma and condensed matter systems. An acoustic wave and a shock wave in a dusty plasma are shown in Figure 6.4.

A decade ago, billions of dollars' worth of semiconductor manufacturing yield was being lost as a result of particles that grew in situ in the processing plasmas. Techniques making use of the new understanding of dusty plasmas were developed to control this contamination. Another area of great practical importance is dust in tokamak fusion plasmas, where sputtered materials can condense to form dust particles. These particles can accumulate in the reactor, where they can contribute to the absorption of large amounts of tritium. Such tritium retention is a serious engineering issue in the design and operation of ITER.

In strongly coupled dusty plasmas, the crystalline and liquid phases and the melting transition have been studied in detail. By levitating dust particles in the

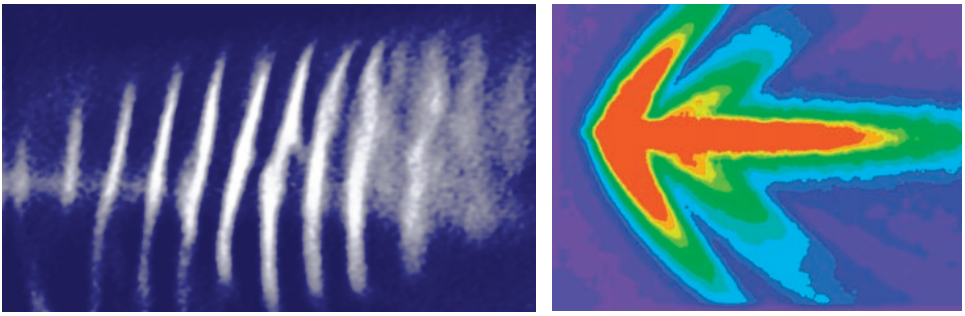

FIGURE 6.4 Waves and instabilities in dusty plasmas. Charged dust particles introduce unique potential structures in plasmas. They alter significantly the short- and long-range forces and can affect the ordering and dynamics of these dust grains. As an example, the dust introduces a slow timescale into the plasma dynamics. Shown here are *(left)* a dust-acoustic wave with centimeter per second speed (slower by five orders of magnitude than typical laboratory plasmas) and *(right)* Mach cone of a dusty-plasma shock wave. Courtesy of J. Goree, University of Iowa.

sheath of a plasma discharge, it has become possible to create an interacting, two-dimensional plasma crystal and a two-dimensional liquid dust plasma. The equilibrium configurations, transport properties, and wave propagation in this novel system have been studied, and new theories of the liquid state have been developed. Work in this area has considerable synergy with soft condensed matter physics. The area is relatively young. As a consequence, there are many opportunities to improve instrumentation that, in turn, will enable new experimental studies.

Dusty plasmas offer a new regime for the study of particle and energy transport in plasmas (Box 6.3). Experiments are needed to test recent predictions for such quantities as the coefficients of diffusion and viscosity, relevant, for example, in industrial processes. Another important issue is the nature of waves and transport in dusty plasmas of astrophysical interest. Finally, study of dusty plasmas in large magnetic fields would enable tests of theoretical predictions for new classes of dusty plasma phenomena.

BOX 6.3
Dusty Plasmas

Dusty plasmas are important in many areas of science and technology. Fundamental studies include ordering and transport in many-body systems; cometary tails and planetary rings in space plasmas; and dust in the ISM: Practical applications include high-tech materials processing, spray coating technology, and other industrial processes.

Laser-Produced and HED Plasmas

There has been dramatic progress in our ability to create, study, and use laser-produced plasmas. Ultraintense, ultrafast lasers, ranging in size from those that require enormous buildings to those compact enough to fit on a tabletop, have revolutionized this field. A vast range of important phenomena can be studied with these systems, and applications abound, including advanced lithographic techniques for nanoscale electronics, simulation of astrophysical phenomena, and a range of issues related to national security. Research at large HED facilities is described in Chapter 3. Small-scale systems can now produce many terawatts of peak power (see subsection on plasma-based electron accelerators in Chapter 3 for more discussion). Owing to such reductions in size, many investigations can be conducted in university- or intermediate-scale experiments. This section describes recent progress and the wealth of opportunities that exist for future research. Several of these examples illustrate the synergistic relationship between pure and applied research—for one thing, novel plasma phenomena are frequently being used as innovative research tools in many areas of science and engineering:

- *Beam physics.* Whereas plasmas in thermal equilibrium are Maxwellian distributions, relativistic beams are typically non-Maxwellian in that different temperatures exist in the perpendicular and parallel directions. Furthermore, the Debye length for a relativistic beam is usually much greater than the radius of the beam itself. Despite these apparent differences, and although a beam is typically nonneutral, it can exhibit many plasmalike phenomena. The propagation of an intense particle beam through a focusing channel, for example, involves many concepts from plasma physics. Examples include the plasma frequency, which is used to quantify the forces due to space charge; the beam emittance, which is a beam-physics measure of temperature; and the utilization of self-consistent field descriptions of collective behavior.
- *Plasma optics.* Because plasmas have an unlimited damage threshold, they are ideal media with which to control very intense light fields, similar to plasma switches that are the method of choice to turn very large electrical currents on and off. Using small-scale lasers, plasmas can be made to act as novel optical elements. The use of plasma wake fields to accelerate electrons is detailed in Chapter 3. Such acceleration techniques, including a newly discovered bubble acceleration mechanism, can be combined with plasma optical elements to enable a new generation of plasma experiments and devices. Examples include preformed plasma lenses, ion channels, and plasma channels, such as that shown in Figure 6.5. Applications include x-ray lasers,

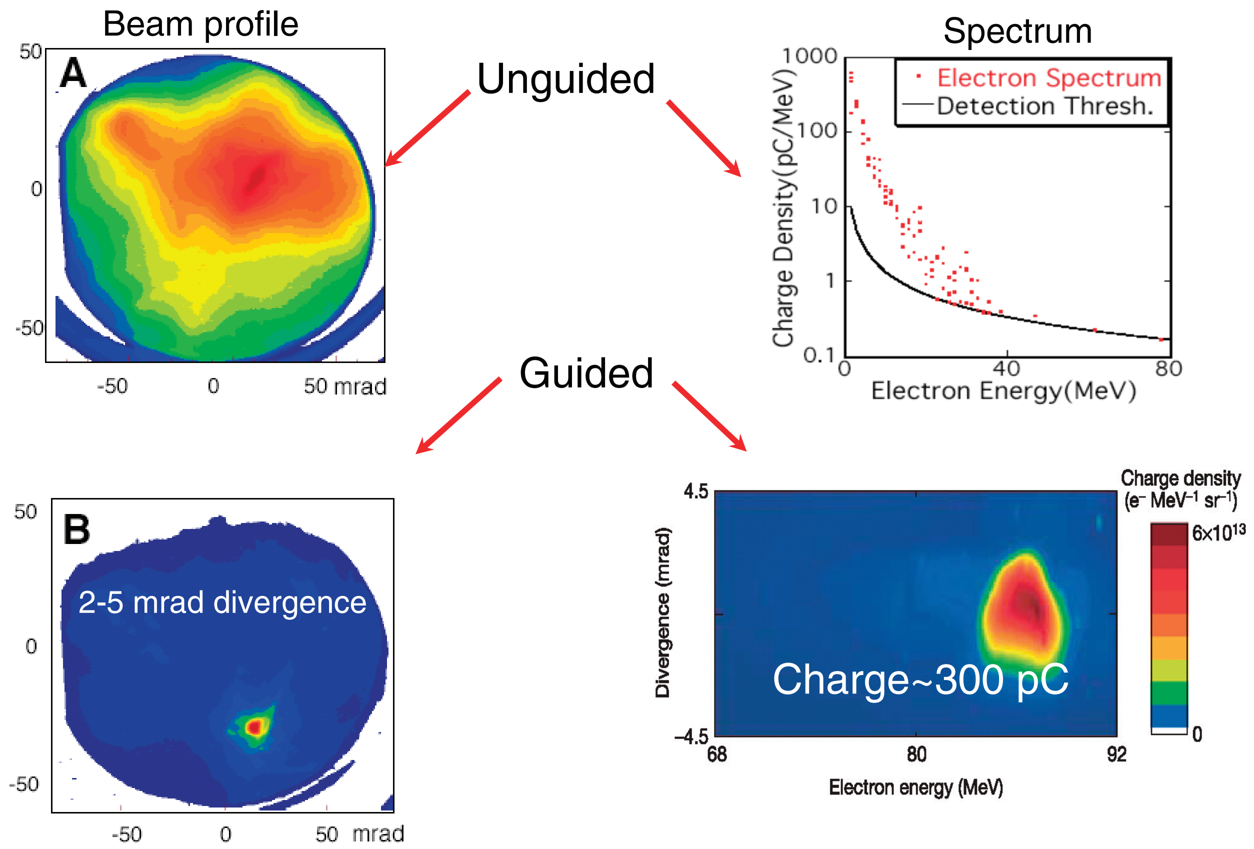

FIGURE 6.5 Example of the potential of plasma optics. Shown are the dramatic effects of plasma-waveguide machining on wake field acceleration of electrons in the bubble-acceleration regime. *Left:* Near-field profile of a laser pulse using a plasma channel (A) unguided and (B) guided. *Right:* The resulting energy spectra of the electrons. Note the dramatic narrowing of the beam energy distribution in (B). Courtesy of W.P. Leemans, Lawrence Berkeley National Laboratory. Reprinted with permission from C.G.R. Geddes, Cs. Tóth, J. van Tilborg, E. Esarey, C.B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W.P. Leemans, “Production of high-quality electron bunches by dephasing and beam loading in channeled and unchanneled laser plasma accelerators,” *Physics of Plasmas* 12: 056709 (2005). © 2005, American Institute of Physics.

phase-matching for high-harmonic generation, and mode-control of x-ray radiation.

- *Short-wavelength radiation and attosecond pulses.* There has been significant progress in the generation of coherent extreme ultraviolet (XUV) light using intense lasers interacting with plasmas, including high-order harmonics in the soft x-ray region. The mechanism is now understood to be reflection from a critical-density surface that acts as an oscillating relativistic mirror. It now appears possible that such relativistically driven mirrors could generate XUV light pulses ~100 attosec in duration.
- *Laser–cluster interactions and nanoplasmas.* The interaction of ultrashort laser pulses with small clusters (e.g., ~1000 Å in diameter) is illustrated in Figure 6.6. This technique can produce solid-density nanoplasmas with qualitatively new optical features. These unique plasmas can be used to generate fast ions and fusion neutrons from deuterium clusters and also be used as very bright x-ray sources and to self-guide laser pulses. One future goal is optimizing neutron pulses for use in materials science and other time-resolved studies. Gases of nanoplasmas could be used to study radiation transport under optically thick conditions relevant to solar, astrophysical,

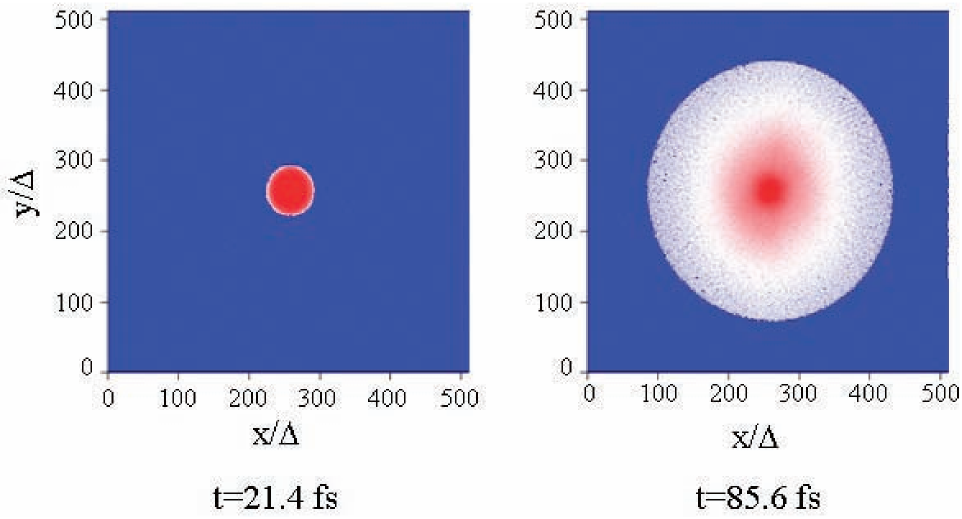

FIGURE 6.6 Simulation of a cluster nanoplasma and subsequent femtosecond timescale explosion due to Coulomb repulsion of the highly charged ions. Spatial distribution of the plasma ions (in units of the initial ion spacing $\Delta = 1.6$ nm) at times of 21 fsec *(left)* and 86 fsec *(right)* after the laser pulse. Red indicates regions of supercritical nanoplasma. The initial cluster was 32 nm in diameter and irradiated with ~10^{17} W/cm^2. Reused with permission from Y. Kishimoto, T. Masaki, and T. Tajima, *Physics of Plasmas* 9: 589 (2002). © 2002, American Institute of Physics.

and weapons physics. One such challenge is understanding laser coupling to larger particles (e.g., particles with sizes about the wavelength of light).

- *Ultrafast radiation sources and new diagnostics.* The recent generation of bright sources of x rays and fast protons is enabling novel plasma diagnostics. One example is shown in Figure 6.7. Relativistic electron beams, fast proton beams, high-harmonic radiation, plasma-based x-ray lasers, and incoherent XUV and x-ray radiation from HED plasma experiments: All offer opportunities for novel probes of materials and dense plasmas. One potential future application is use of femtosecond terahertz radiation to time-resolve changes in DC conductivity—the quantity that determines the return currents in fast-ignition fusion.
- *Relativistic and electron-positron plasmas.* Tabletop lasers make possible new studies of relativistic plasmas, potentially including exotic, positron-electron ("pair"), antimatter plasmas such as those thought to exist near black holes and to play an important role in gamma-ray bursts. The light creates relativistic electrons, which create positrons when they interact with high-Z targets. The associated gigagauss magnetic fields help to confine the plasma. Estimates indicate positron densities ~10^{-3} of the background electron density (i.e., ~10^{22} cm^{-3}), far exceeding densities achievable with other present-day positron sources.

Microplasmas

A new class of devices has been developed recently that uses continuous, low-temperature plasmas with spatial dimensions on the order of tens of microns. These devices open up a range of scientific and technological opportunities. They are an inexpensive alternative to lasers and mercury lamps in applications such as chemical detection and lighting sources for cytology, where intense UV radiation is required. An array of these microplasmas is shown in Figure 6.8. Plasmas with dimensions of between approximately 20 and 30 μm operate at pressures in excess of an atmosphere, sustained by power deposition of about 1 MW/cm^3.

Anticipated scaling of these devices to dimensions <1 μm and pressures of tens of atmospheres approaches the regime in which quantum interactions are important. This raises fundamental issues for plasma science. In extreme cases, plasmas could be maintained in a near-liquid state ($\Gamma \sim 1$). Microplasmas have been created that use semiconductor electrodes. There is a sufficiently large perturbation of the semiconductor conduction band at the plasma–surface boundary (due to electric fields ≥100 kV/cm) so as to blur the boundary between gaseous and solid-state plasmas. As discussed in the section "Future Opportunities" in Chapter 2, fundamental physical phenomena associated with this new class of plasmas are important areas for future research.

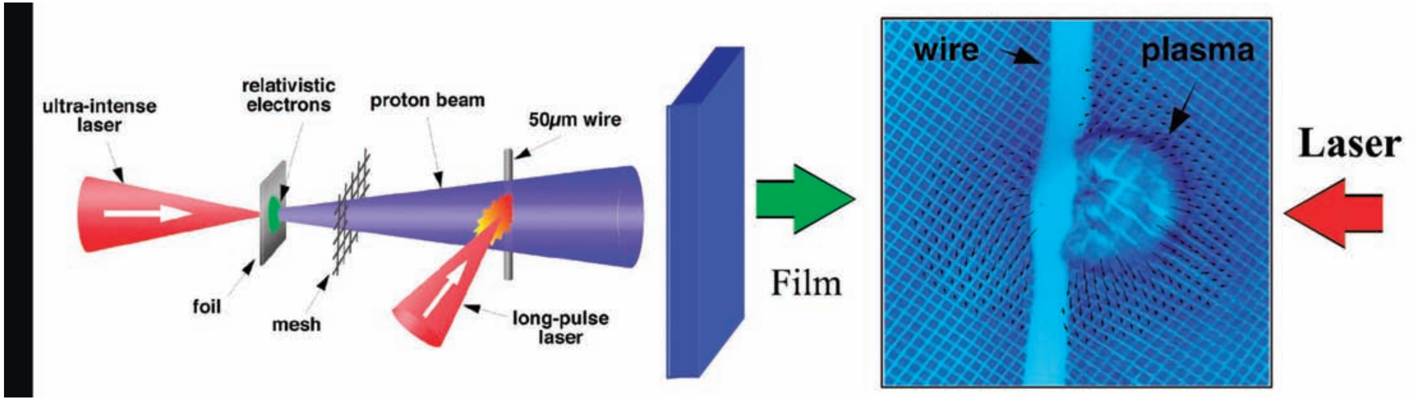

FIGURE 6.7 Ultrafast laser-accelerated protons used as a plasma diagnostic. *Left:* The experimental setup. *Right:* Image of an expanding, laser-produced plasma taken using a laser-generated proton beam. A grid is imposed on an incoming, picosecond-duration proton beam. The resulting beam deflection provides a measure of the electric fields in the plasma. Courtesy of P. Patel, Lawrence Livermore National Laboratory.

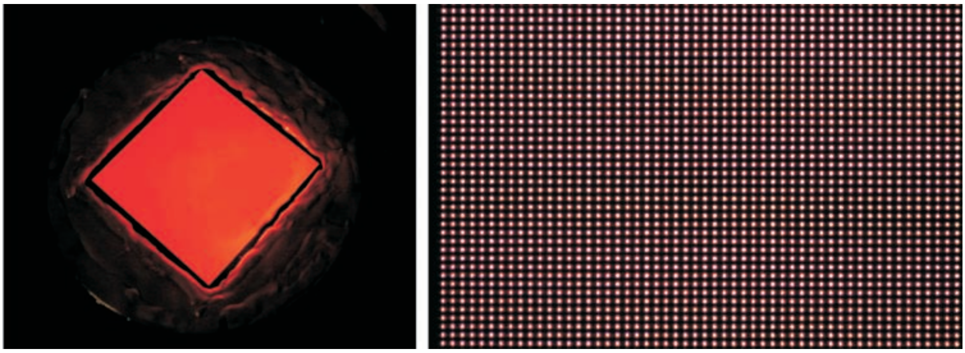

FIGURE 6.8 Photographs of a 500 × 500 array of microcavity plasma devices fabricated in silicon. Each microcavity is an inverted square pyramid with base dimensions (emitting aperture) of $50 \times 50\ \mu m^2$. *Left:* The entire array operating in 700 torr of Ne. *Right:* A 54 × 40 segment of the array (recorded with a telescope and charge-coupled device camera), illustrating the pixel-to-pixel emission uniformity. Advances in this area offer the possibility of studying a new regime in which the interface between the classical discharge plasma and the quantum electron gas in the adjacent electrodes will be important. Courtesy of J.G. Eden, University of Illinois at Urbana-Champaign.

A related research topic is microarc plasmas with similar properties, which are used in very-high-pressure projection lamps. These plasmas operate at pressures >150 atm of mercury vapor at power densities >1 MW/cm^3. The metal at the point of attachment of the cathode spot is liquid—another example of a potentially continuous phase transition from the solid cathode, through a liquid interface, into a gaseous plasma at near-liquid densities. The mechanism for electrical conduction through these three phases is an important outstanding question.

Turbulence and Turbulent Transport

The vast majority of naturally occurring plasmas are turbulent, and turbulence is hard to avoid in laboratory plasmas. As discussed in Chapter 1, understanding the nature of plasma turbulence and its consequences is a key outstanding question in plasma science. Such turbulence can take many forms, from the large-scale turbulence in clusters of galaxies to the micron-scale turbulence in laser-produced plasmas. The challenge for basic plasma science is to isolate the underlying physical mechanisms and develop predictive theories of the turbulence. Considerable progress has been made recently in understanding important aspects of plasma turbulence, and new computational, theoretical, and experimental tools offer great opportunities for progress in the coming decade.

Drift-Wave Turbulence

Turbulence due to drift waves is a ubiquitous feature of magnetically confined plasmas, such as those in tokamaks. Drift waves can be driven to be unstable, for example, by radial gradients in temperature and density. They propagate in the direction perpendicular to the magnetic field and perpendicular to the gradients in plasma density and temperature. Early experiments elucidated the linear and weakly nonlinear properties of these waves. Later, studies in tokamaks indicated the presence of significant levels of drift-wave turbulence and turbulent particle and heat transport, so understanding these phenomena is of considerable importance.

In the past decade, small linear and toroidal experiments were constructed to study these phenomena. Figure 6.9 compares a computer simulation of drift-wave

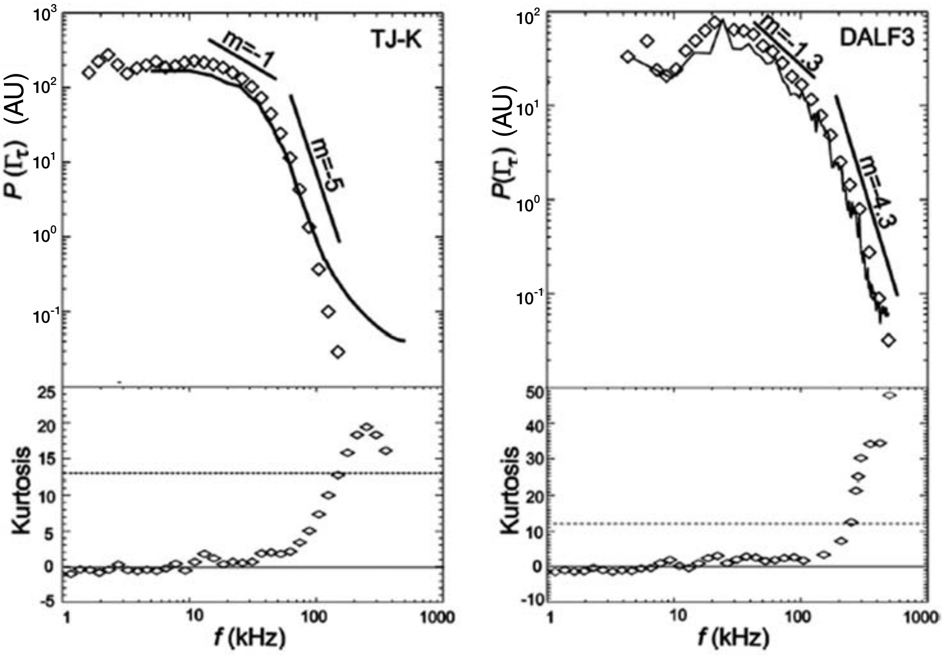

FIGURE 6.9 Turbulence measured in a low-temperature toroidal plasma *(left)* compared with results from a drift-wave turbulence simulation *(right)*. *Upper panels:* frequency spectra of the probability distribution function (PDF). *Lower panels:* The kurtosis, which is a measure of the intermittency of the turbulence. The ability to make such direct, quantitative comparisons between theory and experiment signals the beginning of a new era for plasma turbulence studies. Reprinted with permission from U. Stroth, F. Greiner, C. Lechte, N. Mahdizadeh, K. Rahbarnia, and M. Ramisch, "Study of edge turbulence in dimensionally similar laboratory plasmas," *Physics of Plasmas* 11: 2558-2564 (2004). © 2004, American Institute of Physics.

turbulence with the results of a recent experiment in a low-temperature, toroidal plasma. Similar turbulence occurs near the edges of tokamak fusion plasmas. This and similar studies demonstrate the important role small-scale experiments can play in benchmarking computer simulations and in testing theories of the turbulence. Particle transport in the edge regions of tokamak plasmas is frequently dominated by the intermittent convection of turbulent "blob" and "hole" structures. Shown in Figure 6.10 are data from a recent laboratory study of this phenomenon.

Zonal Flows and Transport Barriers

In magnetically confined plasmas, the magnetic field inhibits the flow of heat from the hot core of the plasma to the edge. However, even in plasmas where violent MHD instabilities are absent, drift-wave turbulence can transport heat across the

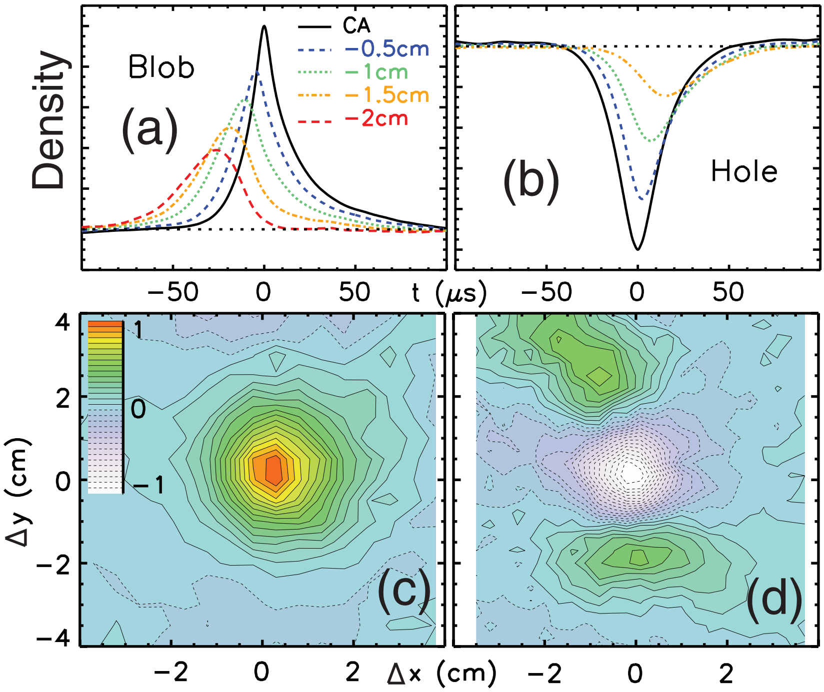

FIGURE 6.10 Localized, intermittent, turbulent structures studied in a linear plasma device: *(a)* Blobs of high-density plasma convected outward. *(b)* Holes convected inward. Panels *(c)* and *(d)* show the two-dimensional structures of a blob and hole. Turbulent structures such as these can play an important role in edge transport in tokamak plasmas. Courtesy of T. Carter, University of California at Los Angeles.

field. Instabilities of this type are being studied not only in fusion experiments but also in small-scale, basic physics experiments, where diagnosis is easier. Motivated by the experimental discovery of good confinement in special types of tokamak plasmas (so-called H-mode discharges), experiment and theory in the last decade have focused on whether the turbulence associated with these states might be regulated by interactions with sheared ("zonal") plasma flows. This phenomenon is believed to occur by the transfer of energy from the turbulence to large-scale flows, which then act to stabilize the turbulence. Current research focuses on the crucial issue of establishing a causal link between zonal flows and transport rates. If the zonal-flow paradigm does turn out to be correct, there is the possibility that one might someday be able to routinely improve plasma confinement using this mechanism.

Dynamo Action, Reconnection, and Magnetic Self-Organization

Magnetic fields play a critical role in many plasmas, so understanding their behavior is a central issue in basic plasma science. This subsection describes studies of three key questions: How can magnetic fields be generated through dynamo action? How can they disappear through magnetic reconnection? How can they rearrange and reconfigure through self-organization?

The Birth of Magnetic Fields—Dynamo Action

Magnetic fields are generated in situ in a plasma through the process of dynamo action. In this process, the plasma motion amplifies small "seed" fields, in turn producing large-amplitude, large-scale magnetic fields by converting mechanical energy into magnetic field energy. The process is not well understood. For several decades, dynamo action remained outside the reach of experiment and computer simulation, but the situation is changing.

A recent breakthrough in dynamo physics was the first observation of self-excited dynamo action in the laboratory. Using liquid sodium as the conducting medium, several groups have been able to study the way in which magnetic fields are self-generated from the kinetic energy of the fluid flow. While these liquid-metal flows are governed by the MHD equations (as are plasmas), they do not require external magnetic fields to confine the conducting medium, which is a considerable simplification. Practical limits restrict the range of operation to slow-dynamo action, which evolves on resistive timescales rather than so-called fast-dynamo action, which evolves much more quickly. Results from one of the first slow-dynamo experiments are shown in Figure 6.11. Dynamo action requires the field lines to twist and stretch. This was accomplished using external, fluid-circulation patterns. Magnetic self-excitation was observed above a threshold value of the controlling

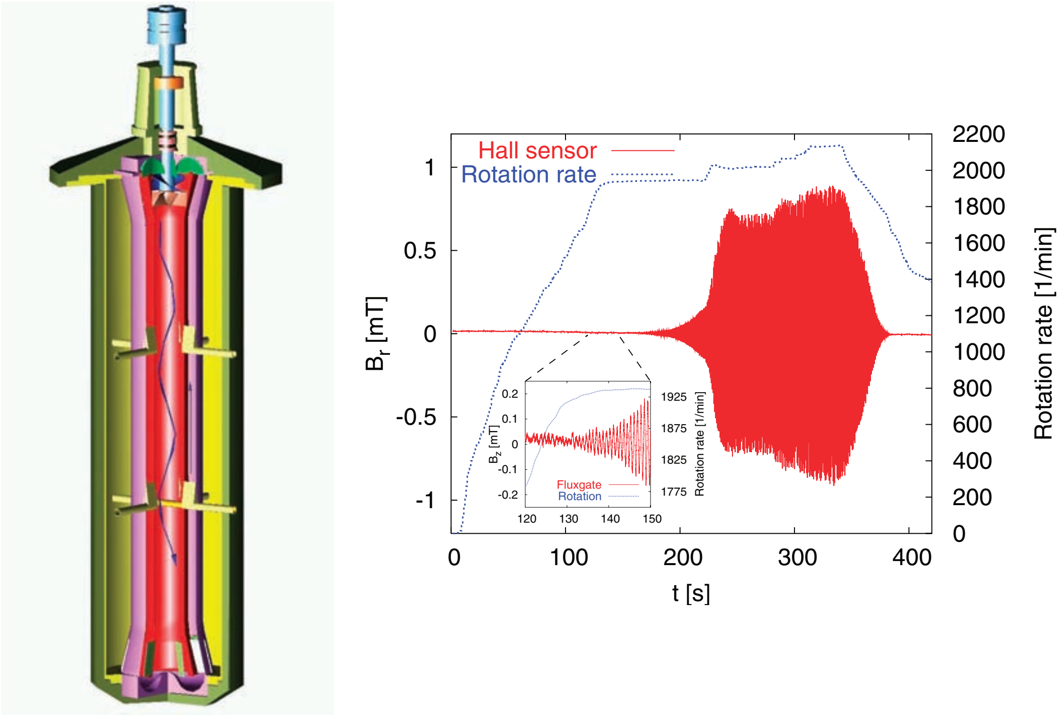

FIGURE 6.11 Observation of dynamo action in the laboratory, with a magnetic field generated spontaneously by a helical flow pattern in liquid sodium. *Left:* Schematic diagram of the experiment. *Right:* Time history of the magnetic field and the rotation rate of the propeller used to drive the flow. Courtesy of A. Gailitis, University of Latvia, and F. Stefani, Forschungszentrum Dresden-Rossendorf. SOURCE: A. Gailitis, O. Lielausis, E. Platacis, G. Ferbeth, and F. Stefani, *Reviews of Modern Physics* 74: 973 (2002).

parameter, the so-called magnetic Reynolds number, R_M.[1] Future experiments will test whether flows in less constrained geometries can self-excite. Yet to be answered is the fundamental question whether dynamos exist in spite of turbulence or because of it.

The outlook for progress in understanding an important class of dynamo action is excellent. Experiments under way or in the planning stages will have more highly developed turbulence and larger values of R_M. They will also be able to study MHD turbulence in the important regime where the kinetic energy of the flow and the energy in the magnetic field are comparable.

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[1] R_M is proportional to $L\upsilon/\eta$, where L and υ are characteristic length and velocity scales of the system and η is the electrical resistivity.

The Disappearance of Magnetic Fields—Reconnection

Magnetic energy is dissipated by the process of reconnection, whereby oppositely directed components of magnetic field annihilate, converting magnetic energy into the energy of the plasma particles. The release of magnetic energy requires global rearrangement of currents at the largest scales, while dissipation occurs in narrow boundary layers. One important question is how fast, fine-scale dynamics proceed simultaneously with the slow, fluidlike behavior of the system. Recent progress has occurred through complementary laboratory experiments, satellite observations (see Chapter 5), and theory and modeling.

In the past decade, there have been several laboratory experiments in the United States and Japan dedicated specifically to reconnection studies. These experiments are small in scale (~1 m) and can explore the regime in which the ion gyroradius is small compared to the size of the plasma. Results from one of these experiments are shown in Figure 6.12. These experiments are able to study rapid reconnection of magnetic field lines at modest magnetic Reynolds numbers ($R_M \approx$ 100-1,000). Important results include the observation of the predicted ion heating, acceleration of ions to high velocities, and the dynamical three-dimensional evolution of the reconnection.

Typically, magnetic reconnection takes place on very rapid timescales, in distinct disagreement with the predictions of simple MHD models. A recently developed "Hall-reconnection" model predicts reconnection rates that are consistent with the observations. At small spatial scales, the motions of the electrons and ions in the presence of a magnetic field cause charge separation and decoupling of the motions of the electrons and ions, which now act as two interpenetrating fluids and render MHD models invalid. The smoking gun signature of fast reconnection is the self-generated, out-of-plane, quadruple component of magnetic field. A recent triumph of the laboratory experiments is direct observation of this quadrupole field (see, for example, Figure 1.11).

These results and complementary satellite measurements of reconnection in space plasmas bring to closure a longstanding scientific problem of great importance. However, a number of outstanding challenges remain, including understanding the dynamics of the decoupled electron and ions and the partitioning of energy release between the plasma particles and bulk plasma flows. This will require measurements of the separate electron and ion distribution functions, which have recently become possible. The important question of what mechanisms trigger reconnection events is discussed in Chapter 5.

While these and similar experiments are making significant contributions, they are severely limited by the inability to provide adequate separation from plasma boundaries and by other constraints imposed by the reconnection geometry. As is

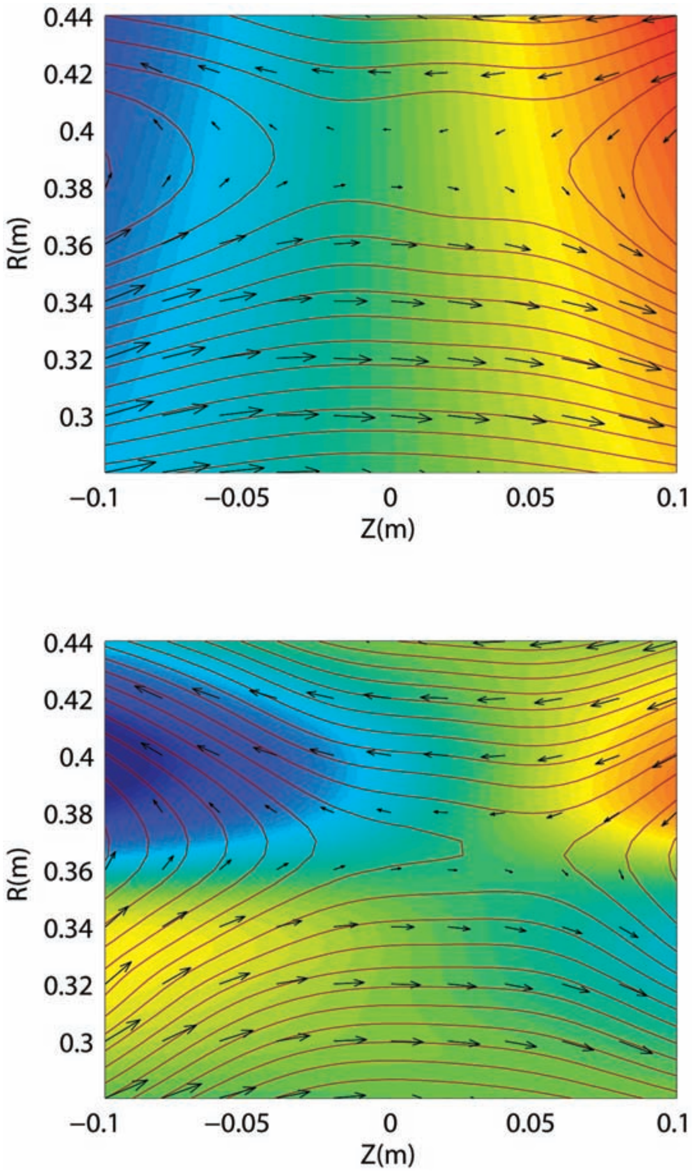

FIGURE 6.12 A laboratory study of fast magnetic reconnection. Arrows and lines show the in-plane magnetic field, and colored contours (red/blue ± 5 × 10^{-3} tesla) show the out-of-plane field. These data illustrate the dramatic narrowing of the reconnection region on going from the collisional regime *(above)* to the collisionless regime *(below)*. Experiments such as these have tremendous potential to unravel the underlying physics of reconnection. Courtesy of M. Yamada, Princeton Plasma Physics Laboratory.

discussed below, a new generation of reconnection experiments at larger scale will be critical to further progress in this important area.

Magnetic Self-Organization

Plasmas frequently rearrange their large-scale magnetic structure spontaneously. Although the specifics vary, the underlying self-organization mechanisms appear to be common to laboratory, space, and astrophysical plasmas. Here the committee discusses two important consequences of the self-organization. The critical issue for magnetic fusion of controlling such events is discussed in Chapter 4.

Momentum Transport. Many toroidal plasmas are observed to rotate in the toroidal direction, thereby developing toroidal angular momentum. During magnetic self-organization events, this angular momentum can be transported radially. The leading theoretical explanation of the transport is that the momentum is altered by a magnetic Lorentz force due to MHD instabilities, but other models have also been proposed, such as momentum transport along stochastic magnetic fields. The next decade promises important tests of these flow-driven instabilities in liquid-metal experiments, such as those described above.

Ion Heating. Frequently the plasma ions heat during magnetic reconnection. Examples where this is an important effect include reversed-field-pinch plasmas and spherical-tokamak plasmas and when plasmas are merged. While this ion heating is well documented in experiments, the underlying heating mechanism has yet to be understood and remains a challenge.

Plasma Waves, Structures, and Flows

The focus of this section is recent studies of fundamental plasma processes such as particle acceleration and plasma instabilities, which can drive plasma waves, structures, and flows. Experiments can now provide measurements of relevant quantities, including the electrical potential, density, magnetic field, and particle distribution functions—all at thousands of spatial locations and at very high data acquisition rates to allow comparison with new theories and a new generation of plasma simulations. Phenomena believed to trigger the instabilities, such as the explosive instabilities highlighted in Chapter 1, can be varied in a controlled fashion and thresholds determined. The experiments described here contribute to our understanding in different ways depending on the nature of the topic under study. In fortuitous cases, experiments can be conducted that can be scaled to a situation of direct, practical relevance—for example, in a space or astrophysical plasma. More often, fundamental insights can be gained that are of benefit to both the particular application and our general understanding of plasma behavior. Finally, for many important problems, theory and simulations can be tested and benchmarked.

Laser-induced fluorescence (LIF) has recently been used to study weakly damped low frequency modes that are not adequately described by either collisional or collisionless models. These studies could have implications in many areas of plasma physics.

Great progress has been made recently in understanding the roles played by Alfvén waves in laboratory plasmas and naturally occurring plasmas such as those in the solar wind and fusion devices (Box 6.4). Shown in Figure 6.13 is one such example where Alfvén waves were created by the currents generated when a dense plasma expands into a less dense magnetized plasma. This is similar to the process that occurs in coronal mass ejections.

Alfvén waves with fine cross-field structure can produce heating and cross-field energy transport. A theory of Alfvén waves with large transverse wave numbers has been developed and its predictions verified in experiments. Alfvén waves can also play an important role in generating turbulence at small spatial scales (through a cascade of waves to short wavelength). The details of this Alfvén-wave cascade have been explored theoretically and computationally in the last decade using an MHD formalism. The cascade often continues to length scales where an MHD description is not valid, motivating simulations that are now able to calculate the fluctuation spectrum and turbulent heating. Future research will focus on comparing the results of detailed laboratory experiments with new theory and simulations.

There is now a wealth of new opportunities for laboratory experiment and complementary theory and modeling. The following are some key examples:

- *Particle acceleration by waves.* Particle distribution functions frequently contain particles that have experienced nonlocal acceleration processes, which can now be studied in detail. The physics of charged-particle beams is closely related to that of plasmas in a moving reference frame. This provides opportunities to address outstanding questions in charged-particle-beam

BOX 6.4
Alfvén Waves

Alfvén waves are oscillations of the field lines in a magnetized plasma. While ubiquitous, they are difficult to study in the laboratory owing to their relatively large spatial scales. Alfvén waves have now been studied in detail for the first time in laboratory experiments, including Alfvén-wave maser action. Applications include understanding the aurora, the solar wind, coronal mass ejections from the Sun, and fusion plasmas.

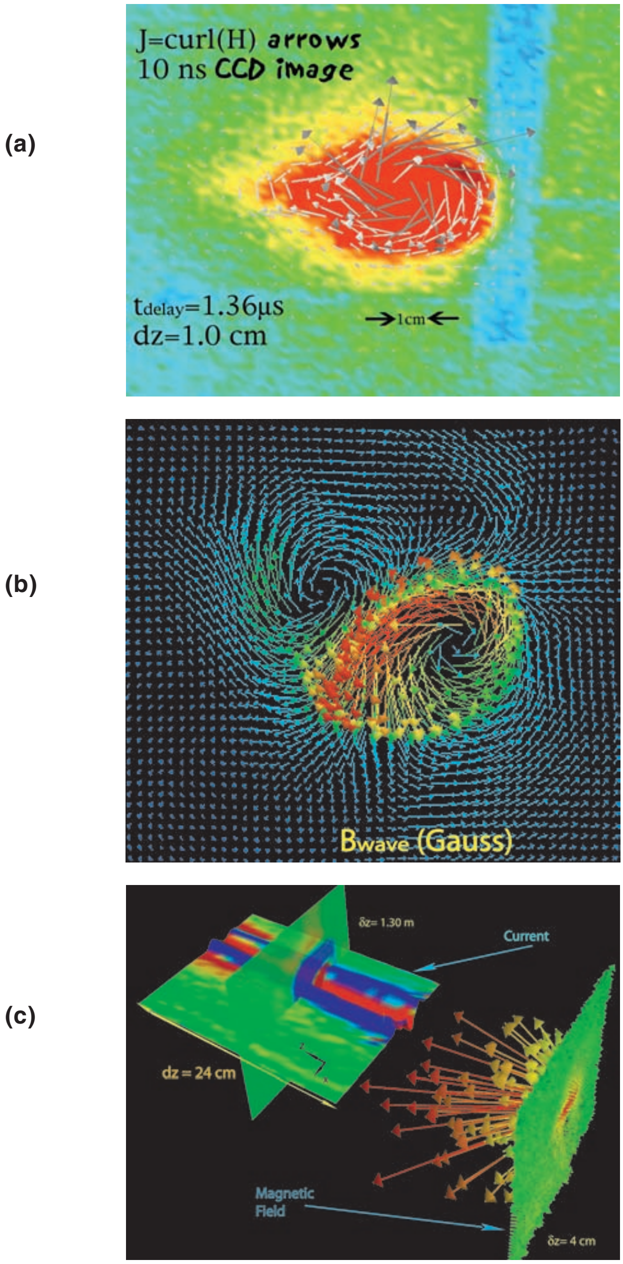

FIGURE 6.13 Laser-produced plasma expanding, from right to left, into a lower-density background plasma. *(a)* Current density in a plane near the generation point. *(b)* Magnetic field of expansion-driven Alfvén waves downstream. These data illustrate the state of the art in high-resolution, multiparameter, multiple-point measurements that can now be brought to bear on a wide variety of important plasma problems. *(c)* Overview of the expansion of the laser-produced plasma. Courtesy of W. Gekelman, LAPD Plasma Laboratory, University of California at Los Angeles.

physics—for example, in simplified geometries such as radio-frequency traps.

- *Turbulent resistivity.* Frequently, the resistivity due to turbulence is much greater than that due to Coulomb collisions. This can now be studied, even on the timescale of electron motion.
- *Structure in plasmas.* Opportunities here include the study of magnetic, field-aligned density perturbations, filaments of enhanced temperature and/or potential, and the effects of localized beams.
- *Plasma flows.* A variety of wave phenomena can be driven by plasma flows. This will be an important area for future work exploiting the synergies between laboratory and space plasma studies.
- *Expanding, high-density plasmas.* A new generation of high-power, high-repetition-rate lasers offers great potential for studying transient processes where high-density plasma expands into a magnetized background plasma. Important phenomena include collisionless shocks, collision of flowing plasmas, magnetic field generation, and magnetic reconnection.

IMPROVED METHODOLOGIES FOR BASIC PLASMA STUDIES

A number of developments over the past decade hold much promise for future progress. Experimental and technical capabilities continue to expand. New sensors and new optical and laser systems enable experiments unheard of a decade ago. There has been progress in the optimization of many probes of plasma properties. LIF has become a valuable diagnostic of ion temperature. Experiments have benefited greatly by the revolutionary progress made in computing power and data collection capabilities. Massive amounts of data can now be collected at high rates and analyzed and stored cheaply. Experiments can be done with much higher precision and greatly improved spatial and temporal resolution, frequently in three spatial dimensions. Examples include the magnetic reconnection data in Figure 6.12 and the study of Alfvén waves shown in Figure 6.13.

In the future, microelectromechanical systems technology will offer the possibility of a qualitatively new generation of microprobes with sub-Debye-length spatial resolution (tens of GHz) and sufficient temporal resolution to resolve electron motion. Analyzers could be arranged in clusters to directly measure the three-dimensional particle distribution functions. In principle, thousands of these probes could be placed in a plasma and complete spatial and temporal data acquired without perturbation of the system.

On the theory front, great changes have come from improved computational technology and algorithms and the development of new theoretical models. The ability to carry out realistic simulations of actual experiments has improved similarly, so that detailed and accurate comparisons can be carried out in a wide variety of situations. Examples include the phase transitions in the three-dimensional ion crystals shown in Figure 6.2 and the comparison of turbulent drift-wave spectra in a toroidal plasma device in Figure 6.9.

However, considerable challenges remain—for example, in modeling multiscale problems such as magnetic reconnection—due to the enormous range of spatial scales involved. New embedding techniques are needed to deploy kinetic models in regions of a large-scale computation where simpler fluid models fail. Resources dedicated to developing such models need to be a priority if the modeling of large-scale plasma phenomena is to be successful.

On a related theoretical front, it is the observation of many in the plasma community and members of the committee that the past decade has seen a significant decline in activity in areas of mathematical physics relevant to plasma science. While this probably reflects a shift in activity to computation and simulation as those capabilities continue to improve, the importance of continued development of new plasma-science-related mathematical physics techniques cannot be overestimated. The field would benefit greatly if the plasma community and the federal agencies would consider carefully how this growing deficiency might be remedied.

Finally, there is the important issue of coordinating basic research activities. In areas such as fast reconnection, for example, satellite measurements, dedicated laboratory experiments, and a new generation of theoretical and computational models have brought significant advances to our understanding. Such coordinated efforts are essential in optimizing progress in many areas, including understanding dynamos, magnetic reconnection and self-organization, plasma turbulence, and turbulent transport. In the past decade, there has been an increased appreciation by members of the plasma community of complementary and related activities in other areas of the field, and this has led to many productive synergies and successful collaborative efforts. To optimize future progress, it will be very important for this positive trend to continue and grow.

CONCLUSIONS AND RECOMMENDATIONS FOR THIS TOPIC

Many important new research opportunities in basic plasma science come about from progress and new discoveries in the last decade. Such opportunities exist for studies in dusty plasmas, a new generation of laser-driven and HED plasmas, and micro- and ultracold plasmas, in addition to studies of new and fundamental aspects in areas such as Alfvén-wave physics and magnetic reconnection and self-organization. However, there are two potential roadblocks to progress:

- Access to support for basic plasma science investigations.
- The need for intermediate-scale experimental facilities for basic plasma studies.

Addressing both of these concerns would be aided greatly by this report's principal recommendation, namely that there is need for the Office of Science to assume stewardship for plasma science. As pointed out in a 1995 report,[2] plasma science is a fundamental discipline similar, for example, to condensed-matter physics, fluid mechanics, or chemistry. The diversity of scales of research in plasmas, from university laboratory to space missions and billion-dollar-class megascience projects, has hindered the articulation of scientific themes that unite research in plasma science and engineering across a campus or even a geographic region.

University-Scale Investigations

Conclusion: Basic plasma science—often university-based research and at a small scale—is a vibrant field of research through which much new understanding of plasma behavior is being developed. Basic plasma science offers compelling research challenges for the next decade because it has extended by orders of magnitude the range of plasma parameters amenable to study, identified new phenomena, and developed new theoretical, computational, and experimental methods.

There has been a considerable shift in the funding of university-scale basic plasma investigations in the last decade. The committee now gives a brief overview of the changes. Further details can be found in Appendix D. Partly in response to recommendations made in the 1995 NRC report, the joint NSF/DOE Partnership in Basic Plasma Science and Engineering was created in 1997. Typically proposals have been solicited triennially. This joint program between NSF and the DOE Office of Fusion Energy Sciences (OFES) has been funded at approximately $6 million per year. The program has become a critical source of funding for basic plasma research and is responsible for much of the progress described in this chapter. In parallel, OFES created a General Science Program to fund basic research at DOE laboratories and a very successful Young Investigator Program to fund research by junior faculty at colleges and universities. In addition, DOE and NSF recently supported the creation of the Center for Magnetic Self-Organization of Laboratory and Astrophysics Plasmas. Programs such as these have had a strong, positive influence on the development of basic plasma science in the last decade.

The emerging programmatic support at DOE's NNSA in the past decade, through the Stockpile Stewardship Academic Alliance program, has provided a new level of stewardship of the growing area of laboratory explorations of HED plasmas. Paradoxically, during the same period (1995-2006), a vital and effective

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[2] NRC, *Plasma Science: From Fundamental Research to Technological Applications*, Washington, D.C.: National Academy Press, 1995.

program for basic plasma research at the Office of Naval Research, funded at $4 million per year, was terminated when U.S. Navy priorities changed.

> **Conclusion: The collaborative partnership for basic plasma science and engineering between the National Science Foundation and Department of Energy has been critical to progress in basic plasma science. Focusing on single-investigator and small-scale research and aided by an effective system of peer review, it is an efficient and effective instrument to fund basic plasma research. Recent solicitation for the partnership program has had very high proposal pressure—in part owing to the triennial rather than annual solicitation schedule.**

The NSF/DOE Partnership in Basic Plasma Science and Engineering has been effective in terms of important research progress as judged, for example, by publication in premier scientific journals such as *Physical Review Letters.* It has also contributed greatly to the education of new scientific and technical personnel for the field as judged by the number of Ph.D.'s granted in plasma science. It has made important connections with other areas of science and has achieved greater recognition for plasma science in the broader scientific community. The program is also very effective for providing research support for tenure-track faculty.

It is the opinion of this committee that the success of this program is limited by the relatively small funding base. In the latest round of solicitations, only 20 percent of the proposals were funded, with the average grant size at $100,000 per year. A second limitation is the current emphasis on a triennial solicitation cycle for proposals to the Partnership. Simply put, science does not proceed on a 3-year cycle. Opportunities are lost if a new research project must wait several years to be considered for funding. This can be a particularly critical problem for young investigators and those in competition with foreign researchers. It is also a great impediment in maintaining momentum in an established research program. Years can be lost before a proposal is considered, and more delay if the first proposal has a correctable flaw that further postpones funding pending revision and resubmission. For a university assistant professor, who typically has 6 years to establish a research program before a tenure decision is made, loss of even 1 or 2 years of funding can be a critical event.

> **Recommendation: To realize better the research opportunities in basic plasma science, access to timely and adequate funding is needed. The Partnership for Basic Plasma Science and Engineering between the National Science Foundation and the Department of Energy should be expanded by going from the present triennial solicitation of proposals to an annual schedule.**

As discussed in Chapter 1, there is great potential for the Department of Energy to play a greater role in furthering all of plasma science, including its most fundamental aspects.

Conclusion: Basic plasma science has benefited significantly from the increased stewardship of plasma science provided in the last decade by the Office of Fusion Energy Sciences of the Department of Energy. It would be further improved by even more comprehensive stewardship by that office.

The intellectual synergies between basic plasma science and the subfields of plasma research would be greatly enhanced by leveraging more of the infrastructure that the subfields have in common. The committee believes that the DOE Office of Science would provide a natural environment in which to accomplish this objective. Two areas of critical importance to DOE's mission are low-temperature and HED plasmas. As discussed in this chapter and elsewhere in this report, these areas offer a wealth of opportunities and challenges for basic plasma science. A broader framework would, for the first time, create a structure that promotes the scientific kinship of these areas. HED and magnetic fusion plasma science would benefit from the closer connections to other plasma science areas. Such a framework would also serve as a common gateway for researchers from other fields whose interests bring them into contact with plasma science researchers. It would, for example, enhance the intellectual connections between the basic plasma science community and NASA-supported space and astrophysical missions, providing NASA program managers and scientists with a natural mechanism to interact more effectively with the basic plasma science research community.

Intermediate-Scale Facilities

The appropriate size for a basic plasma experiment varies depending on the problem being addressed. Researchers must weigh the merits of a particular experimental effort against the required costs to carry out this research. While much of this chapter focuses on small-scale and single-investigator projects, it is important to emphasize that some important problems cannot be addressed by this mode of investigation—the nature of the science sets the scale. For example, study of the physics of burning plasmas must be done in what are now the state-of-the-art magnetic fusion devices. There is much forefront, fundamental plasma science research that requires intermediate-scale facilities—experimental facilities larger than can be easily fielded by a single investigator but smaller than those at the larger national research installations.

A recent and successful example of such an intermediate-scale experimental research effort is the creation of a national facility to study basic plasma problems that require large volumes of magnetized plasma. By cooperative agreement in 2001, the NSF and DOE OFES initiated support for the operation of a device of this type as a national facility. The research program, highlights of which are discussed in the subsection on plasma waves, structure, and flows, studies Alfvén-wave physics and associated phenomena, including electron acceleration mechanisms, electron heat transport, and the formation of localized structures. This program allows teams of researchers nationwide to come together to study important phenomena that require very large volumes of magnetized plasma and a suite of state-of-the-art diagnostics. This project can be regarded as a model for addressing basic plasma science problems that require facilities larger than required by the typical effort of a single principal investigator.

During the course of the committee's work, the plasma community indicated that other scientific problems would benefit from intermediate-scale facilities of this type. One example is a facility to study HED phenomena intermediate in scale between the tabletop laser scale and the largest facilities such as that at the University of Rochester and at the National Ignition Facility. The limited access and shot rate and the program-oriented focus of the large HED facilities makes difficult their use for basic HED plasma science. The forefront of basic high-intensity laser research now rests with petawatt-class lasers. These systems, while smaller than that at NIF, are large enough to make it difficult to maintain outside a national lab or a large university-based center. To remain a leader in this field and to exploit fully the new opportunities presented by ultrabright lasers, the United States should support and operate, either separately or jointly with other programs, mid-scale laser user facilities (including petawatt-class lasers) for unclassified research.

A second example of the need for a mid-scale facility, and also one with widespread community support, is the need for a new experiment to study magnetic reconnection in three dimensions. As has been discussed, there has been dramatic progress in the last decade in studying reconnection through a new generation of computer simulations and laboratory experiments. These successes provide a roadmap for further progress toward a more complete and general understanding of this fundamental and important class of phenomena that are relevant to magnetic confinement fusion as well as to space and astrophysics. As discussed above, present magnetic reconnection experiments do not have sufficient separation of spatial scales to isolate the physics of the reconnection process from plasma boundaries. This inhibits the study of many important phenomena, such as plasma flows and the associated slow shock waves predicted to originate in the reconnection region.

> **Conclusion: There are important basic plasma problems at intermediate scale that cannot be addressed effectively either by the present national facilities or by single-investigator research.**

Several areas of basic plasma science would benefit from new intermediate-scale facilities. For instance, at the present time, there is a clear need for a national facility for the exploration of reconnection phenomena. Similarly, there is also a need for intermediate-scale user facilities, including petawatt-class lasers, to study HED plasma phenomena. Constructing and operating such facilities may require additional resources. The DOE Office of Science should serve as a framework for soliciting, evaluating, and prioritizing such proposals and resources.

> **Recommendation: The plasma community and the relevant federal government agencies should initiate a periodic evaluation and consultation process to assess the need for, and prioritization of, new facilities to address problems in basic plasma science at the intermediate scale.**

Appendixes

A

Charge to the Committee

An assessment of plasma science in the United States is proposed as part of the decadal assessment and outlook, *Physics 2010*. Since publication of the previous decadal study of this area in 1995, the field has undergone rapid advances and significant changes—ranging from a refocused mission of the DOE fusion science program to new plasma processing technologies arriving in the commercial marketplace to significant advances in understanding how to confine plasmas. A new field called high-energy-density physics has been defined that foretells new connections between astrophysical phenomena and laboratory experiments. It is timely and important to identify the compelling science opportunities in plasma science and to frame a strategy for realizing them. Also, recommendations from the last decadal study have been implemented by the agencies and an assessment to provide feedback is now appropriate.

A committee of about 15 members with broad expertise in plasma science will be convened to address the following tasks in a report that will communicate well to policy makers and scientists in other fields:

1. Assess the progress and achievements of plasma science over the past decade.
2. Identify the new opportunities and the compelling science questions for plasma science, frame the outlook for the future, and place the field in the context of physics as a whole.
3. Evaluate the opportunities and challenges for the applications of plasma science to fusion and other fields.

4. Offer guidance to the government research programs and the scientific communities aimed at addressing these challenges and realizing these opportunities.

B

International Thermonuclear Experimental Reactor

The Sun is currently the site of the only self-sustaining fusion reactions in our solar system. The goal of research on magnetic confinement fusion is to build a controlled “star on Earth”—a fusion reactor—by confining a deuterium-tritium plasma at thermonuclear pressures with magnetic fields. Progress in this grand quest has been steady and dramatic (Figure B.1). In the mid-1990s, two magnetic confinement fusion devices produced multimegawatts of fusion power for a few seconds. Thus the 11-MW Tokamak Fusion Test Reactor (TFTR) in Princeton, New Jersey, and the 16-MW Joint European Torus (JET) in Great Britain demonstrated it is possible to confine, heat, insulate, and control a large volume of thermonuclear plasma in the laboratory, at least transiently; the similar-sized JT-60U experiment in Japan extended these results in deuterium plasmas.

The next and critically important step is to show that one can obtain more heating from fusion reactions than is put into the reaction from external sources—a fusion burning plasma. In both the U.S. and European landmark fusion experiments, the self-heating of the plasma from fusion reactions was less than the applied external heating. The next major step in the worldwide magnetic confinement fusion research will be to achieve a fusion burning plasma in which the plasma is dominantly self-heated by the fusion reaction products. This step will be taken in the International Thermonuclear Experimental Reactor, now simply known as ITER, whose construction is slated to begin at Cadarache, in the south of France, in 2008 (Figure B.2).

The objectives of the ITER project are as follows:

> The overall programmatic objective of ITER is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes.
>
> ITER will accomplish this objective by demonstrating high power amplification and extended burn of deuterium-tritium plasmas, with steady-state as an ultimate goal, by demonstrating technologies essential to a reactor in an integrated system, and by performing integrated testing of the high-heat-flux and nuclear components required to utilize fusion energy for practical purposes.
>
> These objectives maintain the strategy to take a single step between today's experiments and the first plant (often called DEMO) to demonstrate reliable electricity production using fusion power.[1]

Specifically, ITER seeks to achieve its first plasma in 2016 and produce 500 MW of fusion power for hundreds of seconds in about 2020. Key physical parameters of ITER are these: the plasma cross-section will be approximately 4 meters wide by 7 meters tall; magnetic field strength, 5.3 tesla; current in the plasma, 15 MA; and external heating power, 40-50 MW. The construction costs of ITER are estimated at €5 billion over 10 years, and another €5 billion are foreseen for the 20-year operation period. The ITER Parties will for the largest part give components for the machine, so-called in-kind contributions.

The ITER project was launched as a Reagan-Gorbachev Presidential Initiative in 1985, with equal participation by the United States, Europe, Japan, and the Soviet Union through the 1988-1998 initial design phases of the original ITER project. After the fusion program budget was cut by 33 percent and the fusion program was restructured from an energy technology development program to a science-focused program in the late 1990s, the United States withdrew from the ITER project. From 1998 through 2002 the ITER project was continued by Europe, Japan, and Russia and evolved into the current smaller ITER project with reduced objectives. It adopted much of the science-driven reduced scope and advanced concepts the United States had pushed for when it participated in the earlier ITER phases.

The NRC Burning Plasma Assessment Committee (BPAC) recommended (in December 2002) that the United States should again participate in the ITER project. The United States then rejoined the ITER negotiations in January 2003 as a Presidential Initiative. Participation in ITER is now identified as the number one priority future project over the next 20 years by the DOE Office of Science. In the Energy Policy Act of 2005 (Public Law 109-58, August 8), Congress authorized the negotiation of "an agreement for United States participation in the ITER." Achievement of the U.S. scientific community and government consensus on rejoining ITER was a major accomplishment over the past decade.

The partners in the ITER project (host Europe, 45 percent; nonhosts—China,

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[1] As defined on the ITER Web site at http://www.iter.org/a/index_nav_1.htm. Last viewed May 15, 2007.

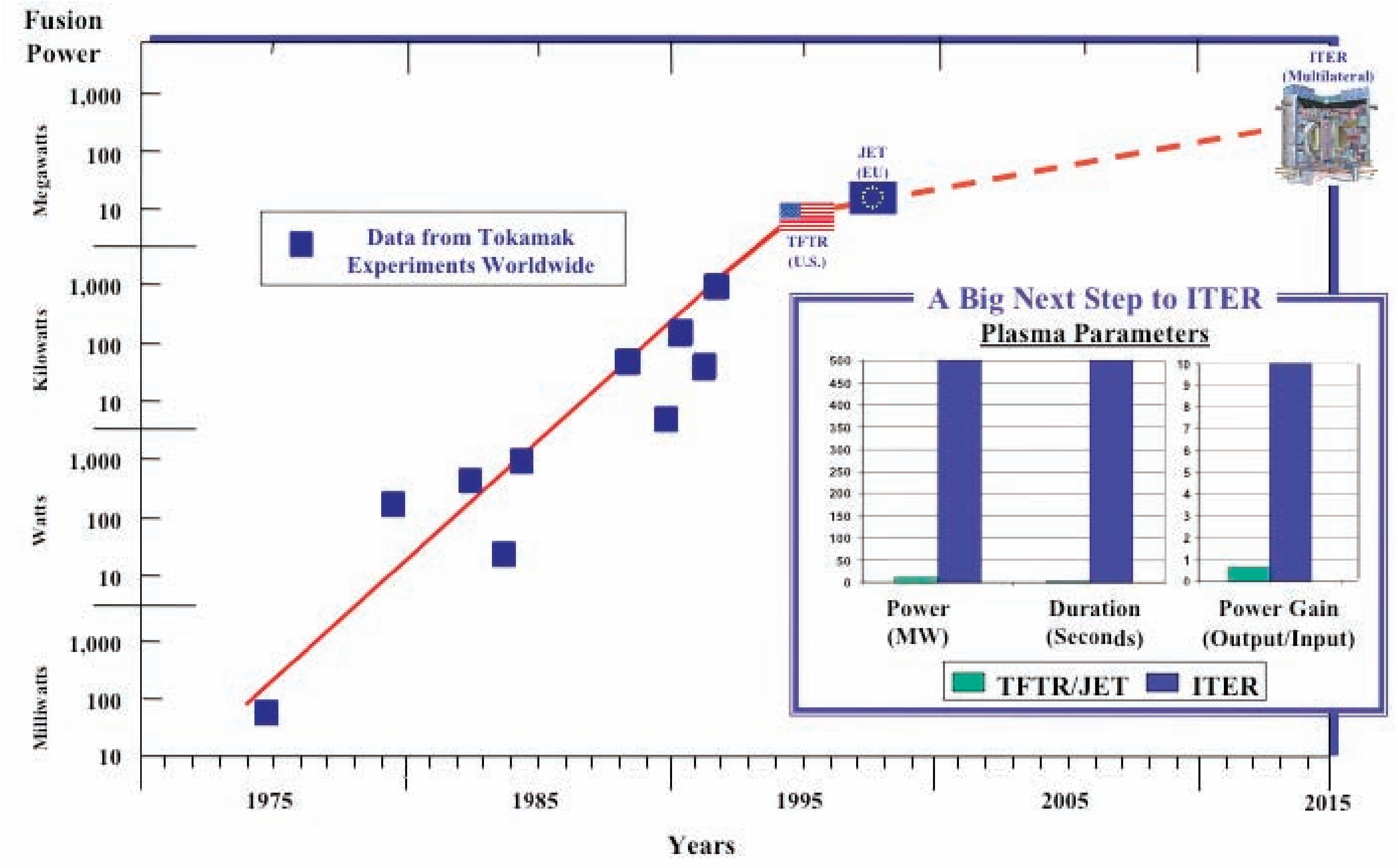

FIGURE B.1 The fusion power produced in magnetically confined plasmas has been increasing continuously and dramatically for decades. On average it doubled every year until the mid-1990s, twice as fast as Moore's law for the increase in computing power of semiconductor chips. ITER is projected to extend fusion power and duration to the crucial burning plasma regime.

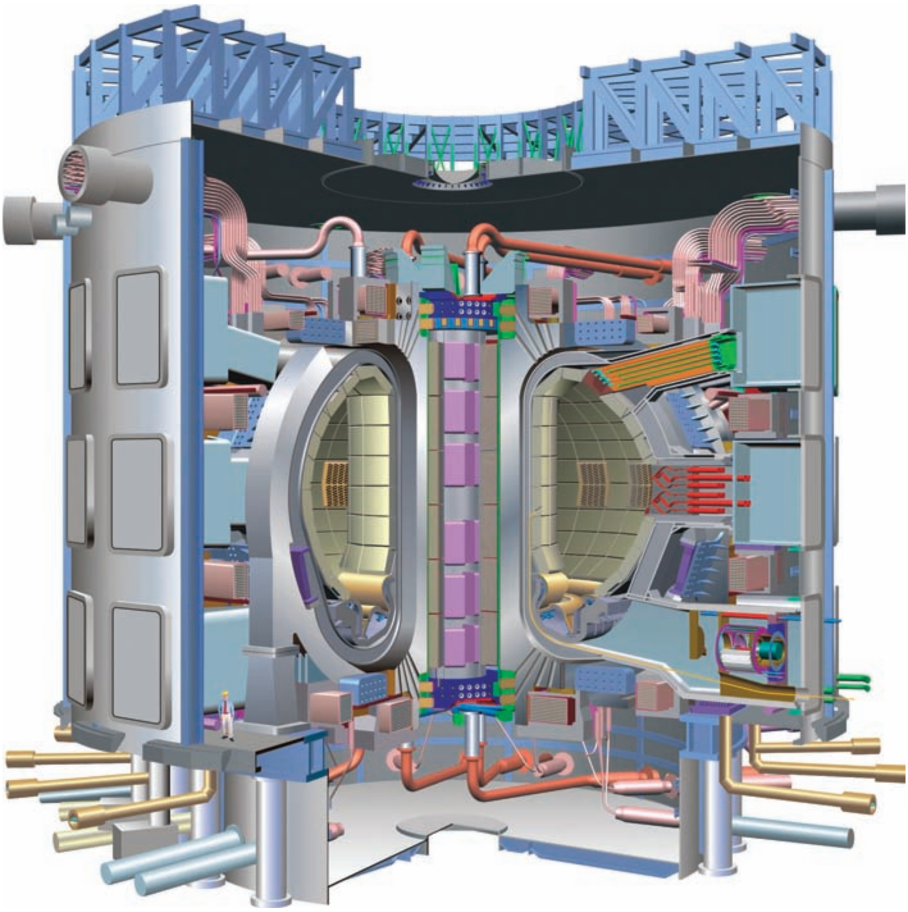

FIGURE B.2 Cutaway drawing of the International Thermonuclear Experimental Reactor (ITER) to be built over the next decade in Cadarache, France. A man shown in the lower left corner indicates the scale of the device. Detailed characteristics of the ITER device and of the overall ITER project can be obtained from http://www.iter.org. Published with permission of ITER.

India, Japan, Russia, South Korea, and the United States—9.1 percent each), decided on the Cadarache site on June 28, 2005, and initialed an agreement on May 24, 2006. Final governmental signatures on the ITER Agreement were obtained on November 21, 2006. Because the ITER project has been truly international from its inception in 1985 as an initiative of Presidents Reagan and Gorbachev and is the largest joint international scientific endeavor ever undertaken, it will probably become the model for large international science experiments.

Magnetic fusion research has a long history of strong international collaboration ever since it was declassified at the United Nations Atoms for Peace conference in 1958. During the 1960s, the major players were the United States, Great Britain and the Soviet Union; scientific exchanges began then, but there were few close collaborations. A notable turning point in fusion research was the achievement in 1968 of excellent plasma confinement in the Soviet T-3 tokamak experiment and subsequent confirming measurements by a collaborating team of British scientists. This achievement launched a worldwide quest for fusion energy based primarily on the tokamak concept. The major players became the United States, Europe (Great Britain, France, and Germany), the Soviet Union, and Japan. The United States had about a third of the world fusion budget in 1980 and became the dominating leader in fusion science and technology in the late 1970s; its leadership continued into the early 1990s. Close collaborations between experimental teams on different fusion devices around the world are now quite common, most often to check scaling of the behavior of plasma phenomena across different sizes and types of experiments. While the primary U.S. objective in ITER is burning plasma science (understanding and control of burning plasmas), the primary objective of the European and Japanese programs remains development of fusion energy for commercial electricity production.

C

National Ignition Facility

Research on inertial confinement fusion (ICF) and high energy density (HED) physics has been pursued intensively in the United States for many years. The National Ignition Facility (NIF) is being built to move that research program forward to a demonstration that ICF can be achieved in the laboratory. An additional goal is to enhance substantially the range of HED states of matter that can be studied in the laboratory. The NIF, under construction at Lawrence Livermore National Laboratory (LLNL) in California, will deliver up to 1.8 MJ of ultraviolet light (354 nm wavelength) in 192 convergent laser beams (Figure C.1). The NIF is being constructed as part of the Stockpile Stewardship Program by the National Nuclear Security Administration (NNSA) to ensure the safety, security, and reliability of the nation's nuclear stockpile without underground nuclear testing. The NIF's role in the stewardship program is to provide relevant data for the weapons program and to test our scientific understanding of the physics of nuclear weapon explosions through successful fusion ignition experiments in the laboratory. The completion of the NIF and the beginning of experiments that will lead to full-scale ignition tests are scheduled for 2009. These ignition experiments, which will utilize the most highly developed approach of indirectly driven hot spot ignition, will be the culmination of more than two decades of experimental campaigns that were performed at the Nova laser at LLNL (the predecessor of the NIF), the OMEGA laser at the University of Rochester, the Z-machine at Sandia National Laboratories, the Nike laser at the Naval Research Laboratory, and other lasers elsewhere. Successful ignition experiments at the NIF will be a key stepping-stone to inertial fusion as an energy source.

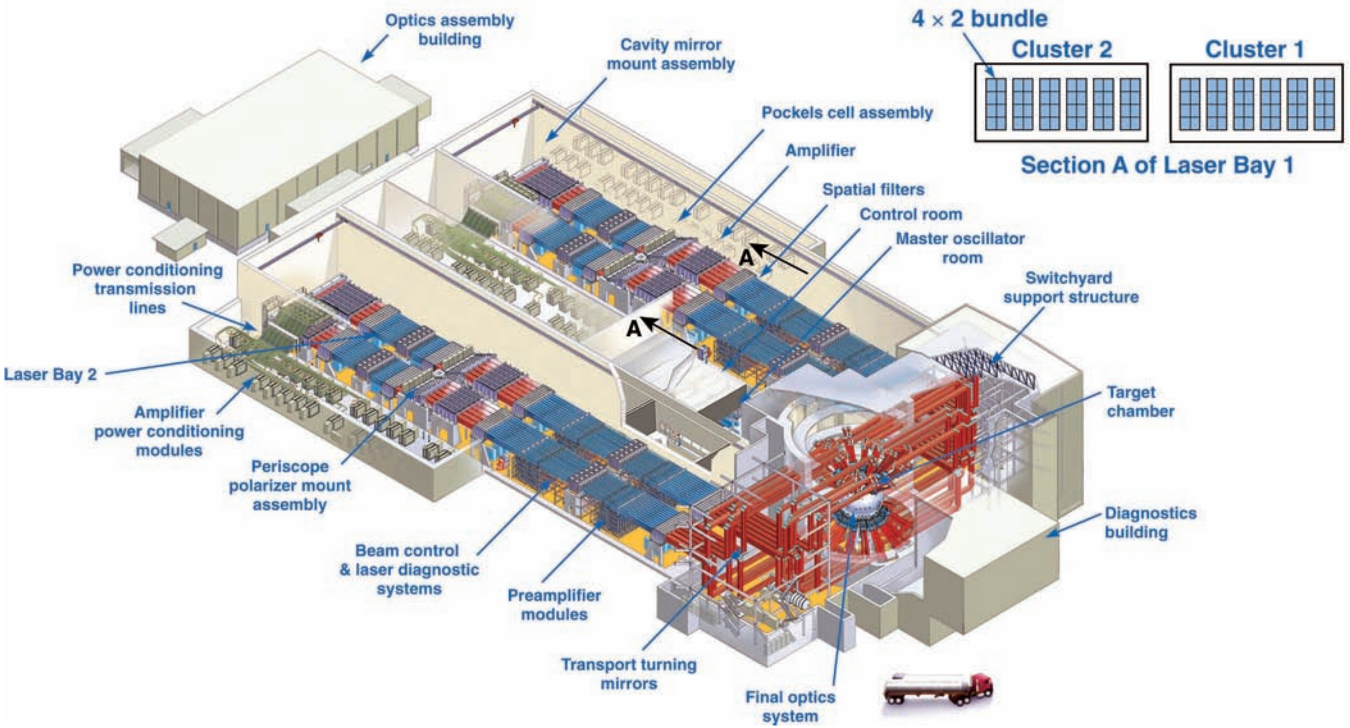

FIGURE C.1 Rendering of the ~2 MJ National Ignition Facility (NIF) that is currently under construction at LLNL showing the location of various components and support facilities. When completed, the NIF will be the nation's highest-power MJ-class HED physics facility; it is being built primarily for weapons-relevant HED physics research, including ICF. Up to 15 percent of the laser time is planned to be available for basic science experiments. Courtesy of LLNL.

The flagship mission of the NIF is to demonstrate fusion ignition—the combining or “fusing” of two light nuclei to form a new nucleus. The NIF’s powerful array of lasers is intended to ignite enough fusion reactions in a carefully designed capsule containing the heavy hydrogen isotopes that constitute the fusion fuel to produce more fusion energy than the laser energy delivered to the target. The physical processes involved in ICF and the physics challenges that must be overcome to achieve ignition are detailed in Chapter 2. The NIF is crucial to the NNSA Stockpile Stewardship Program because it will be able to create the extreme conditions of temperature and pressure that exist on Earth only in exploding nuclear weapons and that are therefore relevant to understanding the operation of our modern nuclear weapons. Understanding the physics of the ignition process and the dynamics of matter under HED conditions, together with the HED materials data that will be provided by the NIF, will allow supercomputer modeling tools to be used by our nuclear stewards to assess and certify the aging stockpile without carrying out actual nuclear tests. For example, NIF experiments will investigate the physics regimes associated with radiation transport, secondary implosion, and ignition and will enable testing the consequences for weapons operation of the effects of aging of some weapon components. Please see Chapter 3 for additional details on the scientific needs of stockpile stewardship.

Other benefits to stockpile stewardship of the NIF are to help maintain the skills of present nuclear weapons scientists, who must assess the aging-related conditions that could compromise the reliability of nuclear weapons, as well as to attract bright young scientists to the program by offering them the excitement of working with a world-class laser facility. Finally, the committee notes that the NIF is to be used for basic science experiments 10-15 percent of the time after 2010. Although not directly relevant to stockpile stewardship, such use will encourage cross-fertilization of ideas and transfer of best-practices between HED scientists at universities and national laboratory scientists and help enhance the database on HED materials properties, extending it beyond the properties of direct relevance to weapon scientists.

NATIONAL IGNITION FACILITY TECHNOLOGY

The laser design at the National Ignition Facility (NIF) represented a break from the master-oscillator power-amplifier architecture that had been used in previous high power lasers used for ICF research, such as the Shiva or Nova lasers. This new multipass architecture (see Figure C.2 for a representation of 1 beamline out of 192) was chosen to increase wall-plug efficiency (from 0.2 percent) and decrease cost by building only one type of amplifier component in a more compact footprint. In this design, light is injected from the preamplifier, passes through the power amplifier, then makes four passes through the main amplifier and, finally,

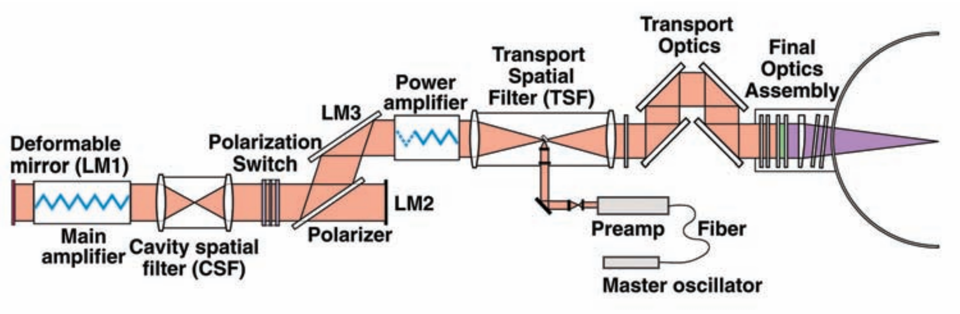

FIGURE C.2 The multipass architecture that is common to all of the 192 beamlines of NIF. There are four passes through the main amplifier and two passes through the power amplifier. Courtesy of LLNL.

another pass through the power amplifier and out to the final optics assembly. This strategy required development of several technologies: full-aperture (40-cm) optical switches, a full-aperture deformable mirror for wave front correction, full-aperture potassium dihydrogen phosphate (KDP) frequency conversion crystals, and full-aperture mirrors and polarizers. The optical switch is a Pockels cell that is energized by electrodes in the optical path. For this reason plasma electrodes are used. Providing enough KDP crystals for switches and frequency conversion (from 1.056 μm wavelength light to one-half or one-third of that) required development of rapid growth techniques; a factor of 6 was achieved. The wall-plug efficiency to produce the 0.33 μm light to be used for ICF experiments starting in 2009 is about 0.5 percent, much less than is needed for fusion energy but suitable for a research laser. (For the fusion-energy application, diode-pumped lasers are being developed so that broadband 10 percent efficient flashlamps pumping neodymium-doped glass can be replaced by 60-70 percent efficient narrow-band light-emitting diodes pumping crystals or ceramics. Efficiencies for these laser systems are projected to be 15-20 percent.)

The NIF, which can produce 4.5 MJ (6 MJ if all possible amplifier glass slabs are installed) of 1.056 μm (infrared) light (3 MJ at half that wavelength and 1.8 MJ at one-third that wavelength) has an area of three football fields. The laser energy can be focused to a 100-μm spot. It was not possible to make the entire NIF laser bay into a clean room by optical standards. Therefore, individual components are packaged as line-replaceable-units that are assembled in a clean area and can be quickly installed in hermetic beam lines. This will also reduce downtime.

The number of high-yield shots will be limited by the time for induced radioactivity of the chamber to decay (about a week) and the maximum yearly yield of 1,200 MJ specified in the Environmental Impact Statement.

D

Federal Support for Plasma Science and Engineering

Plasma science and engineering is diffusely supported across the federal portfolio of science and technology. One aim of this report is to identify those research efforts more precisely and to communicate the common intellectual threads. This appendix describes some of the levels of federal support for plasma science and engineering. Because the research is so seemingly fragmented, the activities are discussed agency by agency.

A further cautionary note is necessary. Because plasma science and engineering are supported in such different capacities by such different programs, the committee was unable to obtain an authoritative and comprehensive view of federal investments. As an approximation, the committee reports here the most identifiable plasma-related funding.

Finally, the following list may be helpful in connecting agency programs with the scientific topics discussed in the report:

- DOE's Office of Fusion Energy Sciences (OFES) is the primary supporter of magnetic fusion science. OFES also participates in the NSF/DOE Partnership for Basic Plasma Science and Engineering, which supports basic plasma science. It is also starting to support some HED physics.
- DOE's National Nuclear Security Administration (NNSA) is the chief supporter of inertial confinement fusion (ICF) and HED physics.
- DOE's Office of High Energy Physics manages an advanced technology R&D program that includes work on plasma-based accelerators.

- DOE's Office of Nuclear Physics supports research in quark-gluon plasmas, a topic related to the HED science discussed in this report.
- The Office of Naval Research (ONR) supported research activities in basic plasma science, low-temperature plasma science and engineering, and space plasma physics but terminated its support for them in 2003.
- The National Science Foundation's (NSF's) Engineering Directorate is the primary supporter of low-temperature plasma science and engineering through distributed involvement in the National Nanotechnology Initiative (NNI) and through its Combustion, Fire, and Plasma Systems program.
- NSF's Mathematical and Physical Sciences Directorate supports plasma research through its Astronomy Division (space and astrophysical plasmas) and its Physics Division (mostly basic plasma science). There are no dedicated plasma programs; the Physics Frontier Center program does include several centers with plasma research topics. NSF's Geosciences Directorate supports a large number of atmospheric and space plasma activities.
- The National Aeronautics and Space Administration (NASA) supports space and astrophysical plasma research diffusely as part of the science component of its satellite missions. NASA also supports a small program in laboratory astrophysics whose focus on atomic, molecular, and optical spectroscopy has some overlap with plasma science.

DEPARTMENT OF ENERGY

DOE's support for plasma science is dominated by its investments in the areas of inertial confinement fusion (ICF) and magnetic confinement fusion (Figure D.1). The leading programs in these areas are at OFES and NNSA.

Office of Fusion Energy Sciences at DOE

OFES in DOE's Office of Science has been a traditional steward for fusion science as well as plasma science (Figure D.2). The mission of the program is to advance plasma science, fusion science, and fusion technology—the knowledge base needed for an economically and environmentally attractive source of fusion energy.[1]

The approximately $150 million funding of the OFES science program in FY2006 included support for theory ($25 million), advanced computing ($4 million: Scientific Discovery through Advanced Computing), and research on tokamak experiments ($46 million: major facilities DIII-D in San Diego, and C-Mod

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[1] The committee extends its grateful appreciation to Al Opdenaker and Francis Thio for their expert assistance on these matters.

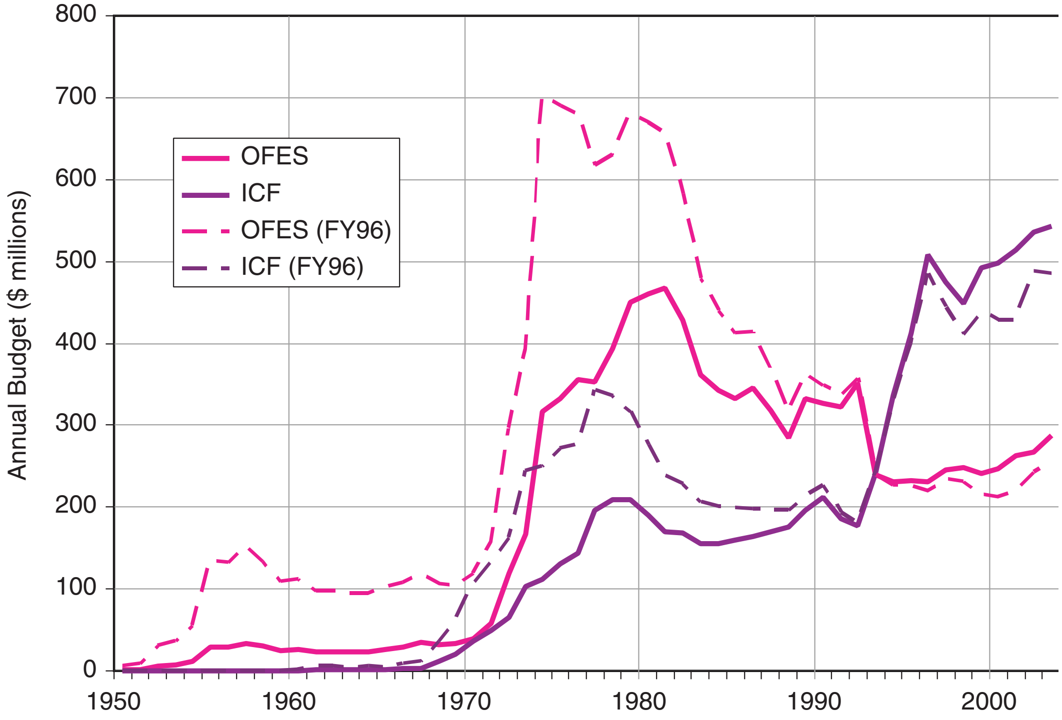

FIGURE D.1 Historical perspective on federal funding for fusion research. The dashed lines have been corrected for inflation in terms of FY1995 dollars. The OFES line represents (roughly) the total DOE/OFES annual budget (dominated by magnetic fusion); the line for ICF represents an estimate of the DOE defense program's support for inertial fusion. SOURCE: Fusion Power Associates, compiled from historical budget tables; available at http://aries.ucsd.edu/FPA/OFESbudget.shtml.

in Cambridge, Massachusetts, as well as international collaborations, diagnostics, and other activities), alternative concepts ($60 million: NSTX at Princeton, the Madison Symmetric Torus at the University of Wisconsin, and high energy density projects, plus about 10 other plasma experiments elsewhere), and general plasma science activities ($14 million).

The OFES general plasma science program supports several areas of plasma research. The Partnership for Basic Plasma Science and Engineering program is jointly sponsored by DOE and NSF, to which DOE contributed (in FY2006) $4.7 million for university research, $2.4 million for national laboratory research, $1.3 million for the Junior Faculty Development Program, and $1.1 million for the Basic Plasma Science Facility at the University of California at Los Angeles. In addition, the general plasma science program supported two recently established fusion sci-

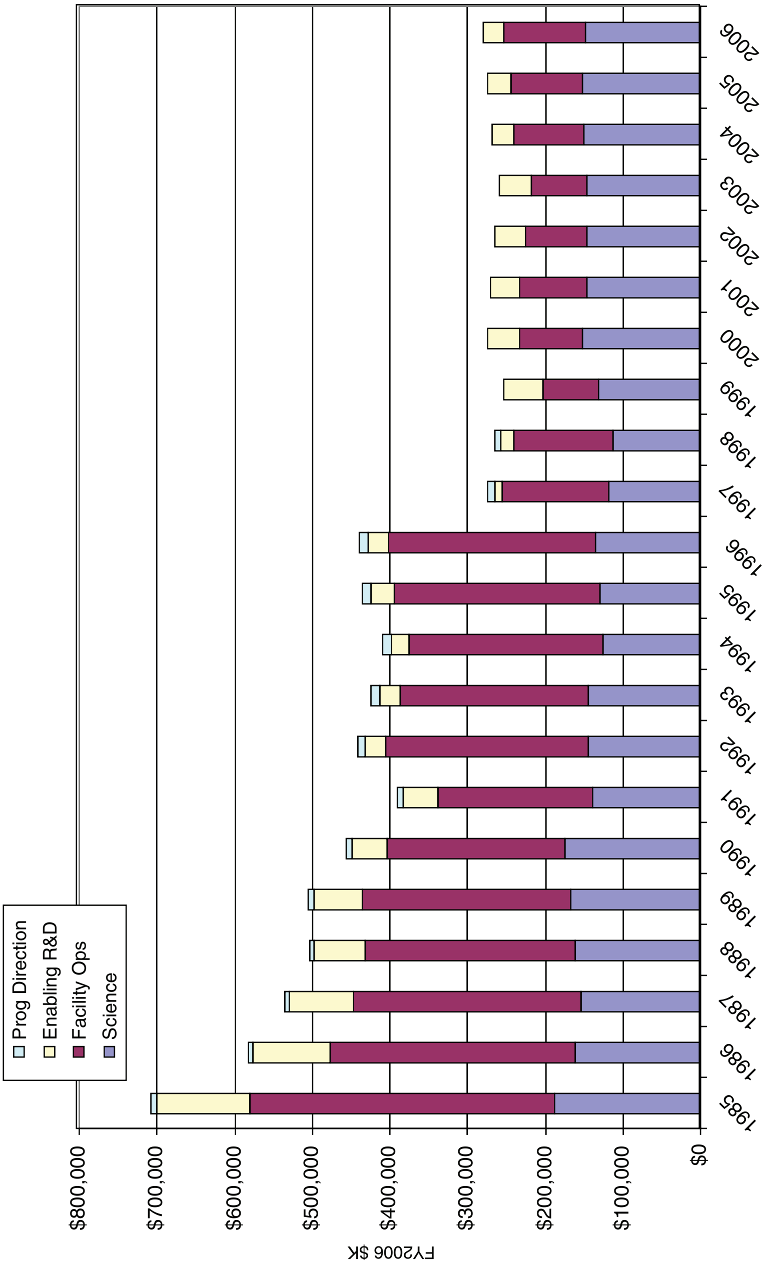

FIGURE D.2 Breakdown of the major components of the OFES annual budget, 1985-2006.

ence centers ($2.5 million: Multi-Scale Plasma Dynamics, Extreme States of Matter) and fusion-related atomic physics and several other activities ($2.1 million).

Inertial Fusion Energy and HED Physics at DOE/OFES

Planning for transitioning the OFES inertial fusion energy (IFE) program to a program addressing the HED physics issues that have potential applications to inertial fusion began in FY2003. The budget for this line of programs from FY2004 to FY2007 is as follows: FY2004, $17.3 million; FY2005, $14.7 million; FY2006, $16 million; and FY2007, $11.9 million.

Before FY2005, the OFES program was focused on the development of the heavy ion beam as a driver for IFE. In FY2004, $16.3 million was used for research in heavy-ion-driven IFE. The remaining $1 million was used to fund a small effort in fast ignition and research in the behavior of dense plasma in very high magnetic fields. In heavy-ion-driven IFE, $15.2 million was for research related to the development of the heavy-ion accelerator science, and $1.1 million was for research in the target physics and designs for heavy-ion-driven IFE. In accelerator development, there were three research components: the ion source, the transport of the beam, and the focusing and compression of the beam.

In redirecting the heavy ion research toward a program in HED physics, the goal of the program was redefined to one of developing a user facility for warm dense matter research. Research on the transport of the beam was further curtailed and concentrated on compressing and focusing the beams to increase the intensity of the beam about 100-fold. Such beam intensities are required in order to produce warm dense matter. A new initiative was launched in FY2005 with a call for research in fast ignition, plasma jets, and dense plasmas in high magnetic fields, resulting in a total funding for these subfields of HED physics of $3.4 million, leaving $11.3 million for heavy-ion-related HED physics research.

In FY2006, Congress increased the funding for fast ignition by $2 million, which included work on target physics, with a corresponding reduction in heavy-ion-beam research. Congress also added $1 million for research in dense plasmas in high magnetic fields using the Atlas pulsed-power facility. Thus the total funding for fast ignition, plasma jets, and dense plasmas in high fields was increased to $6.7 million while the funding for heavy ion beams was reduced to $9.3 million.

The President's FY2007 budget further reduced research in heavy-ion-related HED physics to $8.2 million, while the research for fast ignition, plasma jets, and dense plasmas in high fields was reduced to $3.7 million.

National Nuclear Security Administration at DOE

Established by Congress in 2000, the NNSA is a semiautonomous agency within the U.S. Department of Energy responsible for enhancing national security through

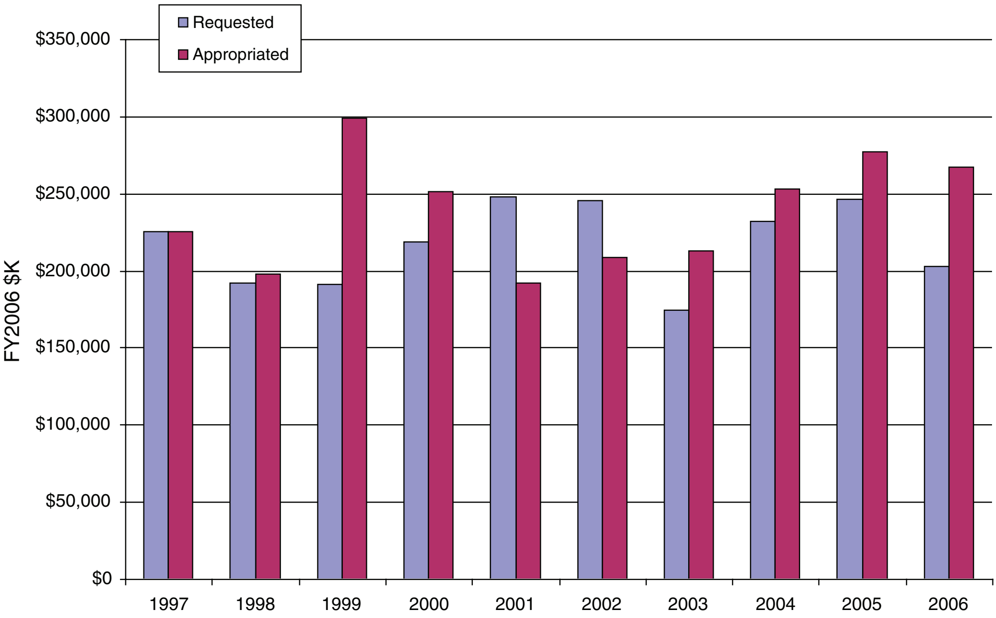

FIGURE D.3 NNSA budget for plasma and HED science, corrected for inflation, during the past decade.

the military application of nuclear energy.[2] Part of the NNSA mission is to maintain and enhance the safety, reliability, and performance of the United States nuclear weapons stockpile, including the ability to design, produce, and test, in order to meet national security requirements.

To accomplish these objectives and others, NNSA runs a series of campaigns. The most relevant ones for plasma research are the Science Campaign, which focuses primarily on certification of warhead readiness, and the Inertial Confinement Fusion (ICF) and High Yield Campaign, which focuses on developing laboratory capabilities to create and measure extreme conditions of temperature, pressure, and radiation.

As shown in Figure D.3, support for the component of the ICF and High Yield Campaign that involves plasma science (primarily HED physics) has consistently been about $200 million per year. Figure D.4 breaks out the component of that funding that supports activities at universities, including the University of Rochester's Laboratory for Laser Energetics (LLE).

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[2] The committee extends its grateful appreciation to Christopher Keane and Joe Kindel for their expert assistance on these matters.

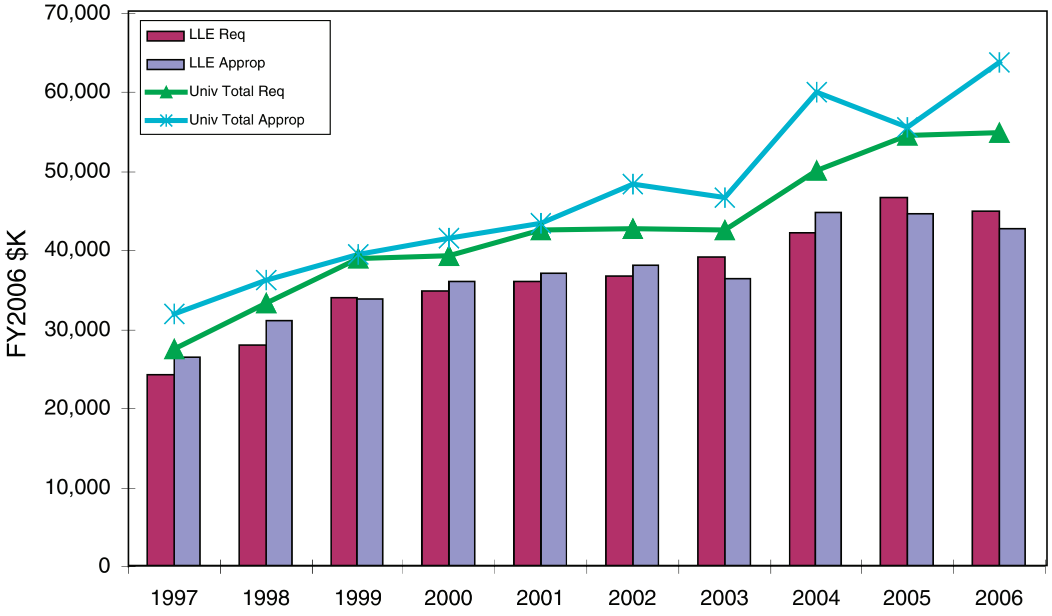

FIGURE D.4 NNSA funding for university programs, corrected for inflation, for plasma and HED science over the past decade. Funding for the LLE at the University of Rochester is shown as a portion of the overall budget.

Stewardship Science Academic Alliance at DOE/NNSA

- In FY2005, the eight awards made to individual investigators represented a total investment of $8.4 million over 3 years. One center of excellence award involved funding of $4 million projected over 2 years. The aggregate average level of annual funding will be $4.8 million.
- In FY2002, the eight awards made to individual investigators represented a total investment of $7.3 million over 3 years. Two centers of excellence awards were made (Cornell University and University of Texas) and involved $16 million over 3 years. The aggregate average level of annual funding was nearly $7 million.

Advanced Accelerator Research and Development Program at DOE/HEP

DOE's Office of High Energy Physics (HEP) manages a suite of programs supporting research into advanced accelerator concepts in support of DOE's overall mission (see Figure D.5).[3] This program has traditionally been a strong supporter

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[3] The committee expresses its grateful appreciation to Glen Crawford for his expert assistance on these matters.

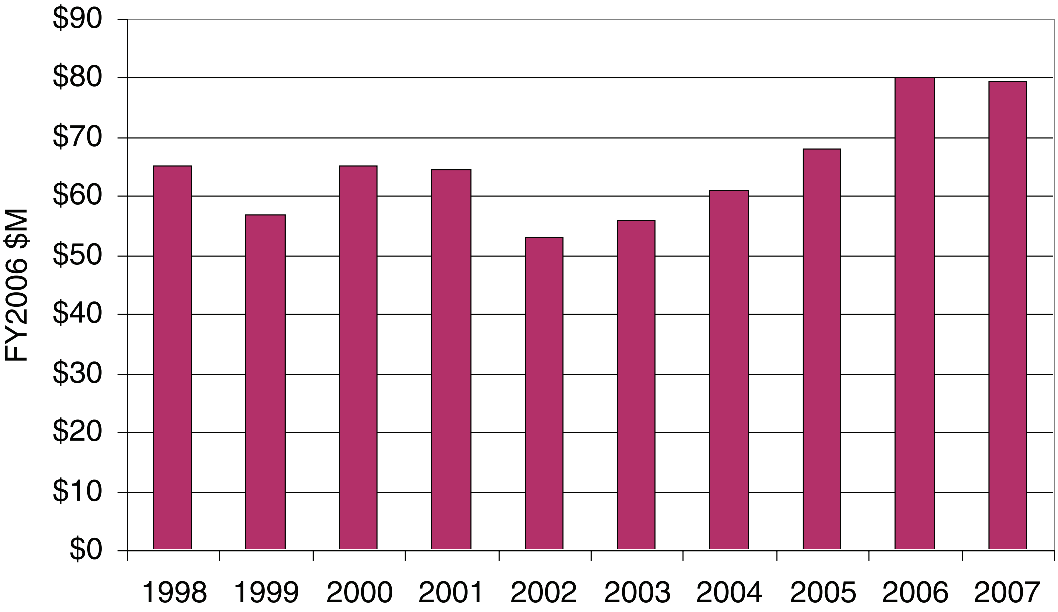

FIGURE D.5 Total funding in inflation-adjusted dollars for the DOE advanced accelerator R&D program.

of laser–plasma and beam–plasma interactions because of their potential applications to future accelerators such as the plasma-wake field accelerator described in the report. Perhaps 10 percent of this program is devoted to explicit plasma science such as wake field acceleration.

In a recent report prepared by the DOE/NSF High Energy Physics Advisory Panel (HEPAP) that examined the future directions for this program, the authoring committee wrote as follows:

> Another difference is that the European AARD activity emphasizes multi-national, multi-laboratory efforts, cross-institutional networking, and cross-disciplinary work between HEP, nuclear physics, light source, and laser acceleration laboratories. There has also been a recent flowering of ultra-high intensity, short pulse laser acceleration R&D in smaller institutes and universities, particularly in Asia. The US is rapidly being overtaken in this area, with US laser development oriented more towards NIF and related programs. With the closing of FFTB at SLAC and ensuing hiatus in the beam-based wakefield program, the US leadership in long range, plasma acceleration R&D is being effectively challenged.[4]

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[4] HEPAP, *Report of the HEPAP Subpanel on the Assessment of Advanced Accelerator Research and Development*, Washington, D.C.: Department of Energy, 2006, p. 31.

OFFICE OF NAVAL RESEARCH

The Office of Naval Research supported a strong program in plasma science although its investments were relatively modest. However, because of changing priorities at the Navy, these programs have been discontinued. In earlier years, ONR supported the following research areas:

- Basic laboratory plasma physics (1988-2002), $2.5 million/year,
- Initiatives in microwaves (1982-1987), $1.0 million/year,
- Initiative in particle beams (1982-1987), $1.0 million/year,
- Basic research in nonneutral plasma (1994-2002) at $1.5 million/year, and
- Advanced accelerator research at $2 million/year for 5 years.

Taken together, ONR's investments represent more than $60 million over nearly 20 years.

NATIONAL SCIENCE FOUNDATION

The NSF has traditionally supported plasma research in a number of different programs because the science cuts across many disciplines. For instance, the study of basic plasma science has traditionally been directed by NSF's Physics Division while much of the low-temperature plasma science and engineering work has been overseen by its Engineering Directorate. Space plasma science has been strongly supported by NSF's Geosciences Directorate. To some extent, NSF's participation in the NNI has provided some additional connections between plasma science and the core programs.

Engineering

NSF's Engineering Directorate is undergoing some reorganization but the Combustion, Fire, and Plasma Systems program has traditionally been a source of limited support for plasma research (Figure D.6).[5]

The committee notes that aside from the NSF engineering support for low-temperature plasma science, there is no other stable support for this research. The NSF/DOE partnership for basic plasma science invests only modestly in low-temperature research, and participation in that program has been decreasing.

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[5] The committee expresses its grateful appreciation to Phillip Westmoreland and Geoffrey Prentice for their expert assistance in these matters.

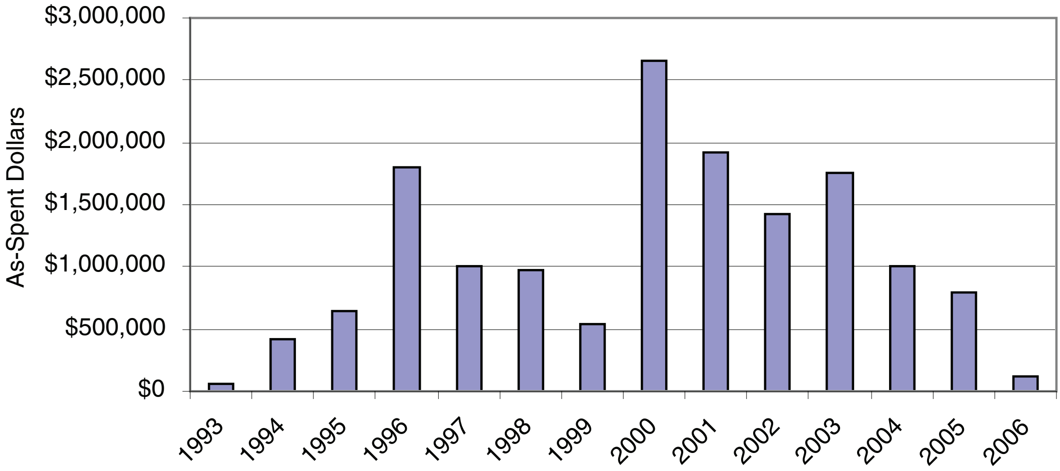

FIGURE D.6 Support from the NSF Engineering Division for low-temperature plasma engineering research over the past decade. Data for 2005 and 2006 are estimates.

DOE's Office of Basic Energy Sciences does not support low-temperature research except for several grants that cross over into chemistry.

Astronomy

The NSF Astronomy Division occasionally participates in the NSF/DOE Partnership for Basic Plasma Science and Engineering. Space and astrophysical plasma research also figures in its general university grant portfolio. Based on an informal analysis of the FY2006 program, it was estimated that the program included about $4 million of research support that was plasma science per se.[6] By comparison, the entire FY2006 budget for traditional single-investigator programs was about $39 million; thus explicit plasma science represents about 10 percent of the portfolio.

In terms of involvement in the NSF/DOE partnership, the Astronomy Division records show the following: FY2006, $137,000; FY1999, $250,000; FY1998, $250,000; and FY1997, $250,000.

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[6] The committee extends grateful appreciation to Nigel Sharp for his expert assistance in this regard.

Physics

Using an informal analysis of the NSF abstracts and awards database, the annual investment in plasma science through the NSF Division of Physics was tracked (Figure D.7). In addition to the individual grants program of about $3 million per year, a Physics Frontier Center was launched in 2001. Based jointly at the University of Michigan and the University of Texas, the name of its program describes its research focus: Frontiers in Optical Coherent and Ultrafast Science. NSF also launched the Physics Frontier Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas (CMSO) in September 2003. It receives about $2 million per year and encompasses activities at University of Wisconsin at Madison, the University of Chicago, the Princeton Plasma Physics Laboratory, and five other institutions. CMSO aims to investigate basic problems in plasma physics common to the laboratory and the cosmos.

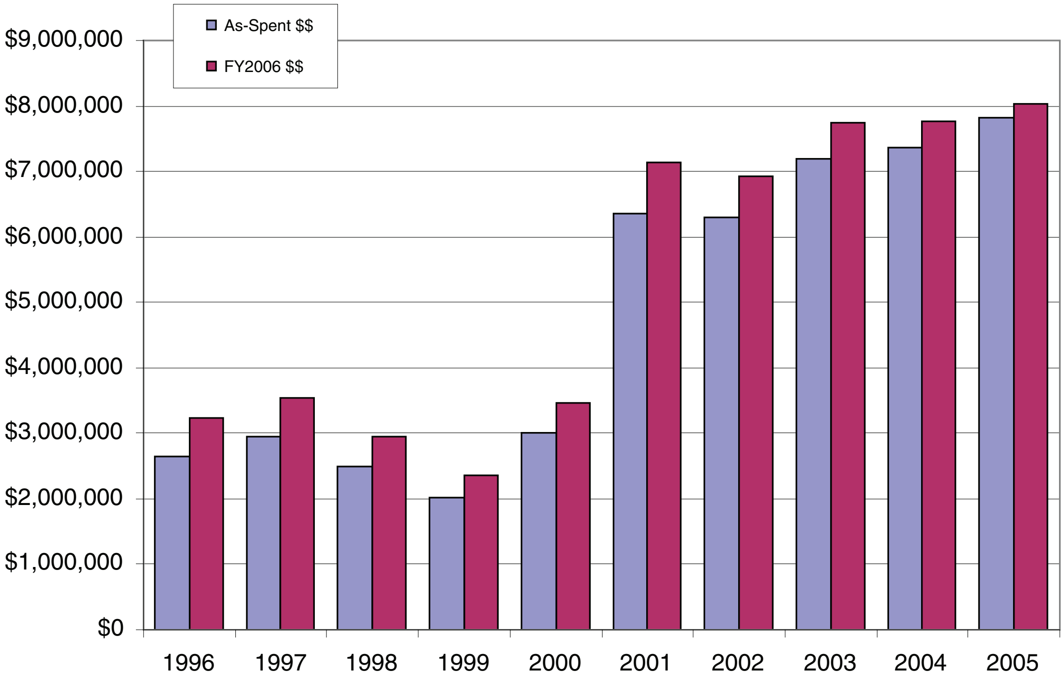

FIGURE D.7 History of support for plasma science from the NSF Division of Physics (estimated). The significant increase in FY2001 marks the beginning of the University of Michigan Physics Frontier Center. Physics Division grants made through the NSF/DOE Partnership in Basic Plasma Science and Engineering are included.

NSF/DOE Partnership in BASIC Plasma Science and Engineering

Examining the NSF abstracts and awards database, NSF's annual participation in the joint partnership with DOE for support of basic plasma science and engineering can be deduced (Figure D.8). The first grants were awarded in the fall of 1997. The three directorates most heavily involved have been Engineering, Geosciences, and Mathematical and Physical Sciences.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA supports a significant portfolio of astronomy and astrophysics research probably because at least 99 percent of the visible universe is composed of plasmas. Because the agency is organized around mission themes, however, it is difficult to estimate the fraction of NASA science programs that addresses plasma science.

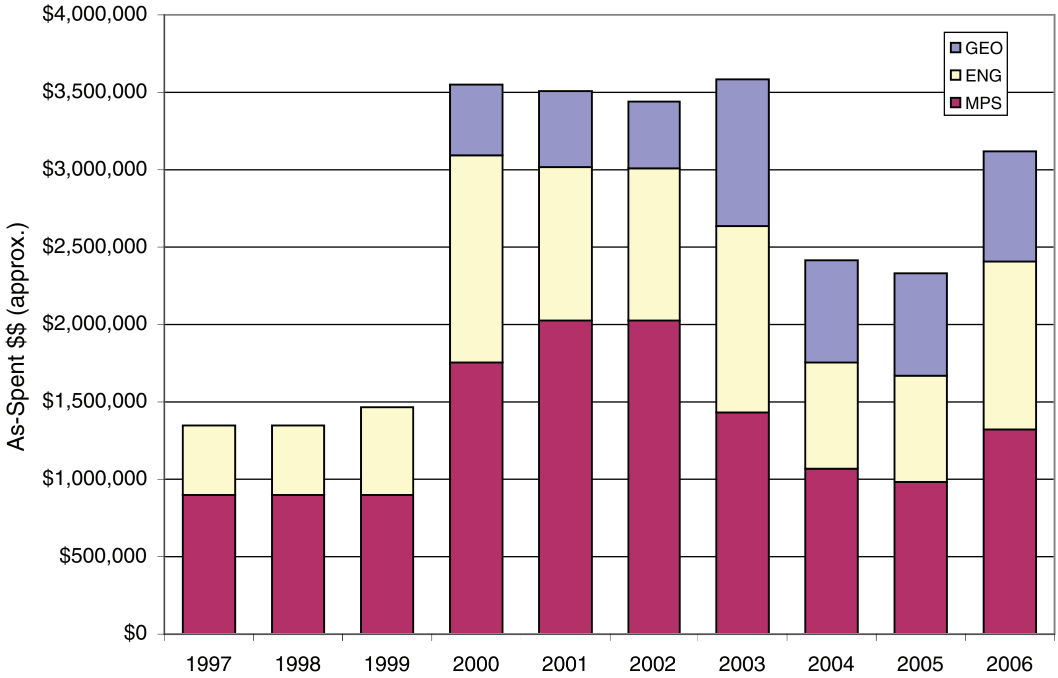

FIGURE D.8 Annual levels of participation from three directorates at NSF in the NSF/DOE Partnership for Basic Plasma Science and Engineering. The three directorates are mathematical and physics sciences (MPS), engineering (ENG), and geology (GEO).

For instance, much of space weather science is plasma science. The space and solar physics budget at NASA has been around $400 million per year, and perhaps 10-20 percent of that funding could be identified as going to plasma science, in the strict sense, and as much as half could be space-plasma research.

Because NASA does not programmatically recognize plasma science as a discipline, the committee was unable to achieve a finer level of detail.

E

Reprise of Past NRC Reports on Plasma Science

Since 1994 the National Research Council (NRC) has produced five reports examining various aspects of plasma science: the last decadal study, *Plasma Science: From Fundamental Research to Technological Applications* (1995). *Database Needs for Modeling and Simulation of Plasma Processing* (1996), *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program* (2000), *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science* (2003), *Burning Plasma: Bringing a Star to Earth* (2004), and *Plasma Physics of the Local Cosmos* (2004). In this appendix, the committee considers the impact of these reports and the response to their report recommendations. To emphasize the historical nature of the issues discussed in this report, the committee also comments on the NRC report *Plasmas and Fluids* (1986).

In the 1995 study *Plasma Science: From Fundamental Research to Technological Applications*, it was recognized that support for basic plasma science had dropped to a perilously low level. More than half of the report's principal recommendations dealt with this issue. Key facets of these recommendations were as follows:

- Emphasis should be placed on university-scale research programs.
- The National Science Foundation should provide increased support for basic plasma science.
- The Department of Energy Office of Basic Energy Sciences, with the cooperation of the Office of Fusion Energy Sciences (OFES), should provide increased support for basic experimental plasma science.
- Approximately $15 million per year for university-scale experiments should

be provided and continued in future years to effectively redress the current lack of support for fundamental plasma science.

- The allocation of funds between larger, focused research programs and individual-investigator and small-group activities should be reassessed.
- The agencies supporting plasma science should cooperate to coordinate plasma science policy and funding.
- The plasma community should work aggressively for recognition of plasma science as an academic discipline eligible for tenure.

Partly in response to recommendations made in the 1995 report, the joint NSF/DOE Partnership in Basic Plasma Science and Engineering in was created in 1997. Proposals for basic laboratory plasma research have been solicited triennially. The matter of which programs at an agency participate in the solicitation generally depends on the subject matter of the proposals submitted. At NSF, the divisions of physics, astronomy, atmospheric sciences, and several programs in engineering have been involved; at DOE, only the OFES has been involved. The joint NSF/DOE program currently operates at a funding level of approximately $6 million per year (see Appendix D for more description). This program has become an important funding source for basic plasma research in the last decade; it is responsible for much of the research progress described in this chapter. In parallel, OFES created a General Science Program to fund basic research at DOE laboratories and a very successful Young Investigator Program to fund research by junior faculty at colleges and universities. Extending the legacy cooperation in supporting laboratory plasma science, DOE and NSF recently supported the creation of the Physics Frontier Center for Magnetic Self-Organization in Laboratory and Astrophysics Plasmas, a center of excellence based jointly at the University of Wisconsin and the Princeton Plasma Physics Laboratory and involving six other institutions at the level of several million dollars per year. Programs such as these have had a strong positive influence on basic plasma science and increased connections between the fusion program and the broader scientific community.

During the same period (1995-2006), a vital and effective program for basic plasma research at the Office of Naval Research at the level of $4 million per year was terminated owing to changing U.S. Navy priorities. In some ways, however, emerging programmatic support at DOE's NNSA (e.g., the Stockpile Stewardship Academic Alliance program) has helped offset this loss by providing stewardship for the growing area of laboratory explorations of HED plasmas.

The NSF/DOE Partnership in Basic Plasma Science and Engineering has been effective in terms of important research progress as measured, for example, by publication in *Physical Review Letters*. It has also contributed greatly to the production of new scientific and technical personnel for the field as measured by the production of Ph.D.'s in plasma science. It has made important connections with other areas of science and has achieved greater recognition of plasma science by the broader scientific community. The program has been a very effective vehicle in providing support for the research being done by tenure-track faculty.

The success of this program is limited by the relatively small funding base and a triennial funding cycle in which unfunded proposals must generally wait 3 more years for reconsideration. In the latest round of solicitations, only 20 percent of the proposals were funded, with the average grant size being $100,000 per year.

The 1995 report also had some specific comments about low-temperature plasma science. Many positive science and technology trends foreseen at that time have in fact been realized:

- Cathodes and sheaths are the subject of collaborative efforts around the world.
- A U.S. research consortium investigated the sources of infrared radiation (waste energy) from high-intensity discharge lamps.
- The use of plasmas for air and water treatment continues to grow.
- Plasma propulsion has grown enormously, well beyond the expectations of the 1995 report.

Other predictions and trends have been more ambiguous:

- Large-scale computation, though having had considerable impact, has not had as wide a role as anticipated, nor have methods to tailor models of the electron-energy distribution for higher efficiency.
- The historical importance of gas lasers, isotope separation, and magnetohydrodynamics to the field was highlighted, but there were few predictions about the future. In fact, there has been little research in these fields outside the classified work by the national laboratory communities.

The conclusions and recommendations of the 1995 report are still quite relevant:[1]

- “Research in low-temperature plasma has decreased substantially, primarily because the largest source of funding, the federal government, has had a shrinking budget for such activities in the last several years.” There are few agencies or programs today within the U.S. government to which proposals for basic low-temperature science can be submitted, virtually the only one being the relatively modest NSF/DOE Partnership. This program awards a few millions of dollars every 3 years. During the last solicitation, only a

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[1] NRC, *Plasma Science: From Fundamental Research to Technological Applications*, Washington, D.C.: National Academy Press, 1995, pp. 1-3.

few funded projects addressed low-temperature plasmas of technological interest.

- "Research has also been adversely affected by the recent recession and a general move of large U.S. companies to divest themselves of manufacturing." This trend continues today. Only the highest-value research and manufacturing are not being moved offshore.
- "The panel recommends that one agency within the government be given the responsibility for coordinating research in low-temperature plasma science." Today, no U.S. government agency is charged with stewardship of low-temperature plasma science and engineering.

In the spring of 1994, the Plasma Science Committee and the Committee on Atomic, Molecular, and Optical Sciences of the NRC established a panel to organize and conduct a workshop on database needs in plasma processing of materials. The report of that workshop was published in 1996 as *Database Needs for Modeling and Simulation of Plasma Processing.* The primary purpose of the workshop was to bring together experts to develop a prioritized list of database and diagnostic needs based on their potential impact on plasma-processing science and technology. At the time, plasmas in one form or other were used in about 30 percent of all semiconductor manufacturing processing steps, and about the same fraction of processing equipment is plasma-based in a typical microelectronics fabrication facility. An important trend accompanying this growth in the industry is the fact that the capital cost of constructing a new microelectronics fabrication facility is similarly escalating and is now on the order of $1 billion or more. Estimates are that as much as 60 percent of this capital cost has been for processing equipment, including plasma equipment.

The report contains a host of findings, conclusions, and recommendations. Little specific progress at the federal level has occurred, although recent interagency discussions on database needs have resumed. In part, the report found that federal funding agencies should make greater and more systematic efforts to support development of an improved database for plasma modeling and that a spectrum of plasma models should be developed for a variety of uses. The committee also recommended that at least one data center should be established to archive, evaluate, and disseminate the existing and future database for models of plasma materials processing in integrated circuit manufacturing.

The 2000 report *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program* considered the effectiveness of the OFES science program. The key recommendations of this report are these:

- Achieving scientific understanding should be a recognized goal of the program.

- The scientific isolation of the field should be reduced.
- New fusion science centers should be created at universities.
- The fusion community should develop the case for and support a burning plasma experiment.
- The NSF should expand its role in sponsoring general and fusion plasma science.
- Fusion energy and fusion energy science should be reviewed periodically by an external panel.

The report also recognized the growing predictive capability in fusion science.

The response to this report was good but not complete—indeed, the committee revisits some of the same issues in this report. The establishment by OFES of two fusion science centers and the funding of the NSF Physics Frontier Center at Wisconsin have greatly increased connections to universities and reduced scientific isolation. As is discussed in greater detail below, the case for a burning plasma experiment was developed by the fusion community and articulated effectively in the 2004 report *Burning Plasma: Bringing a Star to Earth*. The mechanism for reviewing (and planning) the future strategy of the OFES program is still an issue of concern.

In *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science*, the emerging trends in HED physics were examined. The key recommendations were these:

- Increase access to NNSA facilities by external users interested in basic HED physics.
- Increase NNSA and other agency funding of HED research at universities.
- Maximize the ability of facilities to explore fundamental HED science.
- Support university-scale HED science.
- Improve the integration of computational and experimental results.
- Strengthen interagency cooperation to foster basic HED science.

The response to these recommendations has been promising. The interagency working group that was assembled charged a task force with identifying the key components of a national HED science program. While the elements have indeed been identified, the goal of providing some structure and coordination for the field has yet to be realized. In any event, the key issues in HED science are revisited and updated in the present report.

The Burning Plasma Assessment Committee (BPAC) was charged with assessing the importance of a burning plasma experiment, the readiness to perform such an experiment, DOE's plan for such an experiment, and the best strategy for making progress toward fusion energy. BPAC reported first in a letter that urged the U.S. government to rejoin ITER, the international burning plasma experiment. The key recommendations of the report *Burning Plasma: Bringing a Star to Earth* are these:

- The United States should participate in a burning plasma experiment; if possible, this should be ITER.
- The U.S. fusion program should be strategically balanced, which will require an augmentation of funding beyond ITER construction funds.
- The U.S. fusion program should make a focused effort to recruit and train a new generation of fusion scientists for the burning plasma era.
- The fusion program should undertake a prioritization process, recognizing that in order to expand burning plasma research, some facilities will have to be shut down over time and that hard choices must be made.

The response to the report has been mixed. The United States is proceeding as a partner in ITER, and plans for the U.S. role in ITER are being formulated. However, there is still no plan that outlines how facilities will evolve up to and including ITER. The strategic balancing issues identified in the *Burning Plasma* report are discussed in the final section of Chapter 4 of this report.

Plasma Physics of the Local Cosmos (2004) provides a detailed description of the scientific challenges in space plasma science. Specific recommendations are contained in the parent volume *Sun to the Earth—and Beyond: Panel Reports.* However, these are outside the scope of the present report.

The 1986 study *Physics Through the 1990s: Plasmas and Fluids* was the first NRC decadal survey of physics to explicitly include plasma science. The panel was cochaired by Ronald Davidson and John Dawson and included four separate subpanels whose membership extended beyond that of the main panel. The report identified promising research opportunities in plasma physics and made general recommendations in addition to many subfield-specific comments. Of particular note, the committee made two overarching recommendations:

- Because fundamental understanding of plasma properties precedes the discovery of new applications, and because basic plasma research can be expected to lead to exciting new discoveries, increased support for basic research in plasma physics is strongly recommended.
- The impact of plasma physics on related sciences and technology has continued to grow since the birth of modern plasma physics in the late 1950s and will continue to grow for the foreseeable future, provided a strong research base for plasma physics is maintained.

F

Committee Meeting Agendas

FIRST MEETING
WASHINGTON, D.C.
SEPTEMBER 30-OCTOBER 1, 2005

Friday, September 30, 2005

Closed Session

8:00 a.m.	Introductions —S. Cowley, J. Peoples (*Co-chairs*)
8:15	Balance and composition discussion —D. Shapero, Board on Physics and Astronomy
9:15	Welcome to the NRC —T.I. Meyer, Board on Physics and Astronomy
9:30	General discussion

Open Session

10:30	Perspectives from DOE/OFES —A. Davies, DOE Office of Fusion Energy Sciences
11:00	Perspectives from DOE/NNSA —C. Keane, DOE National Nuclear Security Administration

11:30	Perspectives from the NSF Directorate of Engineering —L. Blevins, National Science Foundation
Noon	Lunch
1:00 p.m.	Perspectives from NSF Physics Division —J. Dehmer, National Science Foundation
1:30	General discussion
2:30	Break
3:00	High-energy-density physics —D. Meyerhoffer, University of Rochester
3:45	Astrophysical plasmas —R. Rosner, Argonne National Laboratory
4:30	Burning plasma physics —R. Fonck, University of Wisconsin
5:15	Perspectives from the Office of Management and Budget —J. Parriott, Office of Management and Budget
5:45	Adjourn

Saturday, October 1, 2005

Open Session

8:30 a.m.	Low-temperature plasmas —G. Hebner, Sandia National Laboratories
9:15	Basic laboratory plasma science —C. Surko, University of California at San Diego

Closed Session

10:00	Perspectives from the last decadal survey —C. Surko, University of California at San Diego

Open Session

10:45	Space plasmas —G. Zank, University of California at Riverside (by video)
11:30	General discussion
Noon	Working lunch

Closed Session

1:00 p.m.	General discussion

2:30	Discussion of work plan —S. Cowley, J. Peoples (*Co-chairs*)
3:00	Adjourn

SECOND MEETING
IRVINE, CALIFORNIA
FEBRUARY 4-5, 2006

Saturday, February 4, 2006

Closed Session

8:30 a.m.	Welcome and plans for the meeting —S. Cowley, J. Peoples (*Co-chairs*)
9:00	Reports from writing groups
Noon	Lunch
1:00 p.m.	Reports from writing groups (continued)
4:00	General discussion
5:15	Adjourn

Sunday, February 5, 2006

Closed Session

9:00 a.m.	Discussion
Noon	Lunch
1:00 p.m.	Discussion
4:30	Adjourn

THIRD MEETING
WASHINGTON, D.C.
MAY 6-7, 2006

Saturday, May 6, 2006

Closed Session

9:00 a.m.	Welcome and plans for the meeting —S. Cowley, J. Peoples (*Co-chairs*)

9:15	Reports from writing groups: findings and recommendations
12:15 p.m.	Lunch
1:15	Reports from writing groups
3:15	Break

Open Session

3:30	Discussion of strategies for crosscutting government initiatives National Nanotechnology Initiative —T.I. Meyer/M.H. Moloney Physics of the Universe Interagency Working Group —P. Looney, Brookhaven National Laboratory (by phone) HED Task Force/Working Group —R. Davidson, Princeton University (by phone)

Closed Session

4:45	Discussion of Chapter 1 —S. Cowley (*Co-chair*)
5:30	Discussion of findings and recommendations
6:30	Adjourn

Sunday, May 7, 2006

Closed Session

9:00 a.m.	Convene, plans for the day; objectives for breakouts —S. Cowley, J. Peoples (*Co-chairs*)
9:15	Discussion of report findings and recommendations
10:00	Discussions
12:15 p.m.	Lunch
1:00	Discussion
4:30	Adjourn

FOURTH MEETING
WASHINGTON, D.C.
NOVEMBER 11-12, 2006

Saturday, November 11, 2006

Closed Session

8:30 a.m.	Welcome and plans for the meeting —S. Cowley, J. Peoples (*Co-chairs*)
8:45	General discussion
Noon	Lunch
1:00 p.m.	General discussion
6:30	Adjourn

Sunday, November 12, 2006

Closed Session

8:30 a.m.	Convene
9:00	General discussion
Noon	Lunch
1:00 p.m.	General discussion
3:00	Adjourn

G

Biographical Sketches of Committee Members and Staff

COMMITTEE MEMBERS

Steven C. Cowley, *Co-chair*, earned his Ph.D. from the Department of Astrophysical Sciences at Princeton University in 1985. Following his graduation he served as a lecturer at Corpus Christi College at Oxford University and as a senior scientific officer at the U.K. Atomic Energy Authority (Culham Laboratory). He then returned to the United States to work at the Princeton Plasma Physics Laboratory and later accepted a professorship at the University of California at Los Angeles (UCLA). Since 2001, Dr. Cowley has also been a professor at Imperial College London at the Blackett Laboratory. His research interests at Imperial include fusion theory; plasma and atomic theory associated with x-ray laser development; space and astrophysical plasmas; and multiphoton processes. Dr. Cowley served in 1997 on the Fusion Energy Sciences Advisory Committee (FESAC) International Thermonuclear Experimental Reactor (ITER) physics review panel. He has served as a member of the organizing committee for the annual Sherwood Fusion Theory meeting and as chair of the NRC Plasma Science Committee (1999-2001). Dr. Cowley was also a member of the NRC Physics Survey Overview Committee, which produced the overview volume for the Physics in a New Era decadal physics survey and was a member of the NRC's Burning Plasma Assessment Committee. Dr. Cowley is a fellow of the American Physical Society (APS) and the Institute of Physics (IOP), the recipient of a number of awards for excellence in teaching at UCLA, and the recipient of a number of fellowships, including the Harkness Fellowship and the Charlotte Elizabeth Proctor Fellowship.

John Peoples, Jr., *Co-chair*, is director emeritus of Fermilab and a member of the Fermilab Particle Astrophysics Center. Currently, he is project director of the Dark Energy Survey, an astrophysics project that plans to measure the dark energy and dark matter content of the universe. He received his Ph.D. in physics in 1966 from Columbia University. Subsequently he served on the faculties of Columbia University and Cornell University. He joined the Fermilab staff in 1972 and during the next 17 years served in a succession of management positions. During that time he led the construction and commissioning of the Fermilab Antiproton Source, which completed the transition of the Tevatron into an antiproton-proton collider. He was appointed director in 1989 and director emeritus in 1999. Between 1998 and 2003 he served as director of the Sloan Digital Sky Survey. He is a fellow of the APS and the American Association for the Advancement of Science (AAAS). He served on the executive committee of the APS Division of Particles and Fields and was its chair in 1984. He served on the executive committee of the APS Division of Physics of Beams and was its chair in 1999. He was a member of the High Energy Physics Advisory Panel from 1976 until 1980 and again from 1984 through 1985. He was a member of the International Committee for Future Accelerators from 1990 to 1997 and served as chair from 1993 until 1997. He served on the NRC Committee on the Physics of the Universe that produced *Connecting Quarks with the Cosmos*. He received the Distinguished Associate Award in 1995 from the Secretary of Energy for his work as director of Fermilab and he received the Distinguished Service Award from the Directorate for Mathematical and Physical Sciences of the National Science Foundation (NSF) in 1999.

James D. Callen, a fusion plasma theoretician, is D.W. Kerst Professor Emeritus of Engineering Physics and Physics at the University of Wisconsin in Madison. He received his Ph.D. from the Massachusetts Institute of Technology (MIT) in 1968 in the applied plasma physics option of nuclear engineering, on Atomic Energy Commission (AEC) and NSF fellowships. Subsequently, he held an NSF postdoctoral fellowship at the Institute for Advanced Study, Princeton, taught at MIT (1969-1972), did research at Oak Ridge National Laboratory, where he was head of the Fusion Theory Section (1975-1979), and then moved to the University of Wisconsin at Madison (UW-Madison) in 1979. He has taken sabbaticals at the Joint European Torus fusion laboratory near Abingdon, England, and Princeton Plasma Physics Laboratory. Dr. Callen established UW-Madison's Center for Plasma Theory and Computation in 1988 and directed it until 2005. His research interests are in developing and applying plasma theory and computation to present plasma confinement experiments, and fusion reactor design studies. He has served on and chaired a large number of Department of Energy (DOE) fusion review panels. For example, he established the fusion-community-wide Transport Task Force in 1988 and led it for its first 3 years. Also, he chaired the Scientific Issues Subcommittee of the DOE's FESAC, whose work and recommendations provided the technical justification and impetus for the 1996 major restructuring of the fusion program to focus on science. His honors include a Guggenheim Fellowship, a DOE Distinguished Associate Award, a Fusion Power Associates Distinguished Career Award, and a UW-Madison Vilas Associate Award and Byron Bird Award for a research publication. He is a past chair (1986) of the Division of Plasma Physics of the APS and a fellow of the APS and the American Nuclear Society. He was elected to the National Academy of Engineering (NAE) in 1990 for his pioneering work in the development of models of neutral beam heating, tokamak discharge macroscopics, and anomalous (turbulent) transport in plasmas. Dr. Callen remains active in fusion research and is a principal and co-principal investigator on grants from the Office of Fusion Energy Sciences.

Franklin R. Chang-Díaz is founder and current chairman and CEO of Ad Astra Rocket Company, a Houston firm developing advanced plasma rocket technology. In 2005 Dr. Chang-Díaz completed a 25-year career as a NASA astronaut, during which he became a veteran of seven space missions. He has logged over 1,600 hours in space, including 19 hours in space walks. In 1994, in conjunction with his astronaut training at NASA, he founded and directed the Advanced Space Propulsion Laboratory (ASPL) at the Johnson Space Center, where he managed a multicenter research team developing advanced plasma rocket propulsion concepts. Dr. Chang-Díaz is the inventor and principal developer of the VASIMR engine, a high-power plasma rocket currently under development for in-space applications. He has over 30 years of experience in experimental plasma physics, engineering and high-power electric propulsion and 25 years of experience in the management and implementation of research and development programs at NASA. Dr. Chang-Díaz holds a Ph.D. in applied plasma physics from MIT and a B.S. in mechanical engineering from the University of Connecticut. Prior to his work at NASA, Dr. Chang-Díaz was involved in magnetic and inertial confinement fusion research at MIT and the Charles Stark Draper Laboratory. He is an adjunct professor of physics at Rice University and the University of Houston.

Todd Ditmire is a professor of physics at the University of Texas at Austin and the director of the Texas Center for High Intensity Laser Science. His research interests include experimental study of ultrafast high-intensity laser interactions with atoms, molecular clusters, and plasmas. He earned his Ph.D. from the University of California at Davis in 1995. He is chair of the Optical Physics section of the Optical Society of America and was a scientific delegate representative for DOE to the OECD Global Science Forum on ultrafast high-field science.

William Dorland is associate professor of physics at the University of Maryland at College Park. Dr. Dorland received his Ph.D. in astrophysical sciences from

Princeton in 1993. After working at the Institute for Fusion Studies in Austin for 4 years, he moved to Maryland in 1998. His research interest is in understanding the properties of matter at very high temperatures and the generic properties of turbulence in magnetized plasma. His principle tools are large-scale numerical codes. He is especially interested in calculating turbulence-induced heating and transport in laboratory and astrophysical systems. He has published extensively on turbulent transport in magnetic confinement fusion experiments. More recently, he has been working on understanding the energetics of accretion flows. He has a strong interest in developing new numerical algorithms to simulate plasma turbulence, which is generally characterized by very disparate time and space scales.

Walter Gekelman is a professor of physics in the Department of Physics and Astronomy at the University of California at Los Angeles (UCLA), where he has been since 1974. He has been a member of the NRC Plasma Science Committee and served on the NRC Burning Plasma Assessment Committee. He is also a fellow of the APS. He received a B.S. in physics from Brooklyn College in 1966 and a Ph.D. in experimental plasma physics at Stevens Institute of Technology in 1972. His research interests include exploring under controlled laboratory conditions fundamental plasma processes that play a major role in the behavior of naturally occurring plasmas. These include the auroral ionosphere, the magnetosphere, the solar wind, the solar corona, and the interstellar medium. Dr. Gekelman operates the Large Plasma Device at UCLA, a unique user facility dedicated to the experimental study of a broad range of plasma phenomena. At UCLA, Dr. Gekelman has developed three different plasma devices, each becoming progressively larger and more sophisticated technologically to solve problems at the frontier of basic plasma research.

Steven L. Girshick is professor of mechanical engineering and a graduate faculty member in chemical engineering and materials science, University of Minnesota. He is the editor of *Plasma Chemistry and Plasma Processing*. He was the recipient of the 2005 Plasma Chemistry Award of the International Plasma Chemistry Society, which he served as president from 2000 to 2003. Research interests include plasmas, plasma synthesis of nanoparticles and thin films, and nucleation theory. Current projects include plasma synthesis of superhard nanoparticle coatings, thermal plasma chemical vapor deposition of thin films, and particle nucleation in low-pressure plasmas. The types of plasmas of interest to Dr. Girshick range from atmospheric-pressure thermal plasmas to low-pressure nonequilibrium plasmas. He is particularly interested in the nucleation, growth, and transport of nanoparticles in plasmas.

David Hammer is the J. Carlton Ward Professor of Nuclear Energy Engineering and professor of electrical and computer engineering at Cornell University. Dr.

Hammer worked at the Naval Research Laboratory in 1969-1976, was a visiting associate professor (part time) at the University of Maryland in 1973-1976, and was an associate professor at UCLA in 1977; in 1983-1984, 1991, and 2004, he was a visiting senior fellow at Imperial College, London. He has been a consultant to several corporations and government laboratories. Dr. Hammer has authored or coauthored more than 110 articles that have appeared in refereed journals and about 60 that have been published in refereed conference proceedings. He also holds three patents. His research is supported by the DOE Office of Fusion Energy Science, by the National Nuclear Security Administration (NNSA), and by Sandia National Laboratories. Dr. Hammer is a fellow of the APS, a fellow of the Institute of Electrical and Electronic Engineers (IEEE), and a fellow of the AAAS. He has held several offices in the Division of Plasma Physics (DPP) of the APS, including chair of the DPP in 2004, and he is presently the DPP's representative to the APS Council. His current research interests and activities center on studies of pulsed-power-driven high energy density (HED) plasmas and their applications, with emphasis on wire-array z-pinches, and on plasma measurements by optical techniques.

Erich P. Ippen is the Elihu Thomson Professor of Electrical Engineering and a professor of physics at MIT. He is also principal investigator of the optics and quantum electronics group at the MIT Research Laboratory of Electronics. He has made seminal contributions to nonlinear optics in guided media and to ultrashort laser pulse generation. Dr. Ippen discovered low-power stimulated scattering in the optical fibers used in light-wave communications and pioneered the field of femtosecond optics by generating the first pulses shorter than a picosecond and applying them to studies of ultrafast phenomena in materials and devices. His research and technical interests lie in the field of optics, with particular focus on femtosecond science and ultra-high-speed communications. Dr. Ippen is a member of the Board on Physics and Astronomy and has been involved in numerous National Academy of Sciences (NAS) and NRC activities. He is a member of the NAS and the NAE.

Mark J. Kushner is dean of the College of Engineering at Iowa State University. He received a Ph.D. in applied physics from the California Institute of Technology (Caltech). His undergraduate degrees are in astronomy and nuclear engineering. He previously served on the technical staffs of Sandia National Laboratories, Lawrence Livermore National Laboratory, and Spectra Technology and on the faculty at the University of Illinois. His research interests include low-temperature plasmas, plasma materials processing, lasers, lighting plasmas, pulsed-power plasmas, and thin films. He consults for a number of laboratories and businesses. He is the recipient of numerous awards, including the Technical Excellence Award from the Semiconductor Research Corporation. He is a fellow of the Optical Society of

America, the APS, the IOP, and the IEEE. Dr. Kushner has served on many NRC committees.

Kristina A. Lynch is an associate professor of physics and astronomy at Dartmouth College. Her research interests include auroral space plasma physics; ionospheric and mesospheric sounding rocket experiments; instrumentation and data analysis; and wave–particle interactions in the auroral ionosphere. Dr. Lynch leads the Lynch Rocket Lab at Dartmouth, where her team studies the structure and dynamics of auroral acceleration. Their work involves utilizing sounding rocket missions to look at variations in auroral precipitation; studying the FAST auroral satellite data set, which allows statistical investigations of the auroral processes; and developing a large calibration/plasma vacuum chamber for characterizing particle detector responses to the auroral plasma. She received her Ph.D. in 1992 from the University of New Hampshire.

Jonathan E. Menard, Princeton Plasma Physics Laboratory (PPPL), received the Presidential Early Career Award for Scientists and Engineers in 2004. He is an experimental plasma physicist who works primarily on the National Spherical Torus Experiment (NSTX) at PPPL. Dr. Menard's research interests include the linear and nonlinear magnetohydrodynamic (MHD) stability properties of spherical torus (ST) plasmas, advanced operating scenarios in the ST, plasma startup, and wave physics. After receiving a bachelor's degree in nuclear engineering from UW-Madison in 1992, Dr. Menard went on to receive a master's degree in 1994 and a Ph.D. in 1998 from Princeton University, Department of Astrophysical Sciences. He conducted postdoctoral research at PPPL before joining the research staff in 1999. Among his honors, Dr. Menard was a recipient of the Kaul Prize in 2006, received the "Best Student Paper" award from the American Nuclear Society Fusion Energy Division in 1998, the Princeton University Honorific Fellowship in 1996, and the DOE Magnetic Fusion Science Fellowship in 1993. The PPPL is funded by the DOE and managed by Princeton University.

Lia Merminga is director of the Center for Advanced Studies of Accelerators at the Thomas Jefferson National Accelerator Facility. She received her B.S. in physics from the University of Athens, Greece, in 1983, and then attended the University of Michigan, where she received her Ph.D. in physics in 1989. She worked at the Stanford Linear Accelerator Center from 1989 to 1992 prior to joining the Accelerator Division at the Jefferson Lab as a staff scientist. Her research interests include advanced accelerator systems and nonlinear dynamics, with a recent focus on the design and development of energy recovery radio-frequency linear accelerators and their applications to high-power, free-electron lasers, synchrotron radiation sources, and electron-ion colliders for nuclear and particle physics. In 2005 she cochaired the first international Workshop on Energy Recovery Linacs. She has taught courses at the U.S. Particle Accelerator School and is currently serving on several machine advisory committees, as well as on the editorial board for *Physical Review Special Topics—Accelerators and Beams*. Dr. Merminga is a fellow of the APS.

Eliot Quataert is associate professor of astronomy at the University of California at Berkeley and is the director of Berkeley's Theoretical Astrophysics Center. He is also a member of the Center for Multiscale Plasma Dynamics, a DOE-funded science center. His primary research interests include studies of compact objects, high-energy astrophysics, and galaxies. Dr. Quataert earned his Ph.D. in astronomy from Harvard University in 1999 and was a postdoctoral fellow in the School of Natural Sciences at the Institute for Advanced Study for 2 years before going to Berkeley. He has received the Alfred P. Sloan Fellowship and a Packard Fellowship for Science and Engineering.

Timothy J. Sommerer is a physicist at General Electric's Research Center in Niskayuna, New York. His research interests are the simulation and application of low-temperature plasmas, particularly where it is necessary to integrate scientific disciplines ranging from the electronic structure of atoms and molecules to chemical kinetics and the properties of both inorganic and organic materials. For the past 8 years he has led various interdisciplinary global research teams. He served on the executive committee of the APS Gaseous Electronics Conference for 7 years, including a 4-year rotation at its chair. He received his Ph.D. from the University of Wisconsin at Madison in 1990, has authored 21 journal papers, and has been awarded four U.S. patents.

Clifford M. Surko, University of California at San Diego, is developing techniques to accumulate, store, and manipulate large numbers of positrons and to make state-of-the-art cold positron beams a reality—in essence, to make low-energy antimatter in the laboratory. His group is also interested in using these collections of antimatter to study a number of scientific topics. He conducted the first study of electron-positron plasmas and a number of precision studies of the interaction of positrons with atoms and molecules. The positron traps that he developed are now used in a variety of applications, including positron-atomic physics and the formation of cold antihydrogen. Dr. Surko's previous research includes studies of waves and turbulence in tokamak plasmas using novel laser scattering techniques that he and his colleagues developed. Dr. Surko served on the NRC Burning Plasma Assessment Committee and was co-chair of the NRC Panel on Opportunities in Plasma Science and Technology, which prepared the last decadal survey.

Max Tabak is associate program leader for HED physics target design in the Fusion Energy Program, Physics and Advanced Technologies, at Lawrence Livermore National Laboratory (LLNL). His research interests include inertial fusion, hydrodynamics, fast ignition, transport of intense particle beams, HED physics, and radiation transport. Dr. Tabak's current research centers on designing proof-of-principle, fast-ignition experiments for the OMEGA/EP and NIF lasers. He received a B.S. in physics from MIT in 1970 and a Ph.D. in experimental elementary particle physics from the University of California at Berkeley in 1975 studying meson resonances. He is the associate editor for inertial fusion for *Nuclear Fusion*. He is a fellow of the APS and a 2006 recipient of its Excellence in Plasma Physics Award. Dr. Tabak was a 2005 recipient of the Edward Teller medal of the American Nuclear Society and is currently a Teller Fellow at the LLNL.

NRC STAFF

Donald C. Shapero received a B.S. from MIT in 1964 and a Ph.D. from MIT in 1970. His thesis addressed the asymptotic behavior of relativistic quantum field theories. After receiving the Ph.D., he became a Thomas J. Watson postdoctoral fellow at IBM. He subsequently became an assistant professor at American University, later moving to Catholic University and then joining the staff of the National Research Council in 1975. Dr. Shapero took a leave of absence from the NRC in 1978 to serve as the first executive director of the Energy Research Advisory Board at the Department of Energy. He returned to the NRC in 1979 to serve as special assistant to the president of the National Academy of Sciences. In 1982, he started the NRC's Board on Physics and Astronomy (BPA). As BPA director, he has played a key role in many NRC studies, including the two most recent surveys of physics and the two most recent surveys of astronomy and astrophysics. He is a member of the APS, the American Astronomical Society, the AAAS, and the International Astronomical Union. He has published research articles in refereed journals in high-energy physics, condensed-matter physics, and environmental science.

Timothy I. Meyer is a senior program officer at the NRC's Board on Physics and Astronomy. He received a Notable Achievement Award from the NRC's Division on Engineering and Physical Sciences in 2003 and a Distinguished Service Award from the National Academies in 2004. Dr. Meyer joined the NRC staff in 2002 after earning his Ph.D. in experimental particle physics from Stanford University. His doctoral thesis concerned the time evolution of the B-meson in the BaBar experiment at the Stanford Linear Accelerator Center. His work also focused on radiation monitoring and protection of silicon-based particle detectors. During his time at Stanford, Dr. Meyer received both the Paul Kirkpatrick and the Centennial Teaching awards for his work as an instructor of undergraduates. He is a member of the APS, the AAAS, the Materials Research Society, and Phi Beta Kappa.

Michael H. Moloney is a senior program officer at the NRC's National Materials Advisory Board. A materials physicist, Dr. Moloney did his Ph.D. work at Trinity College, Dublin, and received his undergraduate degree in experimental physics at University College, Dublin, where he was awarded the Nevin Medal for Physics. Dr. Moloney has served as a study director for various activities at the National Materials Advisory Board (NMAB), the Board on Physics and Astronomy (BPA), the Board on Manufacturing and Engineering Design (BMED), and the Center for Economic, Governance, and International Studies (CEGIS). Associated reports include *Controlling the Quantum World: The Science of Atoms, Molecules, and Photons; Connecting Quarks with the Cosmos; Funding Smithsonian Scientific Research; Frontiers in High Energy Density Physics; Burning Plasma: Bringing a Star to Earth; Globalization of Materials R&D; A Matter of Size: Triennial Review of the National Nanotechnology Initiative;* and *Analyzing the U.S. Content of Imports and the Foreign Content of Exports.* In addition to his professional experience at the National Academies, Dr. Moloney has more than 7 years experience as a foreign service officer for the Irish government and served at the Irish embassy in Washington, the Irish mission to the United Nations in New York, and the Department of Foreign Affairs in Dublin in that capacity.