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SUMMARY

Plasma Science
Advancing Knowledge in the National Interest

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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SUMMARY

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

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Preface

The National Research Council convened the Plasma 2010 Committee in mid-2004, with substantial input from the Plasma Science Committee, to prepare a new decadal assessment of and outlook for the broad field of plasma science and engineering. Support for the project was graciously 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 aimed at realizing these opportunities; the complete charge is reproduced in Appendix A. In addressing its charge, the committee maintained an optimistic and “demand-side” perspective, focusing its work on identifying the most compelling scientific opportunities and the paths for realizing them. Decadal surveys each face a strong urge to fall into a discussion about the need for funding or 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 those in other parts of the world. However, this committee 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 and astrophysics, and basic plasma science), but also several experts from outside plasma science enlisted by the National Research Council 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 in the *Physics 2010* series, a project undertaken by the NRC’s Board on Physics and Astronomy. Each volume examines a subfield of physics and assesses its status and frames an outlook for the future.

Because of the length of the committee’s full published report (about 250 pages), the committee will also make available an extract that includes only the front matter, the Executive Summary, and the first chapter, entitled “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 subfield 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 and the organization of federal support for plasma science (see Appendix D for a short summary) as well as past NRC reports on plasma science; a brief reprise is 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, including Massachusetts Institute of Technology, Princeton University, University of Wisconsin, Naval Research Laboratory, University of Rochester, Sandia National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, University of California at San Diego, General Atomics, and so on. The committee appreciates the time and effort expended by its hosts in each of these visits; the discussions were enlightening and invaluable. The committee also held a series of town-hall meetings in coordination with conferences of the various professional societies, including meetings of the American Physical Society's Division of Plasma Physics and Division of Atomic, Molecular, and Optical Physics, the University Fusion Association, the American Geophysical Union, the IEEE International Conference on Plasma Science, the American Vacuum Society, 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 different responses were received that 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 to prepare this report. Their shrewd questions and creative suggestions substantially elevated the level of our discussions. Finally, we also thank 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
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Jonathan S. Wurtele, University of California at Berkeley
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.

Contents

The contents of the entire report,
from which this summary is extracted,
are listed below.
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APPENDIXES

Executive 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, 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.

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 growth in 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 federal plasma science portfolio as currently organized is not equipped to exploit optimally. These are fundamental low-temperature plasma science, discovery-driven high energy density plasma science, intermediate-scale plasma science, and cross-cutting 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 stronger than ever.

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

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 expand well beyond the present mission and purview of the Office of Fusion Energy Sciences. It would include a broader portfolio of plasma science as well as the research OFES currently supports. Included in this portfolio would be two new thrusts: (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 within the Office of Science.

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

- 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;
- 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.

CHAPTER 1

Overview

plas·ma: `'plaz-m&` (*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.**

1.1. 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 (see Figure 1.1).

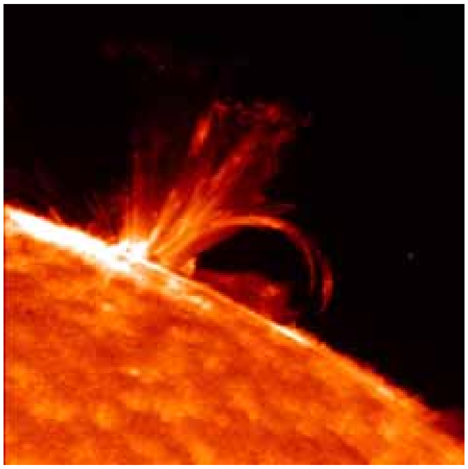

Figure 1.1. Exploding plasma on the Sun. X-ray image of one of the most dramatic of natural phenomena, the solar flare, caused by the sudden destabilization of the magnetized plasma in the sun's outer atmosphere (the corona). The eruption is lifting plasma above the sun's surface. The bright lines are 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.

One of the great achievements of plasma science is to show that the bewildering variety and complexity of plasmas is understandable in terms of some very elemental ideas that bind the field together (see 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, a lot in common with many areas of modern complex system research ranging from climate modeling to condensed matter studies. Indeed, plasma scientists have played a pivotal role in the development of nonlinear dynamics and chaos theory that have a multitude of applications to complex systems.

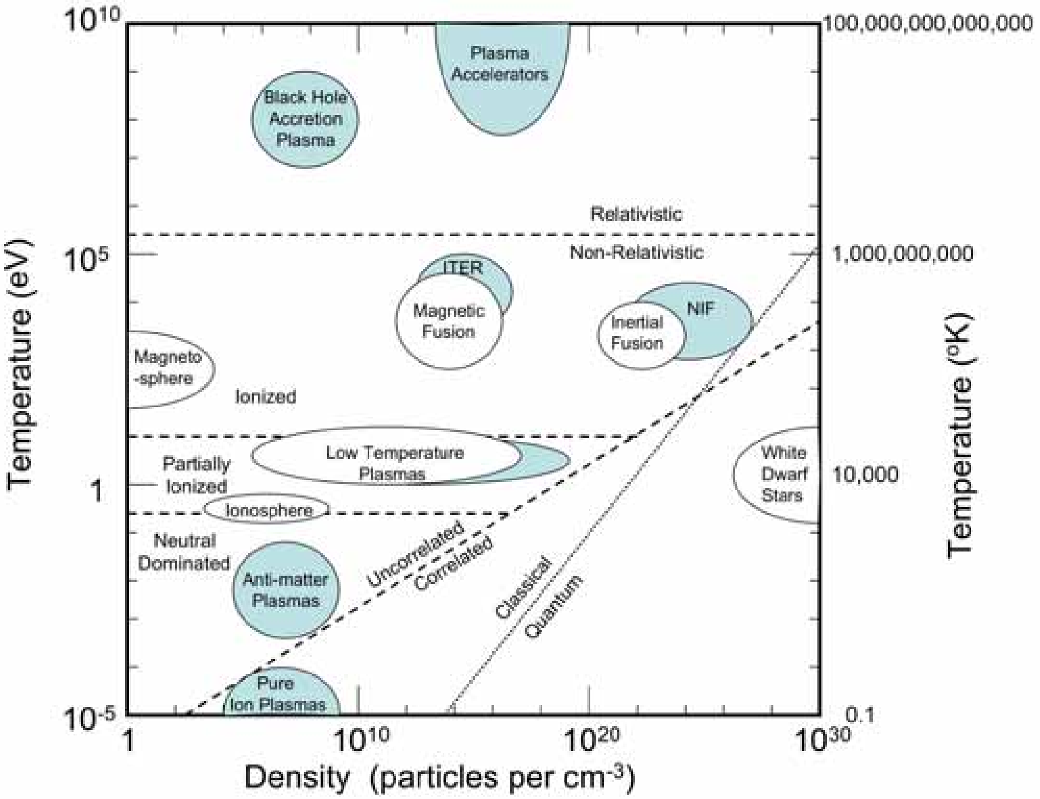

Figure 1.2. New Regimes – New Physics. Plasma science is expanding into new territory and discovering new phenomena. Diagram shows some of the range of plasma phenomena. Regimes that are new areas of study since 1990 are indicated in blue (including the future regimes of NIF— National Ignition Facility—and ITER, the international magnetic fusion experiment).

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 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. A detailed analysis is contained in five chapters representing the subfields of low-temperature plasma science and engineering; high-energy density plasma science; magnetic fusion plasma science; space and astrophysical plasmas; and basic plasma science. The remainder of this chapter summarizes key issues raised by this analysis. The next section (Section 1.2) 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 Section 1.3. While these examples by no means constitute a comprehensive survey, they give a flavor of the breadth and depth of the field. Section 1.4 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 Section 1.5, and they appear repeatedly in the topical chapters. Section 1.6 presents the major conclusions and the central recommendation of this report.

1.2. 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 progress 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.

1. **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. Micro-electronics devices simply would not exist in their advanced state if not for the tiny features etched onto semi-conductor wafers by plasma tools. Surfaces of materials are hardened,

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[1] See, for example, the recent National Academies report, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* Washington, D.C.: National Academies Press, 2006.

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 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.)

2. **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 as an alternate energy resource should remain a priority for the nation. The challenge of fusion (the fusing of hydrogen nuclei to make helium nuclei, neutron, and energy) is that it requires plasmas with temperatures greater than that of the center of the Sun. Plasma science has made great strides controlling and confining such plasmas (see Chapter 4 for a discussion of the science). The international experiment ITER (see Section 1.3.3.), 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 alternate paths to fusion is also proceeding rapidly. In the meantime, plasma science has contributed to near-term innovations in energy efficiency. For example, there are more than one billion light sources in operation in the United States using 22 % 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 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).
3. **National security:** High energy density plasma science is central to Science-Based Stockpile Stewardship—the program that ensures the safety and reliability of the nation's nuclear stockpile. The study of high energy density 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 National Ignition Facility (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.

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[2] Alfonso Velosa III, "Semiconductor Manufacturing: Booms, Busts, and Globalization," presentation to National Academy of Engineering, September 2004.

These facilities and experiments are central to the stockpile stewardship program (see Chapter 3 for 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 biohazards are answering homeland security needs. Atmospheric pressure plasma sources are being employed as “plasma hoses” to decontaminate surfaces after a chemical spill or attack.

4. **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. 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, currents in the cosmic plasma must create the magnetic field that pervades much of the universe. But it is not known when these fields and currents first appeared in the universe or how they were generated (see 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]

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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% 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*, Washington, D.C.: U.S. Department of Energy, 2004 (DOE/SC-0086) and E. Scime, K. Gentle, 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.]

01—Plasma TV
02—Plasma-coated jet turbine blades
03—Plasma-manufactured LEDs in panel
04—Diamondlike plasma CVD eyeglass coating
05—Plasma ion-implanted artificial hip
06—Plasma laser-cut cloth
07—Plasma HID headlamps
08—Plasma-produced H_2 in fuel cell
09—Plasma-aided combustion
10—Plasma muffler
11—Plasma ozone water purification
12—Plasma-deposited LCD screen
13—Plasma-deposited silicon for solar cells
14—Plasma-processed microelectronics
15—Plasma-sterilization in pharmaceutical production
16—Plasma-treated polymers
17—Plasma-treated textiles
18—Plasma-treated heart stent
19—Plasma-deposited diffusion barriers for containers
20—Plasma-sputtered window glazing
21—Compact fluorescent plasma lamp

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, the use of plasmas. The result is an improvement in our quality of life and economic competitiveness.

Sidebar 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.

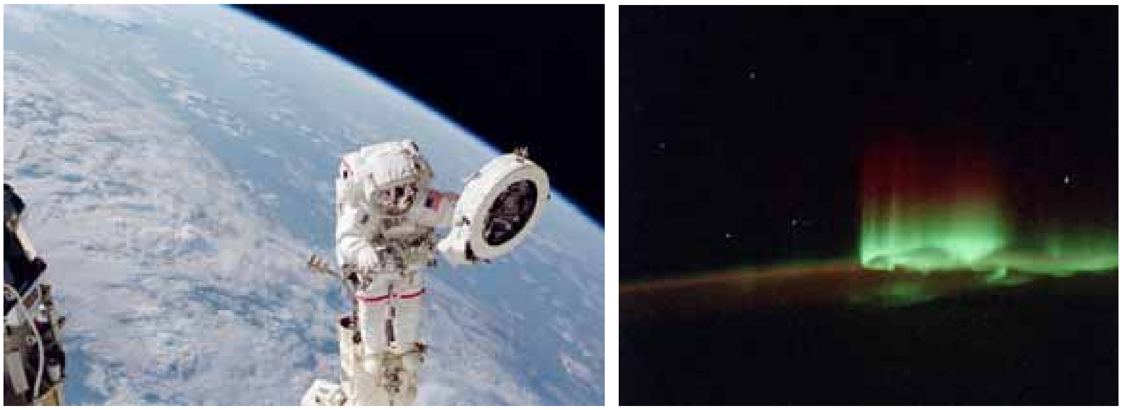

Figure 1.1.1. LEFT: Committee member Franklin Chang-Diaz conducting assembly tasks outside the International Space Station (ISS) in June 2002. Courtesy of NASA. RIGHT: Aurora Australis photographed during a spacewalk on mission STS 111 in June of 2002. The ISS routinely flies through the auroral plasma. Courtesy of NASA.

The plasma environment surrounding the space station is itself a hazard since electrons from the plasma charge up the structure. The space station's pressurized modules 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 has significant daily variations as the spacecraft moves from equatorial to polar regions and during the day and night passes.

The charge buildup is neutralized (and the astronauts protected) by devices called "plasma contactors" that serve the same function as grounding rods in well-designed homes on Earth. The space station's 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.

1.3. Selected Highlights of Plasma Science and Engineering

We describe here six selected highlights from 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 sample 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 (see Section 1.5) are the common threads that weave through all these applications.

1.3.1. Biotechnology and Health Care

Sitting in dental chairs, 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 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 depositing material or modifying the surface characteristics of the material. (See Figure 1.4.)

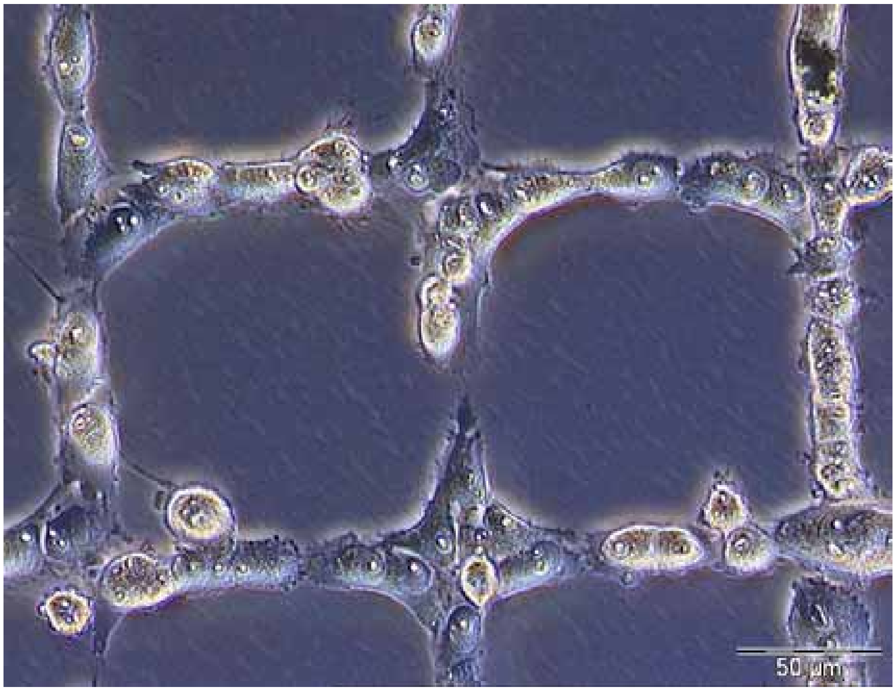

Figure 1.4. Plasmas and biology. Using low temperature, reactive plasmas, the surface of polymers may be functionalized and patterned to be cell adhering. In this example, amine functional groups were patterned on a polymer resulting in a predetermined network of adhering cells. Courtesy of A. Ohl, INP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

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 thermo-sensitive 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 ultraviolet photons can only travel line-of-sight—combined they offer further promise for developing local, efficient 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. What is emerging -- and already in some use -- are new plasma “knives” that generate nonequilibrium plasmas “streamers” (like mini lightning bolts) in conducting liquids (saline). These streamers explosively evaporate water in bubbles to cut soft tissue. Here is the convergence of almost every science theme 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 current 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 metabolic behavior of cells and trigger cell detachment.

The potential future for plasmas in healthcare might best be viewed as an analog to the use of plasmas in semiconductor manufacturing. Four-bit microprocessors were manufactured in liquid acid baths. Plasmas entered the scene and made possible eight- and sixteen-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' memory, all enabled by plasmas. If this same physical and chemical precision can be brought to plasmas in healthcare, will the benefits be any less dramatic?

1.3.2. Accelerating Particles with Plasma Wake Fields

When an electron bunch moves near 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 "wakefield" that also moves near the speed of light.

Some electrons sitting just at the back of the hole are accelerated forward towards the bunch. These "surfing" electrons can reach energies greater than the electrons in the driving bunch—this is the principle of the *plasma wakefield accelerator*. An alternate 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 wakefield accelerators is the enormous accelerating force on the electrons—currently greater than 50 GV/m or equivalently 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 wakefield acceleration (see Figure 1.5) are steering the experimental program. The standard computational 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 ultra relativistic 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 (and plasma science quite markedly) relies on all three components.

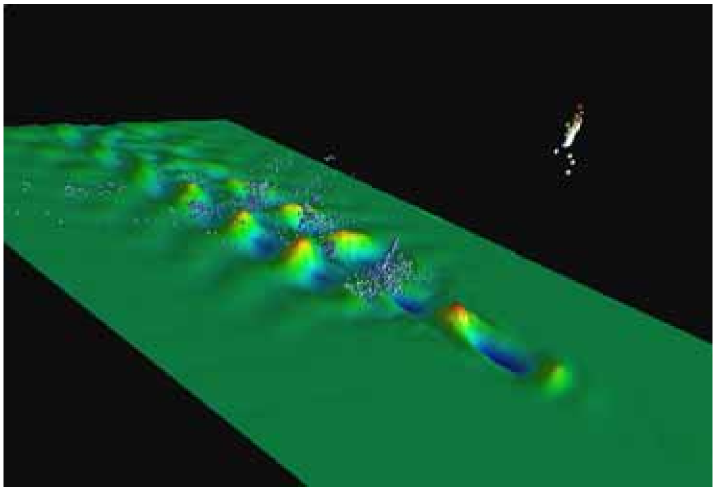

Figure 1.5. A computer simulation of laser wake field acceleration. The laser pulse is moving forward followed by a deficit of electrons, a hole in the electron density. The green sheet represents the electron density with holes colored blue and peaks red. The accelerated electrons are shown and the 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.

Continuing progress in high-energy physics is hampered by the limits set by conventional accelerator technology. The enormous accelerating fields in a plasma-wakefield accelerator suggests a path to compact accelerators at a lower cost. Such compact accelerators would have many uses as sources of both high-energy particles and photons. However, for the wakefield accelerator to be useful, the accelerated electrons must be unidirectional and have a uniform, 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 two years at the Stanford Linear Accelerator, a beam-driven plasma-wakefield 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 meter-long plasma (see Figure 1.6).

While recent progress in plasma wakefield 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?

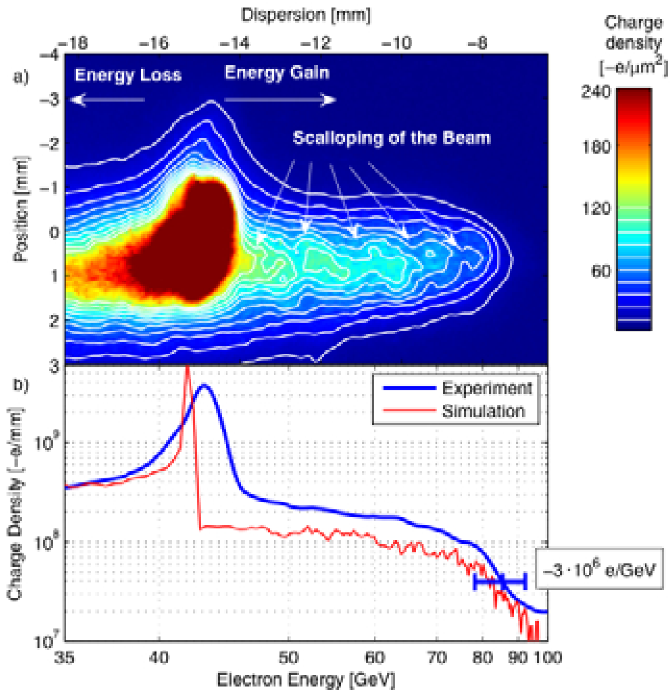

Figure 1.6. Demonstration of energy doubling of 42 GeV electrons in a meter-scale plasma wakefield-accelerator at Stanford Linear Accelerator Center. (a) The energy spectrum of the dispersed electron beam after traversing an 85 cm long, 2.7 x 10^{17} cm^{-3} lithium plasma. (b) The comparison between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

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

1.3.3. 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. (See Sidebar 1.2. entitled "Nuclear Fusion" for more details.) In the *magnetic confinement* approach to fusion, a 100-million degree deuterium-tritium plasma is contained in a magnetic bottle while 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.

Sidebar 1.2. 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. 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 corresponding to 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 energy that warms the Earth.

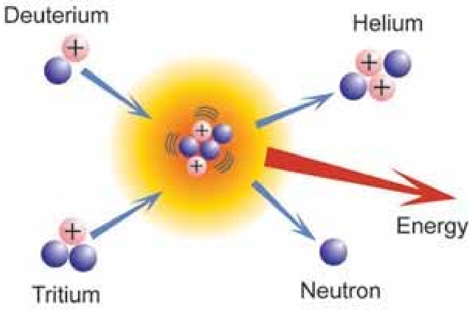

Figure 1.2.1. The Deuterium-Tritium fusion reaction. The Helium nucleus (alpha particle) is released with 3.5MeV and the neutron with 14MeV. A 1 GW power station would use 250 kg of fuel per year. Published with permission of ITER.

A principal goal of magnetic confinement fusion is to build magnetic field configurations that contain the plasma stably for long times without much leakage of heat to the walls through turbulence (see Figure 1.7). Electrons and ions spiral along magnetic field lines staying inside the plasma. The helium nucleus produced in the fusion reaction ia 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—i.e., enough to balance the heat lost through plasma collisions, turbulence, and radiation.

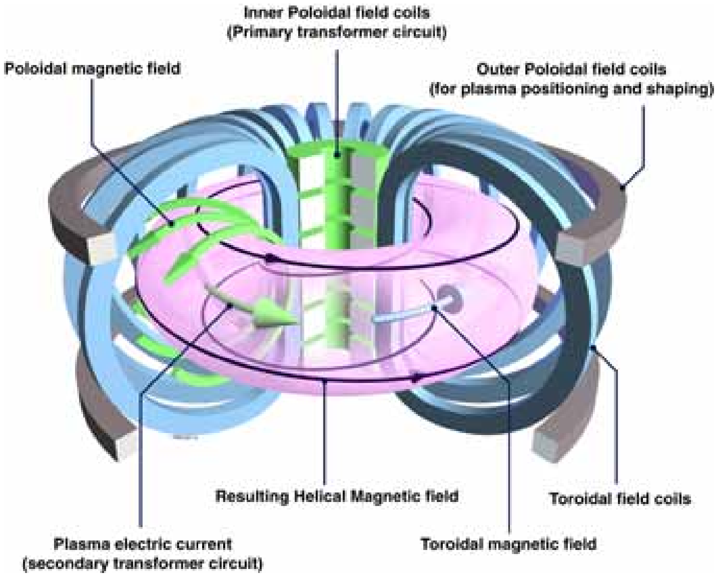

Figure 1.7. Plasma confinement in the tokamak magnetic configuration. This type of configuration has produced plasmas at fusion temperatures and densities. The confined plasma is illustrated as the semi-transparent pink donut shaped volume. This is the configuration chosen for ITER. Courtesy of the Joint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

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 TFTR and 16 MW in JET (see Figure 1.8). But neither TFTR nor JET had significant heating from the fusion alpha particles and were therefore not in the *burning plasma* regime. This was, nonetheless, a major milestone in 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. The ITER experiment is that step. ITER is a large tokamak experiment using superconducting, long-pulse magnets that is being built in southern France by an international consortium that includes the United States.[5]

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[5] The detailed argument for the United State joining this experiment was laid out in the NRC report *Burning Plasma: Bringing a Star to Earth.* A short summary of the structure of the project is given in Appendix B.

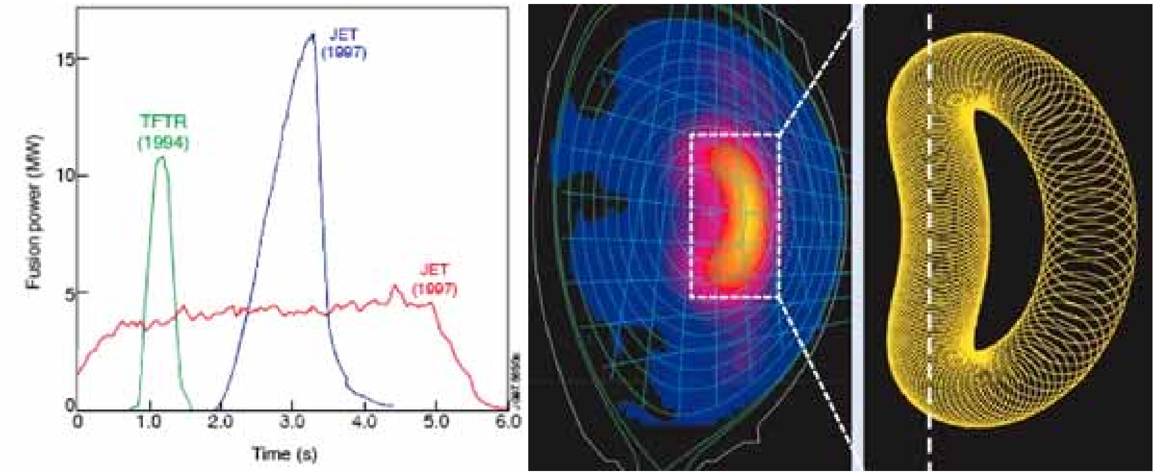

Figure 1.8. First fusion. LEFT: fusion power versus discharge time for the US experiment TFTR in 1994 and two discharges for the European experiment JET in 1997. RIGHT: confining alpha particles. Gamma rays reveal the spatial distribution and temperature of alpha particles in JET (image in center). On the far right is the calculated alpha particle trajectory. Images courtesy of the Joint European Torus (EFDA-JET).

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 megawatts 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 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.

1.3.4. Magnetic Reconnection and Self-Organization

The magnetic field protruding from the surface of the sun into the surrounding coronal plasma is impressively complex (see 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—i.e., 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 the earth's magnetosphere and in fusion experiments. However, in the last decade, processes that enable fast magnetic reconnection have been discovered and illuminated 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.

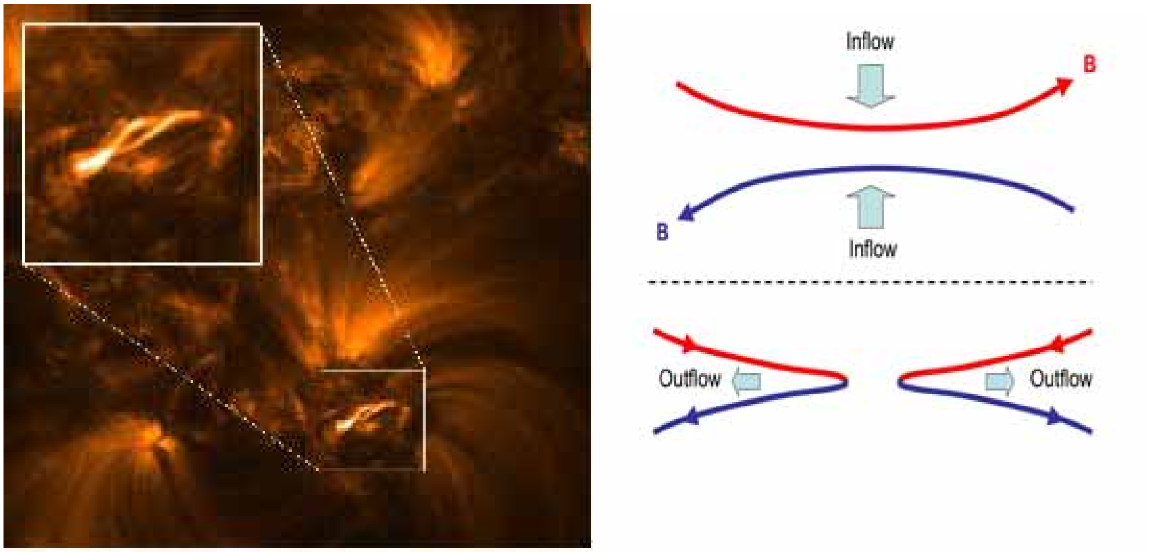

Figure 1.9. Magnetic reconnection. LEFT: Image of the sun's coronal plasma from the Transition Region and Coronal Explorer satellite (TRACE). The striations indicate the direction of the magnetic field. Sometimes TRACE observes coronal loops that are wrapped around each other (generally once, rarely 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.

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 (see Fig. 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 (see Figure 1.10) and in observations of magnetospheric reconnection.

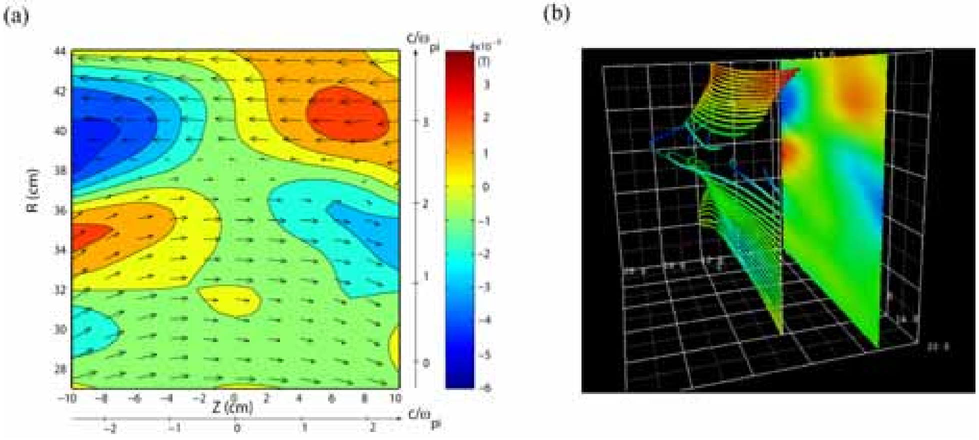

Figure 1.10. Hall mechanism for fast magnetic reconnection – the smoking gun. (a) Results from a recent laboratory experiment showing color contours of the out-of plane quadrupole magnetic field (definitive signature of the two-fluid Hall currents that produce the reconnection), superposed on vectors of the magnetic field in the reconnection region. Field lines flow in towards the line R=38 and outflows are along this line. Ion decoupling begins at a distance of about $2c/\omega_{pi}$ above and below R=38, whereas electron decoupling begins at about $\pm 0.8c/\omega_{pi}$. (b) 3D plot of reconnecting the field lines showing the way in which they are distorted; color projections are the quadrupole components. Courtesy M. Yamada, Princeton Plasma Physics Laboratory.

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 turbulence 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 sub-storms, and certain tokamak disruptions. If reconnection were always fast and effective, however, it would be impossible to store significant energy in the field. That's because reconnection would remove energy as soon as it is built up. Thus, reconnection must be triggered—but it is not known how or when. 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 major challenge—but nonetheless an exciting one. It is clear that there is an opportunity to make progress on a fundamental problem that has confounded plasma scientists for fifty years. Such progress would enhance predictive capability in a huge number of plasma applications from fusion to astrophysics.

1.3.5. Fusion Ignition in an Exploding Pellet

In 2009, the 1.8 megajoule National Ignition Facility (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 on 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 (see Figure 1.11). As is obvious to anybody who has tried to squeeze a balloon by a factor of two, squeezing a pellet by a factor of 20-30 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 high-energy density 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.

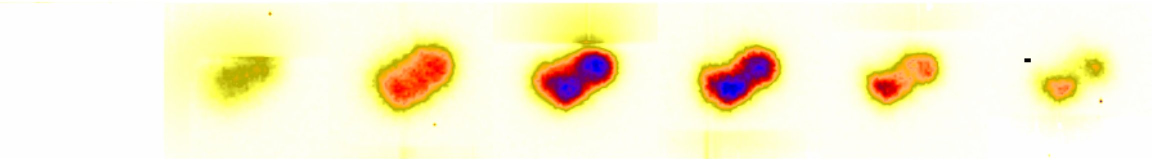

Figure 1.11. Images of the last stage of compression of a capsule (by the Omega Laser at Rochester LLE.). These x-ray images from Argon emission are spaced 35 picoseconds apart and magnified 87 times. This experiment achieved a factor of 15 compression in radius. Courtesy R.E. Turner, Lawrence Livermore National Laboratory.

The NIF will deliver its 1.8 megajoules 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 drive a central hot spot in the imploded fuel to a high enough temperature to initiate fusion reactions that will spread to the surrounding more dense 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 high energy density 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. Ultra short, 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 provide new avenues for fundamental research.

1.3.6. 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 either via its gravitational influence on surrounding matter or via the electromagnetic radiation produced when plasma falls towards the black hole and heats up as it is accelerated to nearly the speed of light (see 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. In addition to these roughly solar mass objects, there is now compelling evidence that nearly every galaxy contains a much more massive black hole at its center—these range in mass from a million to a billion solar masses.

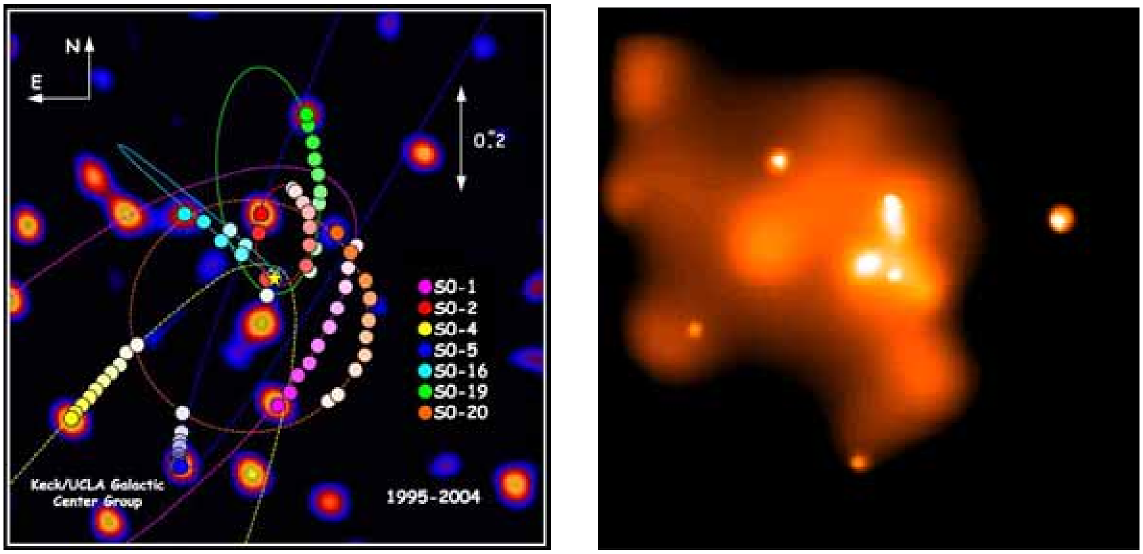

Figure 1.12. LEFT: Detecting a black hole by it's influence on the orbits of nearby stars. Infrared image of stars in the central 0.1 light-year of our galaxy, a region comparable in size to our solar system. Every star in the image has been seen to move over the past decade. For approximately a dozen stars, this motion can be well-fit 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., 2005, ApJ, 620, 744. RIGHT: Detecting the emission from plasma falling towards 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 towards the black hole, this plasma heats up and produces a bright source of radiation. The point source at the lower left of the central 3 sources is coincident with the location of the massive black hole from the left panel. Courtesy of NASA/MIT/PSU.

Accreting black holes power the most energetic sources of radiation in the universe and produce powerful outflows. The central difficulty in understanding 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 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 Figure 1.13.

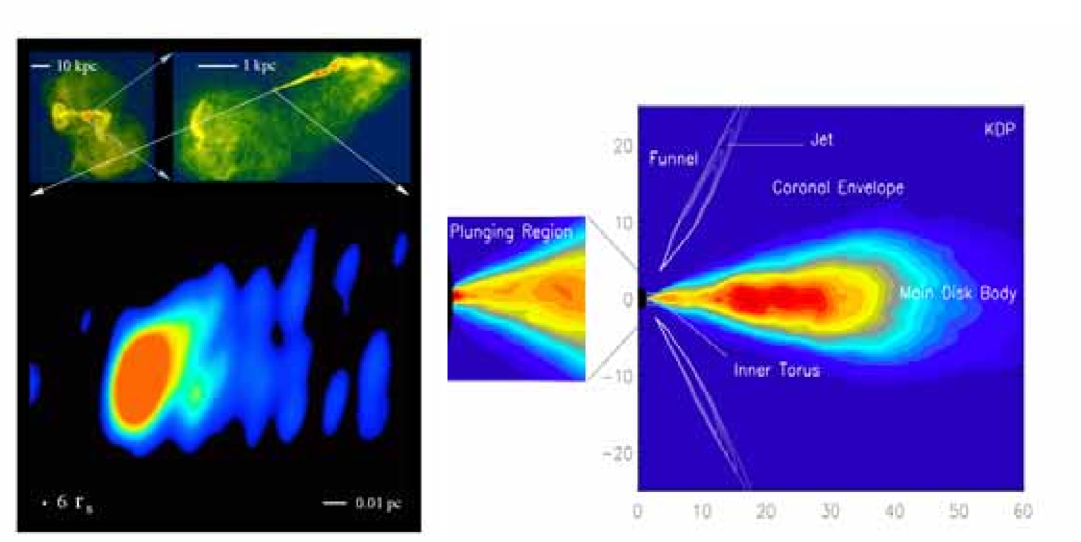

Figure 1.13. LEFT: Radio images of the galaxy M87 at different scales (1kpc = 3,260 light-years) show, top left, giant, bubble-like structures on the scale of the galaxy as a whole where radio emission is powered by relativistic outflows ("jets") from the galaxy's central black hole; top right, the jets 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 6Rs 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 / Associated Universities, Inc. / National Science Foundation; based on data from Junor, Biretta, and Livio, Nature, 401, 6756, 891. 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 inwards. In the past decade, it has been realized that magnetic fields in accretion disks are amplified by a powerful instability known as the magneto-rotational 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, both via direct images of plasma near the event horizon (e.g., the picture of M87 above) and via 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.

Sidebar 1.3. Plasma Research Goes Global

The past decade has seen an acceleration of foreign research, investment, and discoveries in plasma research. The increasing levels of foreign participation are testament 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 highly 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% foreign; *Plasma Physics and Controlled Fusion* – 78% foreign; *Physics Review E* (selecting the plasma-related articles by keyword) – 75% foreign; *Physics of Plasmas* – 39% foreign; *Plasma Sources Science and Technology* – 72% foreign; *Physical Review Letters* (selecting the plasma-related articles by keyword) – 54% foreign. Twenty years ago, the U.S. share would have been much higher.

While these results might suggest that the U.S. “market share” of plasma research is decreasing, the underlying cause is the large surge in research activities overseas. There aren’t fewer U.S. papers—there are more and more foreign ones! This exercise does tend to support the impression that the United States has a globally significant community in basic plasma science and high energy density physics.

1.4. Key Themes of Recent Scientific Advances

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

1. Plasma science is developing a significant *predictive capability*.
2. 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 previous section. More complete descriptions of the scientific advances and questions are contained in the ensuing topical chapters.

1.4.1. 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 has arisen primarily because of 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 make accurate predictions of 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 the development cost and time. Nonetheless, 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 Section 1.5. That is, the next generation of improvements in predictive capabilities will likely be driven by theoretical insights.

1.4.2. New Plasma Regimes

New facilities and experimental techniques have revealed new plasma regimes. The highly relativistic plasma physics in the beam plasma interaction at the Stanford Linear Accelerator is a good example (see Section 1.3.2). 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 micro-plasmas that blur the distinction between the solid, liquid and plasma state 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, further 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 National Ignition Facility will seek to produce a fusion burn in a pellet compressed by lasers.

1.5. 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 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, there are six critical plasma processes that are not well understood. These yield some of the great questions of plasma science. Progress on any one of these questions 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 ten to a thousand seconds. It is not understood when and how plasmas explode.
- **Multiphase Plasma Dynamics.** Multiphase plasmas—plasmas that are interacting with non-plasmas (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 with a particular color, destroying a pollutant or sterilizing a surface. A host of basic questions about these plasmas are at best partially understood.
- **Particle Acceleration and Energetic Particles in Plasmas.** In supernova shocks, laser plasma interaction, the wakes of particle beams, solar flares, and many other instances, 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 in the lab.
- **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, the sun’s turbulent plasma produces an ordered magnetic field that cycles with an almost constant 22-year period—it is not known how. 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, high energy density systems, laboratory experiments and in 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 in space/astrophysics. Other phenomena can be best understood through a series of small-scale, laboratory experiments whose objectives are to peel back the layers of complexity. Nonetheless, it is clear that much can be gained from recognizing that progress on understanding these six fundamental processes benefits a broad range of applications. Such developments in understanding will lead (via modeling and simulation) to improvements in predictive capability.

1.6. Conclusions 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 National Ignition Facility (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.

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 (see Section 1.5). Therefore, and as this report shows, plasma science is much more than a basket of applications. The committee asserts that it is important to nurture growth in 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 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 current organization of federal plasma science portfolio is not equipped to exploit optimally. These are:

- **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 High Energy Density Plasma Science.** Fueled by new large facilities and breakthroughs in technologies that have enabled access to previously unexplored regimes, our understanding of the science of high-energy density plasmas has grown rapidly.[6] Mission driven high-energy density 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) 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 emerges 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 high-energy density plasmas cannot grow inside the facilities' parent programs that are dedicated to explicit missions. However, there is no other home for this research in the present federal portfolio.
- **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 above the scale of 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.
- **Cross-cutting Research.** Federal stewardship of plasma research is disaggregated and dispersed across four main agencies—DOE, NSF, DOD, and NASA—and within those, across many offices (e.g. Magnetic Fusion in the DOE Office of Science and Inertial Confinement Fusion in 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 and the current federal structure fails to exploit them.

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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.: 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 OSTP's interagency working group on the Physics of the Universe.

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 has been 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 of the science is necessary.

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

- *Continue the current structure of federal plasma science programs unchanged.* It is apparent that many plasma science programs have been 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 current structure is impeding broad progress in plasma science.
- *Form a plasma-science interagency coordinating organization.* Interagency working groups have facilitated cross-cutting 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 in 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 may help stimulate some cross-cutting research it would not, in itself, create research initiatives in fundamental low-temperature plasma science and discovery-driven high-energy density 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.
- *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

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

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 simply create more problems than it would solve.

- *Expand the stewardship of plasma science at DOE's Office of Science*. Since the heart of the science at stake resides within DOE this option would address directly the four problems identified by the committee. As the home of many large plasma science applications (fusion, stock-pile-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) at 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 focused stewardship 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.

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 expand well beyond the present mission and purview of the Office of Fusion Energy Sciences. It would include a broader portfolio of plasma science as well as the research OFES presently supports. Included in this portfolio would be two new thrusts: (1) a non-mission-driven high-energy density 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 within 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. High-energy density 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 National Nuclear Security Administration would remain with NNSA. 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 high energy density physics.[8] Finally, current programs at NIST and NSF wrestling with 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. This planning should:

- 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;
- Identify the major risks and develop strategies to avoid them.

The committee recognizes that there is no optimal strategy without risk. Indeed, the current status quo is neither optimally nor minimally risky. Mitigation of the most obvious risks would require:

- 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 phase, however, the committee has two observations. First, NNSA's support for high-energy density science will become uncertain when NIF and Z complete their stockpile stewardship missions.

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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 high energy density physics. A report from this group is expected by mid-2007.

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 fusion-energy development, DOE's fusion science program is likely to change dramatically. The fusion-energy development effort may move outside the Office of Science. Who 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.