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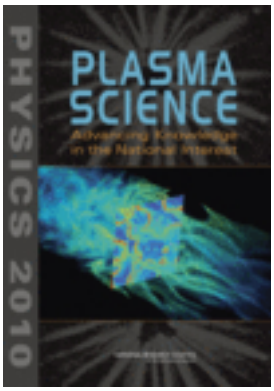

Plasma Science: Advancing Knowledge in the National Interest

Plasma 2010 Committee, Plasma Science Committee, National Research Council

ISBN: 978-0-309-10943-7, 280 pages, 7 x 10, paperback (2007)

As part of its current physics decadal survey, Physics 2010, the NRC was asked by the DOE, NSF, and NASA to carry out an assessment of and outlook for the broad field of plasma science and engineering over the next several years. The study was to focus on progress in plasma research, identify the most compelling new scientific opportunities, evaluate prospects for broader application of plasmas, and offer guidance to realize these opportunities. The study paid particular attention to these last two points. This "demand-side" perspective provided a clear look at what plasma research can do to help achieve national goals of fusion energy, economic competitiveness, and nuclear weapons stockpile stewardship. The report provides an examination of the broad themes that frame plasma research: low-temperature plasma science and engineering; plasma physics at high energy density; plasma science of magnetic fusion; space and astrophysical science; and basic plasma science. Within those themes, the report offers a bold vision for future developments in plasma science.

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.

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

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Contract No. DE-AT01-05ER54778 between the National Academy of Sciences and the Department of Energy, Grant No. PHY-0425966 between the National Academy of Sciences and the National Science Foundation, and Contract No. NNG04G-I-30G between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

Library of Congress Cataloging-in-Publication Data

National Research Council (U.S.). Plasma 2010 Committee.
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.
p. cm.
Includes bibliographical references.
ISBN 978-0-309-10943-7 (pbk.) — ISBN 978-0-309-10944-4 (PDF) 1. Plasma (Ionized gases)—Research—United States. I. Title.
QC718.6.N38 2007
530.4'4072073—dc22

2007041991

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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Printed in the United States of America

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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*
Plasma 2010 Committee

John Peoples, Jr., *Co-chair*

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,
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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.

Contents

APPENDIXES