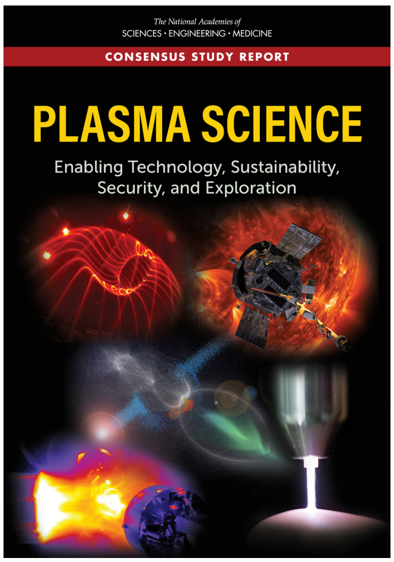
Consensus Study Report

HIGHLIGHTS

Plasma Science: Enabling Technology, Sustainability, Security, and Exploration



Plasma science and engineering (PSE) is a technological and scientific success story. Advances in plasma science support the U.S. economy and national security by enabling critical technologies that benefit society, from materials processing and healthcare to forecasting space weather. The National Academies of Science, Engineering, and Medicine was tasked to assess progress and achievements in plasma science over the past decade and to identify major science challenges and opportunities for the next decade. The resulting report, *Plasma Science: Enabling Technology, Sustainability, Security, and Exploration* also makes recommendations to improve the health of the plasma science field, covering workforce development, the role of the United States in international collaborations, and the optimum deployment of resources to meet the science challenges.

Research in the fundamentals of plasma science is primarily funded by the Department of Energy (DOE), National Science Foundation (NSF), Department of Defense (DOD), and National Aeronautics and Space Administration (NASA). However, the science and technologies enabled by plasmas and which leverage this fundamental research are critical to almost all U.S. federal agencies and departments. The interdisciplinary impact of PSE cuts across many current and proposed federal initiatives. For instance, nanoscience, advances in artificial intelligence, machine learning, and quantum-based computing are made possible by applications of plasma materials processing of microelectronics devices. Similarly, advanced accelerators will be increasingly based on plasma-laser interactions, exploration of the solar system by unmanned probes is enabled by plasma-fueled electric propulsion, NNSA's (National Nuclear Security Administration) stockpile stewardship depends on high energy-density plasmas, and predicting space weather requires understanding of the plasma filling the Sun-Earth system.

GRAND CHALLENGES OF PLASMA SCIENCE AND ENGINEERING

PSE transforms fundamental scientific research into powerful societal applications. This outstanding strength of PSE is captured in the following "PSE Grand Challenges"—high-level goals, presented without ranking, in which mastery of the complexities of plasma science benefits society:

- ***Understanding the behavior of plasmas under extreme conditions*** will enable predictive and efficient controllable energy conversion by plasmas, addressing the challenges of sustainability, economic competitiveness, and national security, while expanding our knowledge of the most fundamental processes in the universe.

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- ***Mastering the interactions of the world's most powerful lasers and particle beams*** with plasmas will enable precision X-ray imaging for medical science, advances in national security, compact particle accelerators, advanced materials and sustainable energy sources, while opening new regimes for high-energy and quantum physics.
- ***Developing fusion-generated electricity will tap the virtually unlimited fuel in seawater***, to bring the benefits of energy independence and carbon-neutral power to the nation, through economical, deployable, and sustainable fusion systems enabled by advances in experimental and computational plasma physics.
- ***Demonstrating that lasers and pulsed-power devices can produce inertially confined fusion ignition*** by producing plasma-based extreme states of matter that will support stockpile stewardship, further the goal of sustainable energy, energy independence, and expand our knowledge of high energy density physics that is so important to astrophysics and cosmology.
- ***Electrifying the chemical industry***—that is, driving chemical processing by electrical means facilitated by plasmas, by controlling the flow of power through low-temperature plasmas—will produce predictable chemical transformations in gases, solids, and liquids, on scales capable of economically establishing a future based on renewable and sustainable electricity, and addressing pandemic threats to our health through plasma sterilization of surfaces and tissue.
- ***Developing timely and actionable space-weather forecasting and nowcasting*** will enable us to mitigate the potentially damaging effects of extreme solar plasma storms on spacecraft, humans, power grids, and infrastructure.

STEWARDSHIP AND ADVANCEMENT OF INTERDISCIPLINARY RESEARCH

Fundamental research in PSE can and does rapidly translate to societally relevant technologies with benefits that cut across the missions of many federal agencies. The support for fundamental research in plasma science by several Federal agencies, and particularly by the NSF/DOE Partnership in Basic Plasma Science and Engineering, is critical to addressing the grand challenges of PSE.

The PSE community is currently divided into isolated subdisciplines. This fragmentation prevents federal agencies from taking advantage of synergies between fundamental research in the subdisciplines of PSE and applications. For example, there is enormous potential for PSE to contribute to one of society's greatest challenges—sustainability. At the NSF, this research would best be performed in the Engineering Directorate while other areas of more fundamental plasma science would find their homes in the physics directorate. This has made it difficult to develop long-term PSE strategies to address critically important challenges such as sustainability.

RECOMMENDATION: Federal agencies directly supporting plasma science and engineering and those federal agencies benefiting (or potentially benefiting) from PSE should better coordinate their activities extending into offices and directorates within larger federal agencies.

RECOMMENDATION: Federal agencies and programs within federal agencies that are separately focused on fundamental plasma research, and those that are focused on science and technologies that utilize plasmas, should jointly coordinate and support initiatives with new funding opportunities.

RECOMMENDATION: The Engineering Directorate of the National Science Foundation should, as a minimum, consistently list plasma science and engineering in descriptions of its relevant programs and consistently participate in the NSF/Department of Energy Plasma partnership.

RECOMMENDATION: More strategically, NSF should establish a plasma-focused program in the Engineering Directorate that would further engineering priorities across the board, including advanced agricultural systems, energy and environment, chemical transformation, advanced manufacturing, electronics and quantum systems.

RECOMMENDATION: Federal agencies focused on plasma research, and DOE in particular, should develop new models that support the translation of fundamental research to industry. Programs that support vital industries depending on plasma science and engineering should be developed through relevant interagency collaborations.

EDUCATION AND WORKFORCE DEVELOPMENT

There are strategic opportunities for new university faculty in PSE to address sustainability, investigate laser-plasma produced quantum effects, make space weather predictions, and explore exotic states of matter. However, the current trends in PSE demographics and hiring practices are eroding the ability of the field to meet these challenges and national priorities. A multidisciplinary approach has been at the heart of the success of the field of plasma science, while simultaneously working against its long-term vitality in academia. Faculty members investigating plasma physics are in the minority in nearly every university department containing plasma-focused faculty, which span the physical, biological, medical and agricultural sciences, and engineering, while many physics departments contain no plasma physics researchers. Maintaining and renewing faculty expertise is becoming progressively more challenging as a result of there already not being a critical mass in these departments. Many universities do not require or offer plasma physics classes for undergraduates who are the first step in filling the pipeline that leads to PSE professionals in universities, industries and national laboratories. With a significant portion of PSE faculty and researchers likely to retire in the next decade, there are opportunities and needs for refreshing the PSE workforce.

RECOMMENDATION: Federal agencies—for example, Department of Energy, National Science Foundation, National Aeronautics and Space Administration, and Department of Defense—should structure funding programs to provide leadership opportunities to university researchers in plasma science and engineering areas and to directly stimulate the hiring of university faculty.

PSE is among the least diverse of the science, technology, engineering, and mathematics fields. Rectifying this requires a diverse student pipeline and a commitment to welcome, support and retain members of under-represented groups. Increased emphasis on undergraduate research and internships in PSE, particularly at principally undergraduate institutions, will increase awareness of the field and enable a fuller, more diverse pipeline and research community.

RECOMMENDATION: Federal agencies (e.g., Department of Energy, National Science Foundation, National Aeronautics and Space Administration, and Department of Defense) should structure funding to support undergraduate and graduate educational, training, and research opportunities—including faculty—and encourage and enable access to plasmas physics for diverse populations.

THE COMPETITIVE INTERNATIONAL RESEARCH ENTERPRISE IN PLASMA SCIENCE AND ENGINEERING

U.S. research in PSE has made a broad impact over the past decade; however, international investments have outstripped U.S. funding for large fusion devices, powerful lasers, and research networks. Given such strong international investment, incremental upgrades to current U.S. facilities are insufficient to maintain leadership in the field.

RECOMMENDATION: Federal agencies (e.g., Department of Energy, National Science Foundation, National Aeronautics and Space Administration, and Department of Defense) should support a spectrum of facility scales that reflect the requirements for addressing a wide range of problems at the frontiers of PSE.

RECOMMENDATION: Federal agencies whose core missions include plasma science and engineering—for example, Department of Energy, National Science Foundation, National Aeronautics and Space Administration, and Department of Defense—should provide recurring and increased support for the continued development, upgrading, and operations of experimental facilities, and for fundamental and translational research in plasma science.

Computational plasma science and engineering (CPSE) has become essential across PSE for experiment and mission design and diagnosis, idea exploration, and prediction. For computations to continue to progress in PSE, the next generation of researchers needs to be better educated through the development of plasma-focused computational textbooks and courses, and through participation in funded computational research projects.

RECOMMENDATION: Federal agencies should support research into the development of computational algorithms for plasma science and applications for the heterogeneous device computing platforms of today and upcoming platforms (e.g., quantum computers), while also encouraging mechanisms to make advanced computational methods, physics-based algorithms, machine learning, and artificial intelligence broadly available.

SUPPORTING RESEARCH BEYOND FUSION

Following the recommendations of the Plasma 2010 report, the DOE Office of Fusion Energy Science (FES) broadened the scope of its programs to better serve the plasma science community. The title of the FES office does not now accurately reflect its broader mission, and may actually hamper collaboration within DOE and with other federal agencies on non-fusion research.

RECOMMENDATION: Consistent with our recommendations to broaden the impact of plasma science, the Department of Energy Office of Fusion Energy Science should be renamed to more accurately reflect its broader mission, and so maximize its ability to collaborate with other agencies and to garner non-fusion plasma support. A possible title is Office of Fusion Energy and Plasma Sciences.

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