The National Academies Board on Physics and Astronomy (BPA)

PLASMA SCIENCE:

ENABLING TECHNOLOGY, SUSTAINABILITY, SECURITY AND EXPLORATION

A study conducted under the auspices of the
U.S. National Academies of Sciences, Engineering, and Medicine
https://www.nas.edu/plasma

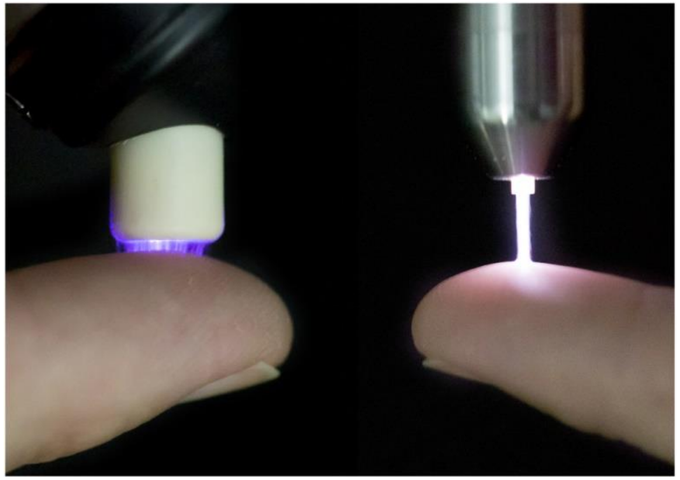
Mark J. Kushner and Gary P. Zank, Co-Chairs

Supported by DOE, NSF, AFOSR, and ONR

28 May 2020

PLASMA SCIENCE AND ENGINEERING: INTELLECTUALLY DIVERSE FIELD

- Plasma Science and Engineering (PSE) is the investigation of fundamental processes of ionized matter and translation to technologies.
- PSE is of the most intellectually diverse sciences.
  - > 10^{10} range in pressure (energy density)
  - > 10^{10} range in spatial scale.
  - Micron-sized cathode-spot plasmas that sputter metals to place thin metal films to the plasma jets that emanate from galaxies.
  - Plasmas with temperatures exceeding that of the center of the Sun to plasmas gentle enough to touch human tissue for biomedical therapies.

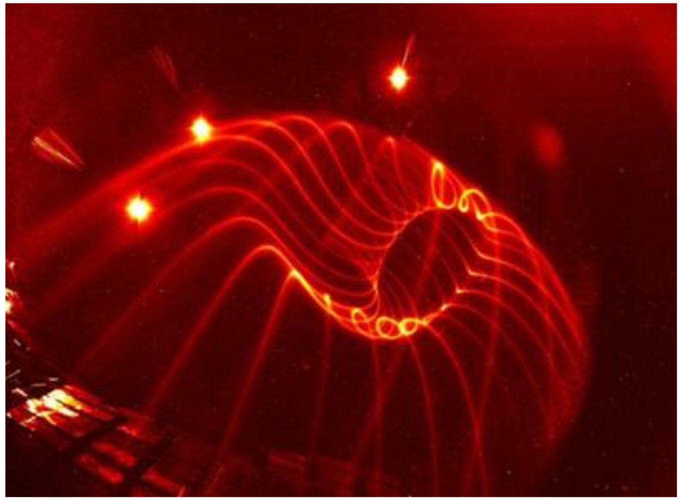


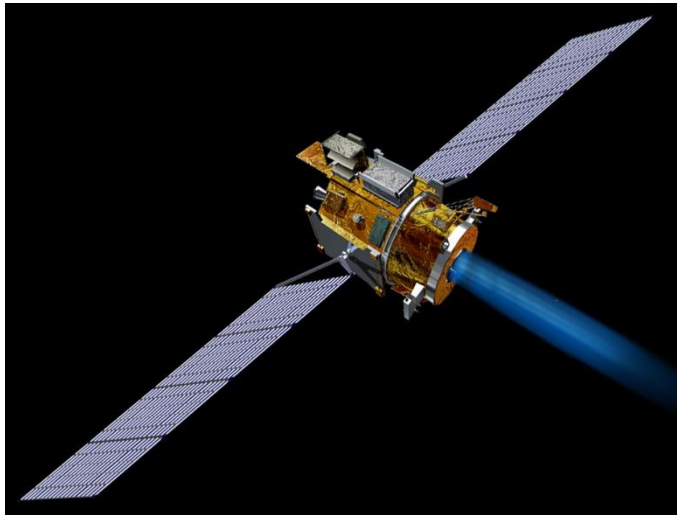
- phys.org/news/2018-03-strange-physics-jets-supermassive-black.html
- K-D Weltmann and Th von Woedtke 2017 Plasma Phys. Control. Fusion 59 014031

PSE: UNITED BY SCIENCE CHALLENGES

Despite vastly different scales and applications, common themes and scientific challenges bring cohesiveness to the PSE field.

- **Complexity arising from multiple scales and phenomena.**
- **Controlling synergistic exchanges in plasma-surface interactions.**
- **Understanding and leveraging how complex phenomena can self-organize into coherent structures.**
- **Controlling the flow of power through plasmas as means of energy and chemical conversion.**
- **Developing ever more capable diagnostics, theories, and computations to characterize this complexity.**





- Nature Communications 7: 13493
- https://photojournal.jpl.nasa.gov/catalog/PIA04242

MASTERING PSE INTELLECTUALLY DIVERSITY: SCIENCE ADVANCES AND SOCIETAL BENEFIT

Mastering the intellectual diversity of PSE advances the science frontiers and, if properly stewarded, brings societal benefit through translational research.

Enabled by PSE Today:

- **The internet, jet turbines, medical implants, lighting, solar cells, nanomaterials, and spacecraft exploring our solar system.**
- **Stockpile stewardship, hypersonic flight, understanding space weather.**
- **Magnetic fields throughout the universe to creation of states of matter that exist only in the center of stars.**
- **Exploring whether life can exist on exoplanets.**

Enabled by PSE Tomorrow:

- **Nearly unlimited carbon-free electricity**
- **Compact particle accelerators for imaging and cancer treatment;**
- **New materials, green chemical production, new modalities for medicine and agriculture,**
- **Secure management of our Nation's most strategic weaponry.**
- **Fundamental knowledge of the creation of the solar system and worlds beyond.**

STATEMENT OF TASK

As part of the Physics 2020 decadal assessment, NASEM will conduct a study of the past progress and future promise of plasma science and technology and provide recommendations to balance the objectives of the field.

- **Engage stakeholders on *the major achievements and challenges* of the past decade and *the most promising areas of plasma research* for the next ten years, and *how plasma research impacts and is impacted by adjacent areas* of S&T.**
- **Assess the progress and achievements of plasma science over the past decade.**
- **Identify the major scientific questions and new opportunities that define plasma science as a discipline, noting connections to and influence on other disciplines.**
- **Discuss the nature and importance of the U.S. in multi-national plasma research activities.**
- **Assess the scope of international research and the standing of U.S. activities.**
- **Discuss how plasma science has and will likely contribute to U.S. national needs both in and beyond plasma science, including workforce, economics, defense.**

STATEMENT OF TASK

- **Assess whether present plasma science workforce and training opportunities are commensurate with future workforce needs.**
- **Assess the role of, and future opportunities for, universities within large national programs organized around major research instruments or community assets.**
- **Assess whether the structure, program balance, and level of the current U.S. research effort in plasma science (federal and private) are best positioned to realize the science opportunities.**

The Committee's recommendations should not alter recommendations from the *Decadal Strategy for Solar and Space Physics*, the mid-decadal assessment of that report, or the *Strategic Plan for U.S. Burning Plasma Research*.

COMMITTEE MEMBERS

Mark J. Kushner (NAE), *Co-Chair,* University of Michigan
Gary Zank (NAS), *Co-Chair,* University of Alabama in Huntsville

Amitava Bhattacharjee, Princeton University
Peter J. Bruggeman, University of Minnesota
Troy A. Carter, University of California-Los Angeles
John R. Cary, University of Colorado
Christine A. Coverdale, Sandia National Laboratory
Arati Dasgupta, Naval Research Laboratory
Daniel H. Dubin, University of California-San Diego
Cameron G. R. Geddes, Lawrence Berkeley National Lab.
Gail Glendinning, Lawrence Livermore National Lab.
Daniel M. Goebel (NAE), Jet Propulsion Laboratory
David B. Graves, University of California Berkeley
Judith T. Karpen, National Aeronautics & Space Admin.
Maxim Lyutikov, Purdue University
John S. Sarff, University of Wisconsin
Adam B. Sefkow, University of Rochester
Edward E. Thomas, Jr., Auburn University

COMMITTEE THANKS THE PLASMA COMMUNITY FOR ITS PARTICIPATION

- **Committee Meetings (+ virtual meetings):**
  - **October 10-11, 2018 (Washington DC)**
  - **January 9-10, 2019 (Irvine, CA)**
  - **March 11-12, 2019 (Washington, DC)**
  - **June 20-21, 2019 (Washington, DC)**
  - **September 16-18, 2019 (Irvine)**
- **Meeting Activities**
  - **Sponsor perspectives and briefings on other studies**
  - **Congressional staff briefings on recent legislation**
  - **Presentations by researchers, lab directors, agency directors**
  - **Organizational discussions**
- **White Papers**
- **Dialogue with parallel DOE-FES CPP study.**

<u>Information Gathering Events</u>

- **November 6, 2018 –** 60th Annual Meeting of APS Division of Plasma Physics, Portland
- **January 23, 2019 –** NASA Goddard/University of Maryland
- **January 2019 –** Dusty Plasma Workshop, Germany
- **April 15, 2019 –** University of Colorado, Boulder
- **April 18, 2019 –** Princeton Plasma Physics Laboratory, NJ
- **May 16, 2019 –** Laboratory for Laser Energetics, U. Rochester
- **May 28, 2019 –** Southeastern (Huntsville, AL)
- **May 2019 –** Southern California
- **June 2019 –** Lawrence Livermore National Laboratory, California
  Lawrence Berkeley National Laboratory, California
- **June 24, 2019 –** 47th IEEE Intl. Conf. on Plasma Sciences, Florida

ORGANIZATION OF THE PLASMA 2020 REPORT

- Report emphasizes cross cutting themes, opportunities for collaborations, cross-agency initiatives in Plasma Science and Engineering (PSE)
- High level Findings and Recommendations
- F&R in chapters addressing sub-areas.

I. Introduction, Overview
   - High level status of field
   - Grand Challenges of PSE
   - Diversity, Equity, Inclusion
   - Collaborative Opportunities
   - High level Findings and Recommendations

II. Basic Plasma Physics and Computations

III. Laser Plasma Interactions

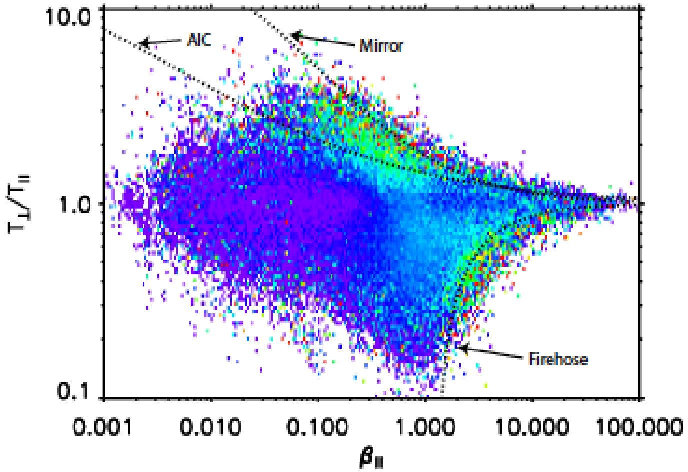
IV. High Energy Density Physics and Inertial Confinement Fusion

V. Low Temperature Plasmas

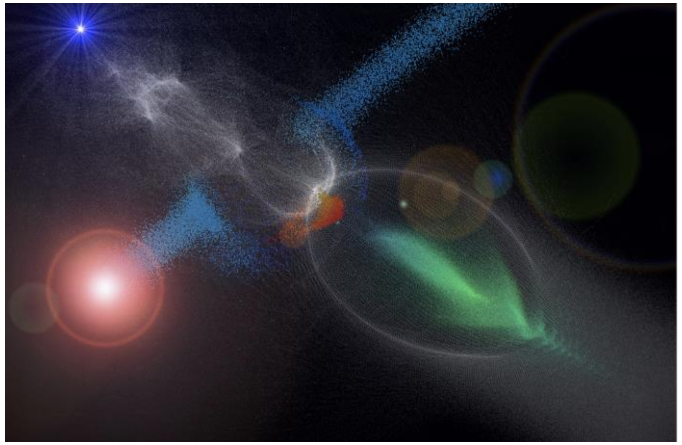
VI. Magnetically Confined Fusion

VII. Space and Astrophysical Plasmas.

GUIDING PRINCIPLES:
GRAND CHALLENGES IN PLASMA SCIENCE & ENGINEERING

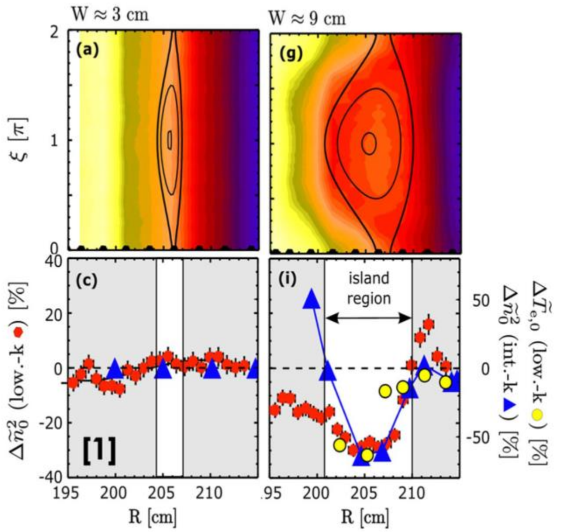


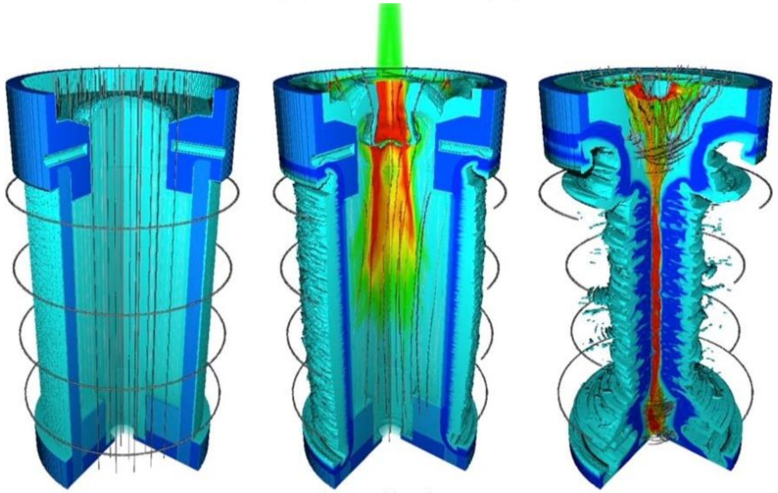
- ***Understanding the behavior of plasmas under extreme conditions*** will enable energy conversion by plasmas to be predicted and controlled, to address sustainability, economic competitiveness, and national security, and expand our knowledge of the most fundamental processes in the universe.



- ***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, materials and sustainable energy, and open new regimes for high energy and quantum physics.

GUIDING PRINCIPLES:
GRAND CHALLENGES IN PLASMA SCIENCE & ENGINEERING

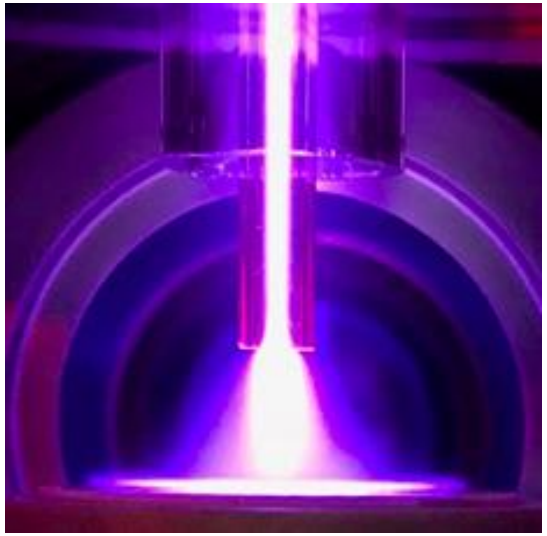




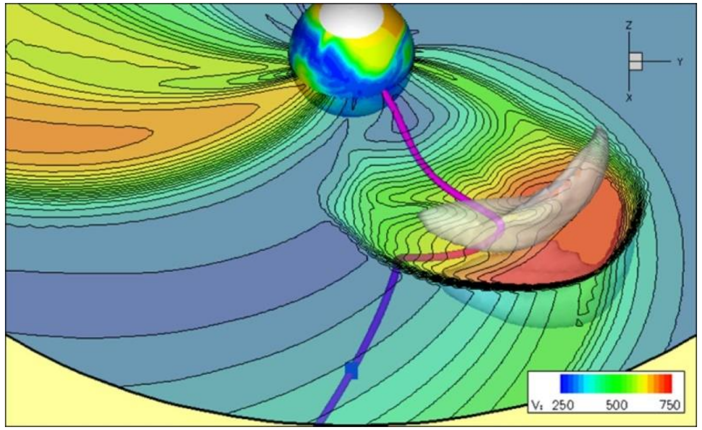
- ***Accelerate the development of fusion generated electricity*****,** tapping the virtually unlimited fuel in sea-water, to bring carbon-neutral power to society, through economical, deployable, and sustainable fusion systems enabled by advances in experimental and computational plasma physics.

- ***Demonstrate that lasers and pulsed-power devices can produce inertially confined fusion ignition*** by producing plasma-based extreme states of matter to support stockpile stewardship, further the goal of sustainable energy, and expand our understanding of high energy-density physics.

GUIDING PRINCIPLES:
GRAND CHALLENGES IN PLASMA SCIENCE & ENGINEERING



- ***Enable electrification of the chemical industry by controlling the flow of power through low temperature plasmas*** to produce predictable chemical transformations in gases, on solids, and in liquids, on scales capable of economically establishing a future based on renewable and sustainable electricity (FBRE).



- ***Develop the capability for timely and actionable space-weather observations.*** With life, technology, and space travel at risk from damaging solar plasma storms, predictions of extreme events will enable mitigation of their potential effects of on spacecraft, humans and power grids.

DIVERSITY, EQUITY AND INCLUSION (DEI) IN PSE

- ***Lack of diversity*** **in core areas of PSE – does not reflect society it serves.** Persistent problem of underrepresentation should be a high priority in the PSE community.
- ***Must increase participation*** of women, ethnic and religious minorities, gender-preference and gender-identity minorities including members of the LGBTQ+ community, and persons with disabilities, recognizing this list may not be fully inclusive of all underrepresented communities in PSE.
- ***Start at home*****:** Assess DEI practices and engage in DEI activities at primary levels in our own organizations.
- **Opportunity to improve diversity in PSE** with looming significant turnover in workforce.
- **Professional societies, universities, national academies, national laboratories, and Federal agencies now actively addressing DEI.**
- ***The Committee strongly endorses the importance of and efforts of PSE to diversify.***

FINDINGS AND RECOMMENDATIONS

(presented in abbreviated form)

STEWARDSHIP – ADVANCING INTERDISCIPLINARY RESEARCH

- ***Finding:*** Plasma science and engineering (PSE) is inherently an interdisciplinary field of research. While the underlying science has common intellectual threads, the community is organized into sometimes isolated sub-disciplines.
- ***Finding:*** Interagency (and inter-program) initiatives would fully exploit the interdisciplinary and multidisciplinary potential PSE in both fundamental and translational research if properly stewarded
- ***Recommendation:*** **Federal agencies directly supporting PSE and those (potentially) benefiting from PSE should better coordinate their activities extending into offices within larger federal agencies.**
- ***Recommendation:*** **Federal agencies and programs focused on fundamental plasma research, and those focused on science and technologies that utilize plasmas, should jointly coordinate and support initiatives with new funding opportunities.**

EXAMPLES OF POTENTIAL INTERAGENCY COLLABORATIONS

	Agencies	Topic
1	DOE-FES, DOE-NNSA, NASA, NSF, ONR	Education and career enhancement programs
2	AFOSR, DOE-FES, DOE-NNSA, NASA, NSF, ONR	Mid-scale facilities and networks of facilities for basic plasma science & translational research.
3	AFOSR, DOE-FES, DOE-NNSA, NASA, NSF, ONR	Multi-Agency Plasma Science Centers
4	AFOSR, DOE-ASCR, DOE-FES, DOE-NNSA, NASA, NSF, NRL	Computational Plasma Science
5	DOE-FES, DOE-NNSA, NASA, NSF	Fundamental research in space and astrophysical plasmas for advancing missions
6	DOE-FES, NASA, NSF, ONR	Laboratory-heliophysics/astrophysics
7	DOE-FES, EPA, NSF, USDA-NIFA	Plasma agriculture and plasmas for food safety
8	AFOSR, ARO, DARPA, DOE-FES, NIH, NSF, ONR	Plasma biology, medicine and biotechnology

- A full list of examples of collaborations with explanations is in Chapter 1.

STEWARDSHIP – ADVANCING INTERDISCIPLINARY RESEARCH

- ***Finding:*** The potential is enormous for PSE to contribute to one of society’s greatest challenges—sustainability extending from fusion-based, carbon-free electrical power to electrification of the chemical industry.
- ***Finding:*** The translational nature of fundamental research in PSE needs greater recognition at NSF.
- ***Recommendation:* The NSF Engineering Directorate (EngD) should consistently list PSE in descriptions of its relevant programs and participate in the NSF/DOE Plasma Partnership.**
- ***Recommendation:* More strategically, NSF should establish a plasma-focused program in EngD broadly advancing engineering priorities – energy, environment, chemical transformation, manufacturing, electronics and quantum systems.**

STEWARDSHIP – ADVANCING TRANSLATIONAL RESEARCH

- ***Finding***: With few U.S. governmental programs designed to translate industrially relevant fundamental science to practice, U.S. industries are at a competitive disadvantage internationally.
- ***Recommendation:*** **Federal agencies focused on plasma research should develop new models that support the translation of fundamental research to industry. Programs supporting vital industries depending on PSE should be developed through relevant interagency collaborations.**

PLASMA SCIENCE AND ENGINEERING COMMUNITY

- ***Finding***: The multidisciplinary approach of PSE has been at the heart of its success of PSE, while working against its long-term viability in academia.
- ***Finding***: Lack of a critical mass of faculty in PSE will lead to an erosion of U.S. capability in PSE. University leadership in PSE is rapidly aging and will need renewal in the coming decade.
- ***Recommendation:*** **Federal agencies (DOE, NSF, NASA, DoD) should structure funding programs to provide leadership opportunities to university researchers in PSE and to directly stimulate the hiring of university faculty.**

PLASMA SCIENCE AND ENGINEERING COMMUNITY

- ***Finding:*** Plasma-specific educational and research programs that also provide opportunities to diverse and less advantaged populations are needed to ensure a critically populated PSE workforce**.**
- ***Finding:*** PSE intern programs and summer schools are needed for undergraduate and graduate students, as are programs for students with incomplete preparation to progress in plasma physics.
- ***Finding:*** Multi-agency investment in PSE education by directly supporting undergraduate and graduate students is critical. The more “duplication” of effort in these areas can only further strengthen PSE.
- ***Recommendation:*** **Funding agencies (e.g., NSF, DOE, NASA, DoD) 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 RESEARCH ENTERPRISE IN PSE

- ***Finding:*** Given impressive investments by other nations, incremental progress in US facilities is insufficient to maintain leadership.
- ***Finding:*** A spectrum of facility scales is required by the sub-fields of PSE to address their science challenges and translational research.
- ***Finding:*** Mid-scale facilities (e.g., $1 million to $40 million) offer particularly good opportunities for broadening participation within academia.
- ***Recommendation:*** **Federal agencies (e.g., NSF, DOE, NASA, DoD) should support a spectrum of facility scales that reflect the requirements for addressing a wide range of problems at the frontiers of PSE.**

THE RESEARCH ENTERPRISE IN PSE

- ***Finding:*** Investment in PSE facilities without the concurrent support of research and operations is not optimum.

- ***Recommendation:*** **Federal agencies (e.g., DOE, NSF, NASA, DoD) should provide recurring and increased support for the continued development, upgrading, and operations of experimental facilities at a spectrum of scales, and for fundamental and translational PSE research using those facilities.**

THE RESEARCH ENTERPRISE IN PSE

- ***Finding:*** Computational Plasma Science and Engineering (CPSE) has become essential across PSE for experiment and mission design and diagnosis, idea exploration, probing of fundamental plasma physics processes, and prediction.
- ***Recommendation:*** **Federal agencies should:**
  - **Support development of computational algorithms for PSE for the heterogeneous computing platforms of today and upcoming platforms (e.g., quantum computers), and**
  - **Encourage development of mechanisms to make advanced computations, physics-based algorithms, machine learning, and artificial intelligence broadly accessible.**

BETTER SERVING THE COMMUNITY

- ***Finding:*** Although most of the DOE-FES budget is for fusion science, the present office title does not accurately reflect its broader mission.
- ***Finding:*** The national interest would be better served by renaming DOE-FES to better reflect its broader mission, maximize its ability to collaborate with other agencies and to garner non-fusion plasma support.
- ***Recommendation:*** **DOE 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*.**

- **Chapter Highlights**

I. Introduction, Overview
- High level status of field
- Grand Challenges of PSE
- Diversity, Equity, Inclusion
- Collaborative Opportunities
- High level Findings and Recommendations

II. Basic Plasma Physics and Computations
III. Laser Plasma Interactions
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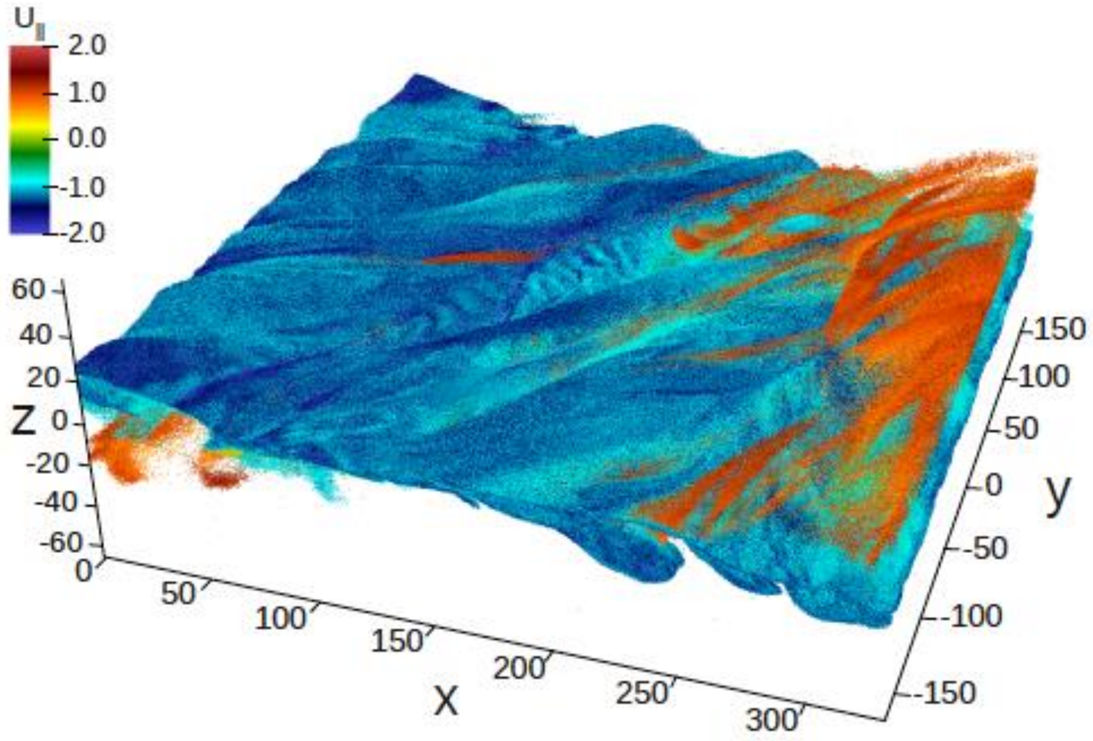
THE FOUNDATIONS OF PLASMA SCIENCE



S. Byna et al., "Parallel I/O, analysis, and visualization of a trillion particle simulation," SC '12: Proceedings of the International Conference on High Performance Computing, Networking, Storage and Analysis, Salt Lake City, UT, 2012, pp. 1-12, doi: 10.1109/SC.2012.92.

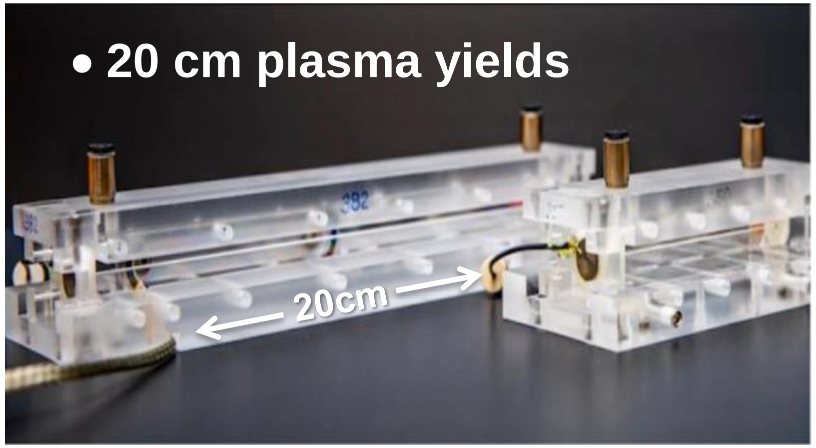
Acceleration of particles during magnetic reconnection in 3D computer simulation.

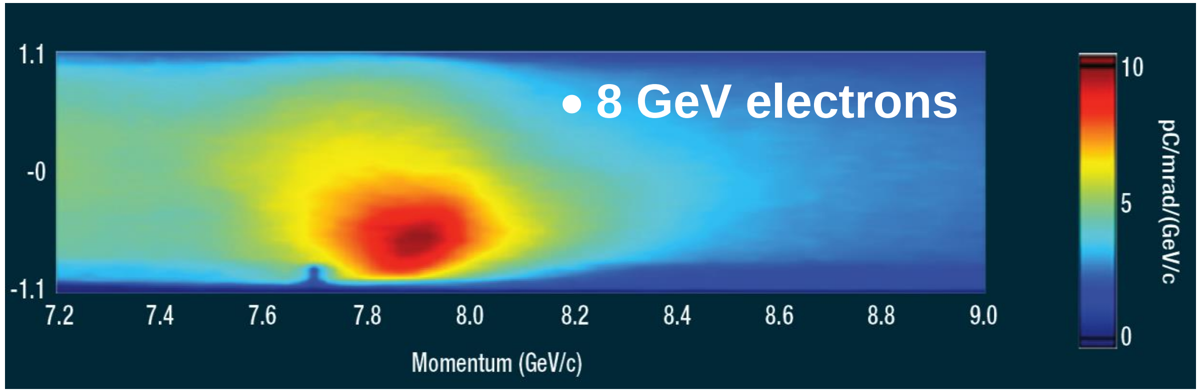
- **Color indicates particle velocity parallel to background magnetic field.**
- **Rope-like structures confine and accelerate particles.**
- **Simulation has 115 billion particles; yields 30 terabytes of data per time-step. Only 0.05% of particles are shown here.**

Advanced computing can provide breakthroughs in understanding.

- **Chapter Lead: Prof. Amitava Bhattacharjee, Princeton University**

LASER-PLASMA INTERACTIONS: COMPACT PARTICLE ACCELERATORS, NEW OPTICS, BRILLIANT X-RAYS





A.J. Gonsalves et al., Physical Review Letters 122, 084801 (2019)

Plasma based accelerators regularly provide multi-GeV electron beams with 8 GeV record from rest.

- **Gradients tens of thousands of times greater than conventional systems**
- **Advances in controlled injection, positron acceleration, high efficiency**

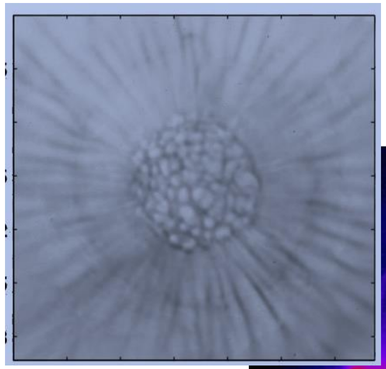
Transformational applications from X-ray sources to particle colliders

Plasma optics and high field physics are opening new physics regimes.

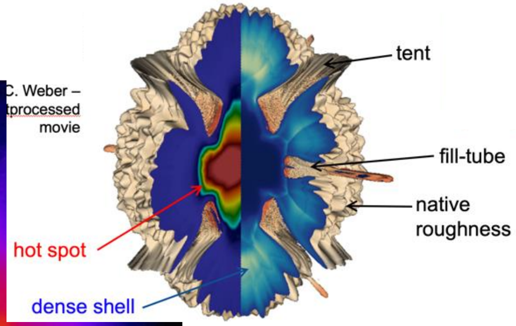
- **Chapter Lead: Dr. Cameron Geddes, Lawrence Berkeley National Lab.**

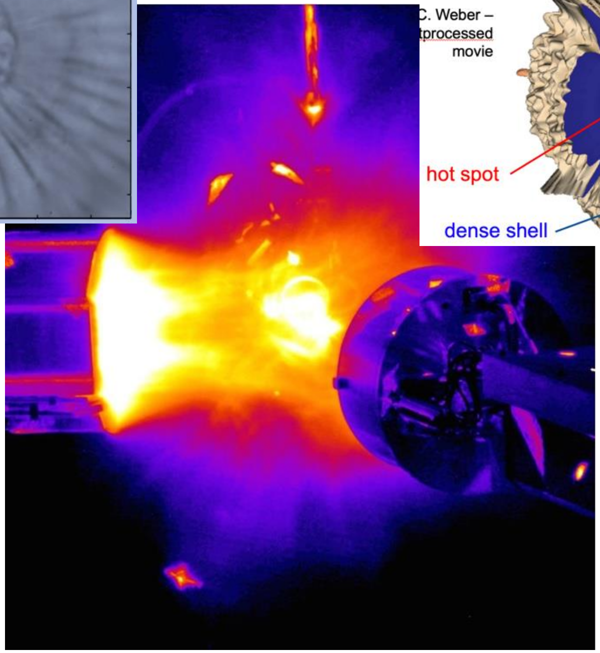
EXTREME STATES OF PLASMAS: HIGH ENERGY DENSITY

Proton radiography



3D simulation of perturbations in an ICF capsule





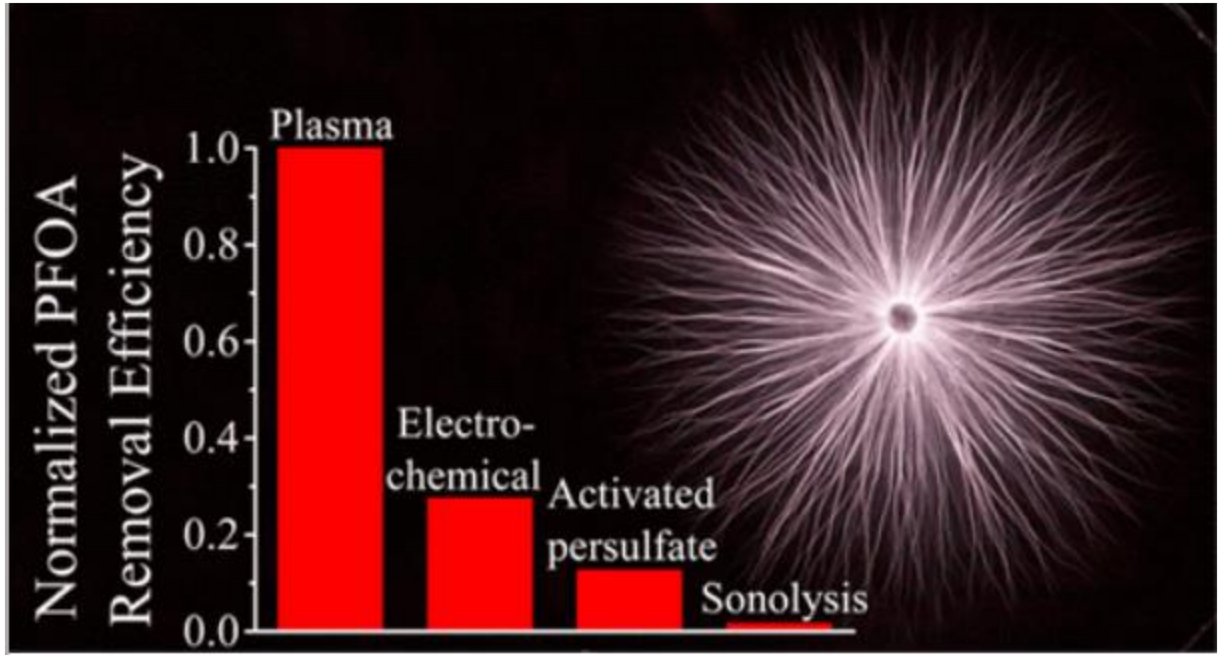
Center of NIF chamber during a shot.

Investigating the most intense plasmas on earth

- Four major new facilities are online in the last decade producing a wealth of new data.
- Novel diagnostics at these facilities enable unprecedented levels of detailed characterization.
- New capabilities in multidimensional simulations enable transformative insights into plasma behavior

- Chapter Lead: Dr. Gail Glendinning, Lawrence Livermore National Laboratory

LOW-TEMPERATURE PLASMAS: A UNIQUE STATE OF MATTER FOR ADDRESSING SOCIETAL NEEDS



Plasma-based water treatment

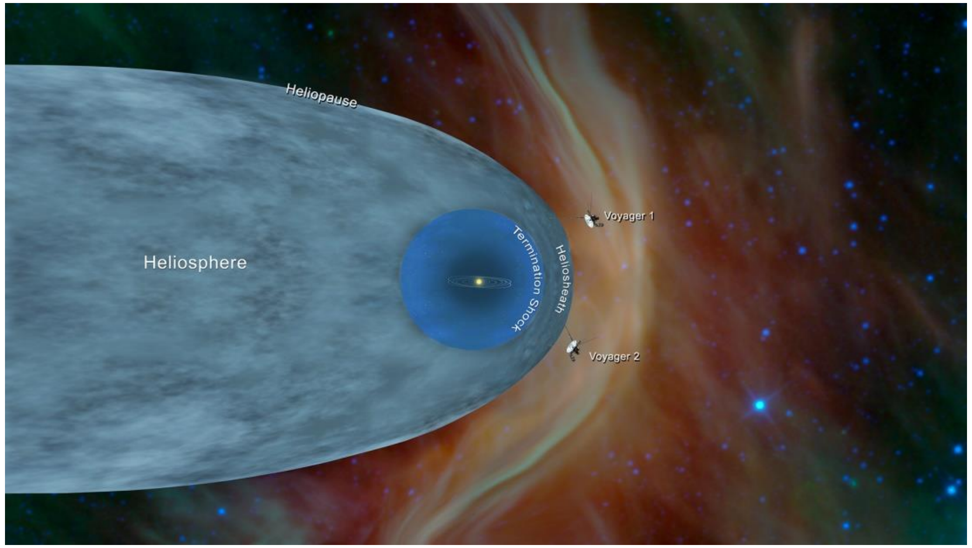
- **Efficient decomposition of perfluoroalkyl substances (toxic to humans and wildlife) in water**
- **New solution required. OH radicals, the key reactive species in typical water treatment, plays a small role.**
- **Improved efficiency is due to unique plasma-induced surface reactions of PFOA with electrons and ions.**

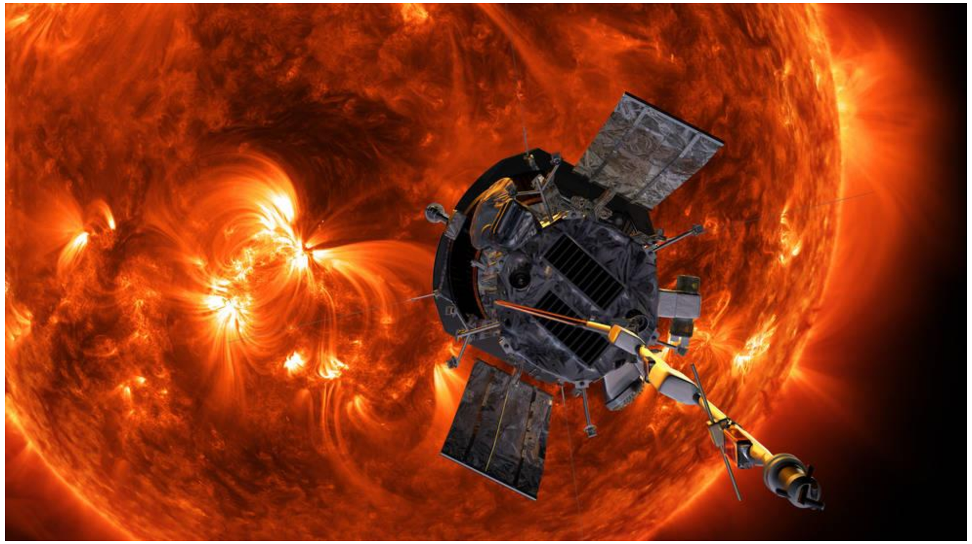
- **Chapter Lead: Dr. Peter J. Bruggeman, University of Minnesota**

MAGNETIC FUSION ENERGY: BRINGING STARS TO EARTH

- **Highlight:** ***Understanding and controlling the plasma edge enables higher-performing fusion plasmas***
  - **Virulent edge instabilities (picture) controlled using 3D magnetic fields**
  - **Progress in understanding edge stability used to reach record magnetically-confined plasma pressure**
- **Highlight:** ***Significant progress on construction of the international ITER experiment; will produce the first "burning" plasma in the laboratory.***
- **Chapter Lead: Prof. Troy Carter, University of California-Los Angeles**

THE COSMIC PLASMA FRONTIER





For the first time, humanity entered the Sun's inner atmosphere and left our solar system in the past decade

- ***Voyagers 1*** **and** ***2*** **are flying in uncharted plasma territory, the** ***Very Local Interstellar Medium***
- ***Parker Solar Probe*** **is drawing ever closer to the Sun, exploring the corona and origin of the solar wind**
- **Both have made ground-breaking discoveries about our heliosphere and the surrounding plasma.**

- **Chapter Lead: Dr. Judy Karpen, NASA Goddard Space Flight Center**

FINDINGS AND RECOMMENDATIONS: TAKE-AWAYS

Stewardship:

Finding: PSE is extraordinarily multi-disciplinary both fundamentally (underlies much of basic physics) and now stretching into biology (epidemiology), information science, quantum, materials, with extraordinary translational value. (See Grand Challenges.)

Opportunity: Broaden interagency structures to support PSE, especially translationally. Structures needed to facilitate cross-talk and funding needed to drive cross-agency collaborations. Aligns with proposed NSF reorganization - Endless Frontiers Act (S. 3832).

Education, Workforce, Diversity:

Finding: Aging PSE workforce, particularly faculty, needs renewal. Next decade brings great opportunity to remake a diverse workforce, rooted in both basic and translational science. Guidance to avoid “duplication” in workforce areas has been a negative.

Opportunity: Agencies need to promote programs to hire new faculty, and provide PSE specific fellowship programs for undergraduates to fill a diverse pipeline and to graduate students to fill positions in academics, national laboratories and industry.

FINDINGS AND RECOMMENDATIONS: TAKE-AWAYS

Research Enterprise and International Competitiveness:
Finding: US is losing its preeminent position in PSE because of i) incremental progress in new and updated facilities (especially mid-scale), ii) lack of concurrent research and operational support to the facilities, and iii) to limited computational (theory, algorithms, codes) capacity.

Opportunities: Support funding for a spectrum of facilities, particularly at universities, and for expanding fundamentals of PSE computations and expanding access.

Finding and Opportunity: Industries reliant on PSE (e.g., microelectronics) are at a competitive international disadvantage due to lack of Federally funded translational research. Support new modes of translational research.

Better Serving PSE Community:
Finding and Opportunity: DOE Office of Fusion Energy Science should be renamed to more accurately reflect its broader mission and support interagency collaborations, e.g., *Office of Fusion Energy and Plasma Sciences.*

- **Chapter Findings and Recommendations, and Collaborations**

THE FOUNDATIONS OF PLASMA SCIENCE

- ***Major Findings***
  - **Fundamental research can/does translate to societally relevant technologies though with a growing gap between fundamental science and applications.**
  - **New theory and computations are essential to leveraging investments in experimental facilities.**

- ***Major Recommendations***
  - **Forging partnerships among agencies is needed to bridge this gap.**
  - **Efforts to foster collaborative activities (e.g., broaden support for Plasma Science Centers) are needed.**
  - **Needs for upgrading and operating basic plasma facilities.**

- ***Partnerships to Advance the Field***
  - **NSF, DOE, DoD, NASA should collectively provide the critical mass to address complex scientific questions cutting across their domains, support early careers and promote diversity.**
  - **Theory is a priority.**

- ***Advancing the plasma science frontier***
  - **Developing and distributing computational tools are needed to advance experimental design, fundamental understanding and unite the field.**
  - **New analytic and computational algorithms for upcoming platforms (including quantum) will be impactful.**

LASER-PLASMA INTERACTIONS: COMPACT PARTICLE ACCELERATORS, NEW OPTICS, BRILLIANT X-RAYS

- ***Major Findings***
  - **Rapid advances enabled by new lasers, ultra-short pulse methods (2018 Nobel)**
  - **Strategic opportunities for US leadership – highest intensities, high repetition rate**
  - **Range of scales needed – Single PI to large facility.**

- ***Major Recommendations***
  - **Formulate a national strategy to develop new classes of lasers**
  - **Extended stewardship program for application-oriented research.**
  - **Strongly support research at range of scales and infrastructure.**

- ***Partnerships to Advance the Field***
  - **DOE, NSF, NNSA, NIH – Laser and application stewardship**
  - **DOE-FES, NSF, DOE-NNSA – Supporting fundamental science**
  - **DOE, NSF – Support of theory and computation of extreme states.**

- ***High field laser & beam-controlled plasmas enable new capabilities and understanding: optics to accelerators***
  - **Compact accelerators, X-ray sources**
  - **Novel optical states and control**
  - **Strong field nonlinear quantum**
  - **Plasmas out of the vacuum**

EXTREME STATES OF PLASMAS: HIGH ENERGY DENSITY

- ***Major Findings***
  - **University facilities and researchers play a crucial role in HED science.**
  - **Outstanding basic science programs at large facilities (NIF, Z, Omega) with small fraction of facility time.**
  - **Critical role of AMO physics to HED.**

- ***Major Recommendations***
  - **Federal support for university HED mid-scale facilities, especially pulsed-power, should be expanded**
  - **Basic science programs at large HED facilities should be expanded**

- ***Interagency partnerships would advance basic HED science***
  - **DARPA, DOE-FES, DOE-NNSA, DTRA, NSF, ONR – intermediate scale pulsed power facilities**
  - **DOE-NNSA, NASA, NSF, ONR - validation of laboratory HED, ICF, and astrophysical HED computations.**

- ***New discoveries extend relevance of HED physics and astrophysics***
  - **ICF near burning plasma regime.**
  - **Lab generation of B-fields as expected in astrophysical systems.**
  - **Accurate measurements of Fe opacity disagree with astrophysical models emphasizing need for HED science.**

LOW TEMPERATURE PLASMA (LTP): A UNIQUE STATE OF MATTER FOR ADDRESSING SOCIETAL NEEDS

- ***Major Findings***
  - **LTP has made society-wide transformations in our quality of life**
  - **Funding agencies have not embraced the multidisciplinary LTP science underpinning these advances leading to a partial loss of US leadership**

- ***Major Recommendations***
  - **DOE-FES should lead and coordinate a multi-agency multidisciplinary LTP Center Program**
  - **NSF should establish consistent inter-directorate support for emerging LTP science, including a program in EngD.**

- ***Partnerships to Advance the Field***
  - **DOE-FES, ONR, ARPA-E, NSF – electrification of the chemical industry**
  - **DOE-FES, DOE-BES – the science of plasma-material interactions**
  - **DOE-FES, NIH, NSF, USDA – plasma-bio-interactions and plasma agriculture**

- ***Fundamental LTP science has been the driver of societal benefiting discoveries***
  - **Fundamental research in LTP has declined in the US over the last decade**
  - **Training of the next generation of scientists and stimulating new faculty hires is needed to sustain discoveries.**

MAGNETIC FUSION ENERGY: BRINGING STARS TO EARTH

- ***Major Findings***
  - **Absence of a consensus strategic plan and roadmap for future research.**
  - **University programs key source of innovation in MFE but are at risk.**
  - **Loss of DOE graduate/undergraduate fellowships in MFE (OMB decision).**

- ***Major Recommendations***
  - **Undertake regular strategic planning, led by the U.S. MFE community.**
  - **DOE FES should structure funding to stimulate faculty hiring at universities.**
  - **DOE SC should restore graduate fellowships and undergrad programs.**

- ***Partnerships to Advance the Field***
  - **U.S. should remain a partner in ITER.**
  - **Support and leverage rapidly growing private investment in fusion.**
  - **Partner with ARPA-E on innovative fusion concepts and technologies.**
  - **Partner with BES, NNSA, ARPA-E on materials for fusion.**

- ***Plan the path to a low-cost U.S. fusion pilot power plant***
  - **Leverage enabling technologies like high-temperature superconductors and additive manufacturing.**
  - **Employ advanced computation and machine learning to resolve challenges.**

THE COSMIC PLASMA FRONTIER

- *Major Findings*
  - Inadequate support for theory and modeling has prevented progress in understanding cosmic plasmas
  - Lab plasma experiments have untapped synergies with cosmic plasmas
  - Establish and standardize open data policies and formats

- *Major Recommendations*
  - NSF/DOE/NASA partnership to expand basic plasma research that would benefit cosmic plasmas.
  - NSF/DOE/NASA partnership to support innovative joint projects.
  - Federal agencies and science community should work together

- *Partnerships to Advance the Field*
  - Multi-agency collaborations (e.g., NSF, DOE, DOD, NASA) enable large-scale and multidisciplinary PSE research
  - Strengthens faculty presence in universities, STEM diversity, public excitement about space.

- *Cosmic Plasma Frontier*
  - Understanding space/astrophysical plasmas requires more international collaborations
  - Societal benefit: space weather prediction relies heavily on plasma research, modeling, and application

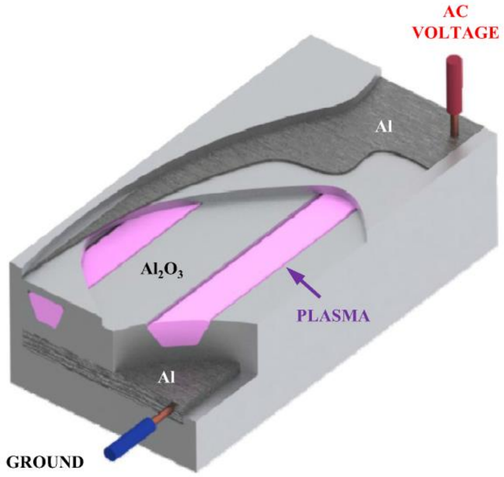
For more information: http://nas.edu/plasma

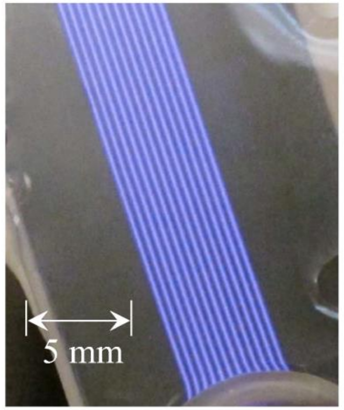
Backup Slides

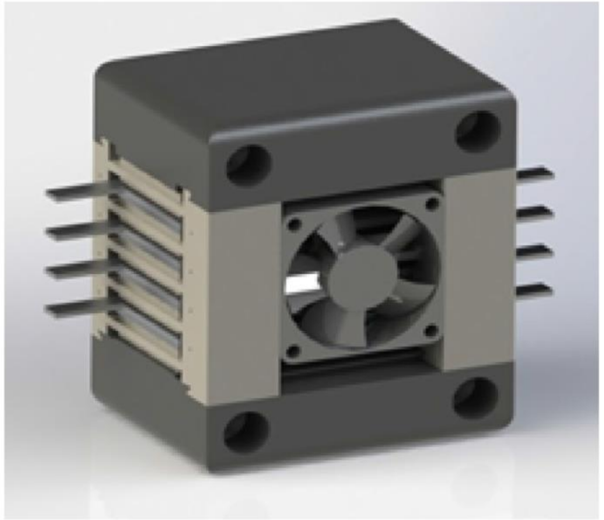
FUNDAMENTAL PLASMA SCIENCE TRANSLATES TO SOCIETAL BENEFIT

- **Fundamental research on micro-plasmas combined with MEMS and microelectronics fabrication produced scalable, modular, solar driven ozone sources for water purification.**
- **Technology is now commercialized.**
- **Non-profit foundation to continue distributing water purification units in developing world.**

- **J. G. Eden, Eu. Phys. J. Special Topics, 226, 2923 (2017)**







4th PLASMA DECADAL STUDY

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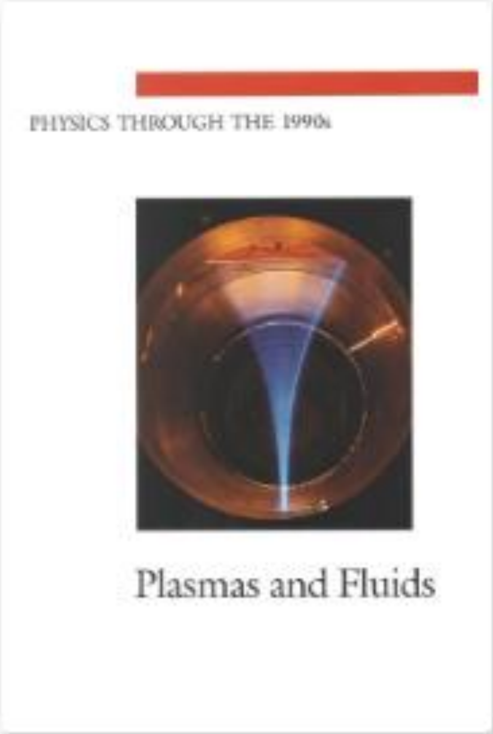

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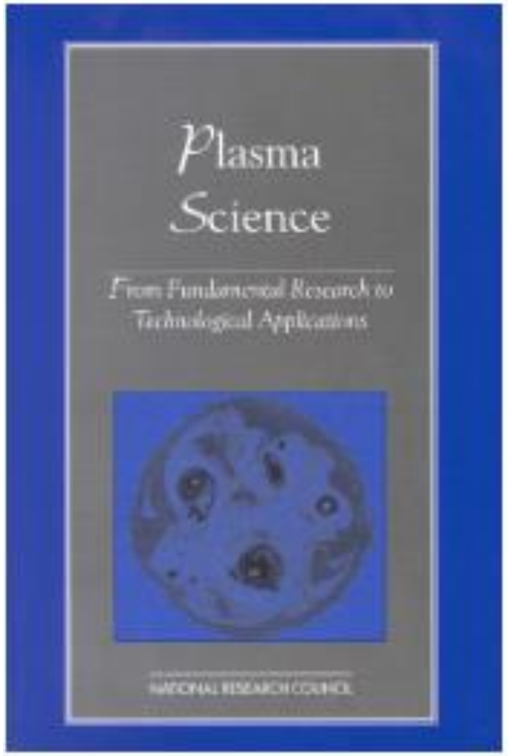

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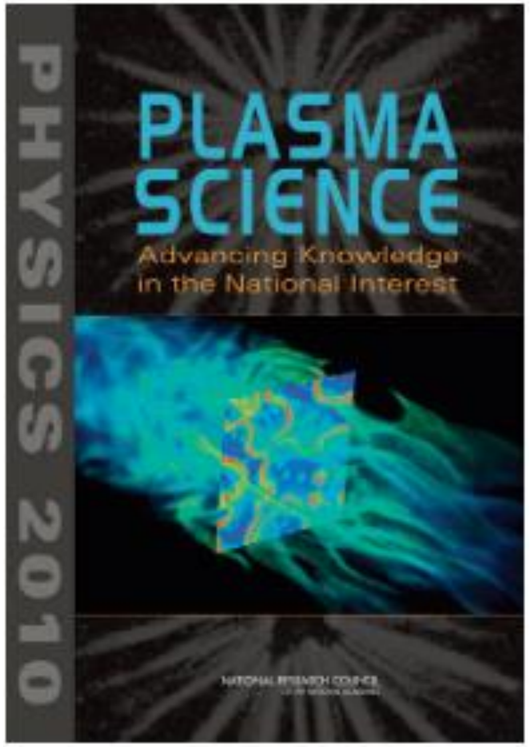

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