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

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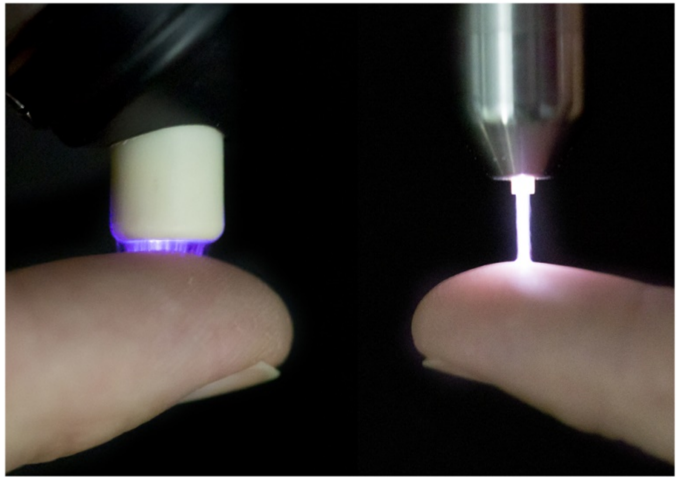
Briefing to the Astronomy and Astrophysics Advisory Committee (AAAC)
22 Sept 2020

PLASMA SCIENCE AND ENGINEERING: INTELLECTUALLY DIVERSE FIELD

- **Plasma Science and Engineering (PSE) is of the most intellectually diverse sciences.**
  - **> 10^{10} range in pressure (energy density)**
  - **> 10^{10} range in spatial scale.**
- ***Despite vastly different scales and applications, common themes and science challenges bring cohesiveness to PSE.***
  - **Complexity arising from multiple scales and phenomena.**
  - **Controlling synergies in plasma-surface interactions.**
  - **Understanding and leveraging self-organization.**
  - **Controlling the flow of power through plasmas for energy and chemical conversion.**
  - **Developing ever more capable diagnostics, theories, and computations to characterize this complexity.**



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

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
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Christine A. Coverdale, Sandia National Laboratory
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Daniel H. Dubin, University of California-San Diego
Cameron G. R. Geddes, Lawrence Berkeley National Lab.
Gail Glendinning, Lawrence Livermore National Lab.
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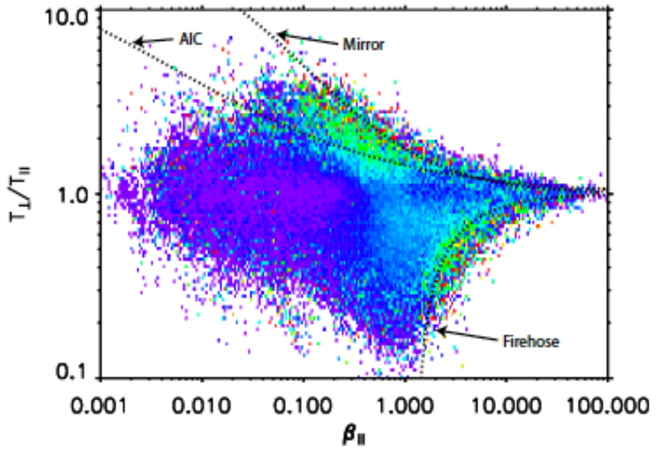
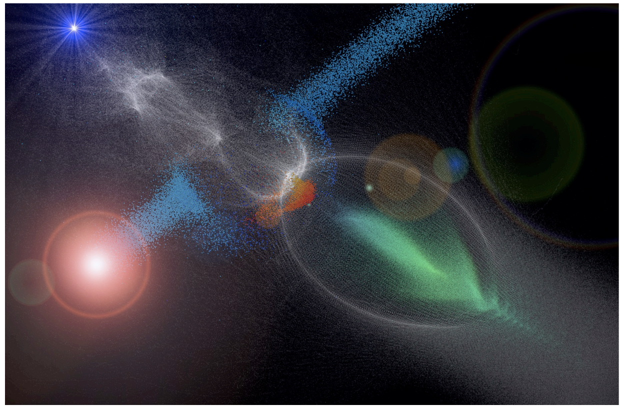
David B. Graves, University of California Berkeley
Judith T. Karpen, National Aeronautics & Space Admin.
Maxim Lyutikov, Purdue University
John S. Sarff, University of Wisconsin
Adam B. Sefkow, University of Rochester
Edward E. Thomas, Jr., Auburn University

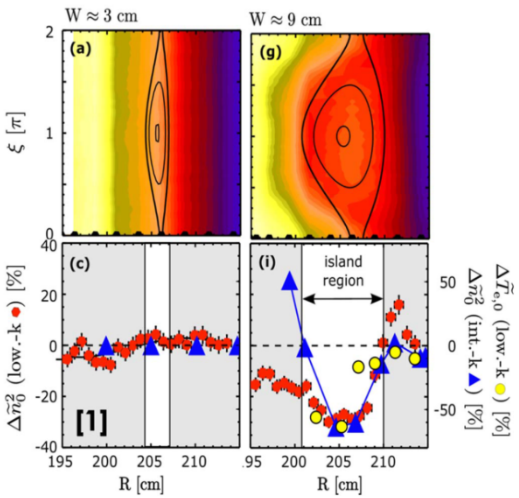
GUIDING PRINCIPLES:
GRAND CHALLENGES IN PLASMA SCIENCE & ENGINEERING



- ***Understanding the behavior of plasmas under extreme conditions***

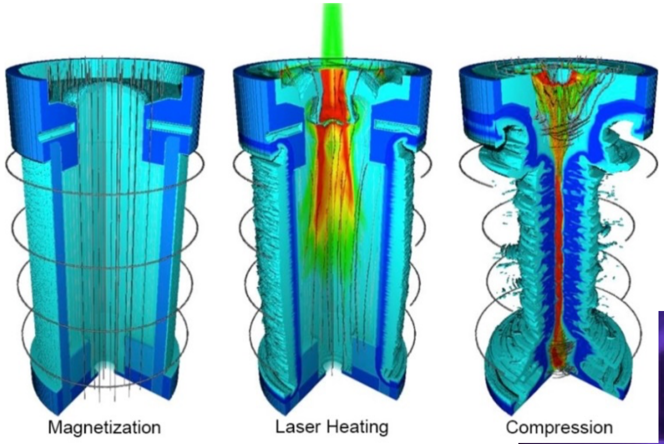


- ***Mastering the interactions of the world's most powerful lasers and particle beams with plasmas*.**

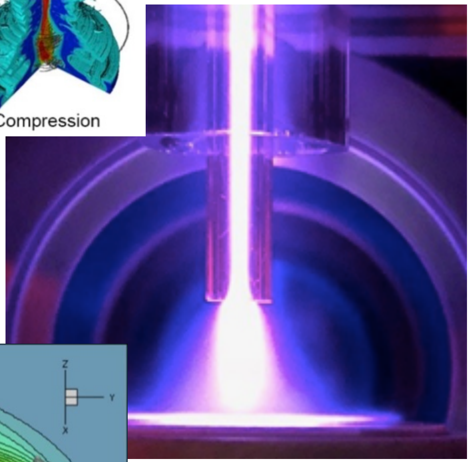


- ***Accelerate the development of fusion generated electricity.***

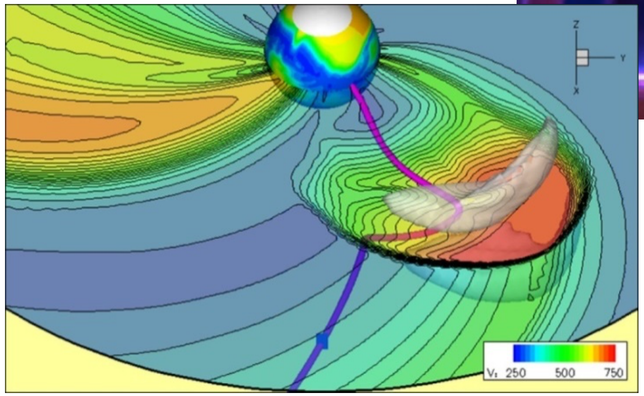
GUIDING PRINCIPLES:
GRAND CHALLENGES IN PLASMA SCIENCE & ENGINEERING



- ***Demonstrate that lasers and pulsed-power devices can produce inertially confined fusion ignition.***



- ***Enable electrification of the chemical industry by controlling the flow of power through low temperature plasmas.***



- ***Develop the capability for timely and actionable space-weather observations and predictions.***

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 and we highlight Astronomy and Astrophysics F&R)

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.

DEEPER DIVE RELATED TO A&A

- **Plasma astrophysics** increasingly important - improved observations and computational capabilities – e.g., gravitational waves to Parker Solar Probe to DKIST - **opportunity for discovery science**
- NSF, NASA, and DOE each support some plasma astrophysics
- NSF ↔ MPS/AST, MPS/PHY, and GEO/AGS
- NASA ↔ SMD/Astrophysics and SMD/Heliophysics
- DOE ↔ SC/FES and NNSA.
- **Limited bi-agency coordination**: ***NSF-DOE Partnership in Basic Plasma Science and Engineering*** [partnership between NSF/MPS, NSF/GEO, NSF/ENG, and DOE/SC/FES] – includes plasma astrophysics
- ***NSF-NASA Next Generation Software for Data-driven Models of Space Weather with Quantified Uncertainties (SWQU)*** program [partnership between NSF/GEO and NASA/SMD/Heliophysics] – focus on solar activity, solar wind, and interaction with planetary magnetospheres – can feed exoplanets and exo-planetary systems research.
- Presently **no scientific or administrative tri-agency coordination** of any activities in plasma astrophysics. Represents important **leadership opportunity for NSF A&A post Plasma 2020.**

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.**
- **Consistent with goals of *NSB Vision 2030*.**

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 **Center for Matter at Atomic Pressures (CMAP)** is a new **NSF Physics Frontier Center** hosted at the University of Rochester in collaboration with researchers at MIT, Princeton, the Universities of California at Berkeley and Davis, the University of Buffalo, and the Lawrence Livermore National Laboratory.

- First major initiative from NSF in the field of **high energy density plasma science**

- **Will discover the nature of planets and stars throughout the universe, as well as the potential for new revolutionary states of matter here on Earth**

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, Findings and Recommendations**

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

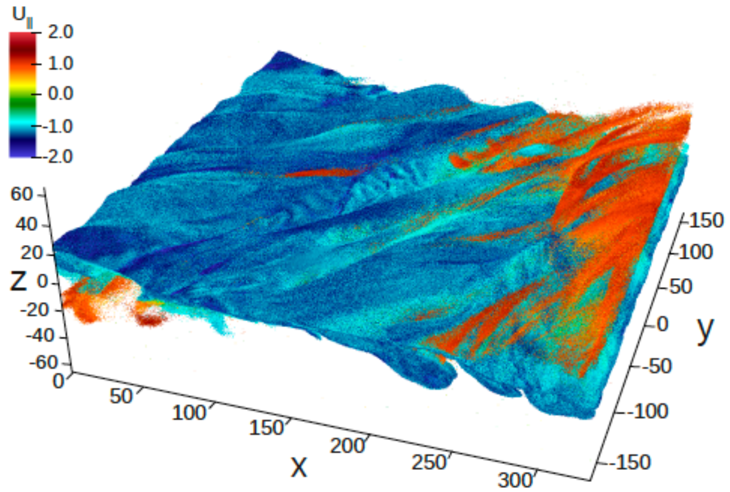
IV. High Energy Density Physics and Inertial Confinement Fusion

V. Low Temperature Plasmas

VI. Magnetically Confined Fusion

VII. Space and Astrophysical Plasmas.

THE FOUNDATIONS OF PLASMA SCIENCE



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

- Color indicates particle velocity parallel to background magnetic field.
- Simulation has 115 billion particles

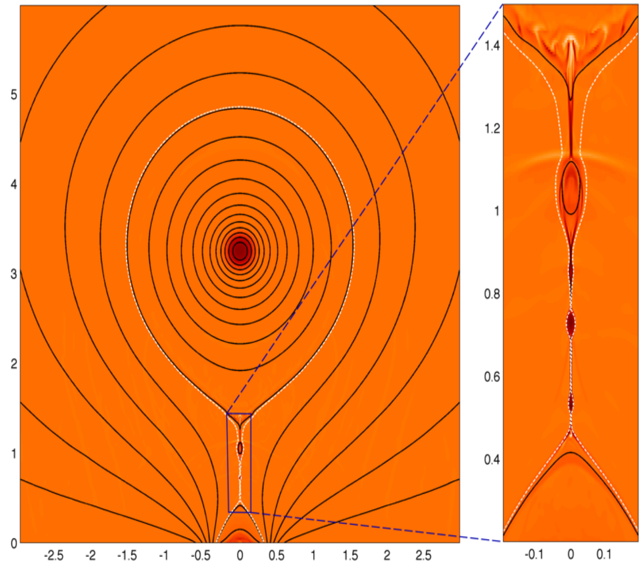
Advanced computing can provide breakthroughs in understanding.

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

- ***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.

EXAMPLE: INTERSECTION OF LAB PLASMA PHYSICS AND PLASMA ASTROPHYSICS

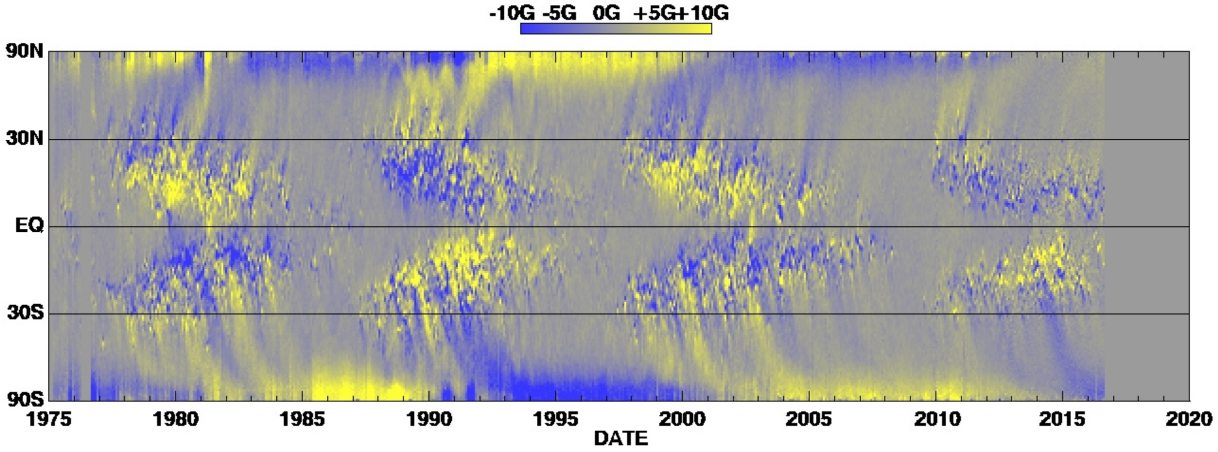
- New **laboratory experiments** at the Facility for Laboratory Reconnection Experiments (FLARE) at Princeton Plasma Physics Laboratory (PPPL) and the Terrestrial Reconnection Experiment (TREX) at the University of Wisconsin-Madison have exceeded the capabilities of earlier experiments (e.g., Magnetic Reconnection Experiment (MRX) at PPPL and Versatile Toroidal Facility (VTF) at MIT) in size and scope.
- These new facilities provide an excellent **complement to space missions** by enabling the exploration of new regimes of reconnection through reproducible experiments and detailed diagnostics.



- High-resolution MHD simulation of intermediate stage CME exhibiting the formation of plasmoids due to the instability of a thin current sheet that forms spontaneously. (Huang)

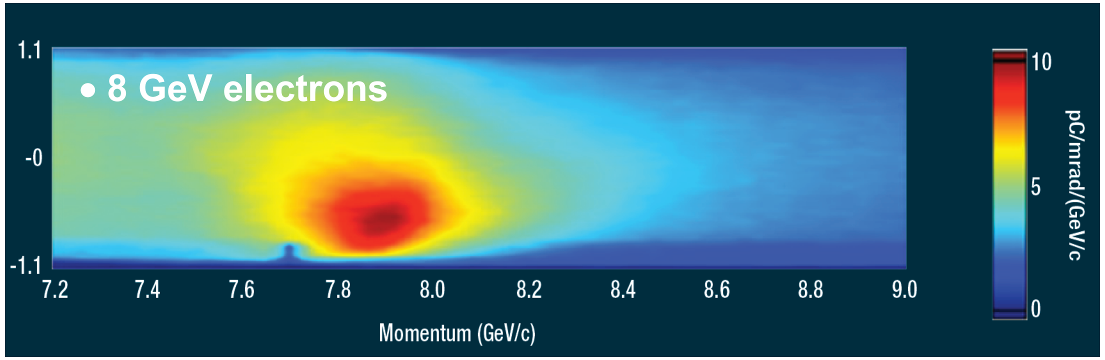
SELF-ORGANIZATION AND THE MAGNETIC DYNAMO EFFECT

- The **dynamo effect** asks why our Universe is magnetized?
- Two classes of dynamos: "**Small-scale**" dynamos amplify magnetic energy but produce negligible magnetic flux. "**Large-scale**" dynamos produce large-scale magnetic field structures with non-zero magnetic flux.
- **Example:** The Sun's magnetic field and its 11-year cycle is an example of large-scale dynamo, illustrating spontaneous emergence of large-scale magnetic fields from disordered small-scale velocity and magnetic field fluctuations.



- The **Butterfly Diagram** for the Sun's magnetic field, spanning the years 1975-2016 (horizontal axis). This diagram, based on observations, tells the story of the 11-year cycle of the Sun's magnetic field. The vertical axis represents latitudes both above and below the equator of the Sun. The colors indicate the magnitude of the solar magnetic field. SOURCE: Courtesy of David Hathaway

LASER-PLASMA INTERACTIONS



Plasma based accelerators provide multi-GeV electron beams (8 GeV record from rest).

- Advances in controlled injection, positron acceleration, high efficiency

Transformational applications from X-ray sources to particle colliders

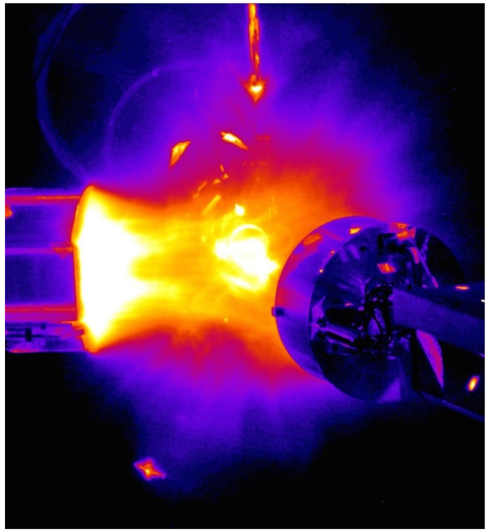
Plasma optics and high field physics are opening new physics regimes.

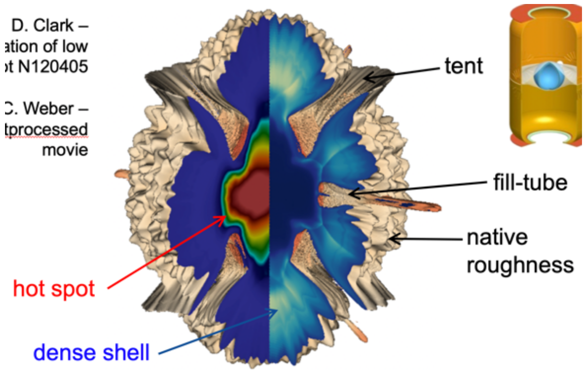
- **Chapter Lead: Dr. Cameron Geddes, Lawrence Berkeley National Lab.**

- ***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.

EXTREME STATES OF PLASMAS: HIGH ENERGY DENSITY





Investigating most intense plasmas on earth

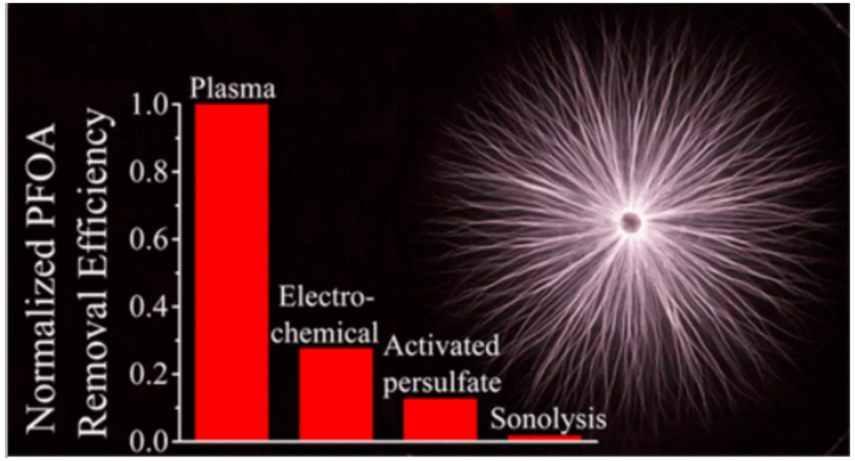
- Four major new facilities are online in the last decade producing a wealth of new data.
- Novel diagnostics enable unprecedented levels of detailed characterization.
- New capabilities in simulations enable transformative insights into plasma behavior

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

- ***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
  - Investments in new diagnostics for HED needed.

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



Plasma-based water treatment

- Efficient decomposition of toxic perfluoroalkyl substances in water
- New solution needed, OH plays small role.
- Improved efficiency due to unique plasma-surface reactions with PFOA.

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

- ***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 (several at $20M over 5-10 years)
  - NSF should establish consistent inter-directorate support for emerging LTP science, including a program in EngD ($6M/year).

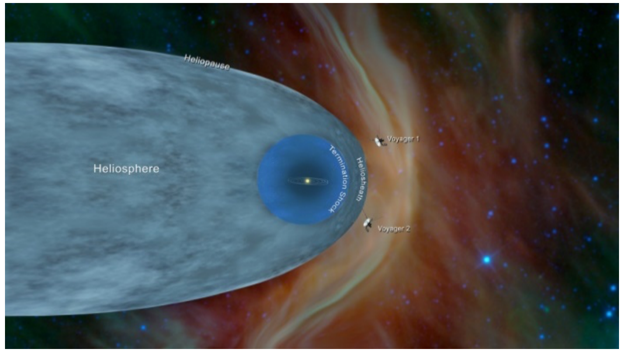
MAGNETIC FUSION ENERGY: BRINGING STARS TO EARTH

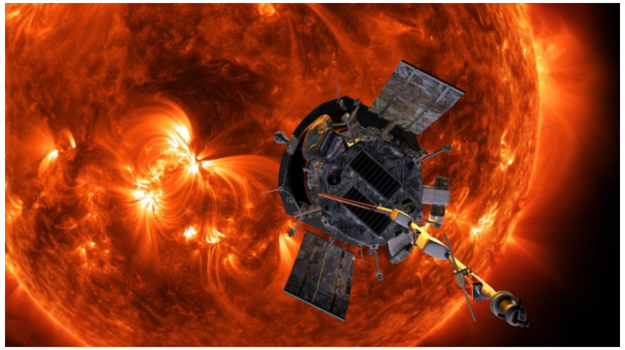
- ***Understanding and controlling plasma edge enables higher-performing fusion plasmas***
  - Edge instabilities controlled using 3D B- fields
  - Understanding edge stability enables record magnetically-confined plasma pressure
- ***Significant progress on construction of ITER will produce the first "burning" lab plasma.***
- **Chapter Lead: Prof. Troy Carter, University of California-Los Angeles**

- ***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.

THE COSMIC PLASMA FRONTIER





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

- *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 solar wind
- Ground-breaking discoveries about our heliosphere and the surrounding plasma.

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

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

- ***Major Recommendations***
  - NSF/DOE/NASA partnership to expand basic plasma research that would benefit cosmic plasmas ($4-$5M/year).
  - NSF/DOE/NASA partnership to support innovative joint projects, lab space science.
  - Interagency standards for data exchange should be developed for domestic and international collaboration.

THE COSMIC FRONTIER: F&R 1

- **Finding:** A lack of support for basic code and simulation development, theory, and novel data-analysis techniques has long been a barrier to advancing our understanding of SAPs and predictive capabilities.
- **Finding:** Unfortunately, the level of funding for the highly successful NSF/DOE *Partnership in Basic Plasma Science and Engineering* has lagged that recommended by the 2000 Plasma Decadal Review, despite its very central role in discovery plasma science and its capacity to create effective multidisciplinary bridges within plasma science.
- **Recommendation: NASA should join the NSF/DOE Partnership in Basic Plasma Science and Engineering to expand interdisciplinary basic plasma research that would benefit SAP. This expanded partnership would leverage strategic contributions from each agency to enable breakthrough progress that benefits a wide range of PSE activities**

THE COSMIC FRONTIER: F&R 2

- **Finding:** Solar, heliospheric, magnetospheric, and ionospheric physics, and astrophysics have untapped synergies with laboratory plasma experiments, with the common goal of understanding ambient plasma conditions and chemistry.
- **Finding:** Strategic funding from NASA and agencies supporting experimental facilities would enable more ambitious, innovative joint projects than a single source could support.

- **Recommendation: NASA and NSF should lead an effort with DoD (especially ONR and AFOSR), DOE, and other stake-holders should develop a collaborative program that enables SAP scientists to collaborate with laboratory plasma experimentalists and advance both fields by leveraging their different needs and knowledge bases.**

THE COSMIC FRONTIER: F&R 3

- **Finding:** Clusters of cubesats and smallsats carrying in-situ and remote-sensing instruments are the best observing platforms for tackling many basic unsolved questions of multiscale SAPs (e.g., reconnection, turbulence, and shocks), and provide essential research and training opportunities for university faculty and students.
- **Finding:** Existing procedures for developing, building, and operating missions are traditionally geared toward large missions, and can pose unnecessary obstacles for single spacecraft and multi-platform missions employing smallsats and CubeSats.

- **Recommendation: With NASA and NSF as lead agencies, NASA, NSF, and DoD, as the primary sources of space missions, should explore avenues, including rideshares, international partners, and partnering with commercial launch providers, for reducing costs, lowering barriers, enabling higher-risk missions, and boosting launch opportunities for these pioneering investigations using Cubesats, smallsats and cluster of these satellites.**

THE COSMIC FRONTIER: F&R 4

- **Finding:** NSF, despite having a limited investment level in their Cubesat program, has broad access to universities and undergraduate and graduate students. This access may be important in providing basic training in PSE relevant to CubeSats. The recent solicitation for a cross-cutting NSF Ideas Lab Program focused on CubeSat innovations to push the envelope of space-based research capabilities is an example of one approach.
- **Recommendation: In view of their limited level of investment, NSF should identify a clearer role and "identity" in their CubeSat program that distinguishes it from its NASA counterpart. To ensure cost and resource efficiencies, NSF and NASA should coordinate on funding opportunities.**

- **Finding:** Increased support is needed to meet the challenge of designing and constructing compact plasma and remote-sensing instrumentation suitable for Cubesats and smallsats.
- **Recommendation: Current NASA programs such as H-FORT, H-TIDES, and the IDP (Instrument Development Program) should be augmented to meet the growing demand for compact plasma and remote-sensing instrumentation suitable for Cubesats and smallsats.**

THE COSMIC FRONTIER: F&R 5

- **Finding:** The SAP community needs to agree on data standards, formatting, and processing levels for publicly available data.
- **Recommendation: Federal agencies that support ground-based and international space facilities (NSF, NASA, DoD, NOAA) should adopt similar open data policies and minimize barriers to international collaboration except where national security is of concern.**
- **Recommendation: NSF should convene a workshop co-sponsored by NASA and DoD to make recommendations for how to establish and maintain open data policies.**
- **Recommendation: Once established, maintaining and updating the open data standards should be the responsibility of governing federal organization such as one of the major contributors (NASA, DoD, NOAA) or a more specialized agency for standards such as NIST.**

- **Finding:** A faculty partnership program introduced by NASA, NSF, and DOE—similar to that presented in the Finding and Recommendation section of Chapter 1 (see Table 1.1)—is needed to strengthen SAP hiring in universities and federal research facilities.

EXCITING NEW NSF FACILITY COMING ONLINE

- NSF's **Daniel K. Inouye Solar Telescope (DKIST)** will be the largest solar telescope in the world, able to view features on the Sun as small as 70 km across.
- Adaptive optics give DKIST's 4.2-m primary mirror and five major instruments the sharpest views ever taken of the solar surface.
- The spatial, temporal, and spectral resolution and dynamic will enable measurements of elemental magnetic structures at and above the photosphere.

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 goals of *NSB Vision 2030*.

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.*

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

Backup materials

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.**

Information Gathering Events

- **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