OUTCOMES FROM THE PLASMA 2020 DECADAL SURVEY

PLASMA SCIENCE: ENABLING TECHNOLOGY, SUSTAINABILITY, SECURITY AND EXPLORATION

An Update – ECLIPSE Meeting and a Recommendation

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

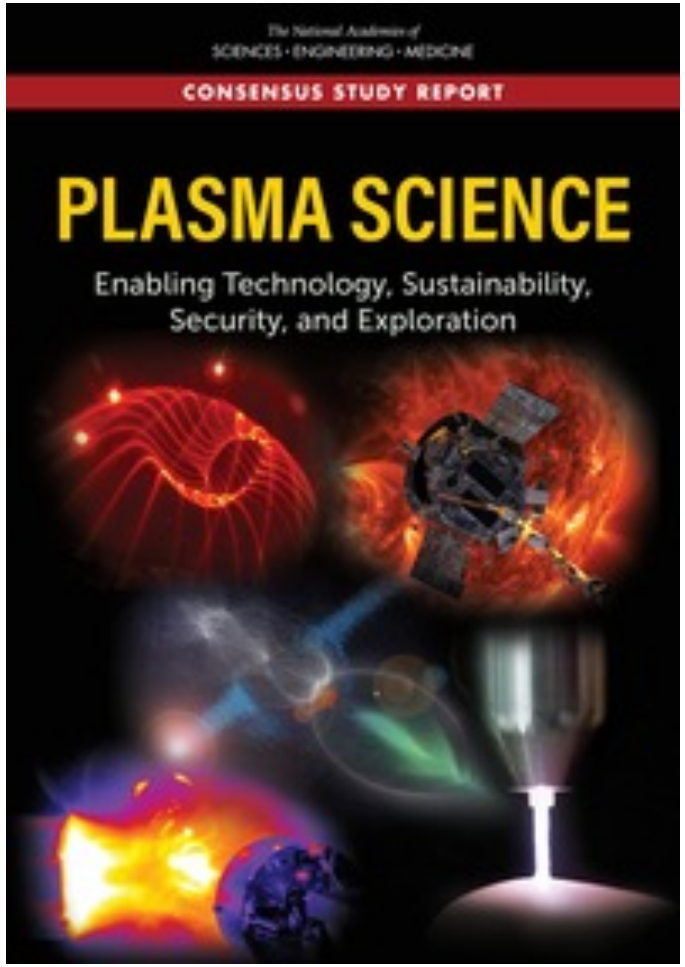
Mark J. Kushner and Gary P. Zank, Co-Chairs

Supported by DOE, NSF, AFOSR, and ONR

Briefing to NASEM Board on Physics & Astronomy and Space Sciences Board
27 April 2022

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

GOAL OF THIS BRIEFING



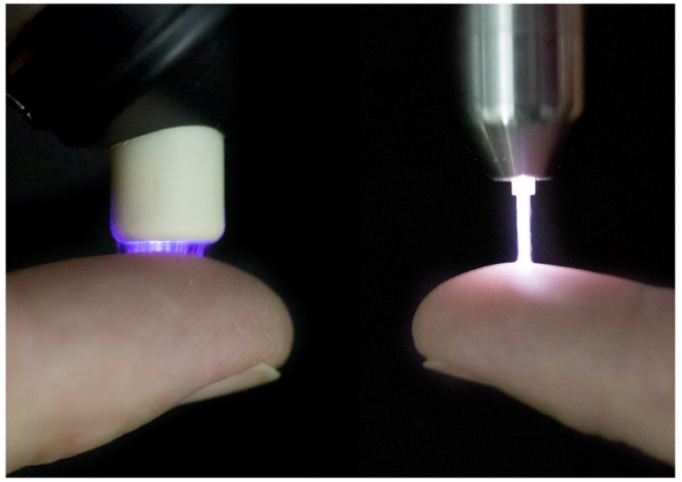
- **A briefing was provided to BPA (11 November 2021) on the then outcomes of the *2020 Decadal Study on Plasma Science and Engineering (PSE)***

  https://www.nap.edu/read/25802/chapter/1
- **This briefing will quickly review**
  - **High-level Findings and Recommendations (F&R) of Plasma 2020**
  - **Assessment of responses and outcomes of report**
- **Discuss an important outcome deriving from the NSF ECLIPSE (*Ecosystem for Collaborative Leadership and Inclusive Innovation in Plasma Science and Engineering)* program.**
- **Make a specific recommendation on the Plasma Science Committee.**

PLASMA SCIENCE AND ENGINEERING (PSE): INTELLECTUALLY DIVERSE FIELD UNITED BY SCIENCE CHALLENGES

Despite vastly different scales and applications PSE has common themes and scientific challenges that bring cohesiveness to the PSE field (> 10^{10} range in energy densities and spatial scales).

- **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.**



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

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.**

PLASMA 2020 STATEMENT OF TASK

- 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.
- Identify the major scientific questions and new opportunities that define plasma science as a discipline, noting connections to and influence on other disciplines.
- Discuss role of U.S. in multi-national plasma research activities, 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.
- 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 U.S. research effort in plasma science (federal and private) are best positioned to realize the science opportunities.

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.***
- ***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.***

HIGH LEVEL FINDINGS AND RECOMMENDATIONS

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 – see later slide.*

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) 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.

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.

FACILITIES AND NETWORKS

- ***<u>Recommendation:</u>*** ***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.***
- ***<u>Recommendation:</u> A community wide workshop led by a partnership of DOE FES and NSF should define the parameters and participation of such a program and network of [basic plasma science] user facilities***

- **Initial meeting to discuss possible "MagNetUS" implementation (August 2021)**
  https://sites.google.com/view/frontier-science-magnetus
  - **MagNetUS is a network of magnetized plasma experimental facilities with the shared goal of studying basic plasma science in a collaborative, inclusive environment.**
  - **Distributed user facility.**
  - **Second meeting planned 7-10 June 2022**

FACILITIES AND NETWORKS
Workshop on Plasma Science Facility Networks

- **Plasma 2020 Recommendation:** A community-wide workshop led by DOE-FES and NSF-MPS should define the parameters and participation of a program and network of user facilities.
  - What is required to establish and operate a network of plasma science user facilities? What facilities or instrumentation can be leveraged, expanded or upgraded for a network?
  - What is the estimated user base for the proposed network? Will expansions or upgrades to existing facilities increase the user base or expand to new plasma science or other sub-fields?
  - What are the best practices for managing transparent and effective operation of user facility networks for plasma science?
  - How can networks broaden access to user facilities, specifically to Minority Serving Institutions and Primarily Undergraduate Institutions?
- The workshop is tentatively scheduled for June 13 – 14 in the DC area
- Organizers: Carolyn Kuranz (U Michigan) ckuranz@umich.edu and Earl Scime (W. Virginia U.) earl.scime@mail.wvu.edu

NSF: MULTI-PETAWATT PHYSICS PRIORITIZATION WORKSHOP

- ***Recommendation:** To restore U.S. leadership, DOE and other agencies should formulate a national strategy to develop and build new classes of high-intensity lasers that enable now inaccessible parameter regimes*
- ***Recommendation:** DOE and NSF should lead a collaborative effort with other agencies to develop an extended stewardship program for long-term, application-oriented research to enable the development of revolutionary laser sources that translate to application*
- **NSF Multi-Petawatt Physics Prioritization (MP3) Workshop: https://mp3.lle.rochester.edu/ (April 20-22, 2022)**
  - **Establish the most important goals and flagship experiments of promising new science enabled by present and new generations of ultra-intense and powerful lasers.**
  - **Identify common interests and joint strategies for developing diagnostics needed for the flagship experiments.**
  - **Discuss a vision for the optimal next-generation high-intensity laser facility to address the frontier science goals.**

NSF ECLIPSE PROGRAM

- **NSF has aggressively followed up with recommendations of Plasma 2020.**
- ***<u>Recommendation:</u> More strategically, NSF should establish a plasma-focused program in EngD broadly advancing engineering priorities – energy, environment, chemical transformation, manufacturing, electronics and quantum systems.***
- **NSF established the new meta-program *ECosystem for Leading Innovation in Plasma Science and Engineering (ECLIPSE)* to address translational research.**
- **Cross foundation including programs in Directorates of Engineering, Math/Physical Sciences, Geosciences. Proposals should**
  - **Articulate the fundamental scientific and/or engineering challenge in plasma science and engineering that may be relevant to more than one NSF program; and**
  - **Discuss how resolution of the stated scientific and/or engineering challenge will address specific societal and/or technological needs identified as priorities by the research communities, policymakers and/or other stakeholders.**

https://beta.nsf.gov/funding/opportunities/ecosystem-leading-innovation-plasma-science-and-engineering-eclipse

DIVERSITY, EQUITY, INCLUSION (DEI)

- ***<u>Recommendation:</u> 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***
  - **New language added to the NSF Plasma Physics program description in the summer of 2020, immediately following and stimulated by the decadal:**
  - **"Principal Investigators (PIs) are encouraged to consider including specific efforts to increase diversity of the plasma physics community and broaden participation of under-represented groups in Science, Technology, Engineering, and Mathematics (STEM) as Broader Impacts of proposed work. Development of new undergraduate and graduate plasma physics curricula, or curricula enhancement to include plasma physics topics in other courses, at institutions lacking such coursework is similarly encouraged."**

NSF / NNSA / AFOSR

- ***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.***
- ***Recommendation:*** ***The NNSA, DOE-FES and NSF should continue and increase support for basic HED science programs at large facilities in collaboration with universities*****.**

- **New multi-agency MoUs (Memoranda of Understanding) to better coordinate and collaborate on plasma science and engineering initiatives.**
- **NSF/NNSA MoU on High Energy Density Science**
- **NSF and AFOSR are taking advantage of pre-existing / concurrently created broader partnership agreements to follow Plasma 2020 recommendations to work closer together in the plasma S&E arena.**

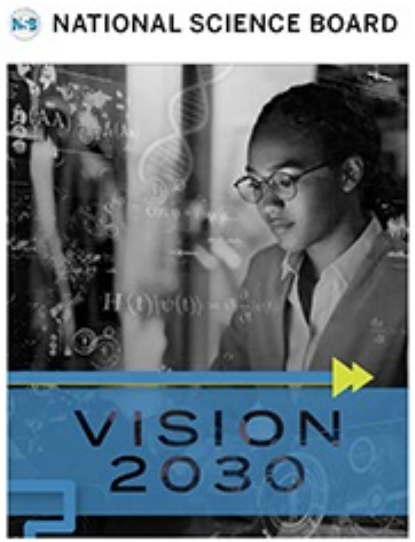
STEWARDSHIP – ADVANCING TRANSLATIONAL RESEARCH

- ***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.***
- **DOE Fusion Energy Sciences** – New round of Innovation Network for Fusion Energy (INFUSE) awards that will allow for collaboration of private industry with DOE national laboratories on overcoming challenges in fusion energy development.
- **NSF stood up a new directorate TIP Directorate for Technology, Innovation and Partnerships. Not a result of Plasma 2020 but an opportunity for implementing Plasma 2020 recommendations.**
- **"**TIP, advances use-inspired and translational research in all fields of science and engineering, giving rise to new industries and engaging all Americans — regardless of background or location — in the pursuit of new, high-wage jobs in science, technology, engineering and math (STEM)."

SYNERGY WITH NSF VISION 2030

- ***<u>Recommendation:</u>*** ***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.***

- **National Science Board (NSB) Vision 2030 released at the same time as Plasma 2020 (https://www.nsf.gov/nsb/NSBActivities/vision-2030.jsp)**
- ***NSB Vision 2030* increased NSF-wide emphasis on translational research, partnerships, and DEI with a number of new funding opportunities**
- **Extreme synergy of recommendations of *Vision 2030* and *Plasma 2020* have enabled new planning and implementation of plasma physics related programs.**



DECADAL SURVEY FOR SOLAR AND SPACE PHYSICS 2024-2033,

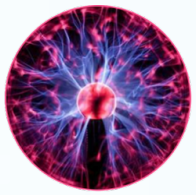
- **Decadal Survey for Solar and Space Physics (https://www8.nationalacademies.org/pa/projectview.aspx?key=52570) "will generate consensus recommendations to advance and expand the frontiers of solar and space physics in the current decade and lay the groundwork for continued advances in future decades."**
- **Supported by NASA, NSF, and NOAA with charge and additional counsel documents having reference to Plasma 2020.**
- ***"The survey report should also consider experimental and theoretical plasma physics investigations that would enhance progress on the prioritized science goals,"***
- ***"In the treatment of the heliosphere and geospace as a natural plasma science laboratory, the survey should take into consideration the alignment of its priorities with the recommendations of the National Academies decadal survey report Plasma Science: Enabling Technology, Sustainability, Security, and Exploration (2021***

NSF MULTI-AGENCY

- **NSF ECLIPSE Workshop (March 2022) https://www.eclipsemeeting.org/**
- **Meeting brought together the plasma community supported by Partner Agencies across the breadth of plasma science and engineering.**
- **Presentations and forward-looking discussions about the exciting scientific and technological horizons across the full breadth of our field, and the ways to make our field more inclusive and welcoming to all.**
- **Address recommendations of *Plasma 2020* in**
  - **Multi-disciplinary research**
  - **Leveraging advances across PSE (HED to Space Plasmas to LTP)**
  - **Translational research**
  - **Open source software**
  - **STEM and DEI**
- **Roundtable discussion by Federal Agencies on implementing Plasma Recommendations and foster inter-agency collaboration.**

A meeting to **bring together** the community supported by NSF and Partner Agencies across **the breadth of plasma science and engineering**

https://www.eclipsemeeting.org/



- Discussions of the scientific and technological horizons across the full breadth of Plasma S&E, and the ways to make our field more inclusive and welcoming to all
- A unique meeting that cut across the traditional sub-discipline boundaries
- Concluded with a first-of-a-kind multi-agency roundtable

Organizing Committee:

Selma Mededovic, Chair (Clarkson U.)
Franklin Dollar (UC-Irvine)
Sean Finnegan (LANL)
Matthew Kunz (Princeton U.)
... with organizational logistics support from Auburn University

ECLIPSE ROUNDTABLE PARTICIPANTS

- Raymond Adomaitis (NSF/ENG/CBET)
- Michael Bakas (DOD/ARO)
- C. Denise Caldwell (NSF/MPS/PHY)
- Brad Carpenter (NASA/SMD/BPS)
- Eric Colby (DOE/SC/ARDP)
- Colleen Hartman (NASEM)
- Scott Hsu (DOE/ARPA-E)
- Christopher Jones (NASEM)
- Thomas Kuech (NSF/ENG/CMMI)
- John Luginsland (DOD/AFOSR)
- Rosa (Ale) Lukaszew (NSF/ENG/ECCS)
- John Mandrekas (DOE/SC/FES)
- Ann Satsangi (DOE/NNSA)
- Quentin Saulter (DOD/ONR)
- Mangala Sharma (NSF/GEO/AGS)
- Nigel A. Sharp (NSF/MPS/AST)
- James Spann (NASA/SMD/Helio).

ECLIPSE 2022 Roundtable

NSF

NASA

DOE

DOD

& NASEM

https://www.eclipsemeeting.org/

ROUNDTABLE AGENDA

- **Self Introductions:**
  - **Personal background**
  - **Purview of agency's (and own program) activities in plasmas science and engineering**
- **Perspectives on top-level recommendation of Plasma 2020:**

  Recommendation: **Federal agencies directly supporting PSE research and those (potentially) benefiting from PSE applications should better coordinate their activities extending into programs within larger agencies.**
  - **Benefits, synergies, opportunities, how-to-get-started, role of broader community, how inter-agency programs might be structured.**
  - **Ground rule – challenges can be overcome! Let's emphasize opportunities**
- **Questions from the audience.**

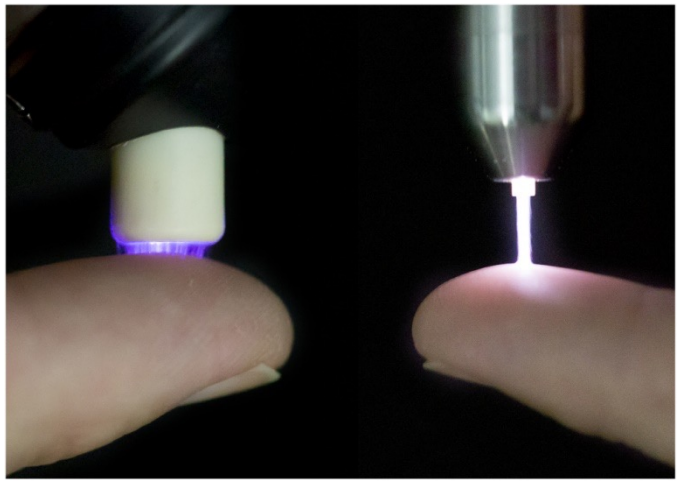
ROUNDTABLE HIGHLIGHTS

- Interagency partnerships need to address a common need for all participants
- Need a formal agreement between agencies to create an umbrella under which collaborations can be conducted
  - Agreements should not be too restrictive
  - Pop-up programs are unsustainable – extremely difficult to budget
  - Not a lot of support for an Interagency Working Group (IWG) – agencies feel they are already talking.
- Need a more organized plasma community to put forward big, visionary initiatives that agencies can run with (and represent to OSTP, OMB)
  - Involve multiple agencies in developing and marketing that vision.
  - Plasma America Initiative - Make case for science, impact on economy, defense
- Decadals are best for prioritizing missions – but commissioned reports are also influential
- Opportunities in collaborative computing facilities and computational support.

ECLIPSE TAKE AWAY – AND BPA ACTION ITEM

Despite vastly different scales and applications PSE has common themes and scientific challenges that bring cohesiveness to the PSE field (> 10^{10} range in energy densities and spatial scales).

- **This is our strength and problem – the extreme intellectual diversity field (much of which is *mission driven*) clouds and sometimes hides common themes and intellectual challenges.**
- **The community needs to self-organize to propose and market the plasma science equivalent of the Quantum Initiative.**
- **The agencies can then organize around this vision.**
- **This is extremely difficult without an umbrella organization with the clout and credibility to marshal the needed forces.**
- ***Action Item - Stand up, support and charge the BPA Plasma Science Committee***



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

STAND UP THE PLASMA SCIENCE COMMITTE

- **The BPA Plasma Science Committee (PSC) had a several decade (?) successful tenure as an umbrella-like organization to oversee what is perhaps the most intellectually diverse of any of the physical sciences and engineering disciplines.**
  - **The PSC was the go-to organization for agencies to speak with the plasma science and engineering community.**
  - **The PSC was the organization that launched and monitored targeted studies and Decadal Surveys**
  - **The PSC was the go-to organization for Congress to solicit input.**
- **For unclear reasons, the PSC was terminated 4 years ago(?) while now the need for such an umbrella organization has never been greater.**
- **Have as a charge to represent and organize the plasma science community, be a node through which interagency collaborations can be vetted, and bring cohesion to the community in fleshing out the vision.**
- **Rename the PSC the "*Plasma Science and Engineering Committee*" to better intersect with and organize new application focused initiatives (e.g., NSF-TIP, Fusion Energy on the Grid), address multi-agency opportunities and liaison with NAE.**

CONCLUDING REMARKS

- **Plasma 2020 made several strong recommendations in areas that created challenges for sponsoring agencies**
  - **Inter-agency collaborations – always a challenge**
  - **Interdisciplinary research**
  - **New facilities**
  - **New Programs addressing translational research**
  - **Engaging with private sector**
  - **Improving inclusiveness and diversity of the discipline.**
- **Sponsoring (and non-sponsoring organizations) have embraced recommendations and are engaged in implementing them.**
- **Not all recommendations have been addressed so far – and we did not expect that to happen. Several recommendations were intended to start discussions, which they have.**
- **A way to speed this process – stand up the *BPA Plasma Science and Engineering Committee.***

BACKUP SLIDES

DIVERSITY, EQUITY, INCLUSION (DEI)

- **New NSF programs synergistic with recommendations of *Plasma 2020*. Unclear how influential report was, however alignment is clear.**
- ***Launching Early-Career Academic Pathways in the Mathematical and Physical Sciences (LEAPS-MPS)***
  - **To help launch the careers of pre-tenure faculty at institutions that do not traditionally receive significant MPS funding (e.g., minority-serving institutions (MSIs), predominantly undergraduate institutions (PUIs), Carnegie Research 2)**
- ***Mathematical and Physical Sciences Ascending Postdoctoral Research Fellowship (MPS-Ascend)***
  - **Support postdoctoral Fellows who will broaden the participation of groups that are underrepresented in MPS fields.**

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

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.**

OUTCOMES: FUSION ENERGY SCIENCES (FES) and POTENTIAL SYNERGIES FOR NASA

- **FES has aggressively followed up with recommendations of *Plasma 2020* in the form of new programs and extending/increasing support of programs that align with the recommendations of *Plasma 2020***

- ***<u>Recommendation:</u> Federal agencies directly supporting PSE and those federal agencies benefiting (or potentially benefiting) from PSE should better coordinate their activities. This coordination, which extending into offices and directorates within larger federal agencies***

  - **FES continued its partnership with NSF in *Basic Plasma Science and Engineering*, and its joint program with NNSA on high-energy-density plasma science.**
  - **Opportunity for NASA to join NSF/DOE partnership to leverage (and top off) NSF/DOE investments in basic plasma and space plasmas, with some steering towards NASA priorities.**

FES: EDUCATION, PIPELINE, DEI, TRAINING

- ***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.***
- ***Recommendation:*** ***The DOE Office of Science should restore discipline-specific graduate fellowships and undergraduate research programs that support MFE research at U.S. universities as a vehicle for attracting new and diverse talent***

  - **In FY 2021, FES established *Plasma Fusion Undergraduate Research Opportunities* (PFURO) https://www.pppl.gov/plasma-and-fusion-undergraduate-research-opportunities-pfuro .**
  - **DOE-wide program focused on DEI – *REaching a New Energy sciences Workforce (RENEW).* In the FY22 President's request, FES has put $3M toward this program. https://www.energy.gov/sites/default/files/2021-06/Overview%206_16_21.pdf**

FES: COMPUTATIONS

- ***Recommendation:*** ***Federal agencies should support research into computational algorithms for PSE for the heterogeneous device computing platforms of today and upcoming platforms, while encouraging mechanisms to make advanced computational methods, machine learning, and artificial intelligence broadly available.***
  - **FES continued to support *Scientific Discovery through Advanced Computing* (SciDAC) projects jointly with the *Advanced Scientific Computing Research* (ASCR) office.**
  - **FES and ASCR are planning for the SciDAC funding re-competition in FY 2022.**
  - **In FY 2021, FES supported the 2nd Computational Physics School for Fusion Research, hosted by MIT.**
  - **In FY 2021, FES provided funding to support additional research projects in Quantum Information Science and in Artificial Intelligence / Machine Learning.**

DOE FES / NASA

- ***Recommendation:*** *Federal agencies that fund PSE should forge partnerships with other plasma-focused agencies as well as agencies focused on applications benefiting from plasmas (or programs within agencies) to close the widening gap between fundamental plasmas science research and translational research leading to applications*
  - **During 2021, FES participated in two meetings with NASA of the Joint Science and Innovation Working Group for discussions of collaborative research opportunities.**
  - **NASA launched a *Space Technology Research Institutes* (STRI) in the area of plasma propulsion for deep space exploration ($15M over 5 years for several universities). https://rh.gatech.edu/news/646735/georgia-tech-shares-15m-nasa-advance-deep-space-exploration**

- **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

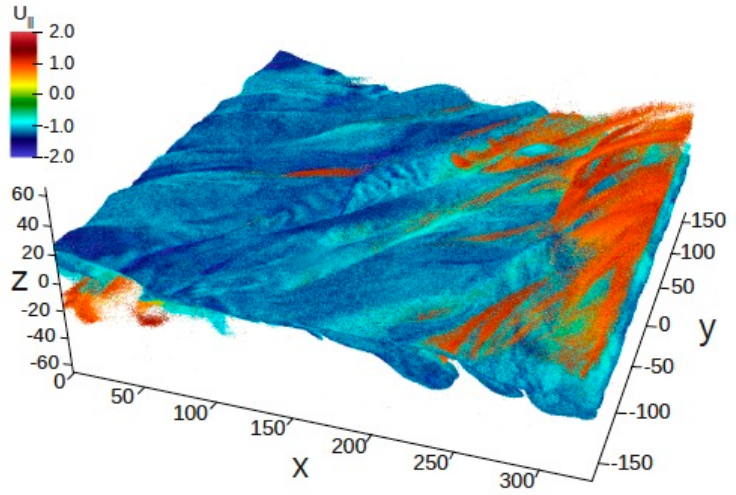
IV. High Energy Density Physics and Inertial Confinement Fusion

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.

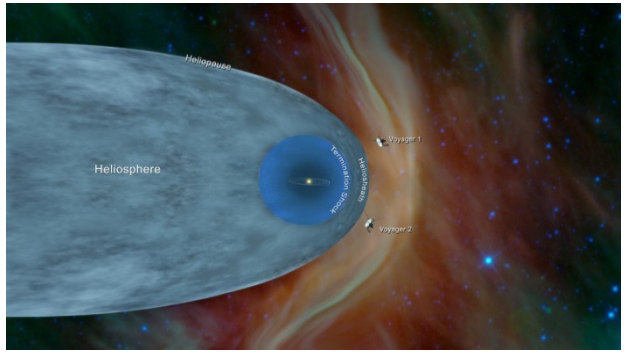
- Color indicates particle velocity parallel to background magnetic field.
- Simulation has 115 billion particles

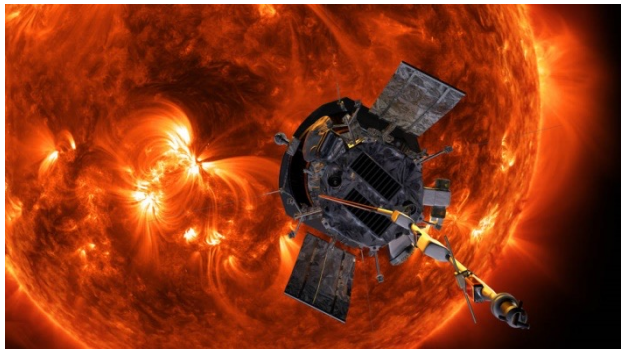
Advanced computing can provide breakthroughs in understanding.

- **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.

THE COSMIC PLASMA FRONTIER





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

- *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.

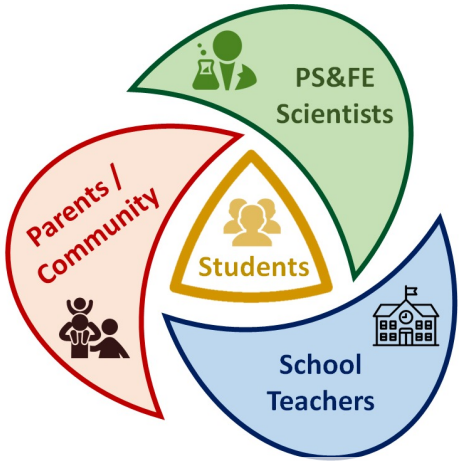
PLASMA 2020 and COALITION FOR PLASMA SCIENCE

- Coalition for Plasma Science (CPS) (https://www.plasmacoalition.org/) has "rebooted" as a consortium to implement recommendations of *Plasma 2020*.

- *Stewardship and Advancement of Interdisciplinary Research*
  - CPS-sponsored reception at APS DPP (joint with Physical Review Journals) hosting a panel discussion on *Frontiers in Interdisciplinary Plasma Science and Engineering*
  - Press highlights of interdisciplinary research (e.g., work with Elizabeth Sterling on *DIII-D Frontiers* campaigns and APS DPP Press Release Committee).

- *Education and Workforce Development*
  - CPS-sponsored reception at APS GEC hosting a panel discussion on career opportunities for undergraduate students.
  - *Plasma Network for Outreach and Workforce (Plasma NOW)* website to increase literacy of PSE and to improve student involvement in related degree/employment opportunities.

- DPP Reception Panelists



- Plasma NOW Structure

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*.**

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.**

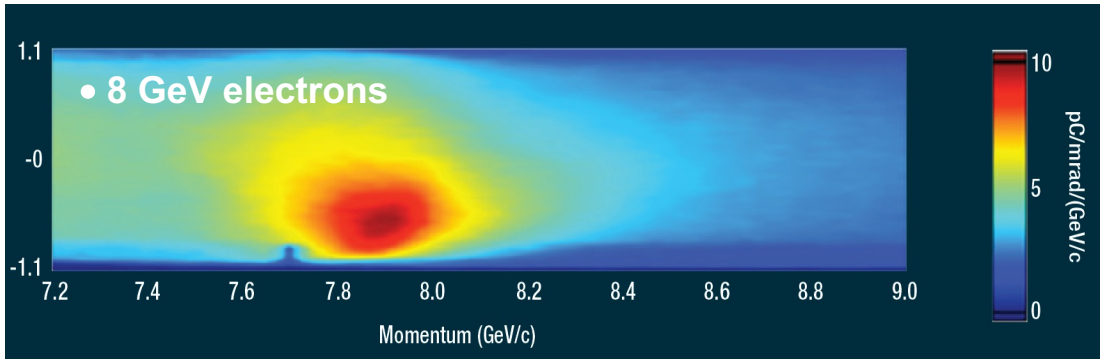
THE RESEARCH ENTERPRISE IN PSE

- ***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*.**

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

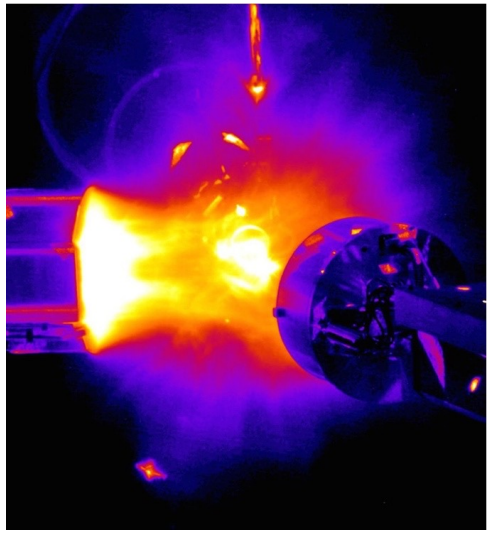
Plasma optics and high field physics are opening new physics regimes.

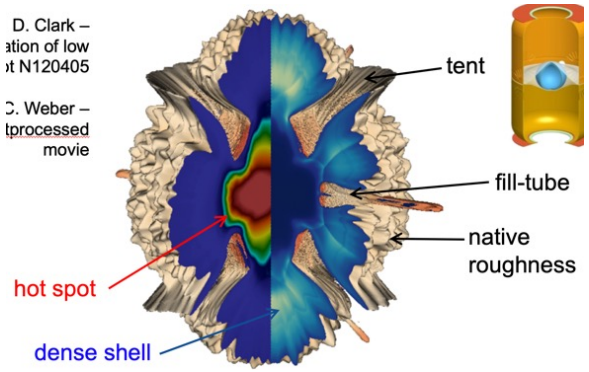
- **Chapter Lead: Dr. Cameron Geddes, Lawrence Berkeley National Lab.**

- ***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

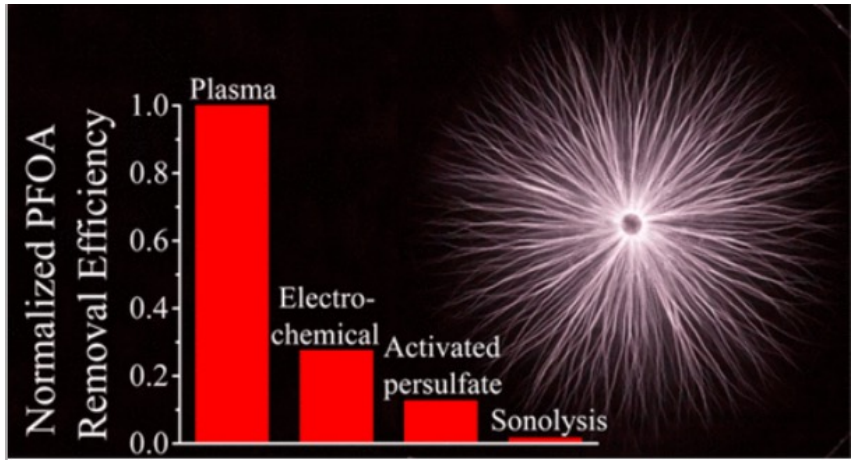
- Four major new facilities are online in the last decade producing a wealth of new data.
- Novel diagnostics enable unprecedented levels of detailed characterization.
- New capabilities in simulations enable transformative insights into plasma behavior

- **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.

NSF: MULTI-PETAWATT PHYSICS PRIORITIZATION WORKSHOP

- *Recommendation: To restore U.S. leadership, DOE and other agencies should formulate a national strategy to develop and build new classes of high-intensity lasers that enable now inaccessible parameter regimes*
- *Recommendation: DOE and NSF should lead a collaborative effort with other agencies to develop an extended stewardship program for long-term, application-oriented research to enable the development of revolutionary laser sources that translate to application*
- **NSF** Multi-Petawatt Physics Prioritization (MP3) Workshop: https://mp3.lle.rochester.edu/
  - Establish the most important goals and flagship experiments of promising new science enabled by present and new generations of ultra-intense and powerful lasers.
  - Identify common interests and joint strategies for developing diagnostics needed for the flagship experiments.
  - Discuss a vision for the optimal next-generation high-intensity laser facility to address the frontier science goals.

FES: FACILITIES

- ***<u>Recommendation:</u> 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.***
  - **FY 2021, FES supported *Opportunities in Frontier Plasma Science* and awarded $7.6M to support nine frontier plasma science projects at five different DOE national laboratories.**
  - **Projects focus on key plasma science areas in MFE, dusty plasmas, and low-temperature plasma-surface interactions for applications to microelectronics and plasma medicine.**
  - **Provides support for DOE scientists to use plasma science facilities at UCLA, Wisconsin, Auburn, PPPL, Sandia National Laboratories, and GA.**
- ***<u>Recommendation:</u> To restore U.S. leadership, DOE and other agencies should formulate a national strategy to develop and build new classes of high-intensity lasers that enable now inaccessible parameter regimes.***
  - **During FY 2021, FES supported an Upgrade for the Matter in Extreme Conditions (MEC) end station on Linac Coherent Light Source (LCLS) at SLAC. This upgrade will bring MEC into new, world-leading parameter and capability regimes.**

FES: HIGH ENERGY DENSITY PHYSICS

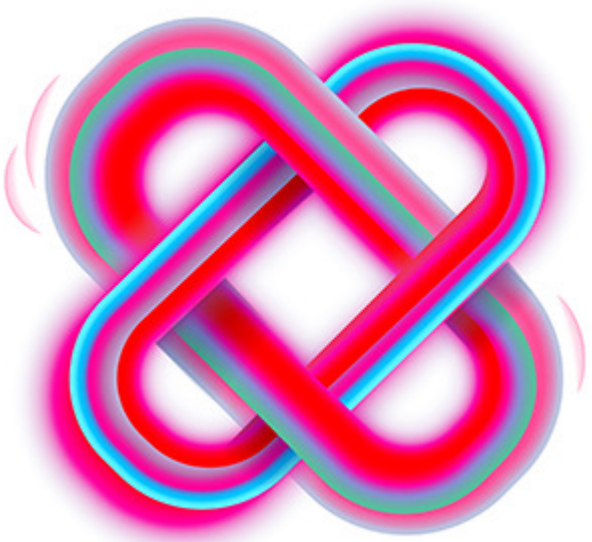
- ***<u>Recommendation:</u> The NNSA, DOE-FES and NSF should continue and increase support for basic HED science programs at large facilities in collaboration with universities*.**
  - **In FY 2021, FES funded nine new and renewal HED science projects through the SC-NNSA Joint Program in High Energy Density Laboratory Plasma Science ($3.1M).**
  - **FES funded HED projects as part of the annual solicitation under the NSF/DOE *Partnership in Basic Plasma Science & Engineering*.**
  - **In FY 2021, FES increased support for the LaserNetUS consortium of high-performance laser facilities at six universities, three national labs, and now also one Canadian institution.**
  - **LaserNetUS is currently pursuing an MOU with LaserLab Europe.**

FES: MFE STRATEGIC PLANNING

- ***Recommendation:*** *DOE FES should undertake regular strategic planning, led by the U.S. [Magnetic Fusion Energy] MFE community, as recommended in the NAS Burning Plasma Report.*
- ***Recommendation:*** *Aligning with the NAS Burning Plasma Report, DOE FES should develop a roadmap for the development of commercial fusion power in the United States.*

- **During FY 2021, the Fusion Energy Sciences Advisory Committee (FESAC) completed a long-range strategic plan *Powering the Future: Fusion and Plasmas*. (https://usfusionandplasmas.org/)**

- **During 2021, an FES-sponsored NASEM committee completed a study *Key Goals and Innovations Needed for a U.S. Fusion Pilot Plant*. (https://www.nationalacademies.org/our-work/key-goals-and-innovations-needed-for-a-us-fusion-pilot-plant)**



FES: COLLABORATIVE RESEARCH WITH PRIVATE SECTOR

- ***<u>Recommendation:</u> Federal agencies funding the development of MFE science and technology (DOE FES and ARPA-E) should leverage privately and philanthropically supported fusion research and vice versa***

- **During FY 2021, FES supported Request for Assistance calls for the *Innovation Network for Fusion Energy (INFUSE)* public-private partnership program and made $4M in research awards. https://infuse.ornl.gov/**
- **INFUSE has now made 39 awards totaling $7.6M, enabling 8 DOE national labs to collaborate with 21 fusion companies in 9 states.**
- **In FY 2022, INFUSE will be expanded to include university participation.**

DOE ARPA-E

- **DOE Advanced Research Projects Administration-Energy (ARPA-E) has long term interests in plasmas preceding and coinciding with Plasma 2020.**
  - ***ALPHA (2015) Accelerating Low-Cost Plasma Heating and Assembly*** **https://arpa-e.energy.gov/technologies/programs/alpha**
  - ***BETHE (2020) Breakthroughs Enabling Thermonuclear-fusion Energy*** **https://arpa-e.energy.gov/technologies/programs/bethe**
- ***Plasma 2020*** **recommendations on multi-agency coordination launched discussions (Program Director Scott Hsu) to explore how ARPA-E could have a better presence in PSE.**
- **Facilitated greater internal coordination between program directors who oversee topics to which low temperature plasmas (LTPs) could contribute.**
- **Discussion group established on translational research using LTPs for chemical conversion and energy storage.**
- **New program director with expertise in LTP and interest in developing new R&D programs in the application of LTP to decarbonization.**

IN THE PIPELINE?

- **Language in current Congressional legislation (HR 3593) for a *High Intensity Laser* initiative which maps to *Plasma 2020* recommendations/discussion following up on the NASEM *Bright Light* report.**
  - **"…This initiative should include research and development of petawatt-scale and of high average power laser technologies necessary for future facility needs in discovery science and to advance energy technologies, as well as support for a user network of academic and national laboratory high intensity laser facilities."**

- ***Creating Helpful Incentives to Produce Semiconductors for America Act or the CHIPS for America Act***
  - **Several conversations with Congressional committees on support for translational research for plasma processing of semiconductors facilitated by *Plasma 2020* recommendations.**