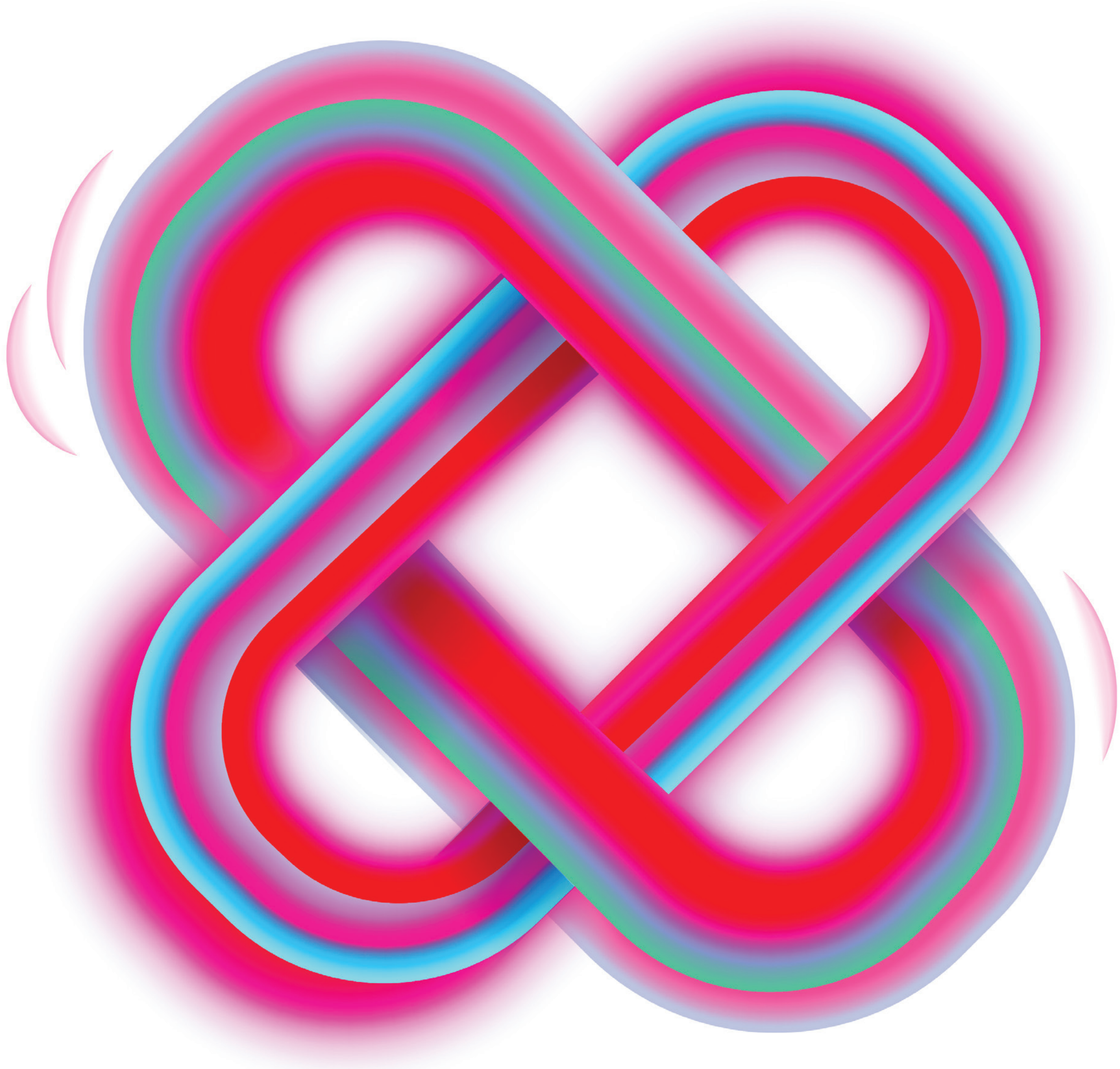
A Report of the Fusion Energy Sciences Advisory Committee

Powering the Future
Fusion & Plasmas



A long-range plan to deliver fusion energy and to advance plasma science

2020

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This report provides a decade-long vision for the field of fusion energy and plasma science and presents a path to a promising future of new scientific discoveries, industrial applications, and, ultimately, the delivery of fusion energy. We identify critical areas for research and development and prioritize investments to maximize impact. The research community worked for more than a year to develop a wealth of creative ideas designed to accelerate fusion energy and advance plasma science. The effort culminated in the consensus Community Planning Process report. Our work is based heavily on that report, and we extend our sincere gratitude to our colleagues for their efforts. Following the research community's lead, we worked through consensus to generate this report. Many ideas were heard and were thoughtfully deliberated until a shared view on each issue emerged. This process allowed us to discuss and appreciate our different points of view and come to consensus language. Ultimately, we speak with one voice in conveying a vision for a vibrant program that will bring significant benefit to society.

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Fusion is the merging of nuclei to release the energy that powers stars; plasmas are ionized gases, the fourth state of matter that makes up stars. The two are inextricably linked. Their shared history exemplifies how basic scientific research translates from a deeper understanding of the universe to technologies that benefit society.

Now is the time to move aggressively toward the deployment of fusion energy, which could substantially power modern society while mitigating climate change. Scientific and technological innovations enable a unique US vision for economically attractive fusion energy, with the goal of a fusion pilot plant by the 2040s. The foundation of a US fusion energy industry is central to this vision and the industry has already taken root, with approximately $2 billion of private capital invested to date.

The technological and scientific achievements arising from plasma research are significant and far-reaching. The US vision for fusion energy is enabled by breakthroughs in the physics of magnetically confined plasmas, in which record confined pressures have recently been achieved. Plasma physics helps us understand not only the confined plasmas that could power an energy-generating fusion reactor, but distant stars and other objects, such as supernovae and black hole accretion disks, that capture our imagination. Understanding the exotic states of matter created using the most intense lasers in the world requires deep knowledge of plasma physics. Plasmas transform society, enabling the development of industry-changing technologies, especially the plasma-enabled manufacturing at the heart of the trillion-dollar information technology industry.

Partnerships will accelerate progress. Partnership in the international ITER fusion project is essential for US fusion energy development, and so is supporting the continued growth of the private-sector fusion energy industry. Public–private partnerships have the potential to reduce the time required to achieve commercially viable fusion energy. The diversity of topics addressed by plasma science is reflected in the wide range of federal agencies that are committed to supporting its development. Increased coordination among those agencies is warranted to maximize progress in research and development.

Fusion and plasma research in the US are leading the world, and continued leadership requires nurturing and agility. The US is poised to take the global lead in the development of a private-sector fusion energy industry, but that opportunity will be lost without strong support. Similarly, the US leadership position in some key research areas is threatened by the absence of investment in major new facilities to address critical gaps in the relevant science and technology.

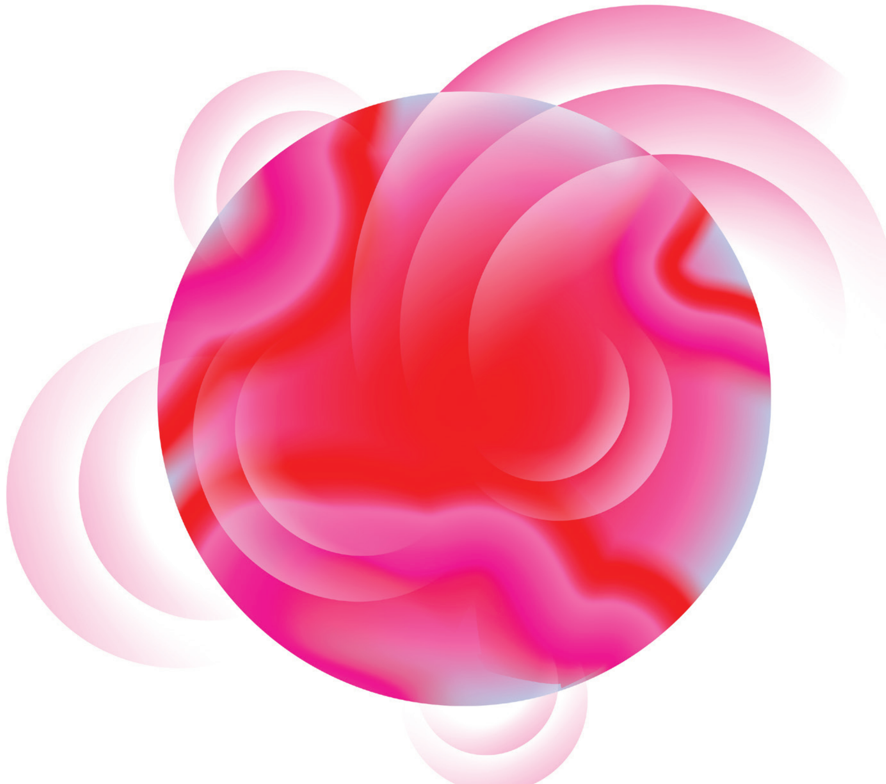
For the first time, scientists have created a long-range plan to accelerate the development of fusion energy and advance plasma science. Earlier, the community undertook a year-long study that identified new opportunities and developed guidance for prioritization. That effort resulted in the Community Planning Process report, which forms the basis for the strategy detailed here. This report calls for important redirections in the Department of Energy (DOE) Fusion Energy Sciences (FES) research programs and is embodied by six technology and science drivers in two thematic areas.

Fusion Science and Technology

The Fusion Science and Technology area should focus on establishing the scientific and technical basis for a fusion pilot plant by the 2040s:

- Sustain a Burning Plasma. Build the science and technology required to confine and sustain a burning plasma.
- Engineer for Extreme Conditions. Develop the materials required to withstand the extreme environment of a fusion reactor.
- Harness Fusion Power. Engineer the technologies required to breed fusion fuel and to generate electricity in a fusion pilot plant by the 2040s.

Plasma Science and Technology



The Plasma Science and Technology area should focus on new opportunities to advance fundamental understanding and, in turn, translate these advances into applications that benefit society:

- Understand the Plasma Universe. Plasmas permeate the universe and are the heart of the most energetic events we observe.
- Strengthen the Foundations. Explore and discover new regimes and exotic states of matter and utilize new experimental capabilities.
- Create Transformative Technologies. Unlock the potential of plasmas to transform society.

This plan makes the difficult choices necessary to embark on these critically important journeys. From the process, recommendations emerged that express an optimized path to achieving our goals. Overarching recommendations are made that identify important programmatic changes:

- Addressing the technology and science drivers will require continuing investment in the design, construction, and operation of facilities that provide important new capabilities. Therefore, resources for ongoing investment need to be established in the program. Opportunities for developing small and midscale facilities aligned with the plan are also needed. Preconceptual design toward new experimental facilities should be a part of regular program activities to better prepare for future strategic planning.
- To achieve efficiencies and maximize technical progress across all the elements of this strategic plan, it will be necessary to build on the existing successful partnerships with the National Science Foundation (NSF), ARPA-E, and the National Nuclear Security Administration (NNSA) and explore opportunities to form new partnerships with other agencies and with industry. The successful Innovation Network for Fusion Energy (INFUSE) program should be expanded and new public–private partnership programs, including milestone-based cost-share programs, should be developed.
- This long-range planning process should be repeated regularly to enable periodic review and update of the strategic plan with strong community engagement.
- Policy changes should be developed and implemented that improve diversity, equity, and inclusion within the research community and allow discipline-specific workforce development.

The strategic plan is developed through a series of recommendations, not in priority order, on needed programs and experimental facilities:

- A fusion pilot plant design effort should begin immediately to develop cost-attractive fusion solutions on the fastest time scale possible.
- The fusion pilot plant goal requires increased investment in research and development of fusion materials and other critical technology. Emphasis is needed on fusion materials science, plasma-facing components, tritium-breeding blanket technology and the tritium fuel cycle. Several key experimental facilities are recommended. The Fusion Prototypic Neutron Source (FPNS) will provide unique material irradiation capabilities, and the Material Plasma Exposure eXperiment (MPEX) and high-heat-flux testing experiments will enable solutions for the plasma-facing materials. Blanket research and the associated Blanket Component Test Facility (BCTF) will provide the scientific understanding and basis to qualify fusion power system blankets for an FPP.
- The successful tokamak plasma confinement concept must be advanced to meet the stringent requirements of a fusion pilot plant. A sustained burning plasma at high power density is required simultaneously with a solution to the power exhaust challenge of mitigating the extreme heat fluxes to materials surrounding the plasma. US partnership in ITER provides access to a high-gain reactor-scale burning fusion plasma, and an accompanying US ITER research team and program to exploit that facility must be developed. Present tokamak experiments in the US and abroad can address key issues in the near term, and new opportunities in the private sector should be leveraged and supported. Addressing the core/exhaust integration challenge requires a new tokamak facility, the EXhaust and Confinement Integration Tokamak Experiment (EXCITE).
- The plan embraces the development of innovative ideas that could lead to more commercially attractive fusion systems and address critical gaps. The quasi-symmetric stellarator is the leading US approach to developing disruption-free, low-recirculating-power fusion configurations and should be tested experimentally with a new US stellarator facility. Liquid-metal plasma-facing components have the potential to ameliorate some of the extreme challenges of the plasma-solid interface and may reveal new plasma operating regimes. Inertial fusion energy research can leverage significant investments in the US to establish new technologies and approaches to energy production. Private investment in alternative fusion plasma configurations has enabled breakthroughs that have potential as fusion energy sources. Strengthening those elements will provide both scientific opportunity and programmatic security.

– A sequence of mid- to large-scale facilities will establish a leadership role in frontier plasma science. To strengthen plasma foundations, the Matter in Extreme Conditions Upgrade (MEC-U) will provide a world-class user facility in high-energy-density science by co-locating a high-intensity (petawatt-class) laser and a long-pulse shock compression laser with the Linac Coherent Light Source free electron laser. Additionally, a multi-petawatt laser will push the frontier of laser intensity and reveal fundamental quantum electrodynamic processes of creating matter and plasma directly from light.

  To understand the plasma universe, a new Solar Wind facility will close key science gaps in plasma turbulence, connecting laboratory experiments with space and astrophysical observations; and a mid-scale Z-pinch facility will allow access to strongly magnetized high-energy-density matter relevant to astrophysics and fusion energy research. To create transformative technologies, a high-repetition-rate high-intensity laser system will dramatically increase the rate at which high-energy-density plasma experiments can be conducted, with the potential to significantly advance the development of plasma-based accelerators.

– A plasma-based technology research program will provide the scientific basis to enable the next generation of technological inventions. Plasmas can enable transformative technologies in manufacturing, microelectronics, biotechnology, medicine, and aerospace. Fulfilling this potential will require a dedicated, nimble research program able to take advantage of the translational nature of this research by connecting the basic science with the breadth of applications.

– Programs that support foundational plasma science research should be emphasized. Foundational science fosters creative exploration that sets new directions for the field, addresses fundamental questions of nature, and explores novel states of matter.

Our prioritization of needed programs and facilities was applied to address three funding scenarios: constant level of effort, modest growth (2% yearly), and unconstrained but prioritized.

In the constant level of effort scenario, programs in fusion materials and technology are grown, the MPEX facility is completed, and construction of FPNS begins. Important scientific and technical progress continues in other areas. However, US leadership in fusion and plasma science is at risk in this scenario. New activities to address other key gaps are significantly delayed, and many opportunities for innovation and enhanced US leadership cannot be acted upon. To provide needed resources for fusion materials and technology programs and facilities, operations and research programs on existing domestic tokamak facilities DIII-D and NSTX-U, which aim to address fusion pilot-plant design gaps, will have to be modestly reduced in the near term. One domestic tokamak facility will likely need to cease operations mid-decade to free the resources required to make progress on FPNS. A nascent ITER research team is developed, and some shift of resources to collaboration with international and private-sector facilities is possible. A limited plasma technology program will be established. Almost all other strategically selected enhancements of experimental capabilities and new program activities will be delayed. Importantly, completing the ongoing MEC-U project is not possible under this constrained scenario as defined by the charge. New facility concept studies will be pursued to build a basis for deliberations on these important facilities.

The return on the investment of the relatively small increment from the constant level of effort to the modest growth scenario is substantial. Fusion materials and technology research is further strengthened and FPNS is accelerated. Increased focus is given to addressing the core/exhaust integration challenge, such that design and start of construction of the EXCITE facility may be possible. Fundamental plasma research and plasma technology program areas are modestly grown, and networks are established and bolstered. However, substantial risks and missed opportunities remain. A similar reduction of activity on existing tokamak programs as in the constant level of effort scenario is envisioned. Other new major facilities are not possible in this scenario, so important research gaps are unaddressed and US leadership opportunities are unfulfilled.

In the unconstrained scenario, the complete strategy as summarized above can be implemented, but prioritization and staging of items beyond the constrained scenarios is proposed. Additional investment beyond the modest growth scenario will have significant return. Major scientific advances would be enabled, and progress toward realizing practical fusion energy would be accelerated. FPNS would be further accelerated to ensure operations as soon as possible. Additional facilities and program enhancements have been identified that capture the opportunities provided by the full breadth and creativity of the program. Priority order for additional facility investment is expressed thusly: the MEC-U project and the EXCITE facility at equal priority; a new quasi-symmetric stellarator device; the blanket component test facility; the Solar Wind facility; a facility for full-size component-level high-heat-flux testing; a multi-petawatt laser facility; and, in collaboration with other agencies, the high-repetition-rate laser facility and the midscale Z-pinch could be pursued. Research programs would be bolstered first to accompany new facility investments. With careful staging of new facility construction, program pivoting, and aggressive utilization of partnerships, we believe that what is recommended in this scenario can be accomplished in a timely manner and under realistic budgets.

Introduction and Overview

Fusion and plasmas: Powering the future

The US is at a critical moment in the effort to develop fusion as a carbon-neutral, sustainable source of energy. The past decade has seen significant progress in the physics and engineering necessary to confine high-temperature plasmas for fusion. Important technological breakthroughs include high-temperature superconductors that enable the advances in magnet technology required to achieve that confinement. We are on the verge of entering an era of burning plasmas, with the international ITER experiment set to begin operation this decade. At the same time, privately financed fusion research and development (R&D) has experienced rapid growth that has spurred an emerging fusion energy industry. For US fusion research, these developments have created a unique and ambitious path toward a low-capital-cost fusion pilot plant (FPP) that will form the basis for economically attractive fusion electricity.

Fusion energy and plasmas are inextricably linked. A fusion reactor requires a confined, controlled, burning plasma at its core. For that reason, fusion research has historically been an important driver for the development of plasma physics as a fundamental field. The link between the two fields is strong but does not fully define either one. Fusion energy requires R&D into materials resistant to neutron irradiation, into technologies for breeding fusion fuel, and into enabling technologies like magnets. The field of plasma science and engineering is intellectually diverse, is highly interdisciplinary, and has myriad applications beyond fusion energy.

Plasma science and engineering has advanced significantly over the past decade, and future opportunities abound. Extreme states of matter have been produced and studied using the world's most intense lasers developed from Nobel Prize-winning research in chirped pulse amplification. Understanding of the most energetic events in the universe requires deep knowledge of plasma physics. Such research is essential to interpreting electromagnetic signatures from events like black hole mergers in this era of multimessenger astronomy. Plasmas enable technologies essential to our everyday lives, including plasma-processing of semiconductor devices, which is key to the trillion-dollar information technology industry. There is potential to expand these applications with significant societal benefit; for example, plasma-enhanced chemistry could help address energy security and climate change by providing ways to make products from carbon-free electricity, purifying water and developing new medical treatments.

This report details opportunities to accelerate the development of practical fusion energy and to advance the frontiers of plasma science and engineering. Importantly, it outlines a strategy for the Department of Energy (DOE) Fusion Energy Sciences (FES) to act on these opportunities.

Embracing opportunities to form partnerships that accelerate progress in R&D is an important theme of this report. Partnership opportunities exist within the federal government, internationally, and with industry. DOE FES is the primary federal sponsor for fusion research, but other agencies have made important investments, including DOE Advanced Research Project Agency-Energy (ARPA-E), DOE Advanced Scientific Computing Research (ASCR), and the DOE National Nuclear Security Administration (NNSA). Because the field is interdisciplinary in nature and offers a multitude of applications, many federal agencies invest in broader plasma science and engineering, including the National Science Foundation (NSF), NASA, DOE High Energy Physics (DOE HEP), the Office of Naval Research (ONR), and the Air Force Office of Science Research (AFOSR). Better coordination among agencies involved in various aspects of fusion and plasma research could result in more efficient use of federal resources and enable more rapid progress in advancing plasma science and engineering and in developing fusion energy.

Fusion energy and plasma science research are global endeavors. Many nations recognize the promise of fusion energy and have made significant investments in R&D. International collaboration has been critically important to progress. This has been particularly true in the quest to address a top priority for the global fusion research community: Experimental access to a burning plasma, in which energy released by fusion reactions is the dominant heating mechanism. The international community, with the US as a key partner, is collaborating to construct the ITER experiment in France to achieve this goal. At the time of this writing, the ITER project is more than 70% complete toward first plasma. The Burning Plasma Report from the National Academies of Sciences, Engineering, and Medicine (NASEM) highlighted the importance of the ITER project to the US fusion program and stated that it provides the most compelling path to accessing a burning plasma at reactor scale. However, significant R&D is required in addition to ITER to produce electricity from fusion. Additional investment supporting that R&D is needed to advance the science and technology of a fusion pilot plant in a timely manner. While other international parties are considering a reactor scaled directly from ITER, the NASEM report recognized that this approach is too large and expensive to be economically competitive in the US market when compared with other carbon-neutral energy technologies. Consequently, the NASEM report instead set forth a unique US vision for fusion energy using scientific and technological innovations to target the development of a low-capital-cost FPP. That emphasis on developing innovative, world-leading solutions makes the near-term investments in R&D even more critical as other nations continue to invest in new fusion facilities that advance their own approaches to fusion energy development.

Research in fundamental plasma science is also vibrant and growing internationally, with activity spanning scales ranging from the subatomic to the cosmic, from low-temperature atmospheric plasmas to the most extreme conditions in the universe. Over the past few decades, shrewd investments by DOE in world-class facilities have placed the US at the forefront of pioneering plasma research. However, such scientific leadership requires agility and continuous nurturing. In some instances, the US is losing its leadership position. For example, the 2018 NASEM report *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*, highlights how the US has already lost leadership in the high-intensity lasers that are essential for high-energy-density science. Although the chirped-pulse laser amplification technology that led to petawatt lasers was developed in the US, the vast majority of high-intensity laser systems are now being built in Europe and Asia. This long-range plan describes a path to regain a leadership position in fundamental plasma science and its applications in the US.

Fusion energy and plasma science research advances fundamental science, but also translates to direct commercial application. The ultimate goal of fusion energy research is the development of commercial fusion power. The fusion energy industry is already taking root, but realizing the ultimate goal of producing power will require additional support to help it become firmly established. The past decade has seen about $2 billion invested worldwide in fusion energy development in the private sector. Internationally, the United Kingdom and China have already established multi-hundred-million-dollar partnership programs to attract private fusion energy companies. Therefore, it is imperative that the US strengthen partnerships in the private sector to accelerate the development of fusion power in the US and maintain a leadership position in the emerging fusion energy industry. For decades, plasma technologies have played a ubiquitous role in manufacturing, crucial for the fabrication of microelectronic circuits, lighting, optics, advanced materials, materials processing, and much more. The future looks even more promising. Recent research suggests that plasmas will influence much of the future economy; they will play a decisive role in technologies that convert electricity from carbon-free sources to the products that drive society, and in future medical treatments, aerospace, particle accelerators, advanced X-ray sources, and agriculture. Countries that can solve the science questions that make these technologies possible and can facilitate technology transfer from academic research to commercial applications will position themselves to lead tomorrow's economy. This long-range plan outlines ways in which the

US can take the lead in both commercial fusion energy and other plasma-based technologies.

This report marks the first time a strategic planning process for DOE FES has been undertaken that addresses both fusion energy and plasma science and that has had a significant community-led portion of the process. The strategic planning process involved two stages: a community-driven stage followed by a stage led by the Fusion Energy Sciences Advisory Committee (FESAC), using input from the community process. The year-long Community Planning Process (CPP), was organized by the American Physical Society's Division of Plasma Physics. The process was invaluable and resulted in the consensus CPP report that not only enumerates scientific and technological opportunities, but also provides guidance for prioritization. The CPP report formed the basis for this strategic plan and remains an essential companion to this report for those looking for more technical detail on specific initiatives. The technical bases for the considerations in both reports were made based on white papers submitted to CPP and the expert groups that evaluated them. This report presents a strategic plan based on the resulting new program elements and facilities.

Technology and Science Drivers

As acknowledged by the recent burning plasma and plasma decadal reports by NASEM and by the CPP report, fusion science and technology has reached a level of maturity that calls for FES to broaden its focus from the plasma core of a fusion reactor toward a comprehensive energy mission. At the same time, these reports show that plasma science and technology outside the fusion energy mission deepens our understanding of the universe and lays the foundation for creating transformative technologies ranging from microelectronics and medicine to particle accelerators and new materials such as advanced alloys, ceramics, and materials for magnets.

The energy mission is driven by the urgent desire to address climate change and energy security on a time scale that requires activities to resolve the critical challenges of fusion energy in the next two decades. This mission-driven program is founded on the steady progress in plasma science, ITER construction, predictive integrated-modeling capabilities, and a burgeoning investment in private fusion enterprises. However, the least developed domain in the mission portfolio is in fusion materials and technology (FM&T). Fulfilling the energy mission demands a shift in the balance of research toward FM&T, which connects the three science drivers: Sustain a Burning Plasma, Engineer for Extreme Conditions, and Harness Fusion Energy. The program's renewed attention to economic viability distinguishes it from other ITER partners. It leverages US innovation, leadership, and technology advances to address the key gaps in fusion plasma science, nuclear science, materials science, and the enabling technology that will be required to construct an FPP, anticipated to be the key remaining step to enable commercial fusion energy. Critical gaps in FM&T will have to be closed for any choice of plasma core in an FPP, and without immediate investment those gaps could become pace-limiting. Such a program will create US leadership in a broad range of disciplines through innovation and rigorous scientific inquiry.

A critical need in the quest for fusion energy production is the ability to sustain a burning plasma by controlling and predicting its dynamics. Burning plasmas, in which the heating is primarily due to the energy released from fusion reactions, pose challenges to stability and control that are not fully addressable in current experiments and for which significant uncertainty exists. Addressing those challenges requires establishing scenarios for maintaining high performance in a burning regime and preventing damage associated with transient events through the development of tools to predict, avoid, and mitigate such events. The tokamak approach for the plasma core is the most technically advanced and mature confinement concept. A tokamak FPP will require completing critical research on existing domestic facilities, and significant participation in the ITER research program. ITER participation will increase knowledge in burning plasma physics and in materials science and technology. New collaborations with industry potentially offer pathways to accelerate access to burning plasma conditions. Complementing these priority areas is research into non-tokamak confinement approaches, including stellarators, inertial fusion energy, and other alternate confinement approaches. Investment in the alternate approaches is important both as a risk-mitigation strategy for the tokamak approach and to support innovations that could accelerate progress toward an FPP and commercial fusion energy.

An FPP will produce heat, particle, and neutron fluxes that significantly exceed those in present confinement facilities, and new approaches and materials need to be developed and engineered for the anticipated extreme reactor conditions. Those intense conditions affect all regions of the reactor in distinct ways, including the plasma-facing components (PFCs); structural, functional, magnet, and diagnostic materials; and ex-vessel components. In an FPP, high fluxes of 14 MeV neutrons produce damaging and poorly understood effects in materials. A scientific understanding of how the properties of materials evolve and degrade due to fusion neutron exposure is needed to safely predict the behavior of materials in fusion reactors. Even those components not directly exposed to high fluxes from the plasma still experience a complex multifactor environment that includes high temperatures, tritium migration and trapping, material interfaces, and high stresses. Innovative approaches and new developments will lead to integrated solutions to those harsh conditions.

Interlinked with a burning plasma and materials are the key systems required to harness fusion power, breed fuel, and ensure the safe operation of a reactor. Before an FPP is constructed, materials and components must be qualified and a system design must ensure the compatibility of all components. Just as the plasma and materials in a fusion reactor will need to advance beyond today's capabilities, the balance of plant equipment, remote handling, tritium breeding, and safety systems will also require significant advances.

The research encompassed by these three technology and science drivers is essential to lowering the risks to an acceptable level for an FPP and will allow the US to pursue a swift, innovative, and economically attractive path to fusion energy production. The societal benefit of establishing a new carbon-neutral power source and developing the industry that supports it cannot be understated. Such a power source would be one of the most transformational technologies in the field of plasma science. On the road to achieving this scientific grand challenge are myriad additional spinoff technologies and fundamental investigations that can reveal new knowledge about the universe.

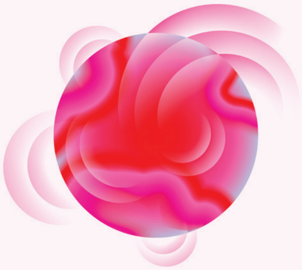
The field of plasma science and technology is a rich and diverse landscape, from the search for accurate theoretical descriptions of the complex emergent behavior of the plasma state to the production of matter at extreme conditions that exceed even those at the core of giant planets or stars. Low-temperature plasma science can also play a critical role in the development of new technologies. Expanding the fundamental understanding of plasmas and their interactions with their surroundings across wide ranges of temperature and density underpins not only fusion physics but the practical application of plasmas for manufacturing, medicine, and agriculture. The plasma science and technology component of the FES mission is impelled by three main drivers: Strengthen the Foundations, Understand the Plasma Universe, and Create Transformative Technologies. Together these drivers tackle the plasma questions of highest scientific impact and urgency, and they foster innovation by spurring exploration as dynamic as the processes in plasmas themselves. The programs, initiatives, and facilities identified here represent an opportunity to increase US leadership by strengthening investment in research areas of high potential, while moving forward with new capabilities and facilities and tapping the collective wisdom of the scientific community through a series of networks, collaborations, and partnerships.

Strengthening the foundations of plasma science deepens our fundamental understanding of nature. Exciting new experimental capabilities are unlocking unprecedented plasma regimes, while new theories and computational methods provide the insight to decipher them. Extremely intense lasers are making compact particle accelerators possible and may soon reach nonlinear quantum electrodynamic (QED) regimes in which pair plasmas will be created directly from light. Pulsed-power facilities compress matter to such high density that the behavior of the resulting warm dense plasma is fundamentally different from known states of condensed matter or plasmas. Because the plasma has high electrical conductivity, magnetic fields can be compressed to approach strengths only found in astrophysical objects such as white dwarfs. Coupling these drivers with X-ray free electron lasers allows exquisite measurements of these novel states of plasma. At the same time, tabletop-scale experiments create and trap exotic states of antimatter and strongly correlated plasmas, which can be so sensitively diagnosed that they can be used to test fundamental symmetries of nature. Strengthening the foundations of plasma science will require facilities and computational hardware at a range of scales, theoretical research that charts next steps, and a hierarchy of computational techniques that connect the microscopic to the macroscopic.

Understanding the plasma universe is essential to learning about the origins and the evolution of the universe. Nearly every aspect of the cosmos is influenced by plasma, from lightning and aurora in Earth's atmosphere to stellar winds that fill the space between planets and stars; from accretion disks surrounding supermassive black holes at the centers of the galaxies to the particle jets launched from the most distant and ancient quasars. All these systems are strongly affected by plasma behaviors that are not yet understood, including magnetic reconnection, turbulence, and particle energization. Viewing astrophysics through the lens of plasma physics is crucial, given recent advances in multimessenger astronomy and spacecraft missions. As spacecraft such as the Parker Solar Probe and Solar Orbiter "touch the Sun," knowledge of plasma mechanisms will play a key role in interpreting this frontier of space exploration. In addition to theoretical and computational studies, exploration of the plasma universe can be conducted through experiments on Earth. The breadth of conditions observed in the plasma universe requires a wide-ranging laboratory approach, from high-energy-density laser experiments to magnetized plasma facilities at multiple scales.

Plasma science and technology lays the foundation for creating transformative technologies unique in implementation and application. The realization of an FPP opens the door to ubiquitous carbon-free electricity. Plasma-based technologies promise unique pathways to bring that electricity to the products that power society. That power could revolutionize the way chemicals are manufactured. Such technologies promise the realization of novel materials that cannot be manufactured by conventional means, such as functionalized nanoparticles for drug delivery and new materials relevant to quantum information systems. The next generation of rockets, powered by fusion, may enable human exploration of the solar system and beyond with faster transit times. The next generation of ultrafast, compact electronic devices, such as cell phones and computers, will rely on plasma science to fuel advances in semiconductor manufacturing. Novel, precise therapies for cancer and for antibiotic-resistant bacterial infections are now within reach, buoyed by advances in atmospheric-pressure plasmas and plasma-based ultracompact accelerators.

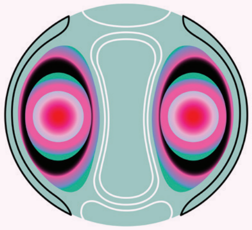
Technology and Science Drivers



Fusion Technology & Science Drivers

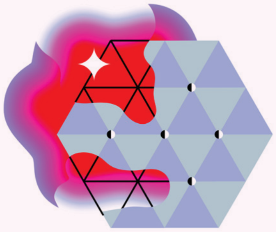
Sustain a burning plasma

Build the science and technology required to confine and sustain a burning plasma.



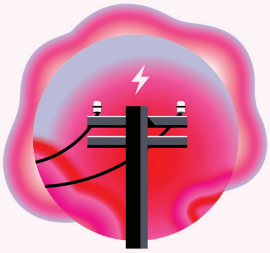
Engineer for extreme conditions

Develop the materials required to withstand the extreme environment of a fusion reactor.



Harness fusion power

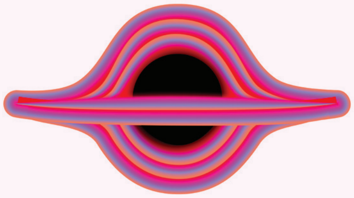
Engineer the technologies required to breed fusion fuel and to generate electricity in a fusion pilot plant by the 2040s.



Plasma Technology & Science Drivers

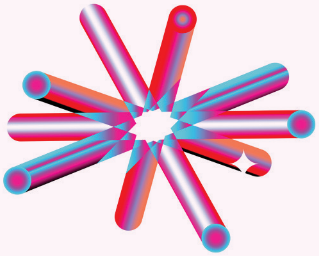
Understand the plasma universe

Plasmas permeate the universe and are the heart of the most energetic events we observe.



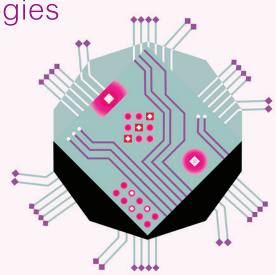
Strengthen the foundations

Explore and discover new regimes and exotic states of matter, enabled by new experimental capabilities.



Create transformative technologies

Unlock the potential of plasmas to transform society.



Programs and facilities to execute the strategic plan

Aligning the program with the six technology and science drivers will require redirection of programs and development of new facilities. Collaborations with international and privately funded research programs are important components of the strategy, and participation in ITER is considered essential for obtaining access to a high-gain burning plasma. Rigorous scientific inquiry is cultivated by leveraging current leadership, partnerships, and priority research areas that advance general plasma science and high-energy-density physics while emphasizing the potential of plasma-based technology for translational research. Success in all of these areas will require robust support for foundational cross-cutting research in theory, modeling, and computation; diagnostic development; and transformative enabling technologies. The multidisciplinary workforce needed for fusion energy and plasma science requires that the community commit to the creation and maintenance of a healthy climate of diversity, equity, and inclusion, which will benefit the community as a whole and the mission of FES.

Research Program Areas

New or expanded research program areas are urgently needed to fulfill the mission of developing our fundamental understanding of plasmas and to move toward a fusion energy source—with FPP readiness by the 2040s. These research program elements are described here at a high level, targeting the specific technology and science drivers identified above, and are not in priority order (prioritization is provided in the budget scenarios in Chapter 2).

FPP System Design and Integration: A central overarching priority is to form a domestic multi-institutional, collaborative FPP mission, design, and study program. This effort will provide the resources and coordination to integrate critical research advances made across the FES portfolio into attractive FPP concepts. It will need to merge advances in the understanding of burning plasma physics with the capabilities of new fusion materials and technologies. Attention also needs to be paid to licensing and safety-related issues (e.g., tritium and activation product transport and stored energy sources including the plasma, magnets, and cryogens). An integrated plant design requires consideration for balance of plant equipment and remote handling capabilities and should address the reliability, availability, maintainability and inspectability (RAMI) of the plant. Participation by private and public stakeholders is essential to ensure economic attractiveness. Innovations made outside the public program are appropriately considered in developing these concepts. An essential component underpinning this effort is a strong theory and computation program, including the advancement of multiscale, multiphysics theory and modeling capabilities necessary to predict the complex interactions between numerous plasma, material, and engineering processes that will occur within an FPP. A vital part of the program is the continued development of validated models at a range of complexities and experimental fidelities, along with the predictive integrated modeling capabilities that utilize them. Creating such models will require continued close partnership between FES and ASCR to fully leverage US investments in high-performance computing, including coming exascale machines. Moreover, accelerated progress and increased readiness of multiple systems are needed to safely design and operate a fusion reactor; those components include advances in diagnostics, instrumentation, data handling, and automated real-time decision making. This design effort should give significant attention to activities contrasting tokamak-based concepts with concept studies for different plasma cores like stellarators, alternates, or inertial confinement fusion energy (IFE). It should also include activities agnostic to the plasma core. Additionally, designs for concept exploration or for devices aiming to extend the performance of successfully tested innovative concepts should be pursued to provide an information basis for the design, decision, and pursuance of new facilities.

Fusion Materials and Technology: Critical developments are needed in fusion materials, magnets, and heating and current drive actuators. Technology advances are needed to handle the extreme conditions expected in future fusion reactors and to harness fusion energy and breed fuel. In addition to advancing key research on existing facilities such as linear plasma devices and in-pile fission irradiation, resource enhancement must allow timely resolution of critical FPP design questions. Because of the significant time scales involved in facility development and subsequent research, immediate action is needed. Increased investment in theory and simulation supporting the research on these facilities is also needed. Focus is given to the development of plasma-facing materials and components, structural and functional materials, and fusion blanket and fuel cycle elements needed for an FPP. Diagnostic advances for fusion materials studies are needed to understand the interaction of materials with the fusion environment. Magnets are an integral feature of magnetic fusion configurations, and it is desirable to develop magnets with higher fields, operating temperatures, and reliability, which are constructed with streamlined manufacturing processes and reduced production costs. All of these factors improve the performance and/or lower the costs of an FPP. Private industry has made significant progress in developing the relevant magnet technology, including high-temperature superconducting magnets, and the federal program should complement and, when possible, collaborate with those activities. Launching structures for radio-frequency plasma heating and current drive actuators must be made of new materials in order to withstand the neutron and plasma environment, have integrated steady-state cooling, and have more acceptable long-pulse reliability. Efficiency improvements in the source, the transmission, and the plasma coupling must be developed to enhance FPP competitiveness. The development of materials and technology appropriate for the nuclear conditions of a fusion reactor is a critical need in the international effort to develop fusion energy. The US is poised for leadership in this area through targeted investments in unique facilities. Collaboration and partnering with the DOE Office of Nuclear Energy in the areas of materials development, generation of qualification-level data, and improved technologies for materials and component irradiation should be cultivated.

Fusion Plasma Core: The tokamak is the most technically advanced approach for use as a fusion reactor power core. The ITER international experiment is the largest single investment by DOE FES, and a US ITER research team needs to be formed to leverage it. That team will make essential contributions to achieving the high gain mission for ITER, exploit unique access to a burning plasma at the reactor scale, and enable US scientists to close the nuclear science and engineering gaps in order to build an FPP. Access to burning plasmas could also be possible in the US-based privately funded SPARC tokamak as early as mid-decade.

SPARC will be parallel and complementary to international fusion efforts, including ITER, and to other ongoing private-sector fusion endeavors. The existing DIII-D and NSTX-U national tokamak facilities are key to preparation for the study of burning plasmas in ITER and in other planned and future private devices. Additional research on these facilities, in combination with private and international collaborations, continuing support of existing university tokamak programs, and utilization of US expertise in theory and simulation, is needed to find solutions to remaining technical gaps. These gaps include disruption prediction, avoidance, and mitigation; plasma-facing component integration; and FPP-relevant scenario development. Advances in technology and in our understanding of plasma physics have opened paths to lower capital cost tokamak FPPs, but have also brought scientific and technical challenges that must be overcome. These challenges motivate the construction of a new world-leading domestic tokamak, which would be uniquely situated to develop integrated solutions in a useful time frame. In order to mitigate risks associated with the tokamak approach, alternative pathways to fusion are also pursued, which could lead to more economic fusion power in the longer term by capitalizing on US expertise. Quasi-symmetric stellarators are considered, as are alternate plasma core solutions beyond the tokamak and stellarator. These alternate pathways are supported at three levels, from basic validation of the physics, through development of self-consistent solutions, to demonstration of integrated solutions. A reestablished IFE program takes advantage of US leadership in high-energy-density physics and progress that the NNSA has made toward high yield in inertial confinement fusion.

General Plasma Science Program (GPS): GPS research explores the fundamental behaviors of plasmas. This includes foundational theoretical descriptions of plasma dynamics, numerical methods to model multiscale behavior, and experiments that test whether our understanding of plasmas is accurate. Such foundational research serves as the basis for all areas of plasma science and technology, ranging from the laboratory to astrophysics. Although motivated primarily by the desire to understand nature, many of the physics processes studied have direct relevance to fusion and other technological applications. The GPS program funds research at a range of scales, including operations and construction of the Basic Plasma Science Facility at UCLA, the Wisconsin Plasma Physics Laboratory, the Magnetized Dusty Plasma Experiment at Auburn, and the Facility for Laboratory Reconnection Experiments at Princeton Plasma Physics Laboratory. A major component of the GPS research program is the long-standing NSF–DOE Partnership in Plasma Science and Engineering.

High-Energy-Density Laboratory Plasmas (HEDLP): HEDLP research explores and applies novel regimes resulting from the extraordinary ability to concentrate power—in many cases more power than the world's total electric generating capacity in an area smaller than the end of a human hair—for a brief fraction of a second. That ability creates new states of matter that include condensed matter, warm and hot dense matter, and plasmas relevant to astrophysical phenomena, stellar properties and processes, and fusion reactors. Self-organized, far-from-equilibrium plasmas are probed and controlled, enabling unique applications such as new accelerators and materials. This program has a successful history of partnering with DOE NNSA, NSF, and DOE HEP to fund research on several midscale laser, pulsed-power, and X-ray free electron (XFEL) facilities.

Plasma-Based Technology Program: Technologies in the plasma science and technology (PST) portfolio include low-temperature plasmas and plasma-based accelerators. These technologies benefit the public by enabling cell phones, computers, advanced drinking water purification, and security and medical methods. They underlie key industries such as semiconductor manufacturing and materials processing, which directly fuel the economy through innovation and maintaining core competence and leadership in those industries. A plasma-based technology program that consolidates and focuses critical efforts will facilitate technology transfer and realize the promise of this area.

Networks: Collaborative networks of researchers and facilities can provide enormous value as a coordinating organization and mechanism for leveraging resources and capabilities. LaserNetUS is a successful model that brings together 10 unique midscale laser facilities and opens up opportunities to a large number of new users. In a similar vein, the establishment of a MagNet centered around basic magnetized plasma and laboratory space/astrophysics, a ZNet for pulsed-power science and technology, and an LTP-Net for low-temperature plasmas could similarly support growth and enable collaborative research in their respective areas. These networks can encourage cross-fertilization as researchers work on multiple facilities and will facilitate the training of students. Coordination and access to computational/theoretical models, diagnostics, and other resources in support of experiments can also be established. These network structures also position the US to be more competitive, because investments, technology development, and future planning can be implemented more strategically by engaging the full community.

Facilities

New mid- to large-scale facilities are urgently needed to meet the goal of FPP readiness by the early 2040s and to realize the goals of plasma science and technology. The elements of the following list are grouped by topical area and are not in priority order.

Fusion Prototypic Neutron Source (FPNS): The science of material exposure to fusion neutron fluxes is a key gap in the international fusion program. No facility exists that can generate the necessary fluence, energy spectrum, and helium production level in the lattice of candidate materials. FPNS concepts that utilize existing facilities like accelerators or commercial units, combined into a cost-effective system, can be a fast track forward. FPNS provides leadership opportunities based on existing expertise in nuclear materials in the US program by enabling the fundamental explorations of fusion nuclear material science, which needs to be combined with a reinvigorated neutron theory and computation program. Moreover, accelerated access to fusion neutron exposure is an area of extreme interest to the fusion industry and has significant opportunities for near-term public–private partnerships.

Material Plasma Exposure eXperiment (MPEX): MPEX is under construction and will provide a unique capability to study plasma-material interactions under conditions that are prototypical for a reactor divertor regime as far as the near-wall plasma-material interface is concerned. The ability to expose irradiated materials to these plasma conditions and conduct rapid turnaround in-situ and ex-situ material characterization are the most important project elements that need to be met as key program deliverables toward an FPP.

High-Heat-Flux (HHF) testing facilities: Testing capabilities to explore properties of materials and plasma-facing components, both solid and liquid, under high heat fluxes address a key gap toward FPP material definitions. Experimental capabilities to conduct fundamental testing on coupon levels (centimeter scale) are a necessary testbed for model validation of material properties. The coupon-level testing is a prerequisite for component-level testing (tens of centimeters to meters scale) to qualify components for an FPP. Accordingly, testing facilities for both levels of high-heat-flux materials research are required.

EXhaust and Confinement Integration Tokamak Experiment (EXCITE): High-magnetic-field approaches to a tokamak-based FPP raise specific scientific and engineering challenges. High-divertor-power exhaust solutions need to be integrated with sustainment of high-power-density plasma cores, which are needed for generation of significant fusion power. Both the NASEM Burning Plasma Report and the CPP report identify the need to address these challenges in an integrated fashion, rather than at separate facilities. This requirement motivates the need for construction of a new domestic tokamak, previously referred to as NTUF (New Tokamak User Facility) in the CPP report.

Blanket Component Test Facility (BCTF): The CPP report outlines an R&D program on blanket materials and transport phenomena that culminates in the design and fabrication of blanket-section prototypes, which undergo staged testing in a Blanket Component Test Facility (BCTF) and Volumetric Neutron Source (VNS). The CPP report describes a BCTF that integrates all non-nuclear features of a fusion blanket and its ancillary systems (prototypic, at-scale complex structures and coolants) under prototypic conditions of temperature, pressure, magnetic field, and mechanical stress, with surrogate surface and volumetric heating and injected hydrogen or deuterium in place of tritium. Concepts successfully vetted in the BCTF, and fission and/or fusion irradiations, could potentially proceed to full nuclear testing and tritium production in the VNS. Further definition and development of these facilities and research plans should be undertaken by the program and the community.

Midscale Stellarator: A proof of concept experiment is needed to demonstrate improved steady-state plasma confinement in combination with a novel non-resonant divertor. Development of this research line provides risk mitigation for the mainline tokamak approach and could lead to a commercially more attractive fusion system. This stellarator facility would therefore be a discovery-oriented facility that could stimulate a great deal of innovation.

Volumetric Neutron Source (VNS): Recognizing the critical need for integral-effect irradiation testing of components or subcomponents, such as blanket modules, the CPP report recommended pursuit of a VNS for this purpose without specifying particular metrics or a confinement concept that would provide fusion neutrons. Multiple VNS concepts have been proposed and a concept assessment study should evaluate any plasma physics developments required to realize each concept, determine the relevance of these configurations to tokamak/FPP components, and assess them against quantitative metrics (e.g., on neutron flux or fluence) to be achieved in advance of FPP operation. This initial assessment activity should identify either a suitable concept for further development, construction, and operation, or identify an alternate approach (e.g., fission reactor irradiation or early phase testing in FPP) that best meets this mission need.

MEC-Upgrade: An upgrade to the Matter in Extreme Conditions (MEC) end-station at the Linac Coherent Light Source (LCLS) would enable the co-location of a PW-laser operating at 1–10 Hz repetition rate and a multi-kJ long pulse laser with our only domestic XFEL. This would enable us to tackle physical and chemical changes at fundamental time scales and explore new regimes of dense material physics, astrophysics, planetary physics, and short-pulse laser-plasma interactions. The MEC-U proposal has achieved Critical Decision 0 and is currently in preparation for CD-1, also having received line-item status in the FY 2020 Congressional budget.

Solar Wind Facility: How the solar wind is accelerated, heated, and driven turbulent is among the most persistent and important open questions in plasma science. It is an opportune moment to develop, in concert with advanced space missions, a next-generation experimental facility to isolate, control, and diagnose plasma phenomena responsible for the complex solar wind behavior, at relevant scales. This facility would leverage and coordinate existing laboratory space/astrophysics research groups, as the experimental conditions needed to pursue solar-wind-related questions can also benefit research in broader astrophysical contexts. Such a venture would be a prime opportunity to coordinate among interested funding agencies, primarily NSF and NASA, but also ONR and AFOSR.

Multi-Petawatt Laser Facility: Tens-of-petawatt laser systems can produce light pressures in the exapascal regime, copious amounts of radiation, and extremely bright beams of energetic particles, including electrons, ions, neutrons, or antimatter. The novel capabilities enabled by multi-PW lasers open new frontiers in R&D such as particle acceleration and advanced light sources, high-field physics and nonlinear quantum electrodynamics (QED), and laser-driven nuclear physics. As identified in the BLI report, there is a need for the US to develop ultrahigh-intensity technology and build an open-access laser user facility with multiple beamlines at 10–100 PW peak powers.

High-Repetition-Rate Laser Facility: New high-repetition-rate (10 Hz to kHz) laser systems coming online represent a fundamentally new system architecture for high energy density (HED). The greater than 1000 times increase in shot rate over today's systems, coupled to emerging technologies such as machine learning and additive manufacturing, will result in an enormous acceleration in the rate of knowledge acquisition. Such high-rep-rate high-energy lasers further open the door to unprecedented temporal and spatial resolution of HEDP phenomena, including GeV-class electron beams and precision HED pumps and probes. Recent community reports from NASEM and BLI have clearly outlined the urgent science case and FES mission-relevant needs for a short-pulse, high-peak-power, high-average-power laser system. This may be an area for partnering with DOE HEP, which may take the lead on this facility.

Midscale Z pinch: Extremely strong magnetic fields over macroscopic volumes are only accessible via pulsed-power facilities, which open up the physics of plasmas in a way that other plasma drivers cannot. Current US facilities are either very large and complex (the 26 MA Sandia Z-Machine with < 1 shot/day) or too small (~1 MA or less) to address the breadth of science expressed by the community. There is clear interest in establishing a pulsed-power facility at an intermediate size (up to 10 MA) accessible to the academic community, with a higher shot rate than Z, yet still capable of fielding fusion-relevant and HED experiments. Further, such a facility could explore driver technologies and pulsed-power science for next-generation larger-scale pulsed-power devices such as a 60 MA “Z-Next.” This facility would provide an opportunity for FES to partner with another agency, such as NNSA or NSF, which might take the lead.

Process and Prioritization Criteria

The following criteria express the principles used to prioritize projects and programs discussed in this report. Consensus criteria and guidance for prioritization within program areas were developed by the research community during the CPP process. That guidance is incorporated in the criteria below, which were used for prioritization of the entire portfolio. In applying the criteria and following the charge language, we assume that the ITER construction project will be successful, and we thus focus on the non-ITER portion of the budget.

Alignment: Align projects and programs with the technology and science drivers to achieve the fusion mission, specifically the path to an FPP, and to advance fundamental plasma science and enable societally beneficial plasma applications. Balance technological development with scientific discovery, recognizing the importance of both as the sources of innovations that benefit the entire program.

Urgency: Prioritize the most expeditious path to fusion energy and other plasma technologies that provide compelling solutions to urgent issues such as sustainable, carbon-free power production, advanced medical therapies, and more efficient industrial processes.

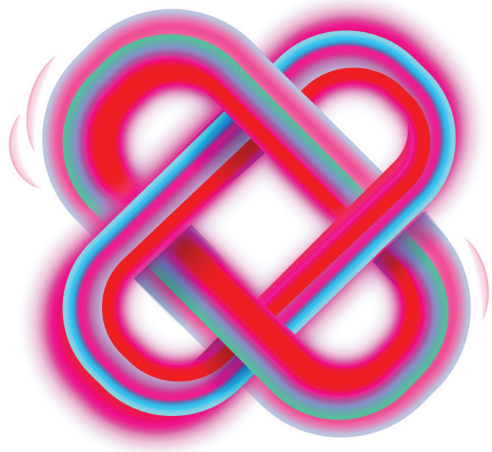
Innovation: Embrace innovative research, new developments in technology, and interdisciplinary connections to address key challenges. Reduce the time and cost to develop usable fusion energy and other plasma applications.

Impact: Implement a logical sequence of programs that increases scientific and technological progress relative to investment, reduces the risks associated with the FPP mission and the technology and science objectives, and takes into account time constraints and impacts on the overall program.

Leadership: Establish and maintain US leadership, including world-leading facilities, science, and industries that attract international participation. Recognize federal, industry, and international efforts in fusion and plasma development and form partnerships whenever possible.

Stewardship: As experimental capabilities are developed and program transitions occur, ensure the continued productivity of an essential workforce to maintain scientific and technological progress. Engage all stakeholders in executing the program, including national laboratories, industry, and universities.

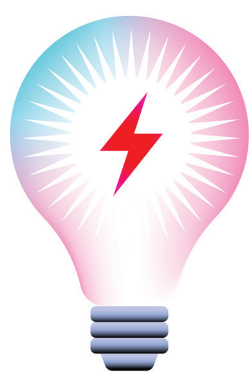
Recommendations and Budget Scenarios



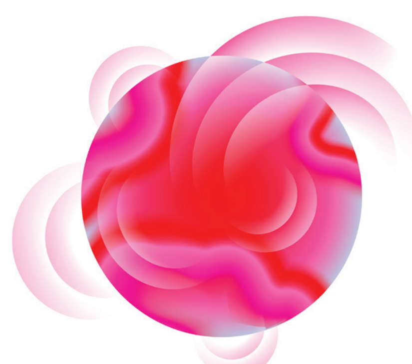
The fields of fusion energy research and plasma science and engineering were described in Chapter 1, along with the scientific and technological opportunities they present. In this chapter, we present recommendations on how the Department of Energy (DOE) Fusion Energy Sciences (FES) research program should capitalize on those opportunities. Acting on the recommendations below would create a research and development (R&D) program that would move aggressively toward practical fusion energy, deepen our understanding of plasma science, and create transformative plasma technologies. Realization of the strategic plan, including enabling the progress needed to confidently prepare for a fusion pilot plant (FPP) by the 2040s, will require timely implementation of all of these recommendations.This requires substantial additional resources to be added to the program compared to the FY19 budget.

The recommendations are grouped into two categories. Overarching Recommendations are independent of specific programs or facilities and viewed as essential to successful execution of the DOE FES research program. Project and Program Specific Recommendations are grouped into three subcategories: Fusion Science and Technology Program, Plasma Science and Technology Program, and Cross-cutting that apply to all programs. The order of presentation of these recommendations does not imply priority; all recommendations should be acted on to fully realize the strategic plan. Prioritization of activities is expressed through the budget scenario descriptions below.

Fusion



Plasmas



Overarching Recommendations

The Community Planning Process (CPP), completed early in 2020, resulted in the fusion and plasma science research communities coming to consensus on new directions for FES-funded research. This first recommendation aligns the strategic plan with the consensus view, as summarized in Chapter 1:

– Recommendation: Align the program with the six technology and science drivers in order to establish the scientific and technical basis for a fusion pilot plant by the 2040s and advance fundamental understanding of plasmas that translates into applications that benefit society.

Experimental research and technology development in fusion energy and plasma science require state-of-the-art facilities, often at large scale. US participation in the international ITER experiment is critical to accessing burning plasmas at reactor scale. The US has invested significantly over the past decade in the design and construction of ITER and will continue to do so over the coming decade to ensure access. However, additional high-priority research gaps will require the development of large-scale facilities to be successfully addressed. Outside the important investment in ITER, there has been little investment over the past decade in the development of major new experimental capabilities. Addressing the technology and science drivers will require continuing investment in the design, construction and operation of facilities that provide important new capabilities. Such investment is necessary to maintain a vigorous scientific program and to achieve necessary breakthroughs in numerous areas. This strategic plan provides a framework for sequencing the development of those new capabilities.

– Recommendation: Resources for ongoing design and construction of major new experimental facilities should be established in the DOE FES budget.

Although large-scale facilities are essential to make progress in many areas, important aspects of the technology and science drivers can be successfully addressed through the development of small and medium-scale experimental facilities. Such facilities are amenable to siting at universities, where investments can have high impact, provide leadership opportunities to faculty and junior scientists, and help develop the workforce needed to execute this strategic plan.

– Recommendation: Opportunities should be provided for developing new experimental capabilities at a range of scales, as appropriate to address the goals of this strategic plan.

The strategic plan should be regularly updated to adapt to new scientific discoveries, technological breakthroughs and other changes in the R&D landscape.

– Recommendation: This long-range planning process, including a strong community-led component, should be repeated no later than every five years in order to update the strategic plan.

Strategic planning is most effective if ideas for major new experimental capabilities are developed to the preconceptual stage, preferably with mission need and scope well defined and a preliminary cost range established. The Critical Decision process within DOE provides a framework for accomplishing this goal, and utilizing this process to routinely refine the design of needed new experimental facilities is highly desirable.

– Recommendation: Maturation of preconceptual designs, scope, and costing for proposed new experimental facilities should be part of regular program activities.

Fusion and plasma science research has strong and growing commercial connections to US industry. These connections exist across the whole portfolio of industry applications, and an opportunity exists for DOE to take a more active role in translating advances stemming from federally funded research into commercial applications. Public–private partnerships (PPPs) should be formed with private industry and used as a paradigm for accelerating fusion and plasma science research to benefit both the government-funded program and private companies. Research conducted in the private sector can benefit from federally supported programs by offering more cost-effective pathways to retire risk in key gap areas while establishing the industrial infrastructure critical for the next steps in fusion energy and plasma technology. Access to public facilities and programs can be leveraged to solve technical problems by private companies that do not have the public sector's capabilities. Public–private partnership should be used as a tool to stimulate industry involvement. DOE FES has already established successful PPP programs, notably the Innovation Network for Fusion Energy (INFUSE). These activities should be expanded, and new PPP programs, including milestone-based cost-share programs, should be developed. Investment in PPP activities should align with priorities in the strategic plan and be balanced by robust investment in federally funded programs to maximize effectiveness of the partnership. Further discussion of specific opportunities in PPP is offered in Appendix B.

– Recommendation: Expand existing and establish new public–private partnership programs to leverage capabilities, reduce cost, and accelerate the commercialization of fusion power and plasma technologies.

Research and development in fusion energy and plasma science and technology is inherently interdisciplinary. Given the broad range of applications where these fields have relevance, there is also a range of federal agencies that currently provide research support, including the Air Force Office of Sponsored Research, DOE ARPA-E, DOE Advanced Scientific Computing Research, DOE High Energy Physics, DOE National Nuclear Security Administration, NASA, the National Science Foundation (NSF) and the Office of Naval Research. Coordination among these federal programs has led to extremely successful research programs; the NSF–DOE Partnership in Basic Plasma Science and Engineering and the Joint Program in High Energy Density Laboratory Plasmas with the NNSA and FES are prominent examples. Expanding on those successes and increasing program coordination, including cooperative construction and support of experimental facilities, could make better use of federal resources and enable more rapid progress toward development of fusion energy and advancement of plasma science and engineering.

–Recommendation: Explore and implement mechanisms for formal coordination between funding agencies that support fusion and plasma science research.

Successfully addressing the challenges of bringing fusion power to the grid and advancing the frontier of plasma science requires innovation, creativity, and a talented, multidisciplinary and diverse workforce. Barriers to assembling this workforce should be addressed in order to achieve the goals in this strategic plan.

First, the fusion and plasma community is not accessing the available talent pool in our current workforce. Data show that our research community has significant deficiencies in workforce diversity, with participation from women and underrepresented minorities below national averages for other subfields of physics and engineering. This is not just an issue of recruiting talent, but also of retaining talent, something that is affected by the culture within the community and that could be addressed through embracing equity and inclusion.

Second, DOE lacks the tools necessary to direct development of the needed workforce to execute this strategic plan. The Office of Management and Budget recently implemented a policy change that significantly limits workforce and outreach programs at DOE. The new policy was intended to reduce duplication of education and outreach activities at federal agencies, but it had the unintended consequence of eliminating discipline-specific outreach and workforce programs that were not being duplicated at other agencies.

Below we offer overarching recommendations on diversity, equity, inclusion, and workforce development. We dedicate Appendix C to more specific recommendations.

– Recommendation: DOE and FES should develop and implement plans to increase diversity, equity, and inclusion (DEI) in our community. Done in consultation with DEI experts and in collaboration with other institutions, this should involve the study of workplace climate, policies, and practices, via assessment metrics and standard practices.

– Recommendation: Restore DOE's ability to execute discipline-specific workforce development programs that can help recruit diverse new talent to FES-supported fields of research.

Program and Project Specific Recommendations

The following recommendations address specific elements of the Fusion Science and Technology (FST) and Plasma Science and Technology (PST) program components. As with the earlier recommendations, resource priorities across and within program components are delineated in the budget scenarios, which follow this section, and not by recommendation ordering.

Fusion Science and Technology

The recommendations described below are aimed at realizing the overall goal of establishing the technical basis for an FPP by the 2040s. It is therefore implicit that all recommendations are implemented in time to be consistent with achieving that goal.

The underlying theme guiding the strategic plan is the need to move aggressively toward the deployment of fusion energy. The design, construction, and operation of a fusion pilot plant (FPP) is recognized as a critical milestone toward that goal. The coordinated program delineated here develops FPP concepts that can advance to engineering designs and rapidly adapt to innovations and advances in understanding. Physics modeling efforts also must be brought together with engineering tools in order to address issues beyond the fusion core, including balance of plant equipment, licensing, remote handling, maintenance, and reliability. Cutting-edge physics, materials and engineering, and integrated models need to be applied to viable confinement concepts and operating scenarios so as to continuously inform research needs and priorities. Both the public and private sectors have a diverse range of stakeholders for an FPP, and they will all need to participate in such a coordinated effort.

– Recommendation: Initiate a design effort that engages all stakeholders to establish the technical basis for closing critical gaps for a fusion pilot plant, utilizing and strengthening the world-leading US theory and computation capabilities and engineering design tools.

Construction of a viable FPP will require significant technology development beyond the burning plasma itself. Critical enabling technologies such as plasma-facing components, structural and functional materials, and breeding-blanket and tritium-handling systems are not yet advanced enough for an FPP. The time required to develop these technologies at present levels of support is incompatible with the goal of a fusion pilot plant by the 2040s. Increased support for these program areas is therefore critical, as is an increased emphasis on foundational fusion materials and technology research. That emphasis includes the expansion of theory and modeling work that supports advancing technology readiness levels (TRLs), accelerating development of diagnostics and measurement systems that will function in fusion nuclear (irradiation-hardened) environments, and rapidly maturing enabling technologies. This includes the expansion of theory and modeling efforts that support advancing technology readiness levels, such as the development of validated models at a range of complexities suitable for inclusion in integrated modeling capabilities needed to accelerate the development and qualification of new materials.

– Recommendation: Rapidly expand the R&D effort in fusion materials and technology.

Fusion nuclear facilities including an FPP will require new materials to be conceived, developed, and qualified for nuclear use. This process is well understood for nuclear components having a clear path that includes laboratory development, standardized testing, and regulatory oversight and approval. While mixed spectrum fission reactors are and will remain the primary workhorse for R&D and for obtaining qualification-level data of irradiated materials, they do not produce the appropriate spectrum for materials irradiated in a fusion reactor core. In this region, the fusion-born neutrons will produce significant, yet largely unknown, effects on structural and nonstructural components of the first wall, divertor, and blanket. To develop materials that withstand high levels of fusion neutron irradiation and can be qualified for FPP service, an irradiation facility that can produce the required damage and transmutation rates is necessary. The Fusion Prototypical Neutron Source (FPNS) recommended here should be highly reliable and have the flexibility to increase the damage rate. The primary utility of this facility will be to translate the measured effects of the fusion spectrum and transmutation products into codes with predictive capability. Toward that end a comprehensive program of modeling, advanced characterization, and high-temperature nuclear-structural design criteria is necessary. These tools, along with the construction of an FPNS, will build upon the US leadership in fusion materials technology.

– Recommendation: Immediately establish the mission need for an FPNS facility to support development of new materials suitable for use in the fusion nuclear environment and pursue design and construction as soon as possible.

Physics-based understanding of plasma-material interactions (PMI), including the development of predictive capabilities for the material response and exhaust solution, is necessary to construct and qualify plasma-facing components (PFCs) for an FPP. Reaching these capabilities will require support for the completion of the scientific infrastructure, of which the Material Plasma Exposure eXperiment (MPEX) is a central piece. MPEX is a linear plasma exposure device that will be uniquely equipped to access prototypical plasma conditions in a fusion reactor divertor. The MPEX is currently in the design-to-build process. Additionally, high-heat-flux testing via a coupon-level (centimeter-scale samples) facility early and a component-level (tens of centimeters to 1 meter scale) facility later will allow for development of materials and qualification of components for an FPP. Together with the existing PMI facilities, these world-leading capabilities will allow for validation of PMI models that will form the base of PFC design tools for an FPP.

– Recommendation: Develop the scientific infrastructure necessary for the study of plasma-materials interactions needed to develop plasma facing components for an FPP by completing the MPEX and additional high-heat flux testing facilities.

Closure of the fusion fuel cycle via successful breeding and extraction of tritium will be critical for the sustained operation of an FPP. However, breeding-blanket technologies are presently at a low technology readiness level and are unlikely to advance to this demonstration stage without significantly increased R&D support. In the near term, this should entail a variety of separate effect test stands and subcomponent fission reactor irradiations to understand fundamental tritium transport properties and phenomena in solid and liquid breeder materials, as well as associated modeling and model validation efforts. Tritium technologies related to fueling and exhaust from the plasma, and subsequent processing, will be demonstrated at significant scale in ITER. The program should involve tritium experts in the US ITER team so as to maximally benefit from this technology demonstration. It should also support additional R&D of technologies necessary to significantly reduce the size, cost, and tritium inventory of a plant based on ITER technologies. Since there is no current path for the US to deploy a test blanket module in ITER, this program should also develop a strategy for component-scale blanket testing in a nuclear environment and support preconceptual design and costing studies for facilities such as a blanket component test facility (BCTF), fission irradiations (e.g., HFIR, ATR), fusion irradiations (e.g., FPNS), and volumetric neutron source (VNS), that accomplish both missions on a time scale necessary to enable the FPP.

– Recommendation: Significantly expand blanket and tritium R&D programs.

To confidently design a low-capital-cost tokamak FPP, several gaps in tokamak physics understanding need to be closed. These include advancing understanding of transport and stability physics for sustaining disruption-free, high-average-power-output operation; energetic particle and burning plasma physics relevant to a high-fusion-gain FPP; and plasma-material interactions and material choices for exhaust solutions. Critical issues must also be addressed to integrate improved understanding into operational scenarios for an FPP. Important issues in tokamak physics can be addressed immediately through a comprehensive, multidisciplinary science program utilizing the world-leading DIII-D and NSTX-U facilities alongside important smaller-scale facilities at universities. Particular areas of emphasis on DIII-D include resolving the disruption and transients challenge and informing long-pulse steady-state operation. Areas of emphasis for NSTX-U include low aspect ratio physics, PMI control, and liquid metal PFC evaluations. A broader set of opportunities on DIII-D and NSTX-U to close key gaps in a timely fashion should be pursued when doing so proves cost effective and accelerates progress toward an FPP. The success of ITER and other future high-current tokamaks assumes that the disruption and runaway electron prevention/avoidance/mitigation techniques developed on existing machines translate to practical solutions for those future devices. If such solutions cannot be developed, then a stronger focus on advanced tokamak or spherical tokamak approaches that utilize lower current, higher beta, and/or higher bootstrap fractions and which have been shown to be less disruptive than high-current scenarios will be required, as well as more vigorous pursuit of alternate confinement concepts including optimized stellarators. Collaborations on planned public and private domestic and international facilities, particularly those that focus on long-pulse conditions inaccessible in the US, will provide unique contributions to advance tokamak physics in these areas.

– Recommendation: Utilize research operations on DIII-D and NSTX-U, and collaborate with other world-leading facilities, to ensure that FPP design gaps are addressed in a timely manner.

In addition, the US should fully exploit its participation in ITER to gain experience with a burning plasma and fusion technology while benefiting from the shared cost through an international partnership. ITER is the baseline path to a reactor-scale burning plasma and provides unique technology advances that will accelerate the FPP development path. To ensure timely involvement by the pre-fusion-power operation phase starting in 2028, the US urgently needs to establish a framework for developing an appropriate workforce. This should be centrally organized, with participation in system design and commissioning efforts in the near term and activities ramping up as the project moves toward first plasma. Other near-term opportunities include integrated modeling for scenario development of the first operational phases and establishing data standards. Once operations begin, there should be a particular emphasis on further advancement and qualification of disruption prevention, avoidance, and mitigation solutions in preparation for final demonstration in ITER DT plasmas; significant US R&D could support this area.

– Recommendation: Ensure full engagement of the US fusion community in ITER by forming an ITER research team that capitalizes on our investment to access a high-gain burning plasma.

Even with existing and planned facilities, it will not be possible to address all outstanding physics issues needed for the US vision of a tokamak-based FPP, followed by an economically attractive power plant. In particular, this vision requires demonstrating integrated strategies for handling exhaust heat fluxes well beyond what is expected in existing or planned devices, while simultaneously supporting sustained high core plasma performance. Specifically, these solutions must be demonstrated to be compatible with FPP-relevant disruption prevention, avoidance and mitigation solutions developed using current domestic tokamaks, collaborations, and ITER operation. A range of options for closing this Integrated

Tokamak Exhaust and Performance (ITEP) gap were considered, including upgrades to existing facilities and collaborations on both private and international tokamaks. While those options provide opportunities to partially bridge this gap, none were judged sufficient to address the fundamental core-edge integration challenge encapsulated by the ITEP gap. Closing that gap is necessary to ensure FPP readiness. Building upon the recommendations of the NASEM Burning Plasma report, we recommend the construction of a new domestic tokamak, named EXCITE (EXhaust and Confinement Integration Tokamak Experiment), as the optimal solution for closing the ITEP gap. The envisioned EXCITE design would offer a unique combination of flexible power exhaust capabilities, plasma-facing component options, control actuators, and access to plasma conditions that would enable continued US leadership in tokamak physics into the 2030s. At the same time, EXCITE is envisioned as a modestly sized high-field device utilizing short-pulse, non-nuclear operation to enable design and construction on an acceptable time scale at manageable cost. This approach requires an immediate, significant design and costing effort to advance solutions to the ITEP gap and confirm the EXCITE mission and scope. The activity should make full use of world-leading US integrated modeling capabilities to develop preconceptual designs for EXCITE. The designs will be utilized in a detailed assessment of cost and technical feasibility and compared to alternative gap-closure approaches such as enhanced collaborations and upgrades. The design effort should include participation from private industry and international groups to accelerate the EXCITE schedule and reduce costs.

– Recommendation: Immediately establish the mission need for an EXCITE facility to close the integrated tokamak and exhaust gap and aggressively pursue design and construction.

A tokamak with solid plasma-facing components is currently the primary path to commercial fusion. Four innovative areas aimed at addressing key vulnerabilities of this approach will potentially lead to more economically attractive commercial fusion power systems while leveraging areas of US leadership.

– Stellarators offer intrinsically disruption-free operation with low recirculating power. The optimized quasi-symmetric stellarator concept is a unique US design approach that is complemented by international collaboration at the W7-X and LHD stellarators. A new domestic midscale US stellarator experiment should be realized.

– Liquid metal plasma-facing components potentially expand the reactor-wall power limits and alleviate lifetime constraints due to material erosion. Low-recycling, liquid lithium walls may open up pathways to high plasma confinement and compact FPP designs. Development of liquid metal plasma-facing-component concepts in non-plasma test stands and existing magnetic confinement facilities should be targeted and should build on PFC concepts developed in the existing domestic program.

– Inertial fusion energy (IFE) utilizes advances in lasers, pulsed power technology, and other innovative drivers to achieve fusion at high fuel density. The enormous progress made with indirect drive at the National Ignition Facility, direct drive, magnetic drive inertial confinement fusion (ICF), and heavy ion fusion underpin the promise of IFE. An IFE program that leverages US leadership and current investments should be targeted.

– Breakthroughs in alternate magnetic-confinement concepts, beyond tokamaks and stellarators, could lead to a lower-cost FPP and subsequently more economically attractive fusion power. Examples of such concepts include those that require no plasma current; have moderate or zero toroidal magnetic field; and are compact, pulsed plasma targets that may eliminate auxiliary heating. A program that supports innovative magnetic fusion energy concepts should be considered.

– Recommendation: Strengthen the innovative and transformative research program elements that offer promising future opportunities for fusion energy commercialization: stellarators, liquid metal plasma-facing components, IFE, and alternate concepts.

Plasma Science and Technology

Fundamental plasma science explores new regimes and deepens our understanding of nature. It includes theories that propose foundational descriptions of plasmas and their nonlinear, multiscale, collective behavior; computational methods required to predict outcomes of those theories; and experiments that test theoretical predictions and validate models. The knowledge these discoveries provide makes possible the innovative plasma-based technologies that will advance the field. The future of plasma science will rely on consistent support through contiguous grant cycles, even when spending fluctuates for construction projects and large program elements.

– Recommendation: Provide steady support for fundamental plasma science to enable a stream of innovative ideas and talent development that will lay the scientific foundation upon which the next generation of plasma-based technologies can be built.

Advances in energy compression with intense lasers and pulsed-power facilities have made it possible to squeeze matter to extreme pressures, creating exotic dense plasma states similar to those thought to exist in the interiors of giant planets and stars. However, our ability to diagnose or probe the structure and dynamics of these high-energy-density (HED) plasmas is inherently difficult due to the very dense and rapidly evolving conditions. Transformational measurement techniques are necessary to develop a physics-based understanding to pursue some of the grand challenges in HED physics, including, for example, warm dense matter (WDM) material properties, relativistic laser-plasma interactions, magnetic field generation, and plasma particle acceleration. X-ray free electron lasers can give such sensitive measurements of HED plasma states that they provide an atom's eye view with attosecond precision and significantly advance the state-of-the-art. Not only is MEC-Upgrade the central piece needed to achieve these HED science goals, it can also lead to breakthroughs in our understanding of materials needed for fusion.

– Recommendation: Complete the design and construction of MEC-Upgrade.

Technologies derived from plasma science investments have had a transformative effect on modern society. The translation of discoveries in low-temperature plasmas, for example, has created the semiconductor manufacturing industry, which provides advanced personal electronics. Plasma-based technologies will continue to improve quality of life with advances in environmental-hazard clean up in air, soil, and drinking water; advanced methods for medical treatment and imaging; and electronics. Plasma-based chemical processing has the potential to revolutionize industry by enabling the production of new materials and an innovative means to recycle plastics and other wastes. It will address climate change by greatly improving the efficiency of typically energy-intensive chemical processes and by offering ways to convert carbon-free electrical energy into the products that power society. Translation of basic plasma science research into actual technologies can be accelerated by a more organized and formal investment, including partnerships with industry and other federal agencies — for example, NSF, the National Institutes of Health (NIH), the Department of Agriculture, and the Environmental Protection Agency.

– Recommendation: Establish a plasma-based technology research program focused on translating fundamental scientific findings into societally beneficial applications.

High-intensity lasers are opening new fields across plasma physics, from high-energy-density science and laboratory astrophysics to new diagnostics and particle sources for science and industry. Two recent reports, NASEM's Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light, and the 2019 Brightest Light Initiative Workshop Report, enumerate the reasons to invest in intense ultrafast lasers. A new organization should be developed to maintain the vitality of this research field in the US and to make available the necessary petawatt-scale and high-repetition-rate laser technologies. FES could lead in coordinating a high-intensity-laser research initiative to support needs in discovery science and advance energy technologies. This would resolve fragmentation where no single national funding agency has responsibility for the field as a whole. Agencies making investments in this area include DOE FES, DOE High Energy Physics (HEP), DOE Accelerator R&D and Production (ARD&P), DOE NNSA, the NSF, and DOD.

– Recommendation: Coordinate a High-Intensity-Laser Research Initiative in collaboration with relevant DOE offices and other federal agencies.

Advanced lasers that go beyond the state of the art in high peak power and in very high average power (kilowatts and beyond) would open new frontiers in the laser-based science of particle acceleration, advanced light sources, high-field physics, nonlinear quantum electrodynamics, laser-driven nuclear physics, laboratory astrophysics and exotic materials. Competition in this arena is fierce, with scores of multi-petawatt lasers planned in Europe and Asia and petawatt-class high-repetition-rate laser facilities already in operation internationally. However, the US has an opportunity to stay competitive by leveraging decades-long investments and know-how in laser technology, while combining competencies in multiple emerging technologies — machine learning, advanced manufacturing, diagnostics, and edge computing—to develop a formidable capability that will rapidly accelerate the HED field.

– Recommendation: Pursue the development of a multi-petawatt laser facility and a high-repetition-rate high-intensity laser facility in the US, in partnership with other federal agencies where possible.

Networks provide an organizational structure that supports collaboration by increasing access to experimental facilities, diagnostics, and computational tools. LaserNetUS is an existing, very successful program that partially supports facility maintenance and operation, coordinates users, and evaluates proposals. The program allows researchers that otherwise lack access to state-of-the-art facilities to conduct frontier experiments; it would enable workforce development and facilitate coordination and collaboration. This or a similar model would likely have a comparable impact in other areas of plasma science and technology, including in low-temperature plasmas, laboratory-magnetized plasmas, and pulsed power. In addition to access to experimental facilities and user support, networks should include access to resources for computational modeling and diagnostics. Networks are also a mechanism to organize the community input that defines next-generation user facilities.

– Recommendation: Support networks to coordinate research and broaden access to state-of-the-art facilities, diagnostics, and computational tools.

Space and astrophysical plasma physics are enjoying an exciting time of discovery, as advances in spacecraft missions and remote observations provide insights into previously inaccessible regions in the solar system and beyond. The Parker Solar Probe spacecraft is orbiting close enough to the Sun to directly measure the solar wind at its origin. The mechanisms by which the solar wind is accelerated and heated are among the most persistent and important open research topics in plasma science. Recent advances in deep space imaging have culminated in the first visualization of an accretion disk—the turbulent, rotating plasma that is generated as material is gravitationally pulled toward a black hole. Understanding these phenomena presents a timely opportunity for FES to establish a new laboratory-based space and astrophysical plasma program. Controlled laboratory experiments, for example, can isolate, control, and diagnose plasma phenomena responsible for the complex behaviors seen in plasma systems throughout the cosmos. A partnership could be established with NASA in a focused laboratory space/astro plasma physics program, taking advantage of a recent NASA–DOE memorandum of understanding affirming mutual interest in collaborative activities pertaining to energy-related civil space activities. The existing partnership between DOE and NSF could also be leveraged for such an activity, including collaboration on needed facilities in this area. There is a need within the community to advance the capabilities of experiments, and to develop a solar-wind-relevant midscale experiment, to better compliment the advances in spacecraft technology and observation. Laboratory experiments can be a crucial intermediate between observation and computer simulation. In particular, they can provide specific conditions and environments that can be modeled in great detail in simulation frameworks.

– Recommendation: Strengthen support of laboratory-based research relevant to astrophysical and space plasmas through increased programmatic and facility funding as well as expansion of partnership opportunities.

Cross-cutting Recommendations

To successfully carry out this plan, foundational research activities that reach across the breadth of the FES portfolio must be robustly and continuously supported. Fundamental theoretical research, separate from computation, remains essential for developing new models, insights, and innovations in topics across plasma and fusion science and technology. Foundational theory work also enables the FES community to continue to take advantage of and expand advanced scientific computing and the tools that can further improve our fundamental understanding and predictive modeling capabilities, including new methods in machine learning (ML), artificial intelligence (AI), and quantum information science (QIS). This work is also essential for fusion and plasma research to take full advantage of US investments in exascale computing. All of these investments in theory and computation are vital to the continued development of variously complex validated models, including integrated modeling capabilities, an area in which, historically, the US has shown strength and leadership. A continued close partnership between FES and the Advanced Scientific Computing Research (ASCR) program is therefore essential to realizing these opportunities and to sustaining investment in computational user facilities and capacity computing resources. A healthy program for developing diagnostics, measurement, and control techniques for a reactor environment, and the broader environment of plasmas is needed to support progress toward an FPP and toward deeper understanding of plasma science. Community consensus favors increased support for programs to develop critical enabling technologies that advance plasma and fusion science and technology and reduce the cost of resulting applications, including an FPP. In each of these cross-cutting areas, the CPP report identified a wealth of needs and opportunities that should be addressed and pursued.

– Recommendation: Ensure robust support for foundational research activities that underpin all aspects of plasma and fusion science and technology.

Models and diagnostics in many areas of plasma science rely heavily on fundamental data for physical processes such as cross sections and rate coefficients and for materials properties such as strength and opacity. These essential elements of plasma physics and nuclear science should be more strongly supported. In many instances, models are limited by the absence of accurate input data rather than by a lack of knowledge of plasma physics. Research that both supplies and verifies such fundamental data is essential to advance in many areas of plasma science, including development of models. That type of research does not currently have a clear source of funding.

– Recommendation: Support research that supplies the fundamental data required to advance fusion energy and plasma science and engineering.

Budget Scenarios

Prioritization of projects and research programs is expressed through addressing the constant level of effort, modest growth, and unconstrained (but prioritized) budget scenarios as described in the charge. It should be emphasized that no additional recommendations are made in addressing the budget scenarios. Measures taken to address the constrained scenarios do not represent additional stand-alone recommendations outside the very specific budget scenario being addressed. While the constrained scenarios require difficult choices, they represent a balanced program with prioritization and emphasis on critical elements that advance the fusion energy mission and sustain scientific impact and technological progress. Importantly, the implementation of activities described in the constrained scenarios allows for continued growth should more favorable budgets develop in the future. Nonetheless, the constrained scenarios do not provide sufficient resources to confidently prepare for FPP construction by the 2040s, and large projects in the plasma science and technology area are unfunded. That lack of funding has consequences: It will cost the US its position as a global leader in fusion energy and plasma science and will compromise future developments with important societal implications. Therefore, we do not recommend either of the two constrained scenarios—namely, the constant level of effort or modest growth—and point to the substantial return on investment that comes with pursuing programs and facilities enumerated in the unconstrained but prioritized scenario.

In all three scenarios, there is a conscious decision to direct resources to the activities identified by the community as the most essential and urgent to enable construction of an FPP. That decision includes a strategic pivoting toward R&D in fusion materials and technology (FM&T). The pivot is necessary because FM&T R&D is on the critical path to an FPP, independent of the eventual choice of FPP plasma core(s). The strategic plan in all scenarios emphasizes innovation in both physics and technology as a means of establishing a unique leadership opportunity for the US fusion and plasma community, and recommends corresponding programs be supported in parallel with facility developments. Following the charge, the scenarios start from the FY 2019 budget and specifically focus on the non-ITER construction project portion. The FY 2019 budget did not include significant resources dedicated to design and construction of facilities. For that reason, in the two constrained scenarios below, any recommended new construction is funded by redirecting resources from current facility operations and research programs. This redirection is consistent with the consensus view of the research community, as expressed in the CPP report:

"The community recognizes that designing and constructing major new facilities may not be possible without progressively redirecting resources from existing facilities. Given the possibility of constrained budgets, there is significant support among the community to pivot resources from existing facilities to fund new programs and facilities, if necessary, so that new facilities can be operational within ten years or less. The resources and research programs of existing facilities should immediately evolve to reflect the priorities of this plan. Any such transition must be mindful of the workforce needs and impacts associated with diverting operations budgets to construction."

In addressing the scenarios, redirection is confined within each of the two thematic areas (FST and PST). The PST portion of the FY 2019 enacted budget is relatively small, and redirecting it, even in its entirety, would be insufficient to support yearly costs for proposed major facility construction. As a result, under the two constrained budget scenarios, major facility construction in the PST area is not possible. Importantly, that shortfall results in not completing the ongoing MEC-Upgrade project in the two constrained budget exercises. This project is headed toward Critical Decision 1 during FY 2021 and, notably, has received line-item status in the congressional budget, with significant resources allocated to the project in FY 2020 and in FY 2021. The message to be taken from the budget scenarios below is that new resources are required to support design, construction, and operation of the critically important MEC-Upgrade facility, and that message is consistent with actions already taken by Congress to support this project in FY 2020 and FY 2021. Table 1 (see page 42) summarizes program and facility actions for each scenario.

Summary of the three budget scenarios. Please refer back to report text for details. The unconstrained scenario fully reflects the recommendations in this report; the two constrained scenarios would result in loss of US leadership in key areas.

Portfolio Elements	Scenarios: Constant Level of Effort — Significant loss of US leadership & significant missed opportunities	Scenarios: Modest Growth — Loss of US leadership & missed opportunuties	Scenarios: Unconstrained	Technology and Science Drivers: Sustain a Burning Plasma	Engineer for Extreme Conditions	Harness Fusion Power	Strengthen the Foundations	Create Transformative Technologies	Understand the Plasma Universe
Research, Operations, and Small Scale Construction									
FM&T Programs	Yes, enhance	Yes, enhance	Yes, enhance	•	•	•		•	
US Tokamak Operations and Research	Yes, but reduce	Yes, but reduce	Yes	•	•		•		
Stellarator and Alternates Operations and Research	Yes, but flat	Yes	Yes, enhance	•	•		•		
IFE program	Yes, but limited	Yes, but limited	Yes	•					
FPP Design Effort	Yes, but limited	Yes	Yes, enhance	•	•	•			
GPS Program	Yes, but reduce modestly	Yes	Yes, enhance				•		•
HEDP Program	Yes, but reduce modestly	Yes	Yes, enhance		•		•	•	•
Plasma-Based Technology Program	Yes, but limited	Yes	Yes, enhance			•	•	•	
Theory and Computation	Yes	Yes	Yes, enhance	•	•	•	•	•	•
New Construction of Midscale+ Facilities									
MPEX	Yes	Yes	Yes		•			•	
FPNS	Yes, but highly delayed	Yes, but delayed	Yes		•			•	
MEC Upgrade*	No, but develop further*	No, but develop further*	Yes		•		•	•	•
EXCITE	No	Yes, but highly delayed	Yes	•	•				
Mid-Scale Stellarator	No	No	Yes	•	•				
BCTF	No	No	Yes		•	•			•
Solar Wind Facility	No	No	Yes				•		•
HHF-Component	No	No	Yes		•				
Multi-PW Laser	No	No	Yes				•		•
High Rep. Rate Laser	No	No	Yes, with partnerships				•	•	•
Midscale Z-Pinch	No	No	Yes, with partnerships				•		•
VNS	No	No	Concept Study			•			
Collaborations and Networks									
ITER research team	Yes	Yes	Yes, full	•	•	•			
Private fusion collaborations	Yes, enhance	Yes, enhance	Yes, enhance	•	•			•	
International fusion collab.	Yes	Yes	Yes, enhance	•	•			•	
LaserNetUS	Yes	Yes, enhance	Yes, upgrade				•	•	•
ZNet, MagNetUS, LTPNet	No	Yes, but limited	Yes				•	•	•

*Critical Decision 1 expected for MEC-U during FY 2021, and the project has received line-item status in the congressional budget, with significant resources allocated to the project in FY 2020 and 2021. However, definition of Constant and Modest Growth scenarios for this exercise were extrapolated from the FY 2019 enacted budget, where resources to enable this project are not present.

In the constant level of effort budget scenario, formation of a nascent ITER research team and design of FPNS are initiated immediately. FPNS construction should commence as soon as possible and would likely need to start in the second half of the decade, with operations not beginning until the 2030s. Establishment of EXCITE mission need and initial design should also proceed immediately. Although EXCITE construction costs likely cannot be accommodated within this scenario, it is vital to develop a conceptual design and, if possible, a full construction-ready design in the event budget outlooks improve. Additional options to help close the integrated tokamak exhaust and performance (ITEP) gap, including enhanced collaboration with private companies and international partners, must be developed as well. Increased investments in FM&T enable significant growth in programs (including blanket and tritium breeding research), completion of MPEX on schedule, and the buildup of a domestic collaborative FPP conceptual design effort in the early 2020s. FM&T investment also allows the construction of a high-heat-flux coupon-scale testing facility for PFC development in the second half of the 2020s.

The increased emphasis on these FM&T activities requires a reduction in tokamak research and operations, which are being used to resolve FPP design gaps in the areas of disruptions, burning plasma physics, plasma-facing materials, and operating scenarios. In particular, a modest but immediate reduction in operations funding to the existing major tokamak facilities (DIII-D and NSTX-U) would be required, with a more significant reduction in the mid-2020s, and would likely result in the cessation of operations of one of the two major tokamak facilities. The continued growth of the ITER research team and expanded private and international collaborations would give increased access to the burning plasma regime and help offset the reductions in research at the existing facilities. This pivoting of tokamak research and facility utilization should proceed at a pace that enables total tokamak research funding to continue at a stable level, with changes in facility emphasis and timing clearly communicated in advance to avoid significant workforce continuity challenges. A more aggressive ramp-down of existing facilities (DIII-D and NSTX-U) and programs was considered, but it was concluded that such an approach would only marginally advance timelines at the expense of losing workforce expertise deemed essential to closing the ITEP gap and would delay closure of the remaining tokamak physics gaps.

Foundational research activities in theory, modeling, and measurement innovations, together with all other existing program priorities (including INFUSE, stellarators, liquid metal plasma facing components (PFCs), RF technologies, etc.) continue to be supported at current levels in this scenario, and those activities and priorities should similarly pivot toward FPP-relevant needs. A modest

IFE program, focused on developing enabling technologies, is supported through redirection of existing HEDP funds.

Preconceptual development of facilities that are not started within the 10-year horizon of this charge (e.g., midscale stellarator, blanket-component test facility, or volumetric neutron source) are also supported. It is important to note that the technology readiness levels of the required elements for an FPP would likely remain low, creating significant risk in proceeding with an FPP in the 2040s.

In the PST portfolio of activities, FES should maintain its level of commitment to funding single-principal-investigator researchers, to operations of collaborative research facilities, and to LaserNetUS. FES should specifically form a program focused on plasma-based technology by transitioning support for similar research currently funded through the centers and the NSF–DOE partnership. It is important for FES to continue to develop preconceptual plans for new facilities and articulate mission needs while planning for future upgrades to existing facilities. Funding for these activities would be modest, consistent with identifying R&D needs to bring facility planning to the next critical decision level. The funds would be redirected out of current plasma science facility or experimental user support. In the case of the MEC-Upgrade, a small level of support similar to current funding levels should be extended for pre-project R&D and project planning to reduce the risk associated with entirely new technologies.

Additionally, FES should encourage community organization toward new networks in the areas of magnetized plasma laboratory research (MagNet), pulsed-power plasma research (ZNet), and low-temperature plasma science (LTPNet). Under a constant level of effort budget scenario, this activity will be limited to improving communications and sharing resources within the research community. Particularly in a constrained scenario, it is imperative that FES reaffirm its commitment to funding-agency partnerships including NSF, NNSA, and ARPA-E and that it explore the potential for new partnerships with other NSF divisions and directorates, NASA, NIH, the Office of Naval Research (ONR), DOE Basic Energy Sciences (BES), and the Airforce Office of Sponsored Research (AFOSR).

It is important to emphasize that within the constant level of effort scenario, the new initiatives and pivoting of program elements are only achieved at great cost to existing areas of US strength, and many time-critical opportunities for future innovation, impact, and leadership are missed. The pivot to increased FM&T research is vital for the fusion energy mission, but it cannot proceed in this scenario at a pace sufficient for FPP readiness by the 2040s. Likewise, establishing a new plasma technology program requires reductions of other vital plasma science and technology research efforts. In this scenario, the opportunity to build MEC-Upgrade is lost, initiation of EXCITE construction is highly unlikely, and the US tokamak program is significantly reduced. Many additional opportunities for innovation throughout the portfolio, including some PPP possibilities, cannot be acted upon. And although some domestic tokamak research can be redirected to ITER and collaborative efforts on international and private facilities, the resources to take full advantage of these opportunities are not available. Without adequate resources, possibilities for US leadership are limited in collaborating on international facilities not predominantly funded by the federal program. Therefore, while the measures taken to address this budget scenario help align the FES program with the technology and science drivers, the ability to act with urgency, enable innovation, and drive US leadership is highly constrained.

In the modest growth scenario (2% above inflation), the FPNS schedule is accelerated by 2–3 years, with operations targeted to begin by the end of the 10-year period of this plan. The related structural and functional materials programs are also expanded. Significant funding becomes available to accelerate the effort on the ITEP gap in the latter half of the 2020s, which may allow construction to begin on the EXCITE facility. An expanded ITER research team also becomes possible in the later 2020s. With modest growth, the technology and science drivers are significantly advanced by more robustly funding research programs in general plasma science (GPS) and HED. Additional investments are made in enabling technologies that support plans for new facilities needed to move the field forward. Cross-cutting research that connects topical areas such as multi-scale simulation codes, advanced computing, and diagnostic development should be better supported to increase impact across the FES portfolio. Small enhancements to the existing PST facilities and networks are pursued to extend their lifetimes and increase their availability. Even small investments in new network coordination (e.g., LTPNet and MagNet) will enable leadership in those areas. Other strategic advancement of existing and modest-scale new programs can be evaluated and executed consistent with the recommendations in this report, the priorities listed below, and the guidance from the CPP report. Given that much of this advancement could happen in the later 2020s, future long-range planning activities will also be able to provide more detailed guidance for prioritization.

The return on the investment of the relatively small increment from the constant level of effort to the modest growth scenario is substantial. It accelerates the fusion energy mission and gives excellent science per incremental dollar by continuing to support the high-impact work being done across the program. Furthermore, it aids the development of emerging technologies and innovative R&D to ensure continued progress, while also looking toward new facilities. However, there are still significant costs incurred and opportunities missed in this scenario. Most notably, meeting the goal of FPP readiness by the 2040s remains highly unlikely, significant reductions to the US tokamak program are still required, and some important time-sensitive opportunities for US leadership such as construction of MEC-Upgrade cannot be acted upon.

In the unconstrained, but prioritized, scenario, we have chosen to: (1) invest in the required facilities and program activities to confidently prepare for an FPP by the 2040s and (2) invest in high-impact facilities and programs to significantly advance plasma science while maintaining and extending US leadership in important areas. This can be accomplished using significantly increased but realizable resources, and thus the scenario is not truly unconstrained; it could instead be called “aggressive growth.” A truly unconstrained scenario, requiring substantially more resources, could be envisioned, aimed at further reducing the timeline to commercial fusion power.

It is important to emphasize that, as stated in the charge, the prioritized activities listed here are in addition to or enhancements of those described in the constrained scenarios. In this unconstrained, but prioritized, scenario, the FPNS facility is accelerated further, with operations anticipated in the latter half of the 2020s. Additional facilities and program enhancements have been identified that take advantage of the opportunities provided by the full breadth and creativity of the program. The following facilities and their supporting research programs are recommended, in prioritized order, with the timeliness and urgency of the activities in supporting the strategic plan factored in:

1. At equal priority:

   – Design, construct, and operate EXCITE by 2030 to close the integrated tokamak exhaust and performance gap.

   – Construct and operate the MEC-Upgrade to enable cutting-edge science in laser-plasma interactions, warm dense matter, and dense material physics via the co-location of a high-energy and high-repetition-rate laser with an X-ray free electron laser (XFEL).

2. Design, construct, and operate a new Stellarator Facility to demonstrate theoretically predicted advantages of an optimized stellarator configuration.
3. Design, construct, and operate a Blanket Component Test Facility to perform non-nuclear testing of integral-scale blanket components.
4. Design, construct, and operate a new Solar Wind Facility, potentially in partnership with other federal agencies, to investigate the fundamental processes in magnetized, high-beta plasmas relevant to such phenomena as accretion disks and stellar winds.
5. Design and begin construction of a component-level High-Heat Flux Testing Facility for plasma-facing component (PFC) development.
6. Construct and operate a large-scale multi-petawatt laser facility, potentially in partnership with other federal agencies, for novel studies in high-field physics and the exapascal pressure regimes.
7. Design, construct, and operate a high-repetition-rate laser facility, likely in collaboration with other agencies, for precision studies of complex high-energy-density phenomena.
8. Design, construct, and operate a midscale Z-Pinch facility, likely in collaboration with other agencies, for magnetized high-energy-density plasma studies.

As emphasized above, programs should be created or expanded as needed to support all facility research and operations activities. Beyond the appropriate support for facilities, the following new or expanded programs are recommended in priority order:

1 At equal priority:

– Strengthen FST programs (structural and functional materials, blanket and tritium fuel cycle, magnet development, and solid and liquid PFCs), increase support for research and operations on existing tokamaks in the early 2020s, and ensure optimal support of the national FPP design effort.

– Strengthen programs in GPS and HED to optimize progress and discoveries (consistent with priorities expressed here and in the CPP) in frontier plasma science and the plasma universe.

2 Strengthen support for the plasma-based technology program, with significant expansion in the number of grants, establishment of multiple technology-related centers, and a robust technology transition program.

3 Strengthen additional fusion science programs to optimize progress (stellarator physics, heating and current drive technologies, balance of plant technology), and ensure optimal support of the ITER research teams in the mid to late 2020s.

4 Increase operations support and aggressive upgrades to the LaserNetUS network to expand the base of users while allowing for a diverse set of capabilities that maintain US competitiveness.

5 Establish a program to develop innovative fusion core concepts using rigorous evaluation and metrics.

6 Expand the IFE program to more aggressively pursue IFE requirements and technologies.

7 Explore options for component-scale irradiation testing in a VNS.

8 Strengthen and expand networks to coordinate and leverage researchers and facilities in pulsed power, basic magnetized plasma experiments, and low-temperature plasmas.

These new and expanded programs should be pursued as feasible within a given budget scenario, weighted against the new facility recommendations using the prioritization criteria expressed throughout this report. With this scenario, all necessary elements could be advanced to the appropriate technology readiness level to enable an FPP by the 2040s. Clearly, this scenario grows the FES program significantly beyond the constant level of effort or modest growth scenarios and requires an expanded workforce. However, with careful staging of new facility construction, program pivoting, and aggressive utilization of public–private partnerships, we believe that much of what is recommended in this scenario can be accomplished in a timely manner and under realistic budgets.

Appendix A: Recommendations

Overarching Recommendations

- Align the program with the six technology and science drivers in order to establish the scientific and technical basis for a fusion pilot plant by the 2040s and advance fundamental understanding of plasmas that translates into applications that benefit society.
- Resources for ongoing design and construction of major new experimental facilities should be established in the DOE FES budget.
- Opportunities should be provided for developing new experimental capabilities at a range of scales, as appropriate to address the goals of this strategic plan.
- This long-range planning process, including a strong community-led component, should be repeated no later than every five years in order to update the strategic plan.
- Maturation of preconceptual designs, scope, and costing for proposed new experimental facilities should be part of regular program activities.
- Expand existing and establish new public–private partnership programs to leverage capabilities, reduce cost, and accelerate the commercialization of fusion power and plasma technologies.
- Explore and implement mechanisms for formal coordination between funding agencies that support fusion and plasma science research.
- DOE and FES should develop and implement plans to increase diversity, equity, and inclusion (DEI) in our community. Done in consultation with DEI experts and in collaboration with other institutions, this should involve the study of workplace climate, policies, and practices, via assessment metrics and standard practices.
- Restore DOE's ability to execute discipline-specific workforce development programs that can help recruit diverse new talent to FES-supported fields of research.

Program and Project Specific Recommendations

Fusion Science and Technology

- Initiate a design effort that engages all stakeholders to establish the technical basis for closing critical gaps for a fusion pilot plant, utilizing and strengthening the world-leading US theory and computation capabilities and engineering design tools.
- Rapidly expand the R&D effort in fusion materials and technology.
- Immediately establish the mission need for an FPNS facility to support development of new materials suitable for use in the fusion nuclear environment and pursue design and construction as soon as possible.
- Develop the scientific infrastructure necessary for the study of plasma-materials interactions needed to develop plasma facing components for an FPP by completing the MPEX and additional high-heat flux testing facilities.
- Significantly expand blanket and tritium R&D programs.
- Utilize research operations on DIII-D and NSTX-U, and collaborate with other world-leading facilities, to ensure that FPP design gaps are addressed in a timely manner.
- Ensure full engagement of the US fusion community in ITER by forming an ITER research team that capitalizes on our investment to access a high-gain burning plasma.
- Immediately establish the mission need for an EXCITE facility to close the integrated tokamak and exhaust gap and aggressively pursue design and construction.
- Strengthen the innovative and transformative research program elements that offer promising future opportunities for fusion energy commercialization: stellarators, liquid metal plasma-facing components, IFE, and alternate concepts.

Plasma Science and Technology

- Provide steady support for fundamental plasma science to enable a stream of innovative ideas and talent development that will lay the scientific foundation upon which the next generation of plasma-based technologies can be built.
- Complete the design and construction of MEC-Upgrade.
- Establish a plasma-based technology research program focused on translating fundamental scientific findings into societally beneficial applications.

- Coordinate a High-Intensity-Laser Research Initiative in collaboration with relevant DOE offices and other federal agencies.
- Pursue the development of a multi-petawatt laser facility and a high-repetition-rate high-intensity laser facility in the US, in partnership with other federal agencies where possible.
- Support networks to coordinate research and broaden access to state-of-the-art facilities, diagnostics, and computational tools.
- Strengthen support of laboratory-based research relevant to astrophysical and space plasmas through increased programmatic and facility funding as well as expansion of partnership opportunities.

Cross-cutting Recommendations

- Ensure robust support for foundational research activities that underpin all aspects of plasma and fusion science and technology.
- Support research that supplies the fundamental data required to advance fusion energy and plasma science and engineering.

Appendix B: Public–Private Partnerships

Introduction

Public–private partnerships (PPPs) are highly recommended as a means of rapidly and efficiently enhancing scientific and technological capabilities. Both general and fusion-specific plasma science and technology programs will benefit from robust PPPs. Scientific insights gained from basic and applied plasma science research lead to innovations that ultimately are developed into technologies in partnership with industry. Strategic PPPs can be effective in resolving common technical problems that face fusion and plasma science, in creating a competitive energy source in the US market, and in developing technologies that use plasma processes. Because the nature and missions of the private companies in basic plasma science and fusion energy development differ, and the breadth and maturity of existing PPP programs also differ, the PPP mechanisms for each area are described separately.

Fusion Science and Technology

There is broad agreement across stakeholders that having commercial fusion energy generation developed and based in the US is in the best interest of the DOE and the nation. The fusion energy endeavor is receiving from private entities new and significant contributions intended to address the clean energy market. Currently 22 private entities have raised nearly $2 billion in private capital to develop fusion energy concepts, with some targeting commercialization by the 2030s. Partnership between the public program and private activities can be effective in resolving common technical problems facing fusion as a competitive energy source. Although public and private strategies differ in technical focus and deliverables, significant overlaps exist that are beneficial to both parties and can accelerate progress toward the common goal of bringing fusion power to the grid.

Many private fusion companies are preparing to build facilities to demonstrate that their technologies scale, can be integrated, and can produce fusion-power-relevant plasmas. Examples include burning plasma facilities, next-generation spherical tokamaks, high-temperature field-reversed configurations, high-current pinches, compact stellarators, spheromaks, converging plasmas, impactors, and laser-driven IFE ignition, all aiming toward design of full-scale power plants. International competitiveness is an important consideration in the identification of possible PPP programs, given that the UK, Europe, China, and other countries are supporting development of their burgeoning domestic fusion industries. An Electric Power Research Institute (EPRI) report describing the responsibility of government and industry in the development of fission nuclear power highlighted two salient points: 1) the significant scope of shared partnership and responsibility between government and industry in establishing a new type of energy generation technology, and 2) the gradual transition from government-led to industry-led activities approaching and realizing commercialization.

Candidate PPP programs can take different forms based on the maturity and mission of the technology and on the capital required. The DOE currently has PPP programs to aid in the maturation of low-technology-readiness-level (TRL) technologies and is considering other programs, including a milestone-based cost-share program to demonstrate fully integrated mid-TRL technologies. With 22 members of the Fusion Industry Association (FIA) engaged in at least one of the strategic objectives or program recommendations from the CPP report, there exists significant potential for partnership with the public program to close gaps in those technical areas.

Low-TRL Maturation Programs: Existing technology maturation programs have been successful and should be expanded to enhance the scope and scale for closure of key technology gaps. Examples are ARPA-E ALPHA, ARPA-E BETHE, ARPA-E/FES GAMOW, INFUSE, and Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR). These were established both to help refine specific private-industry fusion-energy concepts and to develop platform technologies that would be useful across many fusion-energy concepts. High interest from the private sector in programs like INFUSE has been evident: Many more applications from private companies were received than could be funded. Given industry demand, additional resources in these programs would enable private fusion activities to grow and even accelerate.

– ARPA-E ALPHA creates tools to develop lower cost pathways to fusion energy

– ARPA-E BETHE delivers more advanced, lower-cost fusion technologies through concept development of less advanced concepts, component development of mature concepts, and capability teams to accelerate development of all concepts

– ARPA-E/FES GAMOW prioritizes R&D in technologies among fusion plasma/balance of plant, high-duty cycle drivers, and cross-cutting areas such as materials and additive manufacturing

– INFUSE accelerates fusion energy development in the private sector by reducing impediments to collaboration involving the expertise and resources available at DOE laboratories

– SBIR/STTR develops innovative techniques, instrumentation, and concepts that have applications to industries in the private sector

As the possibility for commercialization grows, partnerships in which industry may bear a greater burden of the cost become advantageous. Completion of prototype products can be done more quickly as private companies driven by market needs focus on efficient product delivery. A milestone-based 50/50 cost-share program should be created for partnerships to develop enabling technologies that are larger scale than projects funded through INFUSE, ARPA-E, and SBIR/STTR. Such a program could focus on the development of specific components or enabling technology for the fusion program. Examples could include magnets, high-power microwave and radiofrequency sources, neutron sources for materials irradiation, systems for tritium breeding blankets and tritium processing, and plasma-facing components. Some of these technologies could have applicability beyond fusion. Superconducting magnets and cables, for example, have broad commercial applicability in fields such as energy transmission and medical imaging. A cooling technology that can demonstrate power handling of greater than 10 MW/m2, which is needed for tokamak divertors, may also be applicable to applications such as energy concentration for high-energy particle accelerators or heat removal from advanced semiconductors.

Integrated Facility Cost-Share Program: We support the concept of a milestone-based cost-share program that can demonstrate integrated facilities having the potential to more rapidly and cost-effectively close technological gaps in order to achieve fusion energy. Such an activity should be executed as a parallel investment to augment the public long-range plan. This approach would maintain a robust strategy in the federal program while supporting high-risk, high-reward private industry efforts to allow multiple shots on goal in the effort to develop fusion energy.

An example of a new fusion-centered program with private industry was recently proposed by the FIA; it sought near-term investment in order to be relevant for current commercial timelines. The program is based on the NASA Commercial Orbital Transportation Services (COTS) cost-share program. That program, centered on a partnership in which private industry took over more routine operations in low-Earth orbit, proved successful in delivering a space launch vehicle at about 90% lower cost than the public program. Although NASA knew how to accomplish launches to low-Earth orbit, industry innovated with technologies and approaches that demonstrated more cost-effective solutions. Due to the success of the program, that approach is being applied by NASA and other agencies to lower TRL technologies. In the FIA-proposed fusion program, DOE would leverage private-sector creativity to develop new US-based capabilities that would enable fusion commercialization and research access to new user facilities. The program would be driven by market needs and would leverage the focus of private companies for fast and efficient product delivery. Each private-sector participant would meet the milestones agreed upon with DOE to receive the public funds in a proposed 50/50 cost-share agreement. The program would follow a portfolio approach that has multiple awardees in a competitive process. Details should be worked out between DOE and industry stakeholders so that programs could begin as soon as possible.

Facility Development and Shared Programs: The FST program needs experimental facilities that can close the program gaps in a timely fashion and private entities that can help where mutually beneficial activities are identified. Including private-sector input in the design of these facilities has the potential to reduce both costs and development time through private-sector efficiencies. DOE can also look to other PPP models, such as the approach utilized for the DOE Advanced Reactor Demonstration Program. In addition, shared access to operating public- and private-sector facilities can be an efficient method to close technical gaps of mutual interest. Generally speaking, the public program should seek to procure available capabilities and equipment from the private sector.

Information Access: To best equip the public and private sectors for success, FES-funded programs should share information between parties. A pathway for information transfer from public to private partners should exist for public programs. For example, access to ITER design information should be provided to US-based companies by FES. This access will help leverage the investments and technological developments that are occurring and maximize the US investment in ITER. Similar responsibilities lie with private entities that participate in PPPs. Clear delineation of intellectual property protection should occur as programs are formed, with the expectation that progress, milestones, and discoveries will be shared whenever possible. Coordination of efforts among all parties might best be made by consolidation within the FPP preconceptual design effort to minimize duplication of effort and advance the pace of discovery.

Mature Stage Programs: New PPP programs to further aid in the commercialization of fusion energy should be considered. The most aggressive private industry plans seek to put fusion power on the grid in the early 2030s. If these companies succeed, mature stage PPP programs will be needed in advance of groundbreaking for the power-producing facilities, which could occur as soon as the mid to late 2020s, which is within the time frame of this strategic plan. For example, loan guarantee programs have been used to help deploy several successful large-scale energy projects through the DOE Loan Programs Office. DOE could also consider the development of a long-term power purchase agreement program, which would simplify financing for future private-sector fusion power facilities.

Plasma Science and Technology

Basic plasma science research discoveries can lead to innovations that allow US industries to maintain global leadership in their fields. Historically, insight gained from basic plasma science has led to many societally important contributions. Plasma accelerators offer practical applications for cancer treatment and diagnostic imaging. Atmospheric pressure plasmas transfer green-energy-derived electricity to electrons and ions in gas or liquid phase for chemical processing, treatment of disease, water and air purification, material processing, and light production. Advances in low-pressure multifrequency RF discharge technology can position US industry to maintain leadership in semiconductor manufacturing.

The semiconductor industry is an instructive example of how partnerships between universities, government, and industry can come together to successfully revitalize a field. Such a partnership enabled plasma science to play a key role in US semiconductor device processing. In the 1980s, the US had fallen behind in semiconductor manufacturing. The establishment of the Sematech consortium, a partnership of 14 US semiconductor companies and the federal government, focused on improving manufacturing capability. The consortium allowed the US to reclaim its leadership role, and the semiconductor industry now holds nearly 50% of the global market share.

An ecosystem that provides a pathway for forming partnerships with industry to develop and share plasma science innovations does not exist beyond the DOE SBIR/STTR program. Vehicles that facilitate such partnerships are necessary for continued innovation by bridging the gap between science discovery and the formation of new technologies. Such partnerships also allow for the resolution of ongoing and arising engineering problems in industry through applied research. The need for PPPs in the semiconductor arena in particular was highlighted in the 2020 decadal study, which suggested that a private-public incubator be established that prioritized research focused on breakthroughs in the 5- to 10-year time frame to strengthen US leadership in this trillion-dollar market. This incubator would involve collaborative activity between academia, startups, and established companies, with the end goal of advancing research and disruptive breakthroughs for the purpose of commercialization.

Shared Research Programs: Research consortia that bring together public and private sectors to solve common technical problems should be encouraged. Currently, we stand at the threshold of an exciting era in plasma science and technology in which fusion and plasma research offer potentially transformative applications. With the growth of industrial applications, the potential for research consortia increases, as does the likelihood of problem-solving partnerships between private companies and universities. With Sematech as the exemplar, new areas for collaboration abound:

– Control of atmospheric pressure plasmas for chemical processing, the treatment of disease, water and air purification, and light production

– Advances in low-pressure plasma discharges to improve semiconductor manufacturing

– Plasma accelerators that offer practical applications for cancer treatment and diagnostic imaging

Questions raised in private industry that are fundamental and not aligned with commercial goals are often left unanswered. Researchers in universities are well suited to address foundational issues that may not have immediate applicability to a particular company. By pooling resources, public–private consortia can share the burden and reward.

Shared research programs can also shepherd scientific discoveries derived from FES-funded research to technological implementation, either through start-ups or licensing. The model suggested here is akin to that utilized in the NSF. The NSF Partnership in Innovation program provides a funding vehicle for single investigators to carry out customer discovery and develop technology based on prior research. Such programs provide a framework for partnering researchers with interested industrial entities.

Additionally, the current FES SBIR/STTR program should be leveraged to better align with mission goals. FES should convene a community workshop that brings together universities, national laboratories, and the private sector to outline research needs in order to focus the program on market-driven technologies. Thus the program is responsive to new developments and opportunities. This approach is in contrast to the current approach where SBIR/STTR grants and contracts are awarded separately from FES priorities.

To maintain competitiveness a framework is required that facilitates the transfer of technology derived from DOE-funded PST research into innovations that will benefit society. We propose that the recommended newly established PST program contain vehicles that support PPP options, including single investigator innovation development and partnering with industry to address technical challenges that affect overall US global leadership.

Summary

Development of public–private partnerships is recommended as a new paradigm for appropriately chosen program elements. To maintain and enhance competitiveness, a clear framework is required in order to facilitate developing FES-funded research into innovations that will benefit society. The programs described above have been demonstrably successful and should be implemented within FES. Initiatives are proposed to leverage shared public–private interests for maximal mutual benefit. Appropriate resources should be provided for these programs so that strong partnerships can be established. Sharing information on an annual or biennial basis is important so that public programs remain adaptable and private programs can benefit from public accomplishments. Growth of PPP programs will encourage the public and private sectors to work closely to more rapidly develop fusion energy and plasma technologies for the betterment of the US and the world.

Appendix C: DEI, Workforce, and Outreach

The success of this strategic plan requires innovation, creativity, and a multidisciplinary and diverse workforce. This appendix details actions that can achieve a more diverse, equitable and inclusive (DEI) environment for the growth of the needed workforce. The Community Planning Process (CPP) report presented consensus views on the needs in these areas:

"Diversity is expressed in myriad forms, including all ages, socio-economic backgrounds, races, ethnicities, genders, gender identities, gender expressions, national origins, religious affiliations, sexual orientations, family education level, disability status, political perspective—and other visible and nonvisible differences. Equity ensures equal opportunity and the impact of those opportunities in equitable outcomes for all persons; requiring zero tolerance for bias, harassment, and discrimination. Inclusion is the deliberate effort to ensure that our community is a place where differences are welcomed and encouraged, different perspectives are respectfully heard and where every individual feels a sense of belonging."

Data show that the fusion and plasma science research communities have significant deficiencies in workforce diversity, with participation of women and minorities below national averages for other subfields of physics and engineering. This means we are not accessing the available talent pool, and that lack is a clear barrier to our success. The problems involve more than recruiting talent into the field. Retaining diverse talent is affected by the culture within the community, and a community that is not welcoming and supportive will have a difficult time retaining diverse populations. Embracing equity and inclusion is the key to addressing this issue.

A recent policy change by the Office of Management and Budget placed significant limits on workforce and outreach programs at DOE. This policy, intended to reduce duplication of education and outreach activities at federal agencies, had the unintended consequence of eliminating discipline-specific outreach and workforce programs that were not being duplicated at other agencies. Specifically, the Office of Management and Budget (OMB) limits eliminated an important graduate fellowship program and placed restrictions on undergraduate research programs executed by DOE. However, DOE has been able to continue offering opportunities for undergraduates through the Science Undergraduate Laboratory Internships (SULI) program, which brings students to national laboratories for research experience. What was lost was a broader undergraduate research program that placed students at a wide range of institutions, including universities and industries, where they could participate in a broad spectrum of FES research. A new program created by DOE, the Office of Science Graduate Student Research (SCGSR) Program, provides resources that enable students to spend a portion of their graduate programs working with mentors at national labs. Although the program is useful, it does not replace the former graduate fellowship program. The SCGSR cannot be used as a tool to recruit graduate students into the field. It is designed specifically to help students already committed to working in a research area to obtain access to cutting-edge facilities and national lab researchers so that they can complete their thesis work. A graduate fellowship program, however, can target a diverse population of undergraduate students and be used to recruit them into areas supported by DOE.

The following sections detail actions that FES can take to address DEI, workforce, and outreach needs. Though listed separately, the three areas tie together: Effective expansion of the fusion and plasma science workforce requires tapping into the full talent pool, which better reflects the diversities of race, gender, background, and identity, and enacting policies aimed at improving the work climate in the community and institutions to increase recruitment and retention. The dual efforts of improving DEI and developing workforce, in turn, stem from effective outreach that ranges from energizing the imagination of K–12 students and the general public to actively attracting undergraduates and graduate students into the field. This includes expanding and retaining plasma and fusion faculty at colleges and universities throughout the nation. In addition, there are significant opportunities for recruitment of established scientists and engineers working in areas other than fusion and plasma into both the federal program and private fusion and plasma-focused companies. Progress on any one of these fronts will improve all three desired outcomes.

Since the CPP report was community based, many of the recommendations are aimed at the fusion and plasma science research community as a whole rather than at any single funding agency. The CPP report made some recommendations on DEI and workforce, all of which should be acted on. Here we have identified specific recommendations that are actionable by DOE or other federal agencies. We call out a second set of recommendations that DOE could advocate in partnership with other federal agencies and research institutions.

Recommendations actionable by FES

Diversity, Equity, and Inclusion (DEI)

For a diverse, equitable, and inclusive environment in the field of fusion and plasma science and technology, we recommend the following actions:

- Conscious or unconscious bias based on gender, race/ethnicity, or other personal and scientifically irrelevant characteristics can interfere with an equitable funding process and should be discouraged by FES-funded programs. The impact of such bias can be minimized by, for instance, implementing double-anonymous peer-reviewing of proposals. Similar review processes have been successfully implemented in other agencies, such as NASA and NSF. These review processes often utilize a two-step approach, where evaluation of institutional and personnel capabilities is carried out after an initial anonymous technical review.
- Policies that promote work-life balance are essential to achieve better gender and financial-background equality and will improve the overall diversity of the workforce. Although FES has limited power in implementing parental leave policies, a topic that is part of a broader national conversation, the agency can take further action to support family-friendly policies among its funding recipients. For instance, FES should work with principal investigators to adjust milestones and deliverables to accommodate research team members who take family leave. FES has already adjusted deadlines due to the exceptional conditions during COVID-19, which proved that the avenues for these deadline changes exist.
- DEI and workforce improvements should weigh into the awards process. This can be achieved by implementing a requirement in proposals for the consideration of DEI efforts as an integral aspect of the review process for institutions seeking funding from DOE FES.

Workforce development

To attract the best talent and recruit individuals with the skills that the program needs, and to retain them and grow our workforce, we recommend the following:

- As recommended in Chapter 2, restore DOE's ability to execute discipline-specific workforce development programs that can help recruit diverse new talent to FES-supported fields of research. We recognize that this requires action beyond DOE.
- Reinstate and create fellowships to help recruit and retain top students from a diverse applicant pool into FES research areas. Fellowships for new graduate students are critical to recruitment. Expand direct support for students and

postdocs during their tenure (such as internships and SULI for undergraduate and SCGSR for graduate students) and for early career scientists (such as the DOE Early Career Research Program). These programs improve recruitment, facilitate collaboration, and mitigate power imbalances. Programs should emphasize broadening the recruitment pool and increasing opportunities for women, underrepresented minorities, and other underrepresented groups. The programs should support work at national laboratories, universities, and private companies.

– Expand and create programs designed to increase and retain faculty positions at universities and colleges, including faculty start-up grants to incentivize departments to increase their existing fusion or plasma science faculty numbers or to start such a program outright. Although existing Early Career Awards (ECAs) support new junior faculty, no program exists within FES that encourages colleges or universities to hire fusion or plasma science faculty in the first place. Such programs have been successfully implemented at other funding agencies (e.g., NSF's Faculty Development in the Space Sciences Program). Such programs can address equity and diversity by expanding and aiming such efforts at Historically Black Colleges and Universities (HBCUs), Tribal Colleges and Universities (TCUs), and Hispanic Serving Institutions (HSIs). Efforts to support retention of faculty should also include expanding ECAs to non-tenure-track researchers at universities and implementing joint university/national lab faculty development programs.

Outreach

Recruiting the best workforce requires reaching out to a broad sector of the public at every educational level. Although we are aware of the limitations imposed by OMB regulations, we request that FES support outreach to attract a diverse future workforce and publicly promote the role of plasma and fusion in society.

There is an opportunity to use FES resources to promote plasma science and, in particular, fusion science. Actions to do that should come from FES, given that NSF does not currently support fusion science research or outreach, and thus such outreach can be conducted only by national labs. The goal of these outreach activities is to create a broad entrance to the plasma and fusion science and technology workforce pipeline, which will allow access to the wide variety of specific skills required to execute the program.

These FES resources can support the development of a new public-facing website for plasma science and fusion, potentially in collaboration with other programs or agencies, and in coordination with existing resources of this kind. Such resources could also support pre-college outreach to engage the youngest minds with the FES program and inspire students to consider careers in plasma and fusion science. Student outreach approaches could include student design competitions, which have proven successful for the promotion of other scientific fields.

Collaboration with Other Agencies and Institutions

In addition to highlighting recommendations considered directly actionable within FES, the committee encourages FES to engage with other federal agencies and stakeholders on broader DEI and workforce development recommendations laid out in the CPP report.

- Institutions should engage DEI experts to advise our community and develop assessment tools. Such programs, including those led by the American Physical Society Division of Plasma Physics, have been successfully implemented at FES-funded institutions.
- FES-funded institutions and events should adopt and update policies that promote a welcoming workplace environment, including articulating and adopting codes of conduct for conferences and workshops that outline parameters for respectful interactions among attendees; requiring training on bias, cultural competence, and bystander intervention; and investigating how to assess reports of harassment.
- DOE and FES-funded institutions should create a welcoming and accessible environment, compliant with the Americans with Disabilities Act, for all members of our community. All institutions funded by or working in the several fields of FES should expand recruitment pools (geographically, fields of study, types of institutions, etc.) and identify underrepresented areas with linkages to the workforce development topics outlined above.
- Create parental leave policies by working with institutions on more uniform family leave policies to economically support up to 12 weeks of leave taken under the Family and Medical Leave Act. This includes allowing continued support for personnel during principal investigator leave, supporting flexible hours and telecommuting, and access to lactation space.
- Institutions funded by or working in fields of FES should develop flexible postgraduate education options and facilitate employment of scientists and engineers with BS/MS degrees at FES facilities. The facilities should have BS/MS development programs.

Appendix D: Charge Letter

Department of Energy
Office of Science
Washington, DC 20585

30 November 2018

Dr. Donald Rej
Chair, Fusion Energy Sciences Advisory Committee
Program Director, Office of Science Programs at LANL
Los Alamos National Laboratory, MS-A121
Los Alamos, NM 87545

Dear Dr. Rej:

This letter requests that the Fusion Energy Sciences Advisory Committee (FESAC) undertake a new long-range strategic planning activity for the Fusion Energy Sciences (FES) program. The strategic planning activity—to encompass the entire FES research portfolio (namely, burning plasma science and discovery plasma science)—should identify and prioritize the research required to advance both the scientific foundation needed to develop a fusion energy source, as well as the broader FES mission to steward plasma science.

In developing recommendations within this long-range strategic planning activity, FESAC should take into account the following aspects:

- Identifying specific research areas, across the entire FES portfolio, in which the U.S. should establish or enhance global leadership.
- Maintaining a healthy and flexible program, which incorporates the roles and contributions of universities, national laboratories, and industry, to deliver science results throughout the next decade.
- Maintaining, upgrading, and/or pivoting current small-, mid-, and large-scale facilities, including DIII-D and NSTX-U, and also initiating new experiments/facilities/projects.
- Identifying international collaborative opportunities or partnerships that can give U.S. scientists access to devices outside of the U.S. with unique capabilities.
- Providing support for private-public partnership ventures.
- Positioning the U.S. to obtain maximum benefits in the ITER burning plasma science era.
- Considering the future budgetary constraints described below, as well as the technical readiness and feasibility for any activity to proceed.

Your report should provide recommendations on the priorities for an optimized FES program over the next ten years (FY 2022-2031) under the following three scenarios with the FY 2019 enacted budget for the FES program as the baseline:

- Constant level of effort (defined as the published OMB inflators for FY 2022-2031)
- Modest growth (use 2% above the published OMB inflators)
- Unconstrained budget: For this scenario, please list, in priority order, specific activities (beyond those mentioned in the previous budget scenarios) that are needed to achieve and maintain a leadership position addressing the scientific opportunities identified by the community.

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Within each of the three scenarios, assume that the U.S. Contributions to ITER project will continue through this entire period.

You should consider these three budget scenarios as an opportunity to identify priorities and make high-level recommendations. The activities that you recommend should be (to some significant extent) implementable under reasonable budgetary and programmatic assumptions. At the same time, the budget scenarios should not drive the prioritization to the degree that research/projects are promoted solely for their ability to fit within an assumed profile.

The FESAC report should articulate the scientific opportunities that can and cannot be pursued, as well as the approximate overall level of support needed in the FES program to pursue these opportunities within the various funding scenarios identified above.

The FESAC activity in addressing this charge should commence after the completion of community-led activities to provide broad input to this long-range planning. This two-phase approach for long-range planning is similar to that used by both the High Energy Physics program and also the Nuclear Physics program within the DOE Office of Science.

For the first phase, we have asked the American Physical Society's Division of Plasma Physics (DPP) to lead with the organization of community-led activities (such as discussions, town halls, workshops, and any other forums it chooses). We want the community to be actively involved in this long-term planning process. We are grateful that the DPP leadership is willing to provide this valuable sponsorship of the community-driven first phase.

The second phase of the process involves this charge to FESAC. Although this charge will be discussed at the December 6 and 7 FESAC meeting, no FESAC subcommittee to address the charge will be formed at that time. Toward the end of the community's process to develop its important input for planning, a FESAC subcommittee shall be formed to carry out the work of developing the long-range plan.

We would appreciate receiving the report from FESAC by December 2020, if possible. We understand that this is a challenging task; however, your considerations of these issues will be essential input to DOE planning. Please let us know if there is anything we can do to help you in this process.

Sincerely,

JSBinkley

J. Stephen Binkley
Deputy Director for Science Programs
Office of Science

Appendix E: FESAC LRP Subcommittee Members

Troy Carter, chair
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Appendix F: Process and Meetings

This report is the culmination of a two-year, two-phase strategic planning process. The first phase, the Community Planning Process (CPP), was the primary mechanism for all members of the fusion and plasma science community to provide input. The second phase, the FESAC Long Range Planning (LRP) study, used the CPP report as a starting point. During its 10-month study, the FESAC subcommittee sought inputs from the community and other sources, including community focus groups, workshops, and briefings from several federal agencies that support plasma and fusion related activities. That input, along with discussions at weekly subcommittee meetings, facilitated the development of this LRP report. The activities are described in more detail below.

CPP Process

The CPP, organized under the auspices of the American Physical Society (APS) Division of Plasma Physics (DPP), was a year-long, community-led process that occurred just prior to our FESAC LRP activity. The findings of the CPP report were based on the synthesis of community-generated white papers, webinars, town halls at fusion and plasma meetings, and five major workshops. The report described opportunities in fusion and plasma science in order to improve our understanding of them and to facilitate the translation of science to societally beneficial applications. The CPP report included discussions of 1) Fusion Science and Technology, 2) Discovery Plasma Science, and 3) Cross Cutting Opportunities. The CPP report achieved significant community consensus, and its initiatives and priorities formed the basis for our prioritization and development of the budget scenarios in this report.

Community Focus Groups

The FESAC subcommittee gathered input through community focus groups. Nine focus group sessions were carried out through June and July 2020, with a total of 90 participants. Representatives from all program areas, across all demographic categories, and with a wide range of experience levels participated. The focus group sessions had three objectives:

- Address the question of resource division between fusion science and technology (FST) and discovery plasma science (DPS; called plasma science and technology in this report)
- Determine program synergies and identify cross-cutting opportunities
- Gather feedback on the LRP report formulation process

Virtual Workshop

On August 20, 2020, a virtual workshop was held to gather additional information from the community. The meeting provided an opportunity for the fusion and plasma research communities to exchange ideas and understand the priorities of each program area. An additional objective was to merge the mission and vision statements, along with the values developed in the two communities, into a single strategic plan. Input provided by the workshop informed development of a process to merge the plans and allocate resources between the two areas in the constrained budget scenarios. The workshop included approximately 200 participants.

Stakeholder Federal Agency Briefings

The FESAC subcommittee was briefed by representatives from other government agencies and projects with synergistic research interests. The goals of the briefings were to provide insight into plasma-related focus areas and their funding footprint in the various agencies, discuss the potential for partnerships, and learn about the execution of large projects and public–private partnerships by other government agencies. The committee received presentations from the following individuals and agencies:

On synergistic topical reports

–Prof. Mike Mauel (Columbia University), on the 2019 NAS report *A Strategic Plan for U.S. Burning Plasma Research*

–Prof. Roger Falcone (University of California, Berkeley), Dr. Felicie Albert (Lawrence Livermore National Laboratory), and Prof. Jon Zuegel (University of Rochester) on the 2018 NAS report *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*

–Prof. Mark Kushner (University of Michigan) and Prof. Gary Zank (University of Alabama in Huntsville) on the 2020 NAS Decadal Assessment of Plasma Science (a presentation to FESAC)

–Prof. Carolyn Kuranz (University of Michigan), Dr. Lauren Garrison (Oak Ridge National Laboratory), Dr. Nathan Ferraro (Princeton Plasma Physica Laboratory), Dr. Nathan Howard (MIT), and Prof. John Sarff (University of Wisconsin) on the CPP Report

From other agencies

–Ms. Ann Satsangi (National Nuclear Security Administration)
–Dr. Scott Hsu (ARPA-E)
–Dr. Thomas Zurbuchen (NASA)
–Dr. Vyacheslav Lukin (National Science Foundation)

On public–private partnerships

–Dr. Alan Lindenmoyer (NASA) on the Commercial Orbital Transportation Services (COTS) program

–Dr. Dave Petti (Idaho National Laboratory) on the Next Generation Nuclear Plant (NGNP)

–Dr. Adrian Collins (Idaho National Laboratory), on the Versatile Test Reactor (VTR)

Subcommittee Meetings

As with many other activities in 2020, the COVID-19 pandemic obviated all plans for the subcommittee to meet in person. The entire subcommittee met weekly via Zoom for the duration of our activities, for discussions aimed at understanding overall program needs and for synthesizing the strategic plan. Additional weekly meetings included separate DPS and FST meetings to develop program-specific priorities and multiple meetings of smaller subgroups tasked with drafting specific portions of the report or addressing issues for later discussion by the larger group. The overarching goal of the meetings was to formulate a plan for three budget scenarios: constant level of effort, modest growth, and unconstrained but prioritized. Cost estimates for program elements and facilities informed the development of the three budget scenarios in the FESAC Charge (see Appendix C) but were not the sole basis for the scenarios. Status updates were provided at regular virtual FESAC meetings on March 16, June 23–24, and August 24.

Costing and Budget Scenarios

DOE Fusion Energy Sciences (FES) briefed the subcommittee several times on budgets and provided details of the FY 2019 budget that is called out in the Charge along with historic budget information and information on the FY 2020 budget enacted. FES also provided information on costs for ITER operations during the 10-year window of the Charge. Subgroup meetings took place to establish which program elements and user facilities from the CPP report would need to be costed by outside experts. Once the list of those facilities was finalized, outside experts provided cost estimates. Program elements were costed by the subcommittee. The program elements and facilities cost estimates were used in exercises to understand the three budget scenarios in the FESAC Charge. The subcommittee determined that the cost estimates of facilities and program elements could only be used to provide a range of plausible costs, given that the facilities were at a low level of development (a few were even at the preconceptual level). Given the range and the associated uncertainty, the subcommittee decided not to include cost estimates in this report or in the budget scenarios. The resulting budget scenarios are a combination of prioritization within the program as derived from the CPP report and costing exercises targeting each budget scenario.

High-Heat-Flux Facilities

The CPP recognized high-heat-flux testing of materials as a critical step in the development of plasma-facing components for future fusion reactors. However, the CPP did not specify how to fulfill this need. Given the safety-driven limitations of international collaborations in the study of nuclear materials (such as the difficulty of transporting activated samples) and the lack of capability for high-repetition, multi-megawatt heat-flux exposure currently in the US, we concluded that two new facilities are needed for FPP preparation: a coupon-scale (sample sizes of centimeters) high-heat-flux exposure facility for candidate material testing and model validation that form the basis for FPP plasma-facing component designs, both solid and liquid; and a component-scale facility (sample sizes of tens of centimeters up to 1 meter, as needed) for qualification of components and related systems, such as active cooling.

Implementation

This long range plan and its recommendations are advisory input to DOE Office of Science and DOE Fusion Energy Sciences (FES). Implementation of these is the responsibility of DOE.

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Appendix G: Acronyms

ASCR	Advanced Scientific Computing Research program
AI/ML	Artificial Intelligence/Machine Learning
AFOSR	Air Force Office of Scientific Research
APS DPP	American Physical Society Division of Plasma Physics
ARPA-E	Advanced Research Projects Agency-Energy
BCTF	Blanket Component Test Facility
CD	Critical Decision
CPP	Community Planning Process
DEI	Diversity, Equity, and Inclusion
DOD	Department of Defense
DOE	Department of Energy
DPS	Discovery Plasma Science
EPA	Environmental Protection Agency
EXCITE	EXhaust and Confinement Integration Tokamak Experiment
FES	(Office of) Fusion Energy Sciences
FM&T	Fusion Materials and Technology
FPNS	Fusion Prototypic Neutron Source
FPP	Fusion Pilot Plant
FST	Fusion Science and Technology
GPS	General Plasma Science
HED	High-Energy Density
HEP	High-Energy Physics
HEDLP	High-Energy-Density Laboratory Plasmas
HEDP	High-Energy-Density Plasmas
HHF	High-Heat-Flux
ICF	Inertial Confinement Fusion
IFE	Inertial confinement Fusion Energy
INFUSE	Innovation Network for Fusion Energy
ITEP	Integrated Tokamak Exhaust and Performance
LM	Liquid Metal

MEC-U	Matter in Extreme Conditions instrument Upgrade
MPEX	Material Plasma Exposure eXperiment
MFE	Magnetic confinement Fusion Energy
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NIF	National Ignition Facility
NIH	National Institutes of Health
NNSA	National Nuclear Security Administration
NSF	National Science Foundation
NTUF	New Tokamak User Facility
ONR	Office of Naval Research
PFC	Plasma-Facing Component
PFPO	Pre-Fusion Power Operation
PMI	Plasma-Material Interaction
PPP	Public–Private Partnership
PST	Plasma Science and Technology
QIS	Quantum Information Science
R&D	Research and Development
RF	Radiofrequency
SBIR	Small Business Innovation Research
STTR	Small Business Technology Transfer
TRL	Technology Readiness Level
USDA	US Department of Agriculture
VNS	Volumetric Neutron Source
WDM	Warm Dense Matter
XFEL	X-ray Free Electron Laser

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