Powering the Future
Fusion & Plasmas

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

Report of the FESAC Long Range Planning Subcommittee
FESAC Meeting, December 2020

FESAC Long Range Planning Subcommittee


Scott Baalrud


Riccardo Betti


Troy Carter


Tyler Ellis


John Foster


Cameron Geddes


Arianna Gleason


Chris Holland


Paul Humrickhouse


Chuck Kessel


Ane Lasa

Tammy Ma


Rajesh Maingi


David Schaffner


Oliver Schmitz


Uri Shumlak


Lance Snead


Wayne Solomon


Erik Trask

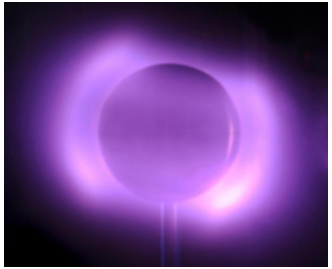

Francois Waelbroeck


Anne White


Don Rej (ex officio)

Thank you!

- → To the research community; for the incredible amount of effort during the Community Planning Process and for continued engagement in “Phase 2” through focus groups and our virtual workshop
- → To Laurie Moret, for her guidance throughout the two-year process
- → To Sam Barish, for his advice and assistance as FES liaison
- → To Michael Branigan & Jim Dawson for graphic design & editing



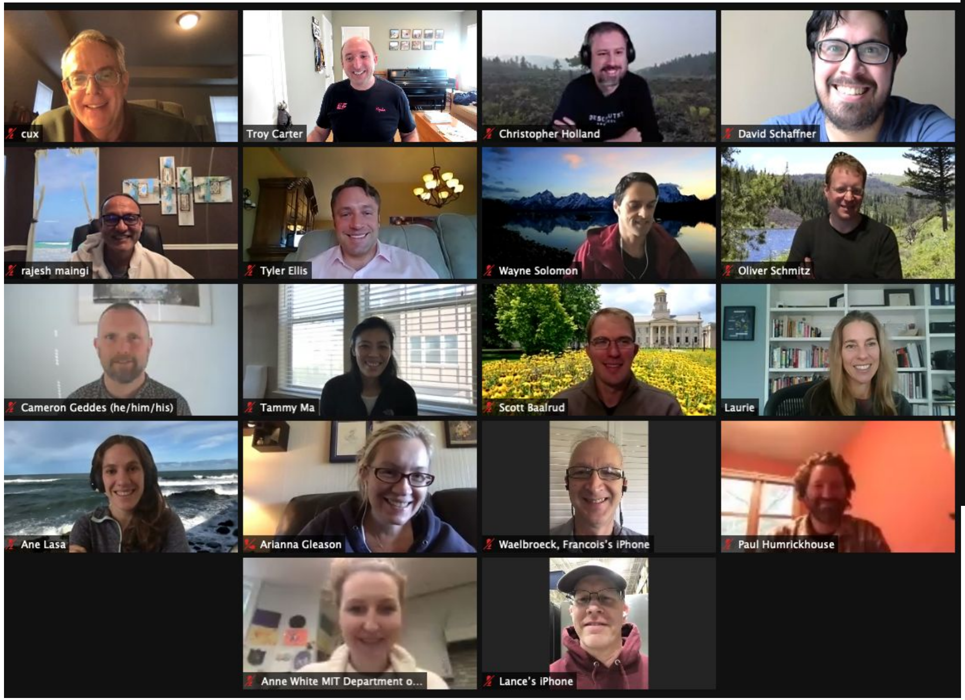
2018 FESAC Charge

- Charge covers entire FES portfolio: "…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."
- Two part process, community driven phase (Community Planning Process) and FESAC-led phase
- "Optimized FES program over the next ten years" (FY22-FY31). Consider three budget scenarios: constant level of effort, modest growth (2% above inflation), and unconstrained but prioritized
- "...assume that the US Contributions to ITER project will continue throughout this entire period": focus on the non-ITER-project portion of the budget.

Subcommittee Process

- Subcommittee work began February, ramped up with delivery of the "Phase 1" Community Planning Process report in March
- Entire process conducted virtually (many subcommittee members have never met before in person). Uncountable number hours spent on Zoom (countable number on MS Teams)
- Many guest speakers: from other federal agencies, on related reports, on private-public partnership models
- Community engagement through focus groups, virtual workshop
- Scenarios developed using extensive budget analysis: utilizing data from FES, range of inputs on facilities costs including costing experts with extensive DOE project experience (Jeff Hoy, Carl Strawbridge)
- Worked by consensus process to produce the final report

Zoom group shots



Executive summary: Now is the time for fusion & plasmas

- ➔ **Now is the time** to move aggressively toward the development of fusion energy. Recent advances point the way toward a unique US vision for fusion development, targeting a fusion pilot plant by the 2040s. Growth of a fusion energy industry is important for this vision and that industry is already seeded.
- ➔ **Plasmas transform society.** Far-reaching impact spans: advances key to enabling fusion energy; deeper understanding of our universe; creating exotic states of matter with the most intense lasers in the world; transformative applications that impact our everyday lives and have the potential to enable a more sustainable society
- ➔ **Fusion and plasmas are inextricably linked,** have strong connections and important shared history

Executive summary: Partnerships and Leadership

- ➔ **Partnerships accelerate progress.** International partnership, especially ITER, is critical. Public private partnerships have the potential to reduce time to commercially viable fusion and support the growth of a fusion energy industry. Interagency partnerships can maximize progress in research and development.
- ➔ **Fusion and plasma research in the US are world-leading; continued scientific leadership requires nurturing and agility.** US is poised to create world-leading fusion industry, should be supported. Leadership in key areas is threatened by the absence of investment in major new facilities to address critical R&D needs.

Executive summary: First time process

➔ **For the first time, scientists have created a long-range plan to accelerate the development of fusion energy AND advance plasma science.** The community-driven CPP process is the foundation of this long-range planning process. Not only identified important new opportunities, but developed guidance for prioritization through a consensus process. The resulting CPP report forms the basis for this strategy.

THANK YOU!

New directions for the FES program

- The Fusion Science and Technology (FST) area should focus on establishing the scientific and technical basis for a fusion pilot plant by the 2040s
- The Plasma Science and Technology (PST) area should focus on new opportunities to advance fundamental understanding, and in turn translate these advances into technologies that benefit society
- These new directions are embodied in six technology and science drivers

Technology and Science Drivers: FST

- **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

Technology and Science Drivers: PST

- ➔ **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

Significant return on increased investment

- ➔ Constant level of effort: redirection can occur and important scientific and technical progress will continue, but major lost opportunities, significant risk to FPP goal and US leadership position
- ➔ Significant return on the investment for the increment from the constant to the modest growth scenario. However, risks and missed opportunities remain, including threat to the goal of an FPP by 2040s.
- ➔ Unconstrained scenario: the complete strategy can be implemented. Additional investment beyond the modest growth scenario will have substantial return. Important scientific advances would be enabled and progress toward realizing practical fusion energy would be accelerated.
  - ◆ With staging, program pivoting, and utilization of partnerships, we believe these additional activities can be accomplished in a timely manner and under realizable budgets

Prioritization Criteria

- In order to prioritize the projects and programs discussed in this report for each of the three budget scenarios, we developed a set of consensus prioritization criteria
- Consensus criteria and guidance for prioritization within program areas were developed by the research community during the CPP process. Additional feedback was provided in the follow-on workshop organized by the sub-committee
- This guidance and feedback were used to develop criteria for whole portfolio prioritization
- 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-project portion of the budget

Prioritization Criteria

- ➔ **Alignment:** Align projects and programs with the technology and science drivers
- ➔ **Urgency:** Prioritize the most expeditious path to fusion energy and other plasma technologies that provide compelling solutions to urgent issues
- ➔ **Innovation:** Embrace innovative research, new developments in technology, and interdisciplinary connections to address key challenges
- ➔ **Impact:** Implement a logical sequence of programs that increases scientific and technological progress relative to investment
- ➔ **Leadership:** Establish and maintain US leadership. 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 the essential workforce to maintain scientific and technological progress

Recommendations Overview

- The recommendations fall into two categories
  - Overarching recommendations are program/facility independent but essential to successful execution of the FES research program
  - Project and Program Specific Recommendations in three subcategories
    - Fusion Science and Technology (FST) Program recommendations
    - Plasma Science and Technology (PST) Program recommendations
    - Cross-cutting recommendations that apply to all programs.

- **The order of presentation of these recommendations does not imply priority; all recommendations should be acted on in order to fully realize the strategic plan**
  - Prioritization of activities is expressed through the budget scenario descriptions

Overarching Recommendations

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 2040's and advance fundamental understanding of plasmas that translates into applications that benefit society

Recommendation: This long-range planning process, including a strong community-led component, should be repeated every five years in order to update the strategic plan

➔ The strategic plan should be regularly updated to adapt to new scientific discoveries, technological breakthroughs and other changes in the research and development landscape

Overarching Recommendations

Recommendation: Resources for ongoing design and construction of major new experimental facilities should be established in the DOE Fusion Energy Sciences budget

- ➔ The US has invested significantly over the last decade in the design and construction of ITER and will continue to do so over the coming decade
- ➔ However, outside of the important investment in ITER, there has been little investment over the last 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 a number of areas

Overarching Recommendations

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

- ➔ Although large scale facilities are essential to make progress in many areas, important aspects of the fusion mission and plasma science and technology 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

Overarching Recommendations

Recommendation: Maturation of pre-conceptual designs, scope, and costing for proposed new experimental facilities should be part of regular program activities

- ➔ Strategic planning is most effective if ideas for major new experimental capabilities are developed to the pre-conceptual 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

Overarching Recommendations

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

- ➔ DOE Fusion Energy Sciences has already established successful PPP programs, notably the Innovation Network for Fusion Energy (INFUSE)
- ➔ These activities should be expanded and new private-public partnership 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
- ➔ More discussion of this topic to come in discussion of Appendix A later in this presentation

Overarching Recommendations

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

- ➔ 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 NSF, ASCR, HEP, NNSA, ARPA-E, AFSOR, and ONR
- ➔ Coordination among these federal programs has led to extremely successful research programs; the NSF-DOE Partnership in Basic Plasma Science and Engineering is a prominent example
- ➔ Expanding on these successes and increasing program coordination could make better use of federal resources and enable more rapid progress toward development of fusion energy and toward advancing plasma science and engineering

Overarching Recommendations

Recommendation: DOE and FES should seek to implement policy changes that improve diversity, equity and inclusion within the FES research community

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

- ➔ 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
- ➔ There are barriers to achieving this workforce that should be addressed in order to achieve the goals in this strategic plan
- ➔ Specific details on recommendations addressing these topics to come in discussion of Appendix B later in presentation

FST Recommendation: FPP Design

Recommendation: Initiate a coordinated design effort that engages all stakeholders and establishes the technical basis for closing critical gaps for a fusion pilot plant.

- Design, construction and operation of a fusion pilot plant (FPP) is recognized as a critical milestone toward deployment of fusion energy
- Effort needed to bring physics modeling efforts together with engineering tools
  - Core, balance of plant, licensing, remote handling, maintenance, reliability
- Domestic multi-institutional, collaborative FPP design and study program, giving significant attention to activities agnostic to the plasma core and contrasting baseline tokamak approach with other plasma cores
- Activity should help inform evolving research needs and priorities

FST Recommendation: Pivot to materials/tech

Recommendation: Pivot the research and development focus toward fusion materials and technology

- ➔ Constructing an FPP requires technology development beyond the burning plasma
- ➔ Critical enabling technologies such as plasma facing components, structural and functional materials, and breeding blanket and tritium handling systems are currently not advanced enough for an FPP
  - ◆ At present levels of support, time to develop these technologies is incompatible with goal of an FPP by the 2040s
- ➔ Support foundational fusion materials & technology research
  - ◆ Theory and modeling, diagnostics systems, enabling technologies

FST Recommendation: FPNS

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

- ➔ Mixed spectrum fission reactors do not produce appropriate spectrum for materials irradiated in a fusion reactor core
  - ◆ Fusion-born neutrons will produce significant, yet largely unknown, effects on structural and non-structural components of the first wall, divertor, and blanket
- ➔ The Fusion Prototypical Neutron Source (FPNS) needed to produce the required damage and transmutation rates and must have high reliability and flexibility
- ➔ A comprehensive program of modeling, advanced characterization, and high-temperature nuclear-structural design criteria is necessary
- ➔ FPNS + programs will build upon the US leadership in fusion materials technology

FST Recommendation: MPEX and PMI

Recommendation: Develop the scientific infrastructure necessary for the study of plasma-materials interactions needed to develop plasma facing components for a fusion pilot plant by completing the MPEX and high-heat flux testing facilities

- ➔ Physics-based understanding of plasma-material interactions (PMI) is necessary to construct and qualify plasma-facing components (PFCs) for an FPP
- ➔ Material Plasma Exposure eXperiment (MPEX), currently in design to build process, is a central piece
  - ◆ A linear plasma exposure device uniquely equipped to access prototypical plasma conditions in a fusion reactor divertor
- ➔ High heat flux testing via coupon-level facility early and component-level facility later, will allow for development of materials and qualification of components for an FPP
- ➔ Together with 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

FST Recommendation: Blankets and Tritium

Recommendation: Significantly expand blanket and tritium R&D programs

- Closure of the fusion fuel cycle via successful breeding and extraction of tritium will be critical for the sustained operation of an FPP
- Breeding blanket technologies at low TRL and unlikely to advance to demonstration stage without significantly increased research and development support
- Understand tritium transport properties and phenomena in solid and liquid breeder materials with separate-effect test stands and fission reactor irradiations
- Tritium technologies will be demonstrated at significant scale in ITER
  - Program should involve tritium experts in the US ITER team
- Support additional R&D to minimize size, cost, and tritium inventory of the plant
- No current path for US to deploy a test blanket module in ITER or any other facility
  - Develop strategy for component-scale blanket testing and support pre-conceptual design and costing for blanket component test facility (BCTF)

FST Recommendation: Existing tokamaks

Recommendation: Close fusion pilot plant design gaps by utilizing research operation of DIII-D and NSTX-U + collaboration with other world-leading facilities

- ➔ Gaps need closing to confidently design low capital cost FPP & prepare for ITER
  - ◆ Transport & stability to sustain disruption-free, high-average-power output
  - ◆ Energetic particle & burning plasma physics relevant to a high-fusion-gain FPP
  - ◆ Plasma-material interactions and PFC integration in a tokamak environment
  - ◆ Operational scenarios for an FPP
- ➔ Significant parts can be addressed immediately utilizing the world-leading DIII-D and NSTX-U facilities alongside important smaller-scale facilities at universities
  - ◆ DIII-D: Resolve disruption and transients, inform long pulse steady state
  - ◆ NSTX-U: ST plasma physics, along with PMI control and liquid metal PFCs
- ➔ Collaborations on planned public and private facilities (esp. long pulse conditions inaccessible in US) provide unique contributions to complete tokamak physics basis

FST Recommendation: ITER

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

- ➔ US should fully exploit its participation in ITER to gain experience with a burning plasma and fusion technology while benefiting from the shared cost
- ➔ ITER is 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 pre-fusion-power operation phase starting in 2028, US urgently needs to establish framework for developing an appropriate workforce
  - ◆ Centrally organized and ramped up as project moves toward first plasma
  - ◆ Near-term opportunities to participate in system design and commissioning

FST Recommendation: EXCITE

Recommendation: Immediately establish the mission need for an EXCITE facility to close the integrated tokamak and exhaust gap and pursue design and construction as soon as possible

- Even with existing and planned facilities, it will not be possible to fully complete the tokamak physics basis needed for the US vision of a tokamak based FPP
  - Requires demonstrating integrated strategies for handling exhaust heat fluxes well beyond what is expected to be accessible in existing or planned devices, while simultaneously supporting sustained high core plasma performance
- 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 providing excellent opportunities to partially bridge gap, none were judged sufficient to close the fundamental core-edge integration challenge encapsulated by the ITEP gap.

FST Recommendation: EXCITE (cont'd)

Recommendation: Immediately establish the mission need for an EXCITE facility to close the integrated tokamak and exhaust gap and pursue design and construction as soon as possible

- ➔ Building upon NASEM BP report, a new domestic tokamak, EXCITE (EXhaust and Confinement Integration Tokamak Experiment) is optimal to close ITEP gap
  - ◆ Unique, world-leading combination of flexible power exhaust capabilities, PFC options, control actuators, access to plasma conditions
  - ◆ Enable continued US leadership in tokamak physics into the 2030s
- ➔ Envisioned to be modestly sized high-field device with short-pulse, non-nuclear operation to enable design and construction on an acceptable timescale at manageable cost
- ➔ Develop pre-conceptual designs for a detailed assessment of cost and technical feasibility, and benchmark against gap closure through collaborations and upgrades
- ➔ Include private industry and international partners to accelerate schedule & reduce costs

FST Recommendation: Innovations

Recommendation: Strengthen the innovative and transformative research that offers promising opportunities for fusion energy commercialization: stellarators, liquid metal plasma facing components, inertial fusion energy and alternate concepts

- ➔ Four innovative areas aim to address key vulnerabilities of a solid PFC tokamak, potentially leading to attractive commercial fusion power by leveraging US leadership
  - ◆ Stellarators offer intrinsically disruption-free operation with low recirculating power. The quasi-symmetric stellarator concept is unique to US and complemented by international collaboration at the W7-X and LHD stellarators. A new domestic mid-scale US stellarator experiment should be realized.
  - ◆ Liquid metal PFCs potentially expand reactor wall power limits and alleviate lifetime constraints due to material erosion. Liquid lithium walls may open up pathways to high plasma confinement and compact FPP designs. Development of liquid metal PFC concepts should be targeted.

FST Recommendation: Innovations (cont'd)

Recommendation: Strengthen the innovative and transformative research that offer promising opportunities for fusion energy commercialization: stellarators, liquid metal plasma facing components, inertial fusion energy and alternate concepts

- ➔ Four innovative areas aim to address key vulnerabilities of tokamak, potentially leading to attractive commercial fusion power systems by leveraging US leadership
  - ◆ Inertial fusion energy (IFE) utilizes advances in lasers, pulsed power technology, and drivers to achieve fusion at high fuel density. Progress with indirect drive at NIF, direct drive, magnetic drive ICF, and heavy ion fusion underpin promise of IFE. An IFE program leveraging US leadership & current investments should be targeted.
  - ◆ Breakthroughs in alternate magnetic confinement concepts, beyond tokamaks and stellarators, could lead to more economically attractive fusion power. A program that supports innovative MFE concepts should be considered.

PST Recommendation: Consistent Support

Recommendation: Consistently support fundamental plasma science to ensure a steady stream of innovative ideas and talent; laying the scientific foundation upon which the next generation of plasma-based technologies can be built

- ➔ Fundamental plasma science explores new regimes and deepens our understanding of nature
- ➔ This includes theories that propose foundational descriptions of plasmas, computational methods required to predict outcomes of these theories, and experiments that test the predictions
- ➔ The knowledge these discoveries provide makes possible the innovative plasma-based technologies of the future
- ➔ The future of plasma science will rely on consistent support, even when spending for construction projects and larger program elements fluctuate

PST Recommendation: MEC-Upgrade

Recommendation: Complete the design and construction of MEC-Upgrade

- ➔ Advances in 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
- ➔ 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 tackle some of the grand challenges in HED physics
- ➔ X-ray free electron lasers can provide such sensitive measurements of HED plasma states that they provide an atom-eye view with attosecond precision, significantly advancing the state-of-the-art

PST Recommendation: Plasma Technology Program

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

- Plasma science technologies have revolutionized industry and our everyday lives:
  - created the semiconductor manufacturing industry
  - advanced environmental hazard clean-up in air, soil and drinking water
  - spawned novel medical treatments and imaging
  - plasma-based chemical processing for the production of new materials, means to recycle plastics and other wastes; improvements in the efficiency of typically energy-intensive chemical processes; methods to convert carbon-free electrical energy into the products that power society
- Translation of basic plasma 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, NIH, USDA, and EPA

PST Recommendation: High-Intensity Laser Initiative

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

- ➔ High intensity lasers are opening new fields across plasma physics, as highlighted in two NAS reports, *"Opportunities in Intense Ultrafast Laser: Reaching for the Brightest Light" and "Plasma Science,"* and the 2019 *Brightest Light Initiative* workshop report
- ➔ A new type of organization is needed to maintain the vitality of this research field in the US and to make available petawatt-scale and high repetition rate laser technologies
- ➔ FES has an opportunity to take a leading role in coordinating a high intensity laser research initiative
- ➔ Support is also needed for a user network of academic and national laboratory high intensity laser facilities
- ➔ This would resolve fragmentation where no single national funding agency has responsibility for the field as a whole

PST Recommendation: Multi-PW & HRR Lasers

Recommendation: Pursue the development of a multi-petawatt laser facility and a high-repetition-rate high-intensity laser facility in the US

- ➔ Advanced ultrafast 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 and nonlinear quantum electrodynamics, laser-driven nuclear physics, and extreme materials and astrophysics
- ➔ Competition in this arena is fierce, with new multi-petawatt and petawatt-class high-repetition-rate lasers already coming online in Europe and Asia
- ➔ 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

PST Recommendation: Networks

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

- ➔ Networks provide an organizational structure that supports collaboration by increasing access to experimental facilities, diagnostics, and computational tools
- ➔ LaserNetUS is a very successful model that provides researchers access to state-of-the-art facilities to conduct frontier experiments, enabling workforce development, and facilitating coordination and collaboration
- ➔ Similar models are likely to have comparable impact in other areas, including in low temperature plasmas, laboratory magnetized plasmas, and pulsed power
- ➔ Networks should include access to resources for computational modeling and diagnostics
- ➔ Networks provide a mechanism to organize the community input that defines next-generation user facilities

PST Recommendation: Lab Astro & Space Plasmas

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

- Space and astrophysical plasma physics are enjoying an exciting time of discovery:
  - The Parker Solar Probe 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 important open research topics in plasma science
  - Deep space imaging has given us the first visualization of an accretion disk
- Controlled lab experiments 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, taking advantage of a recent NASA-DOE MOU. The existing partnership between DOE and NSF could also be leveraged
- Experimental capabilities need to be advanced, including the development of a solar-wind-relevant midscale experiment

Cross-Cutting Rec: Foundational Research

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

- ➔ Foundational research activities across the breadth of the FES portfolio must be robustly supported
- ➔ Fundamental theoretical research is essential for developing new models, insights, and innovations
- ➔ Must continue taking advantage of advanced scientific computing tools that can further improve our fundamental understanding and predictive modeling capabilities, including in Machine Learning (ML), Artificial Intelligence (AI),Quantum Information Science (QIS), and exascale computing
- ➔ A healthy program for developing diagnostics, measurement, and control techniques for a reactor environment and the broader environment of plasmas is important
- ➔ There is community consensus in favor of 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

Cross-Cutting Recommendation: Fundamental Data

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

- ➔ Models and diagnostics in many areas of plasma science rely heavily on fundamental data for physical processes such as cross sections and rate coefficients, as well as materials properties such as strength and opacity
- ➔ These are essential elements of plasma physics and nuclear science which should be more strongly supported
- ➔ In many instances, models are limited by the absence of accurate input data, rather than 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
- ➔ This type of research does not currently have a clear source of funding

Budget exercises: Scenarios

- Plans have been developed for the three budget scenarios as described in the charge
  - constant level of effort [published OMB inflators]
  - modest growth [2% above published OMB inflators]
  - unconstrained (but prioritized)
- Scenarios help convey information about prioritization, but there are no additional recommendations made that stand outside of these specific budget exercises
- Following the charge, the scenarios are considered starting from the FY19 budget, specifically focusing on the non-ITER construction project portion, which does not include significant resources dedicated to design and construction of facilities
- For this reason, in the two constrained scenarios, **any recommended new construction is funded by redirecting resources from current facility operations and research programs. This redirection is confined within each of the two thematic areas (FST and PST).**
- We assume that all costs for programs and facilities are born entirely by FES. All activities, especially major facilities, should seek partnership, but we do not take credit for this in assembling the scenarios, making these conservative projections.

Consequences of Constrained Scenarios

- ➔ While the constrained scenarios require difficult choices, they are constructed to represent a balanced program with prioritization and emphasis on critical elements that advance the fusion energy mission and sustain scientific impact and technological progress
- ➔ Nonetheless, **the constrained scenarios do not provide sufficient resources to confidently prepare for an FPP by the 2040s**
- ➔ **Large projects in the plasma science and technology area are unfunded, including MEC-U,** which is already at CD-0 and heading toward CD-1 this FY
  - ◆ Construction of major facilities can not be supported by redirecting small resources currently in PST program
  - ◆ Combined support for PST elsewhere in federal government substantial; facilities like MEC-U would draw research support outside of FES
- ➔ This has consequences as it **will cost the US its position as a global leader in fusion energy and plasma science**, and compromise future developments with important societal implications

Constant level of effort scenario

- In this scenario, pivoting and redirection of funds enables the program to undertake a number of exciting and vital new activities
  - On-schedule completion of MPEX construction and operation
  - Establish mission need and design for FPNS, construction starts (late in decade)
  - Immediate formation of a nascent ITER research team
  - Buildup of domestic collaborative FPP design effort
  - Increased investment in critical FM&T research programs
  - Construction of a coupon-level High-Heat-Flux facility (late in decade)
  - Small-scale programs continue, theory and computation support maintained with a pivot to support FM&T needs
  - Re-establish a modest IFE program, focus on enabling technology
  - Formation of a limited new plasma-based technology program
  - Maintain support for single-PI researchers, collaborative facilities, and LaserNetUS

Constant scenario: lost opportunities

➔ However, 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**.

- Opportunity to build MEC-Upgrade is lost (R&D can proceed at modest level)
- EXCITE mission need established and design work begins, but initiation of construction highly unlikely to begin within 10-year horizon
- Can't start significant new initiatives
  - Can't build mid-scale stellarator, solar wind facility, BCTF, laser facilities
  - Not able to grow support for alternate confinement concepts
- Plasma-based tech program requires redirection from from existing PST research
- New networks (MagNet, ZNet, LTPNet) encouraged but very limited in scope
- The increased emphasis on FM&T activities also requires a reduction in domestic tokamak research and operations

Constant Scenario: pivoting tokamak effort

- ➔ Given the budget constraints of the charge, and values expressed by the community, **the only viable way to redirect sufficient funds for new FM&T priorities and facility construction within FST is a reduction of existing domestic tokamak operations**
- ➔ A modest but immediate reduction in operations funding to the existing major tokamak facilities (DIII-D and NSTX-U) is required to enable growth of FM&T research programs
- ➔ A more significant reduction (~50%) in the mid-2020s, likely resulting in the cessation of operations of one of the major tokamak facilities, is required to enable FPNS construction
- ➔ More aggressive rampdowns were considered, but it was concluded that this approach would only marginally advance timelines at the expense of losing workforce expertise deemed essential to closing the tokamak physics gap
  - ◆ Less aggressive rampdowns did not provide sufficient urgency to meet the priorities expressed by the community

Constant Scenario: Pivoting tokamak effort

- This pivoting of tokamak research and facility utilization should proceed at a pace which 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
- Continued growth of the ITER research team and expanded private and international collaborations provides increased access to the burning plasma regime and helps offset the reduced research effort on the existing facilities
  - Mid-decade provides natural transition point with end of 5-year plans, next iteration of this process, targeted start of new facilities including ITER first plasma, MPEX completion

Modest growth: Substantial ROI

→ The **return on the investment** of the relatively small increment from the constant level of effort to modest growth scenario is **substantial**

- More robust funding for PST programs advance tech & science drivers
- Small enhancement projects to the existing PST facilities and networks are pursued to expand capabilities and increase their availability
- Investments in new Network coordination enables expansion of US leadership
- FPNS is accelerated 2-3 years, operations targeted to begin within 10-year horizon
  - Related structural and functional materials program expanded
- Possible for construction of EXCITE to begin in later 2020s, as well as pursuit of alternate approaches to closing the tokamak core/edge exhaust challenge
- An expanded ITER research team in later 2020s also becomes feasible
- Increased support for cross-cutting research areas such as theory, simulation, advanced computing, and diagnostic development is available

Modest growth scenario

- ➔ However, **there are still costs incurred and opportunities missed** in the modest growth scenario
  - Meeting the goal of FPP readiness by the 2040s remains highly unlikely
  - Significant reductions to the US tokamak program are still required (equivalent to the constant level of effort scenario)
    - Important to keep at least one tokamak operating as EXCITE is developed
  - Important time-sensitive opportunities for US leadership such as construction of MEC-Upgrade cannot be acted upon

- ➔ While the actions recommended in this scenario help further align the FES program with the technology and science drivers, **the ability to act with urgency, enable innovation, and drive US leadership in this scenario remains highly constrained**

Unconstrained (but prioritized)

- First, **FPNS is further accelerated**, with operations anticipated in later half of 2020s
- The next slides list additional facilities and program enhancements identified to take advantage of the opportunities provided by the full breadth and creativity of the program
- **Prioritization of facilities** and their supporting research programs was determined by factoring in the **timeliness and urgency** of the activities in supporting the strategic plan
- In addition to the supporting research efforts for the facilities, **a prioritized list of new and expanded programs was developed**
- Facility needs are primary cost drivers and would be selected first, along with program changes needed to accompany those new facilities. Once possible facilities investments are identified, additional investment would go into the prioritized list of programs.

Unconstrained: Prioritized Facilities

1. **At equal priority**:
    - Design, construct, and operate **EXCITE** by 2030
    - Construct and operate **MEC-Upgrade**
2. Design, construct and operate a new **Stellarator** facility
3. Design, construct and operate a **Blanket Component Test Facility**
4. Design, construct and operate a new **Solar Wind Facility**
5. Design and begin construction of a **component-level High-Heat Flux Testing Facility**
6. Construct and operate a large-scale **multi-petawatt laser facility**
7. With partnerships, design, construct and operate a **High Repetition Rate laser facility**
8. With partnerships, design, construct and operate a **mid-scale Z-Pinch facility**

For each facility listed here in priority order, **it is essential to grow the supporting research programs** along with facility design, construction, and operation

Unconstrained: Prioritized Programs

1. **At equal priority**:
   - **Strengthen FM&T programs** (materials, blankets, tritium, magnets, 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 PST** to optimize progress and discoveries 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 FST programs** to optimize progress (stellarator physics, heating and current drive (H&CD) technologies, balance of plant technology), and **ensure optimal support of the ITER research team** in the mid to late 2020s

Unconstrained: Prioritized Programs

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 U.S. 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 concepts for volumetric neutron irradiation** to carry out component-scale testing
8. **Strengthen and expand networks** to coordinate and leverage researchers and facilities in pulsed power, basic magnetized plasma experiments, and low temperature plasmas

Unconstrained: Fully realize the strategy

- ➔ With this scenario, all necessary elements could be advanced to the appropriate technology readiness level to **enable readiness for a fusion pilot plant by the 2040s**, and **expand US leadership in plasma science and technology**

- ➔ Clearly, this scenario grows the FES program significantly beyond the constant level of effort or modest growth scenarios

- ➔ 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 realizable budgets**

Appendix A

Public Private Partnerships

Public-private partnerships (PPP) are highly recommended to rapidly and efficiently enhance scientific and technological capabilities

- Both general and fusion-specific plasma science and technology programs benefit from robust PPP collaborations
- Insights gained from basic and applied plasma science research lead to innovations that ultimately are developed into technologies in partnership with industry
- Strategic partnership between public programs and private activities can resolve common problems facing fusion and plasma science in creating
  - a competitive energy source in the U.S. market
  - new technologies utilizing plasma processes
- Nature & missions of private companies in basic plasma science and fusion energy development differ; breadth and maturity of existing PPP programs also differ

Fusion Science and Technology PPP programs

- Low Technical Readiness Level (existing)
- Milestone based facility program (new)
- Mature stage programs (new)
- Facility design collaboration (new)

- Periodic sharing of information is suggested so that public programs remain adaptable, and both sides might benefit from documented accomplishments

Low TRL technology maturation programs should be expanded to enhance the scope and scale for closure of key technology gaps

- **SBIR/STTR** - develops innovative techniques, instrumentation, and concepts that have applications to industries in the private sector
- **ARPA-E ALPHA** - tools to develop lower cost pathways to fusion energy
- **ARPA-E BETHE** - higher maturity, lower cost fusion technology via development of
  - less mature concepts
  - component development of mature concepts
  - capability teams to accelerate development of all concepts
- **ARPA-E GAMOW** - prioritizes R&D in technologies between 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 via collaborations with DOE laboratories
- **Milestone-based cost share program should be created for enabling technologies that are of larger scale than above programs**
  - Magnets, high-power microwave and RF sources, neutron sources for materials irradiation, systems for tritium breeding blankets and tritium processing and PFCs

We support the concept of a **milestone-based cost share program** aimed at the demonstration of **integrated facilities**

- ➔ Potential for rapid and cost-effective technological gap closure
- ➔ Executed as a parallel investment to augment the public long-range plan
- ➔ “Multiple shots on goal”: this strategy maintains robust effort in public program while supporting high-risk, high-reward private efforts to develop fusion energy

- ➔ Example: **FIA proposed facility cost-share program**
  - ◆ Parallels to the NASA COTS program
- ➔ Driven by the market research and identified needs; leverages the focus private companies provide for fast and efficient product delivery
- ➔ Each private sector participant would meet the agreed-upon milestones to receive the public funds in a 50-50 cost share fraction

New **mature stage** PPP programs to further aid in the commercialization of fusion energy should be considered

- Most aggressive industry plans aim for fusion power on the grid in the early 2030s
- Mature stage PPP programs will be needed in advance of the groundbreaking for the power-producing facilities, which could occur as soon as the mid-to-late 2020s
- Examples:
  - Loan guarantee programs
  - Long-term power purchase agreement program, which would simplify financing for the future private sector fusion power facilities

Private entities can help to **develop new experimental facilities** needed to close the FST program gaps in a timely fashion

- Including private sector input in the design of these facilities could reduce costs and development time by leveraging private sector efficiencies and practices
    - Most effective where mutual benefits are evident
    - Generally, the public program should seek to procure available capabilities and equipment from the private sector
- Private access to operating public sector facilities (and vice-versa) can provide an efficient method to close technical gaps of mutual interest

- FES-funded programs should strive to make information available between public and private sectors
    - A pathway for information transfer from public to private should exist
    - E.g. access to ITER design information should be provided to US domiciled companies by FES

Plasma Science and Technology PPP programs

- → Low Technical Readiness Level (existing)
- → Shared Research Programs

Low TRL advancement programs, e.g. SBIR and STTR, should be continued

→ Insight gained from basic plasma science has led to societally important contributions; some of these were advanced via SBIR and STTR programs

- Plasma accelerators as promising techniques for cancer treatment
- Atmospheric plasmas for chemical processing, the treatment of disease, water and air purification, material processing, and light production
- RF discharge technology for semiconductor manufacturing

Research consortia with public and private sectors to solve common technical problems in plasma science and technology are encouraged

- Sematech consortium: a partnership between 14 US semiconductor companies and the federal government, focused on improving manufacturing capability
  - Plasma science plays a key role in the processing of semiconductor devices
  - In the 1980s, the US had fallen behind in semiconductor manufacturing
  - The consortium enabled the US to reclaim its leadership role and now leads globally with nearly 50% of the market share
- A private-public incubator in the semiconductor industry should be established that prioritizes research focused on breakthroughs in the 5-to-10-year timeframe
- New shared research programs would extend beyond SBIR/STTR and more closely align with priorities
  - Atmospheric pressure plasmas, RF plasmas, plasma accelerators
- Technology transfer programs as used by NSF should be considered
  - The NSF Partnership in Innovation program supports single investigators to carry out customer discovery and develop technology based on prior research

Public-private partnerships (PPP) are highly recommended to rapidly and efficiently enhance scientific and technological capabilities

- → Low TRL advancement programs should be enhanced
- → New targeted programs to facilitate fusion energy development and advance plasma science applications are recommended
- → Implementation of these programs will enhance competitiveness and unlock innovations for maximum societal benefit

Appendix B

Developing a Diverse, Equitable and Inclusive Workforce

DEI, workforce & outreach are part of our plan

The **success of this strategic plan** requires innovation, creativity and a talented, multidisciplinary and diverse workforce.

➔ effective expansion of our workforce *requires* tapping into the **full available talent pool**, which better reflects the diversity of race and ethnicity, gender, background, and identity, as well as **enacting policies aimed at improving the social climate** to increase retention.

➔ The dual efforts of improving DEI and developing workforce, in turn, stem from an **effective outreach effort** that spans all stages

This appendix seeks to enable this by detailing actions that can be taken to achieve a more diverse, equitable and inclusive environment and growth of the needed workforce

...and require action from all other stakeholders

The CPP report made a number of recommendations on DEI, workforce and outreach, all of which should be acted on.

➔ Here we have identified and first present **specific recommendations that are actionable by DOE or otherwise within the federal government**.

➔ Later we list recommendations actionable by other agencies, institutions and stakeholders

Diversity, Equity and Inclusion

For a diverse, equitable and inclusive environment in the field of FES, we recommend:

- ➔ Unwarranted conscious or unconscious bias should be discouraged by FES-funded programs, for instance by implementing **double blind peer-reviewing of proposals**
- ➔ Implementing an **additional requirement in proposals for the consideration and promotion of DEI efforts** as an integral aspect of the review process for institutions seeking federal funding from DOE OFES
- ➔ Policies that promote work-life balance are especially essential towards achieving better gender and financial-background equality and will improve the overall diversity of the workforce. FES can take further action to accommodate parenthood among its funding recipients, for instance by **working with principal investigators to adjust milestones and deliverables to accommodate research team members who take family leave.**

Workforce development

In order to attract and recruit the best talent, and to retain them and grow our workforce, it is essential to **restore DOE's ability to execute discipline-specific workforce development programs:**

- ➔ A recent policy change by the Office of Management and Budget (OMB) placed significant **limits on workforce and outreach programs at DOE**, with the unintended consequence of **eliminating discipline-specific programs** that were not being duplicated at other agencies
- ➔ This eliminated an important graduate fellowship program, placed limits on undergraduate research programs executed by DOE, and lost a broader undergraduate research program that placed undergraduates at a wide range of institutions, where they could participate in a wider spectrum of FES research activities

Workforce development

- ➔ **Reinstate or create fellowships to recruit and retain the best students into FES research areas**, including a diverse applicant pool. Expand support directly to students and postdocs and early career scientists. Programs should emphasize broadening the recruitment pool and opportunities for women, underrepresented minorities (URM), and other underrepresented groups and support work at National Laboratories, Universities, and private companies.
- ➔ **Expand or create programs that aim to increase and retain faculty lines at universities and colleges,** including faculty start-up grants to incentivize departments to grow their existing fusion or plasma science/technology faculty numbers or to start such a program. This program can also address equity and diversity, and support retention of faculty by expanding ECAs to non-tenure faculty 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. Thus we recommend that FES support outreach efforts in:

- ➔ Use **FES resources to promote plasma science, and in particular fusion science**. The goal of these outreach activities is to **create a broad entrance to the plasma and fusion science and technology workforce pipeline**, which will enable access to the diversity required to execute the program.
- ➔ 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. The latter could include student design competitions, which have proven successful for the promotion and attractiveness of other fields.
- ➔ These FES resources can be used to support the **development of a new public-facing website** for plasma science and fusion

Actionable by other stakeholders

Some recommendations are only actionable working with other agencies, institutions and stakeholders. **Institutions and agencies funded by or working in fields of FES should**

➔ engage **DEI experts to advise our community and develop assessment tools**

➔ **expand recruitment pools** and identify currently underrepresented areas

➔ adopt or update **Policies and Codes of Conduct** (e.g., for events) and **training**

➔ create an **accessible environment** for all members of our community

➔ In addition to direct FES action as indicated above, FES should work with institutions on **more uniform family leave policies** across institutions

➔ develop **flexible post-undergraduate** education options, facilitate employment of scientists and engineers with **BS/MS degrees** at FES facilities, and establish BS/MS development programs