Fusion Energy Sciences

Overview

The mission of the Fusion Energy Sciences (FES) program is to expand the fundamental understanding of matter at very high temperatures and densities and to build the scientific foundation needed to develop a fusion energy source. This is accomplished through the study of plasma, the fourth state of matter, and how it interacts with its surroundings.

Plasma science is wide-ranging, with various types of plasma comprising 99 percent of the visible universe. It is the state of matter in the Sun's center, corona, and solar flares. Plasma dynamics are at the heart of the formation of galactic jets and accretion of stellar material around black holes. On Earth it is the substance of lightning and flames. Plasma physics describes the processes giving rise to the northern and southern aurora. Practical applications of plasmas are found in lighting and semiconductor manufacturing. High-temperature fusion plasmas at hundreds of millions of degrees are being exploited in the laboratory to become the basis for a future clean energy source. Once developed, fusion energy will provide a clean energy source that is especially well-suited for baseload electricity production, supplementing intermittent renewables and fission. Energy from fusion will be carbon-free, inherently safe, without the production of long-lived radioactive waste, and relying on a virtually inexhaustible fuel supply that is available worldwide. Developing fusion energy is a large driver for the FES subprograms focused on the scientific study of "burning plasma." In the burning plasma state of matter, the nuclear fusion process provides the dominant heat source for sustaining the plasma temperature. Such a self-heated plasma can continue to undergo fusion reactions that produce energy without requiring the input of heating power from the outside, thus resulting in a large net energy yield.

In the FES program, foundational science for burning plasmas is obtained by investigating the behavior of laboratory fusion plasmas confined with strong magnetic fields. The DIII-D National Fusion Facility and the National Spherical Torus Experiment-Upgrade (NSTX-U), the latter of which is currently down for recovery and repair, are world-leading Office of Science (SC) user facilities for experimental research, available to and used by scientists from national laboratories, universities, and industry research groups. Complementing these experimental activities is a significant effort in fusion theory and simulation to predict and interpret the complex behavior of plasmas as self-organized systems. As part of this effort, FES supports several Scientific Discovery through Advanced Computing (SciDAC) centers, in partnership with the Advanced Scientific Computing Research (ASCR) program. U.S. scientists take advantage of international partnerships to conduct research on overseas tokamaks and stellarators with unique capabilities. In addition, the development of novel materials is especially important for fusion energy sciences since fusion plasmas create an environment of high-energy neutrons and huge heat fluxes that impinge on and damage the material structures containing the plasmas. The frontier scientific area of the creation of strongly self-heated fusion burning plasmas, to be enabled by the ITER facility, will allow the discovery and study of new scientific phenomena relevant to fusion as a future clean energy source. At the same time, partnerships with the emerging fusion private sector can shorten the time for developing fusion energy by combining forces to resolve common scientific and technological challenges.

The FES program also supports discovery plasma science in research areas such as plasma astrophysics, high-energy-density laboratory plasmas (HEDLP), and low-temperature plasmas. Some of this research is carried out through partnerships with the National Science Foundation (NSF) and the National Nuclear Security Administration (NNSA). Also, U.S. scientists are world leaders in the invention and development of new high-resolution plasma measurement techniques. Advances in plasma science have led to many spinoff applications and enabling technologies with considerable economic and societal impact, including applications that are relevant to multiple clean energy sources.

The FES program invests in several SC cross-cutting transformational technologies such as artificial intelligence and machine learning (AI/ML), quantum information science (QIS), microelectronics, advanced manufacturing, and high-performance computing. Finally, the unique scientific challenges and rigor of fusion and plasma physics research lead to the development of a well-trained STEM workforce, guided by the principles of diversity, equity, and inclusion.

Decisions about the direction of the FES program and its activities are driven by science. They are informed by reports from the National Academies of Sciences, Engineering, and Medicine (NASEM), the Fusion Energy Sciences Advisory Committee

(FESAC), and community workshops. Specific projects are selected through rigorous peer review and the application of validated standards.

Highlights of the FY 2022 Request

The FY 2022 Request is $675.0 million. The Request is aligned with the recommendations in the recent FESAC Long-Range Plan.[a] Priorities include keeping SC fusion user facilities world-leading, building a new research portfolio of high-performance computing fusion applications, continuing to explore the potential of QIS and AI/ML, supporting high-impact research in fusion nuclear science and materials, maintaining partnerships for access to international facilities with unique capabilities, continuing stewardship of discovery plasma science, continuing to seek opportunities with public-private partnerships, initiating an ITER Research program, and supporting studies of future facilities. Key elements in the FY 2022 Request include:

<u>Research</u>

- DIII-D research: Investigate the role of divertor geometry, optimize plasma performance using non-axisymmetric magnetic fields and plasma shaping, and exploit innovative current drive systems.
- NSTX-U research: Support focused efforts on plasma startup and initial machine commissioning and collaborative research at other facilities for addressing program priorities.
- Partnerships with private fusion efforts: Continue to expand public-private partnerships in critical fusion research areas through the Innovation Network for Fusion Energy (INFUSE) program.
- Enabling technology, fusion nuclear science, and materials: Support research on high-temperature superconductors, advanced materials, and blanket/fuel cycle research. Continue exploring options for a neutron source to test materials in fusion-relevant environments and support the Accelerator Science and Technology and Fundamental Science to Transform Manufacturing initiatives.
- Scientific Discovery through Advanced Computing: A new portfolio of SciDAC projects will continue development of an integrated simulation capability expanding it from whole-device to whole-facility modeling, in partnership with the ASCR program.
- Long-pulse tokamak and stellarator research: Enable U.S. scientists to work on superconducting tokamaks with world-leading capabilities and allow U.S. teams to exploit U.S. hardware investments on the Wendelstein 7-X stellarator.
- Discovery plasma science: Continue support for small- and intermediate-scale basic plasma science and HEDLP facilities including LaserNetUS, and microelectronics research.
- QIS: In support of the National Quantum Initiative, the Request continues support for the SC QIS Research Centers established in FY 2020 along with a core research portfolio to advance developments in QIS and related technology.
- ITER research: Support a national team for ITER research to ensure the U.S. fusion community takes full advantage of ITER research operations after First Plasma.
- Future Facilities Studies: Initiate a program in future facilities studies to address one of the highest-priority recommendations in the FESAC Long-Range Plan for the design of a Fusion Pilot Plant (FPP).
- Reaching a New Energy Sciences Workforce (RENEW): The Office of Science is fully committed to advancing a diverse, equitable, and inclusive research community. This commitment is key to providing the scientific and technical expertise for U.S. leadership in fusion energy sciences. Toward that goal, FES will participate in the SC-wide RENEW initiative that leverages SC's world-unique national laboratories, user facilities, and other research infrastructures to provide undergraduate and graduate training opportunities for students and academic institutions not currently well represented in the U.S. S&T ecosystem. This includes Minority Serving Institutions and individuals from groups historically underrepresented in STEM, but also includes students from communities with environmental justice impacts and the EPSCoR jurisdictions. The hands-on experiences gained through the RENEW initiative will open new career avenues for the participants, forming a nucleus for a future pool of talented young scientists, engineers, and technicians with the critical skills and expertise needed for the full breadth of SC research activities, including DOE national laboratory staffing.

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[a] https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf

Facility Operations

- DIII-D operations: Support 20 weeks of facility operations, representing 90% of the optimal run time, and completion of ongoing machine and infrastructure refurbishments and improvements.
- NSTX-U recovery and operations: Continue the recovery and repair project, whose completion date may slip beyond FY 2022 due to COVID-19 related schedule delays. NSTX-U Operations will support the remaining machine assembly and hardware commissioning.

Projects

- U.S. hardware development and delivery to ITER: Support the continued design and fabrication of the highest-priority in-kind hardware systems. This includes continued fabrication of the Central Solenoid magnet system, which consists of seven superconducting modules, structural components, and assembly tooling.
- Petawatt laser facility upgrade for HEDLP science: Support design activities for a significant upgrade to the Matter in Extreme Conditions (MEC) instrument on the Linac Coherent Light Source-II (LCLS-II) facility at SLAC.
- Major Item of Equipment (MIE) project for fusion materials research: Continue to support the Materials Plasma Exposure eXperiment (MPEX) MIE project with efforts focused on highest-priority items, including the establishment of the project baseline and continuation of long-lead procurements.

Other

- General Plant Projects/General Purpose Equipment (GPP/GPE): Support Princeton Plasma Physics Laboratory (PPPL) and Oak Ridge National Laboratory (ORNL) infrastructure improvements and repairs.

Fusion Energy Sciences
Research Initiatives

Fusion Energy Sciences supports the following FY 2022 Research Initiatives.

(dollars in thousands)

	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Accelerator Science and Technology Initiative	–	–	3,073	+3,073
Artificial Intelligence and Machine Learning	7,000	7,000	7,000	–
Fundamental Science to Transform Advanced Manufacturing	–	–	3,000	+3,000
Integrated Computational & Data Infrastructure	–	–	4,037	+4,037
Microelectronics	–	5,000	5,000	–
Quantum Information Science	7,520	9,520	10,000	+480
Reaching a New Energy Sciences Workforce (RENEW)	–	–	3,000	+3,000
Total, Research Initiatives	**14,520**	**21,520**	**35,110**	**+13,590**

Fusion Energy Sciences
Funding

(dollars in thousands)

	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Fusion Energy Sciences				
Advanced Tokamak	123,500	127,038	124,390	-2,648
Spherical Tokamak	101,000	104,331	101,000	-3,331
Theory & Simulation	44,000	42,000	53,037	+11,037
GPP/GPE Infrastructure	7,000	2,640	1,500	-1,140
Public-Private Partnerships	4,000	5,000	6,000	+1,000
Artificial Intelligence and Machine Learning	–	7,000	7,000	–
Strategic Accelerator Technology	–	–	3,073	+3,073
Total, Burning Plasma Science: Foundations	**279,500**	**288,009**	**296,000**	**+7,991**
Long Pulse: Tokamak	14,000	15,000	15,000	–
Long Pulse: Stellarators	8,500	8,500	8,500	–
Materials & Fusion Nuclear Science	47,500	49,000	59,500	+10,500
Future Facilities Studies	–	–	3,000	+3,000
Total, Burning Plasma Science: Long Pulse	**70,000**	**72,500**	**86,000**	**+13,500**
ITER	–	–	2,000	+2,000
Total, Burning Plasma Science: High Power	**–**	**–**	**2,000**	**+2,000**
Plasma Science and Technology	42,500	32,700	40,000	+7,300
Measurement Innovation	3,000	3,000	3,000	–
Quantum Information Science (QIS)	–	9,520	10,000	+480
Advanced Microelectronics	–	5,000	5,000	–
Other FES Research	4,915	4,271	4,000	-271
Reaching a New Energy Sciences Workforce	–	–	3,000	+3,000
FES SBIR/STTR	14,085	–	–	–
Total, Discovery Plasma Science	**64,500**	**54,491**	**65,000**	**+10,509**
Subtotal, Fusion Energy Sciences	**414,000**	**415,000**	**449,000**	**+34,000**

(dollars in thousands)

	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Construction				
20-SC-61, Matter in Extreme Conditions (MEC) Petawatt Upgrade, SLAC	15,000	15,000	5,000	-10,000
14-SC-60, U.S. Contributions to ITER	242,000	242,000	221,000	-21,000
Subtotal, Construction	**257,000**	**257,000**	**226,000**	**-31,000**
Total, Fusion Energy Sciences	**671,000**	**672,000**	**675,000**	**+3,000**

SBIR/STTR funding:

- FY 2020 Enacted: SBIR $12,348,000 and STTR $1,737,000
- FY 2021 Enacted: SBIR $12,352,000 and STTR $1,740,000
- FY 2022 Request: SBIR $13,360,000 and STTR $1,885,000

Fusion Energy Sciences
Explanation of Major Changes

	(dollars in thousands) FY 2022 Request vs FY 2021 Enacted
Burning Plasma Science: Foundations The Request for DIII-D supports 20 weeks of research operations which is 90 percent of the optimal run time, as well as continued facility enhancements to ensure the world-leading status of the facility. Funding for the NSTX-U program will support the NSTX-U Recovery project and maintain collaborative research at other facilities to support NSTX-U research program priorities. SciDAC will maintain and expand its emphasis toward whole-facility modeling following a recompetition of the portfolio, and will continue to increase its readiness to capture the power of exascale computing. Enabling R&D will focus attention on high-temperature superconductor development. Funding is provided for GPP/GPE to support critical infrastructure improvements and repairs at PPPL and ORNL where fusion research is conducted. Public-private partnership collaborations through the INFUSE program will expand.	**+7,991**
Burning Plasma Science: Long Pulse The Request will continue to provide support for high-priority international collaboration activities, both for tokamaks and stellarators. Materials research and fusion nuclear science research programs are focused on high priorities, such as advanced plasma-facing and structural materials and blanket and fuel cycle research. The Request will also support new activities in relation to the Fundamental Science to Transform Manufacturing Initiative. The Request supports design and R&D activities for the MPEX MIE project, expected to be baselined in FY 2022, and initiates long-lead major procurements. The Request establishes a Future Facilities Studies program to address one of the highest recommendations in the FESAC Long-Range Plan (LRP) for the design of a Fusion Pilot Plant.	**+13,500**
Burning Plasma Science: High Power The Request establishes an ITER Research program to start preparing the U.S. fusion community to take full advantage of ITER Operations after First Plasma.	**+$2,000**

	(dollars in thousands) FY 2022 Request vs FY 2021 Enacted
Discovery Plasma Science For General Plasma Science, the Request emphasizes user research on collaborative research facilities at universities and national laboratories and participation in the NSF/DOE Partnership in Basic Plasma Science and Engineering. For High Energy Density Laboratory Plasmas (HEDLP), the focus remains on supporting research utilizing the MEC instrument of the LCLS user facility at SLAC and supporting research on the ten LaserNetUS network facilities. For QIS, the Request continues to support the crosscutting SC QIS Research Centers established in FY 2020 and the core research portfolio stewarded by FES. FES will continue to support the SC initiative on advanced microelectronics. This subprogram also supports the RENEW initiative to provide undergraduate and graduate training opportunities for students and academic institutions not currently well represented in the U.S. S&T ecosystem and aligns with a recommendation in the FESAC LRP.	**+10,509**
Construction FES will support design activities for a significant upgrade to the MEC instrument. The U.S. Contributions to ITER project will continue design, fabrication, and delivery of highest-priority First Plasma hardware, including the central solenoid superconducting magnet modules.	**-31,000**
Total, Fusion Energy Sciences	**+3,000**

Basic and Applied R&D Coordination
FES participates in coordinated intra- and inter-agency initiatives within DOE and with other federal agencies on science and technology issues related to fusion and plasma science. Within SC, FES operates the MEC instrument at the SLAC LCLS user facility operated by BES, supports high-performance computing research with ASCR, uses the BES-supported High Flux Isotope Reactor (HFIR) facility at ORNL for fusion materials irradiation research, and supports the construction of a high field magnet vertical test facility at Fermilab with HEP. Within DOE, FES operates a joint program with NNSA in HEDLP physics and, in FY 2020, conducted joint solicitations with the Advanced Research Projects Agency-Energy (ARPA-E). FESAC provides technical and programmatic advice to FES and NNSA for the joint HEDLP program. Outside DOE, FES carries out a discovery-driven plasma science research program in partnership with NSF. Research supported through this joint program extends to a wide range of natural phenomena, including the origin of magnetic fields in the universe and the nature of plasma turbulence. The joint programs with NNSA and NSF involve coordination of solicitations, peer reviews, and workshops.

Program Accomplishments
DIII-D expands the range of accessible stable plasma profiles in the tokamak.
Traditionally, tokamak experiments inject microwaves from outside the tokamak toward the core of the plasma to drive electrical currents in the plasma that are necessary for long-pulse or steady-state operation. Recent computer modeling at DIII-D predicted that moving the injection point toward the top of the tokamak and carefully directing it toward precise locations away from the core would dramatically improve efficiency. Based on that modeling, researchers at DIII-D designed and installed a new system with the top-launch configuration that aligns the microwave trajectory with both the magnetic field and the energy distribution of electrons in the plasma. This means the microwaves selectively interact with only the most energetic electrons in the plasma. This approach was experimentally demonstrated to be twice as efficient as that of traditional configurations, helping to bring practical fusion energy closer to reality.

Collaboration between sister spherical tokamaks accelerates plasma startup development.
Through collaborative research, physicists at the Princeton Plasma Physics Laboratory (PPPL) in the U.S. and the Culham Centre for Fusion Energy (CCFE) in the U.K., have developed a specialized simulation framework for developing and testing the plasma startup techniques for both the National Spherical Torus Experiment-Upgrade (NSTX-U) at PPPL and the Mega Ampere Spherical Tokamak-Upgrade (MAST-U) at CCFE. The new simulation capability first required extensive validation work through comparison of predictions with previously collected experimental data. With the validation work now complete, this capability will enable the experimental operators of both facilities to quickly determine the right balance of applied voltages, magnetic field, and gas injection needed to start the plasmas even before the first attempt, significantly reducing the amount of time spent running experiments to successfully fire up the plasma.

Scientists offer new explanation for pressure oscillations in fusion devices.
High-performance computer simulations performed at the National Energy Research Scientific Computing Center (NERSC) by scientists supported by the PPPL-led SciDAC Center for Tokamak Transients Simulations, have largely reproduced the periodic pressure oscillations seen in all tokamak fusion experiments. These oscillations, known as sawtooth oscillations and thought by many to be due to magnetic reconnection, have been shown to occur due to pressure-driven instabilities. When the central pressure increases to a critical value, many localized instabilities develop, leading the magnetic field in the center of the device to become stochastic. This causes the central pressure to drop and the magnetic surfaces to re-form, and the process repeats. A better understanding of the origin of these oscillations is essential for their effective control in order to prevent them potentially disrupting the discharge.

Machine Learning for image correlation to advance materials science.
Crystallographic defects play a vital role in determining the physical and mechanical properties of a wide range of material systems. Although computer vision has demonstrated success in recognizing feature patterns in images with well-defined contrast, automated identification of nanometer scale crystallographic defects in electron micrographs governed by complex contrast mechanisms is still a challenging task. Building upon an advanced defect imaging mode that offers high feature clarity, a team of researchers led by Pacific Northwest National Laboratory (PNNL) developed a new neural network architecture that can identify a number of crystallographic defects important in structural alloys. Results from supervised

training on a small set of high-quality images of steels show high accuracy, with predictions outperforming human experts, promising a new workflow for fast and statistically meaningful quantification of materials defects.

Quantum leap for fusion: First-ever quantum simulation of nonlinear plasma interactions.
The first-ever quantum simulation of nonlinear plasma dynamics was performed on the LLNL Quantum Design and Integration Testbed (QuDIT) quantum computing hardware platform. QuDIT was able to simulate multiple cycles of the dynamics of the three-wave equations of plasma physics with >10x more time steps than other state-of-the-art quantum computing platforms using a novel approach to the codesign of quantum hardware and software. These results provide a first demonstration of the ability of quantum computing hardware to perform useful plasma physics calculations. The new codesign approach represents an advancement for both quantum information science and for fusion energy science.

FES and HEP collaborate on high field vertical magnet test facility development.
Recent advances in high temperature superconductors (HTS) hold the potential for significant breakthroughs for magnet applications, and a world-class test facility is urgently needed by the U.S. community to identify, understand, and resolve technical hurdles associated with the application of HTS materials for high-field magnets, which are critical for future fusion facility development. FES partnered with the High Energy Physics (HEP) program in FY 2020 to jointly pursue the research and development of a novel high-field magnet, designed and fabricated by Lawrence Berkeley National Laboratory, and the installation of this magnet at Fermi National Accelerator Laboratory for usage as a High Field Vertical Magnet Test Facility. The purpose of the new facility is to support research interests, and leverage resources, of both HEP and FES to further science and technology related to high-field magnets and their usage for DOE.

First demonstration of power-law electron energy distribution in 3D magnetic reconnection.
Scientists at the Los Alamos National Laboratory have demonstrated for the first time the formation process of power-law electron energy distribution during 3D magnetic reconnection. The new sophisticated analysis capabilities enabled researchers to identity the self-generated turbulence and chaotic magnetic field lines produced by micro-instabilities associated with 3D magnetic reconnection. The 3D effects allow the high-energy electrons to transport themselves across the reconnection layer and access many main acceleration regions. A new model was developed to explain the observed power-law behavior in terms of the dynamical balance between particle acceleration and escape from the acceleration regions. This finding could provide an explanation for particle acceleration in solar flares and could also contribute to a deeper understanding of how the accelerated electron population interacts with the background turbulent plasma, a physical regime found also in laboratory fusion plasmas.

An international collaboration on the JET facility provides an important test for ITER.
The U.S., through a multilateral international collaboration with the European Union, the U.K., and the ITER Organization, successfully installed, commissioned, and operated a tokamak disruption mitigation system (DMS) on the Joint European Torus (JET), located at the Culham Centre for Fusion Energy in the U.K. Because JET is currently the largest tokamak in the world and has walls like those designed for ITER, this is providing an important test of the planned system for the ITER facility. The DMS is designed to minimize the effects of transient thermal excursions, mechanical forces, and runaway electrons that may result when the plasma current in a tokamak is interrupted abruptly. The planned system is a shattered pellet injector (SPI), originally developed by the Oak Ridge National Laboratory and successfully deployed on the DIII-D tokamak in San Diego and the Korea Superconducting Tokamak Advanced Research (KSTAR) facility in Korea. The SPI test results on JET are expanding the database needed to improve the physics understanding of disruption mitigation, validate the DMS simulation codes, and ready the SPI technology for operation on ITER.

Shock waves mimic supernova particle accelerators.
When stars explode as supernovas, shock waves are produced in the plasma that surrounds them. These shocks blast streams of high-energy particles, called cosmic rays, out into the universe at relativistic speeds approaching the speed of light. Yet how exactly they do that remains a mystery. New experiments using powerful lasers have recreated a miniature version of these supernova shocks in the laboratory. Scientists discovered that small-scale turbulence produced at the shock is key to boosting electrons to these incredible speeds. The results shed new light on the long-standing question of how cosmic accelerators work. Understanding the fundamental science of the cosmic acceleration could pave the way to better particle accelerators on Earth for applications in science, industry, and medicine.

Progress continues on high priority components for ITER.

The U.S. Contributions to ITER project successfully delivered twelve Central Solenoid structural components and Assembly Tooling to the ITER site in France. The structural components and Assembly Tooling are needed for the installation and assembly of the Central Solenoid magnet modules in the center of the ITER tokamak. Design of hardware components needed to achieve First Plasma is progressing with the project team completing six Final Design Reviews (FDR) for various systems. This is a significant achievement since several of the FDR's were accomplished virtually, due to COVID-19 restrictions. Work on the high-priority Central Solenoid modules and Tokamak Cooling Water System continued to make significant progress, with the final preparations being made to ship the first magnet module to the ITER site in early FY 2021. The ITER project is expected to demonstrate the viability of fusion as a significant energy source and will help inform the ongoing and increasingly aggressive efforts to develop demonstration power plants in the U.S. and around the globe.

Fusion Energy Sciences
Burning Plasma Science: Foundations

Description

Burning Plasma Science: Foundations subprogram advances the predictive understanding of plasma confinement, dynamics, and interactions with surrounding materials.

Among the activities supported by this subprogram are:

- Research at major experimental user facilities aimed at resolving fundamental advanced tokamak and spherical tokamak science issues.
- Research on small-scale magnetic confinement experiments for rapid and cost-effective development of new techniques and exploration of new concepts underlying toroidal confinement.
- Theoretical work on the fundamental description of magnetically confined plasmas and the development of advanced simulation codes on current and emerging high-performance computers.
- Research on technologies needed to support continued improvement and capabilities of the experimental program and current and future facilities.
- Support of the Accelerator Science and Technology initiative to advance research and development of high-temperature superconducting (HTS) magnets for future fusion facilities.
- Support for infrastructure improvements at Princeton Plasma Physics Laboratory (PPPL) and other DOE laboratories where fusion research is ongoing.
- Research on artificial intelligence and machine learning (AI/ML) relevant to fusion and plasma science.
- Support for public-private partnerships through the Innovation Network for Fusion Energy (INFUSE) activity.

Research in the Burning Plasma Science: Foundations area in FY 2022 will focus on high-priority scientific issues in alignment with the recommendations in the recent FESAC Long-Range Plan.

<u>Advanced Tokamak</u>

The DIII-D user facility at General Atomics in San Diego, California, is the largest magnetic fusion research experiment in the U.S. It can magnetically confine plasmas at temperatures relevant to burning plasma conditions. Its extensive set of advanced diagnostic systems and extraordinary flexibility to explore various operating regimes make it a world-leading tokamak research facility. Researchers from the U.S. and abroad perform experiments on DIII-D for studying stability, confinement, and other properties of fusion-grade plasmas under a wide variety of conditions. The DIII-D research goal is to establish the broad scientific basis to optimize the tokamak approach to magnetic confinement fusion. Much of this research concentrates on developing the advanced tokamak concept, in which active control techniques are used to manipulate and optimize the plasma to obtain conditions scalable to robust operating points and high fusion gain for future energy-producing fusion reactors.

The Enabling Research and Development (R&D) element develops the technology to enhance the capabilities for existing and next-generation fusion research facilities, enabling these facilities to achieve higher levels of performance and flexibility needed to explore new science regimes.

Small-scale advanced tokamak research is complementary to the efforts at the major user facilities, providing rapid and cost-effective development of new techniques and exploration of new concepts. These activities are often the first step in a multi-stage approach toward the extension of the scientific basis for advanced tokamaks. Recent efforts are focused on improving fusion plasma control physics for advanced tokamaks through application of modern digital tokamak control theory and validation of fundamental plasma stability theory.

<u>Spherical Tokamak</u>

The NSTX-U user facility at PPPL is designed to explore the physics of plasmas confined in a spherical tokamak (ST) configuration, characterized by a compact (apple-like) shape. If the predicted ST energy confinement improvements are experimentally realized in NSTX-U, then the ST might provide a more compact fusion reactor than other plasma confinement geometries. In FY 2022, NSTX-U recovery activities will continue. This recovery effort will ensure reliable plasma operations of the facility.

Small-scale ST plasma research involves focused experiments to provide data in regimes of relevance to the ST magnetic confinement program. These efforts can help confirm theoretical models and simulation codes in support of the FES goal to develop an experimentally validated predictive capability for magnetically confined fusion plasmas. This activity also involves high-risk, but high-payoff, experimental efforts useful to advancing ST science.

Theory & Simulation

The Theory and Simulation activity is a key component of the FES program's strategy to develop the predictive capability needed for a sustainable fusion energy source. Its long-term goal is to enable a transformation in predictive power based on fundamental science and high-performance computing to minimize risk in future development steps and shorten the path toward the realization of fusion energy. This activity includes three interrelated but distinct elements: Theory, SciDAC, and Integrated Computational & Data Infrastructure for Fusion.

The Theory element is focused on advancing the scientific understanding of the fundamental physical processes governing the behavior of magnetically confined plasmas. The research ranges from foundational analytic theory to mid- and large-scale computational work with the use of high-performance computing resources. In addition to its scientific discovery mission, the Theory element provides the scientific grounding for the physics models implemented in the advanced simulation codes developed under the SciDAC activity described below and also supports validation efforts at major experiments.

The FES SciDAC element, a component of the SC-wide SciDAC program, is aimed at accelerating scientific discovery in fusion plasma science by capitalizing on SC investments in leadership-class computing systems and associated advances in computational science. The portfolio that emerged from the FY 2017 SC-wide SciDAC-4 re-competition and follow-up targeted reviews in FY 2018 consists of nine multi-institutional interdisciplinary partnerships, seven of which are jointly supported by FES and ASCR, and addresses the high-priority research directions identified in community workshops. The current portfolio emphasizes increased integration and whole-device modeling, as well as synergy with the fusion-relevant projects of the SC Exascale Computing Project (SC-ECP) to increase the readiness of the fusion community for the upcoming Exascale era.

The Integrated Computational & Data Infrastructure for Fusion element supports efforts that address the growing data needs of fusion research resulting both from experimental and large-scale simulation efforts. This program element is part of the SC crosscutting initiative in this area.

GPP-GPE Infrastructure

This activity supports critical general infrastructure (e.g., utilities, roofs, roads, facilities, environmental monitoring, and equipment) at the PPPL site and other DOE laboratories where fusion research is ongoing.

Public-Private Partnerships

The Innovation Network for Fusion Energy (INFUSE) program provides private-sector fusion companies with access to the expertise and facilities of DOE's national laboratories to overcome critical scientific and technological hurdles in pursuing development of fusion energy systems. Established in FY 2019, this public-private research partnership program, the first of its kind in SC, is modeled after the successful DOE's Office of Nuclear Energy Gateway for Accelerated Innovation in Nuclear (GAIN) Energy Voucher program. The INFUSE program does not provide direct funding to the private companies, but instead provides support to DOE laboratories to enable them to collaborate with their industrial partners. The private companies are expected to contribute 20 percent cost share. Among the areas supported by INFUSE are the development of new and improved magnets; materials science, including engineered materials, testing and qualification; plasma diagnostic development; modeling and simulation; and access to fusion experimental capabilities. The program is managed for FES by two SC laboratories, ORNL and PPPL, which solicit and collect the Request for Assistance (RFA) proposals and carry out the merit reviews.

Artificial Intelligence and Machine Learning

The objective of the FES Artificial Intelligence and Machine Learning (AI/ML) activity is to support research on the development and application of AI/ML techniques that can have a transformative impact on FES mission areas. Research in this area addresses recommendations from the 2018 FESAC report on “Transformative Enabling Capabilities for Efficient Advance toward Fusion Energy,”[a] is informed by the findings of the joint 2019 FES-ASCR workshop on “Advancing Fusion with Machine Learning,”[b] and is often conducted in partnership with computational scientists through the establishment of multi-institutional, interdisciplinary collaborations.

Among the areas supported by the FES AI/ML activity are prediction of key plasma phenomena and plant states; plasma optimization and active plasma control augmented by AI/ML; plasma diagnostics enhanced by AI/ML methods; extraction of models from experimental and simulation data; and extreme data algorithms able to handle the amount and rate of data generated by fusion simulations and experiments at both existing and planned fusion user facilities. Supported activities encompass multiple FES areas, including magnetic fusion, materials science, and discovery plasma science.

Strategic Accelerator Technology

The objective of this initiative is to leverage expertise across SC to maximize research and development progress in high-temperature superconducting magnets for future fusion facilities. One area supported by FES, in collaboration with High Energy Physics (HEP), is the High Field Vertical Magnet Test Facility Project at Fermi National Laboratory, which will be utilized to test HTS magnet conductor for future fusion facilities.

[a] https://science.osti.gov/-/media/fes/fesac/pdf/2018/TEC_Report_15Feb2018.pdf
[b] https://science.osti.gov/-/media/fes/pdf/workshop-reports/FES_ASCR_Machine_Learning_Report.pdf

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Burning Plasma Science: Foundations	**$288,009**	**$296,000**	**+$7,991**
Advanced Tokamak	$127,038	$124,390	-$2,648
Funding supports 18 weeks of operations at the DIII-D facility. Research will utilize newly installed capabilities including innovative current drive systems, tungsten tiles to study the transport of metal impurities, and new diagnostics to study pedestal and power exhaust physics. A new helium liquifier system will be installed and operated to improve availability of the facility. Specific research goals will aim at assessing the reactor potential of current-drive systems to inform the design of next-step devices, integrating core and edge plasma solutions that extrapolate to future fusion reactors, and advancing the understanding of power exhaust strategies. Funding supports research in enabling technologies, including high-temperature superconducting magnet technology and plasma fueling and heating technologies. Funding supports small-scale university-led experiments to develop new optical-based tokamak control schemes, measure boundary and wall current dynamics during plasma disruptions, and refine scrape-off layer current control methods.		The Request will support 20 weeks of operations at the DIII-D facility, which is 90% of optimal. Research will utilize newly installed capabilities including innovative current drive systems to assess their potential as actuators for a pilot plant. Divertor configurations will be studied to understand the role of divertor geometry on power exhaust strategies. New flexible power supplies will be used to optimize performance using non-axisymmetric magnetic fields and plasma shaping. The Request will support continuing research in high-temperature superconducting magnet technology, plasma fueling, heating, and other fusion enabling technologies. The Request will continue support for flexible small-scale experiments developing advanced tokamak control schemes, validating predictive plasma models, and training early career scientists.	Funding will support high-priority DIII-D research activities, enabling research and development, and small-scale experiments, and provide resources for increased DIII-D facility operations, while support for facility enhancements is reduced.

(dollars in thousands)

FY 2021 Enacted	FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Spherical Tokamak $104,331	$101,000	-$3,331
Funding supports recovery procurements, fabrication, and machine reassembly activities that are necessary to resume robust research operations. Research efforts are focused on analysis and modeling activities at other facilities that support NSTX-U program priorities. Funding also supports studies and experiments focused on exploring operational scenarios without a central solenoid, model validation, and detailed core turbulent transport mechanisms observed in plasmas with low recycling liquid lithium walls.	The Request for operations funding will continue to support recovery procurements, fabrication, and machine reassembly activities that are necessary to resume robust research operations. Research efforts will focus on analysis and modeling activities at other facilities that support NSTX-U program priorities, as well as the development and installation of additional diagnostic instrumentation on NSTX-U. The Request will continue to support small-scale ST studies and experiments focused on exploring operational scenarios without a central solenoid, model validation, and detailed core turbulent transport mechanisms observed in plasmas with low recycling liquid lithium walls.	Operations funding will support the continuation of NSTX-U Recovery activities at a reduced level as the Recovery nears completion. Research funding will be focused on the highest-priority scientific objectives that are aligned with the FESAC Long-Range Plan.
Theory & Simulation $42,000	$53,037	+$11,037
Funding supports theory and modeling efforts focusing on advancing the scientific understanding of the fundamental physical processes governing the behavior of magnetically confined plasmas. This activity emphasizes research that addresses critical burning plasma challenges, including plasma disruptions, runaway electrons, three-dimensional and non-axisymmetric effects, and the physics of the plasma boundary. In addition, funding supports the nine SciDAC partnerships, now in their fifth and final year. Emphasis on whole-device modeling and Exascale readiness continues.	The Request will continue to support theory and modeling efforts focusing on advancing the scientific understanding of the fundamental physical processes governing the behavior of magnetically confined plasmas. The Request will support a new SciDAC portfolio from the SC-wide SciDAC-5 recompetition in FY 2022. Emphasis on whole-device modeling and exascale readiness will continue, but will expand to include domains outside the plasma and first wall, as a first step toward whole-facility modeling. The Request will also support Integrated Computational & Data Infrastructure for fusion research activities.	Research efforts in theory will focus on the highest-priority activities. The increase will enhance the SciDAC portfolio to expand toward whole-facility modeling and will support the Integrated Computational & Data Infrastructure activity.

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
GPP-GPE Infrastructure	$2,640	$1,500	-$1,140
Funding supports PPPL as well as other DOE laboratories infrastructure improvements, repair, maintenance and environmental monitoring.		The Request will support PPPL as well as other DOE laboratories infrastructure improvements, repair, maintenance, and environmental monitoring.	Funding efforts will focus on the highest-priority activities.
Public-Private Partnerships	$5,000	$6,000	+$1,000
Funding enables the INFUSE program to provide funding opportunities for partnerships with the private-sector through DOE laboratories at a level consistent with FY 2020. This includes two Request for Assistance calls and an estimated 20 awards.		The Request will support the INFUSE program to continue providing private-sector entities collaborative opportunities through its voucher program.	The increase will allow for further expansion of the INFUSE collaborative voucher program. This will include the possibility of adding universities to the INFUSE network, which is being explored.
Artificial Intelligence and Machine Learning	$7,000	$7,000	$ —
Funding supports five multi-institutional teams applying artificial intelligence and machine learning to high-priority areas including real-time plasma behavior prediction, materials modeling, plasma equilibrium reconstruction, radio frequency modeling, and optimization of experiments using high-repetition-rate lasers.		The Request will support the third and final year of the FES AI/ML research efforts selected in FY 2020.	Research activities will continue at the same level of effort.
Strategic Accelerator Technology	$ —	$3,073	+$3,073
N/A		The request will support the Accelerator Science and Technology initiative to develop high-temperature superconducting magnets for future fusion facilities. Additionally, the request will support the High Field Vertical Magnet Test Facility Project.	Funding will support the SC initiative.

Note: Funding for the subprogram above, includes 3.65% of research and development (R&D) funding for the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs.

Fusion Energy Sciences
Burning Plasma Science: Long Pulse

Description
The Burning Plasma Science: Long Pulse subprogram explores new and unique scientific regimes that can be achieved primarily with long-duration superconducting international machines, and addresses the development of the materials and technologies required to withstand and sustain a burning plasma. The key objectives of this area are to utilize these new capabilities to accelerate our scientific understanding of how to control and operate a burning plasma, as well as to develop the basis for a future nuclear device. This subprogram includes long-pulse international tokamak and stellarator research, and fusion nuclear science, materials research, and future facilities studies.

Long Pulse: Tokamak
This activity supports interdisciplinary teams from multiple U.S. institutions for collaborative research aimed at advancing the scientific and technology basis for sustained long-pulse burning plasma operation in tokamaks. Bilateral research on international facilities with capabilities not available in the U.S. aims at building the science and technology required to confine and sustain a burning plasma as described in the 2020 FESAC Long-Range Plan.[a] Multidisciplinary teams work together to close key gaps in the design basis for a fusion pilot plant, especially in the areas of plasma-material interactions, transients control, and current drive for steady-state operation. Research on overseas superconducting tokamaks, conducted onsite and also via fully remote facility operation, leverages progress made in domestic experimental facilities and provides access to model validation platforms for mission critical applications supported through the FES/ASCR partnership within the SciDAC portfolio. Efforts are augmented by research on non-superconducting tokamaks with access to burning plasma scenarios and mature diagnostic suites.

Long Pulse: Stellarators
This activity supports research on stellarators, which offer the promise of steady-state confinement regimes without transient events such as harmful disruptions. The three-dimensional (3D) shaping of the plasma in a stellarator provides for a broader range in design flexibility than is achievable in a 2D system. The participation of U.S. researchers on the Wendelstein 7-X (W7-X) in Germany provides an opportunity to develop and assess 3D divertor configurations for long-pulse, high-performance stellarators, including the provision of a pellet fueling injector for quasi-steady-state plasma experiments. The U.S. is developing control schemes to maintain plasmas with stable operational boundaries, including the challenges of control with superconducting coils and issues of the diagnosis-control cycle in long-pulse conditions. U.S. researchers will play key roles in developing the operational scenarios and hardware configuration for high-power, steady-state operation, an accomplishment that will advance the performance/pulse length frontier for fusion. The strong U.S. contributions during the W7-X construction phase have earned the U.S. formal partnership status. Accordingly, the U.S. is participating fully in W7-X research and access to data.

U.S. domestic compact stellarator research is focused on improvement of the stellarator magnetic confinement concept through quasi-symmetric shaping of the toroidal magnetic field, which was invented in the U.S. According to the 2020 FESAC Long-Range Plan, the quasi-symmetric stellarator is the leading U.S. approach to develop disruption-free, low-recirculating-power fusion configurations.

Materials & Fusion Nuclear Science
The Materials and Fusion Nuclear Science activity seeks to address the significant scientific and technical gaps between current-generation fusion experiments and a future Fusion Pilot Plant (FPP), as recommended by the 2020 FESAC Long-Range Plan. 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. The goal of the Materials subactivity is to develop a scientific understanding of how the properties of materials evolve and degrade due to fusion neutron and plasma exposure to safely predict the behavior of materials in fusion reactors. Before an FPP is constructed, materials and components must be qualified and a system design must ensure the compatibility of all components. The goal of the Fusion Nuclear Science subactivity is to advance the balance-of-plant equipment, remote handling, tritium breeding, and safety systems that are required to safely harness fusion power in an

[a] https://usfusionandplasmas.org/

FPP. The new SC initiative on Fundamental Science to Transform Manufacturing, which has implications for both the Materials and Fusion Nuclear Science subactivities, is also part of this activity.

Developing solutions for this scientifically challenging area requires innovative types of research along with new experimental capabilities. In the near term, this includes the Material Plasma Exposure eXperiment (MPEX) Major Item of Equipment (MIE) project, which will enable solutions for new plasma-facing materials, and the Fusion Prototypic Neutron Source (FPNS), which will provide unique material irradiation capabilities for understanding materials degradation in the fusion nuclear environment. In the longer term, capabilities like the Blanket Component Test Facility will be needed to provide the scientific understanding and basis to qualify fusion blankets. These experimental capabilities will lead to an increased understanding of materials and of component and system performance in support of an FPP.

Future Facilities Studies

The Future Facilities Studies activity seeks to identify approaches for an integrated fusion plant design, like an FPP, as recommended by the 2020 FESAC Long-Range Plan.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Burning Plasma Science: Long Pulse	**$72,500**	**$86,000**	**+$13,500**
Long Pulse: Tokamak	$15,000	$15,000	$ —
Funding supports U.S. teams to develop prediction, avoidance, and mitigation strategies for potentially damaging transient events in large tokamaks, validate computational tools for integrated simulation of burning plasmas, and assess the potential of solid metal walls as the main plasma-facing material in long-pulse tokamak facilities.		The Request will support multidisciplinary U.S. teams, as identified through competitive solicitation, to conduct research on international facilities with unique capabilities. Ongoing diagnostic contributions to the JT-60SA facility in Japan will continue.	Research efforts will emphasize the highest-priority topics while leveraging unique capabilities on long-pulse superconducting tokamaks.
Long Pulse: Stellarators	$8,500	$8,500	$ —
Funding supports research on W7-X to further the understanding of core and edge transport optimization for stellarators by utilizing U.S. developed state-of-the-art diagnostics and components. Funding also supports experiments on domestic stellarators in regimes relevant to the mainline stellarator magnetic confinement efforts and help confirm theoretical models and simulation codes to support the development of an experimentally-validated predictive capability for magnetically-confined fusion plasmas.		The Request will support U.S. scientists to utilize the continuous pellet fueling system, which will be installed on W7-X, to understand optimum profiles for turbulence suppression. This U.S.-built system, which is critical for long-pulse operation, will help address a number of scientific issues involved with quasi-steady-state operation for the stellarator configuration. The Request will also support research on compact domestic experimental devices that are providing data in regimes relevant to mainline stellarator confinement and experimental validation of theoretical models and codes.	Funding will continue to support research activities at the same level of effort.

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Materials & Fusion Nuclear Science	$49,000	$59,500	+$10,500
Funding supports the core research areas of tritium fuel cycle, breeder blanket technologies, safety, plasma-facing components, and structural and functional materials development, as well as the MPEX MIE project. The research program continues expanding efforts into the areas of novel fusion blanket and tritium fuel cycle research, innovative plasma facing component, novel materials, and advanced manufacturing. In addition, funding continues to support the MPEX MIE project.		The Request will enable expansion of the program, with a focus on critical enabling technologies for an FPP, as recommended by the 2020 FESAC Long-Range Plan. This includes plasma-facing components, structural and functional materials, and breeding-blanket and tritium-handling systems. The Request will also support an expansion of research into additive manufacturing technology, consistent with the new SC initiative. Finally, the request will continue to support the MPEX MIE project, with efforts focused on initiating construction following the combined baselining and approval of construction in FY 2022.	The Request is aimed at enhancing the materials and fusion nuclear science program, consistent with the FESAC Long-Range Plan, which considers this area in need of being strengthened in the fusion mission portfolio. Priority in the materials subactivity will be given to developing key materials required to enable an FPP, as well as increased emphasis on foundational fusion materials. Priority in the fusion nuclear science subactivity will be given to expanding the blanket and tritium fuel cycle research program.
Future Facilities Studies	$ —	$3,000	+$3,000
N/A		The Request will support the Future Facilities Studies activity, which seeks to identify methods for an integrated fusion plant design, as recommended by the FESAC Long-Range Plan.	Funding will support the Future Facilities Studies.

Note: Funding for the subprogram above, includes 3.65% of research and development (R&D) funding for the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs.

Fusion Energy Sciences
Burning Plasma Science: High Power

Description

The Burning Plasma Science: High Power subprogram supports research on experimental facilities that can produce large amounts of fusion power and maintain self-heated plasmas for hundreds of seconds, allowing scientists to study the burning plasma state. In a burning or self-heated plasma, at least half of the power needed to maintain the plasma at thermonuclear temperatures is provided by heating sources within the plasma. For the most common deuterium-tritium (D-T) fuel cycle, this internal heating source is provided by the energy of the helium nuclei (alpha particles) which are produced by the D-T reaction itself. A common figure of merit characterizing the proximity of a plasma to burning plasma conditions is the fusion gain or “Q”, which is defined as the ratio of the fusion power produced by the plasma to the heating power injected into the plasma that is necessary to bring it, and keep it, at thermonuclear temperatures. No existing or past experiment has reached this regime or even produced more fusion power than it consumed, with the current record of Q=0.67 held by the Joint European Torus in 1997.

ITER will be the world’s first burning plasma experiment that is expected to produce 500 MW of fusion power for pulses of 400 seconds, attaining a fusion gain Q of 10. It is a seven-Member international collaborative project to design, build, operate, and decommission a first-of-a-kind international fusion research facility in St. Paul-lez-Durance, France, aimed at demonstrating the scientific and technological feasibility of fusion energy. In addition to the U.S., the six other ITER Members are China, the European Union, India, Japan, South Korea, and Russia. More information about the U.S. Contributions to the ITER project is provided in the FES Construction section.

<u>ITER Research</u>

Presently, ITER is expected to achieve the First Plasma milestone in December 2025, however, because of COVID-19 impacts, this date will most likely be delayed. During the construction of ITER, U.S. contributes ~9 percent and gets 100 percent of the intellectual discovery during ITER research operations. To ensure the U.S. fusion community takes full advantage of ITER research operations after first plasma, it is necessary to organize a U.S. ITER research team to be ready on day one to benefit from the scientific and technological opportunities offered by ITER. Building such a team was also among the highest recommendations in the recent Long-Range Plan developed by FESAC.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Burning Plasma Science: High Power	**$ —**	**$2,000**	**+$2,000**
ITER Research	$ —	$2,000	+$2,000
N/A		The Request will initiate support of a national team for ITER research, to ensure the U.S. fusion community takes full advantage of ITER research operations after achievement of First Plasma.	The FY 2022 funding will support establishing an ITER research team.

Note: Funding for the subprogram above, includes 3.65% of research and development (R&D) funding for the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs.

Fusion Energy Sciences
Discovery Plasma Science

Description
Discovery Plasma Science subprogram supports research that explores the fundamental properties and complex behavior of matter in the plasma state to understand the plasma universe and to learn how to control and manipulate plasmas for a broad range of applications. Plasma science is not only fundamental to understanding the nature of visible matter throughout the universe, but also to achieving the eventual production and control of fusion energy. Discoveries in plasma science are leading to an ever-increasing array of practical applications, some of them relevant to clean energy technologies, including synthesis of nanomaterials and artificial diamonds, efficient solar and fuel cells, fabrication of microelectronics and opto-electronic devices, energy-efficient lighting, low-heat chemical-free sterilization processes, tissue healing, combustion enhancement, satellite communication, laser-produced isotopes for positron emission tomography, and extreme ultraviolet lithography.

The Discovery Plasma Science subprogram is organized into four principal activities: Plasma Science and Technology, Measurement Innovation, Quantum Information Science, and Advanced Microelectronics.

<u>Plasma Science and Technology</u>
The Plasma Science and Technology (PS&T) activities involve research in largely unexplored areas of plasma science, with a combination of theory, computer modeling, and experimentation. These areas encompass extremes of the plasma state, ranging from the very small (several atom systems) to the extremely large (plasma structure spanning light years in length), from the very fast (attosecond processes) to the very slow (hours), from the diffuse (interstellar medium) to the extremely dense (diamond compressed to tens of gigabar pressures), and from the ultra-cold (tens of micro-kelvin degrees) to the extremely hot (stellar core). Advancing the science of these unexplored areas creates opportunities for new and unexpected discoveries with potential to be translated into practical applications. These activities are carried out on small- and mid-scale experimental collaborative research facilities.

The PS&T portfolio includes research activities in the following areas:

- General Plasma Science (GPS): Research at the frontiers of basic and low temperature plasma science, including dynamical processes in laboratory, space, and astrophysical plasmas, such as magnetic reconnection, dynamo, shocks, turbulence cascade, structures, waves, flows and their interactions; behavior of dusty plasmas, non-neutral, single-component matter or antimatter plasmas, and ultra-cold neutral plasmas; plasma chemistry and processes in low-temperature plasma, interfacial plasma, synthesis of nanomaterials, and interaction of plasma with surfaces, materials or biomaterials.
- High Energy Density (HED) Laboratory Plasmas (HEDLP): Research directed at exploring the behavior of plasmas at extreme conditions of temperature, density, and pressure, including relativistic HED plasmas and intense beam physics, magnetized HED plasma physics, multiply ionized HED atomic physics, HED hydrodynamics, warm dense matter, nonlinear optics of plasmas and laser-plasma interactions, laboratory astrophysics, and diagnostics for HED laboratory plasmas.

The PS&T activity stewards world-class plasma science experiments and collaborative research facilities at small and intermediate scales. These platforms not only facilitate addressing frontier plasma science questions, but also provide critical data for the verification and validation of plasma science simulation codes and comparisons with space observations. This effort maintains strong partnerships with NSF and NNSA.

<u>Measurement Innovation</u>
The Measurement Innovation activity supports the development of world-leading transformative and innovative diagnostic techniques and their application to new, unexplored, or unfamiliar plasma regimes or scenarios. The challenge is to develop diagnostics with the high spatial, spectral, and temporal resolution necessary to validate plasma physics models used to predict the behavior of fusion plasmas. Advanced diagnostic capabilities successfully developed through this activity are migrated to domestic and international facilities as part of the Burning Plasma Science: Foundations and Burning Plasma

Science: Long Pulse subprograms. The utilization of mature diagnostics systems is then supported via the research programs at major fusion facilities.

Quantum Information Science

The Quantum Information Science (QIS) activity supports basic research in QIS that can have a transformative impact on FES mission areas, including fusion and discovery plasma science, as well as research that takes advantage of unique FES-enabled capabilities to advance QIS development. The direction of the QIS efforts is informed by the findings of the 2018 Roundtable meeting[a] that was held to explore the unique role of FES in this rapidly developing high-priority crosscutting field and help FES build a community of next-generation researchers in this area. Among the areas supported by the QIS subprogram are near- and long-term quantum simulation capabilities that can solve important fusion and plasma science problems; quantum sensing approaches that can enhance diagnostic capabilities for plasma and fusion science; the use of HEDLP drivers and techniques to form novel quantum materials at ultra-high pressures; the exploration of relativistic plasma science for qubit control and quantum communication; and the refining of plasma science tools for simulation and control of quantum systems. FES also participates in the SC-wide crosscutting QIS research centers.

Advanced Microelectronics

The Advanced Microelectronics activity supports low temperature plasma research in a multi-disciplinary, co-design framework to accelerate plasma-based microelectronics fabrication and advance the development of microelectronic technologies. The direction of the Advanced Microelectronics efforts will be informed by the recent Long-Range Plan developed by FESAC and the NASEM Plasma 2020 decadal survey report.

Other FES Research

This activity supports the Fusion Energy Sciences Postdoctoral Research Program, which supports postdocs in the fusion and plasma science research areas for two years, and multiple fusion and plasma science outreach programs that work to increase fusion and plasma science literacy among the general public, K-12, undergraduate students, and graduate students. Other activities being supported include the U.S. Burning Plasma Organization; peer-reviews for FES solicitations and project activities; FESAC; and other programmatic activities.

Reaching a New Energy Sciences Workforce (RENEW)

This activity supports the RENEW initiative to provide undergraduate and graduate training opportunities for students and academic institutions not currently well represented in the U.S. S&T ecosystem and aligns with a recommendation in the FESAC Long-Range Plan.

[a] https://science.osti.gov/-/media/fes/pdf/workshop-reports/FES-QIS_report_final-2018-Sept14.pdf

Fusion Energy Sciences
Discovery Plasma Science

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Discovery Plasma Science	**$54,491**	**$65,000**	**+$10,509**
Plasma Science and Technology	$32,700	$40,000	+$7,300
Funding supports core research activities in basic and low temperature plasma science focused on supporting research on collaborative research facilities at universities and national laboratories. For HEDLP, the enacted budget supports the LaserNetUS initiative, research utilizing the MEC at SLAC, and the SC-NNSA joint program in HEDLP.		The Request will support core research at the frontiers of basic and low temperature plasma science. In the area of HEDLP, the Request will support basic and translational science, MEC and LaserNetUS operations and user support, the SC-NNSA joint program, and modest inertial fusion energy activities as recommended by the 2020 FESAC Long-Range Plan.	Funding will increase for efforts on basic and low temperature plasma and astrophysical plasma research activities in GPS and basic research activities utilizing facilities in HEDLP. Funding for advanced microelectronics moves to a new activity line in the Request.
Measurement Innovation	$3,000	$3,000	$ —
Funding supports the development of transformative and innovative diagnostics for plasma transient instabilities, plasma-material interactions, modeling validation, and basic plasma science identified in the community engagement workshops.		The Request will continue to support the development of transformative and innovative diagnostics.	Funding will continue research support for measurement innovation.
Quantum Information Science	$9,520	$10,000	+$480
Funding continues to support the third and final year of the QIS awards selected in FY 2019 and the new awards selected in FY 2020 and FY 2021. It also continues to support the FES contributions to the SC QIS Research Centers.		The Request will continue to support the research efforts initiated in FY 2020 and FY 2021 and new awards addressing priority research opportunities identified in community workshops. It will also continue to support the FES contributions to the SC QIS Research Centers.	The increase will expand the FES core QIS portfolio to address additional priority research opportunities.

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Advanced Microelectronics	$5,000	$5,000	$ —
Funding supports high priority microelectronics research as well as a joint announcement to DOE Laboratories, in partnership with ASCR, Basic Energy Sciences (BES), High Energy Physics (HEP), and Nuclear Physics (NP).		The Request will continue to support high priority multi-disciplinary research through a co-design framework to accelerate the advancement of microelectronics technologies.	Funding will maintain research support for microelectronics.
Other FES Research	$4,271	$4,000	-$271
Funding supports U.S. Burning Plasma Organization (USBPO) activities, peer reviews for solicitations, outreach programs, and FESAC.		The Request will continue to support the FES Postdoctoral Research Program, the FES Fusion and Plasma Science Outreach programs, USBPO, peer reviews for FES solicitations and project activities, FESAC, and other programmatic activities.	Efforts will focus on the highest priority activities.
Reaching a New Energy Sciences Workforce (RENEW)	$ —	$3,000	+$3,000
N/A		The Request initiates the RENEW initiative to provide undergraduate and graduate training opportunities for students and academic institutions not currently well represented in the U.S. S&T ecosystem and aligns with a recommendation in the FESAC Long-Range Plan.	Increase supports the RENEW initiative.

Note: Funding for the subprogram above, includes 3.65% of research and development (R&D) funding for the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs.

Fusion Energy Sciences
Construction

Description

This subprogram supports all line-item construction projects for the entire FES program. All Total Estimated Costs (TEC) are funded in this subprogram.

20-SC-61, Matter in Extreme Conditions (MEC) Petawatt Upgrade, SLAC

The National Academies of Sciences, Engineering, and Medicine (NASEM) 2017 report "Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light"[a] recommended that "The Department of Energy should plan for at least one large-scale open-access high-intensity laser facility that leverages other major science infrastructure in the Department of Energy complex." The MEC Petawatt Upgrade project will provide a collaborative user facility which utilizes the LCLS-II light source and is focused on High-Energy-Density Science that will address this NASEM recommendation as well as maintain U.S. leadership in this important field of study. The project received Critical Decision-0 (CD-0), "Approve Mission Need," on January, 4, 2019. The FY 2022 Request of $5,000,000 will support preliminary design activities. The estimated total project cost range is $60,000,000 to $300,000,000.

14-SC-60, U.S. Contributions to ITER

The ITER facility, currently under construction in Saint Paul-lez-Durance, France, is more than 70 percent complete towards First Plasma. ITER is designed to provide fusion power output approaching reactor levels of hundreds of megawatts, for hundreds of seconds. ITER is a necessary next step toward developing a modern carbon-free fusion energy pilot plant that will keep the U.S. competitive internationally. Construction of ITER is a collaboration among the United States, European Union, Russian Federation, Japan, India, Republic of Korea, and People's Republic of China, governed by an international agreement (the "ITER Joint Implementing Agreement"). As a co-owner of ITER, the U.S. contributes in-kind hardware components and financial contributions for the ITER Organization (IO) operations (e.g., design integration, nuclear licensing, quality control, safety, overall project management, and installation and assembly of the components provided by the U.S. and other members). The U.S. also has over 50 U.S. nationals employed by the IO and working at the site. An independent review of CD-2, "Approve Performance Baseline," for the U.S. Contributions to ITER—First Plasma subproject was completed in November 2016 and then subsequently approved by the Project Management Executive on January 13, 2017, with a total project cost of $2,500,000,000. The FY 2022 Request of $221,000,000 will support the continued design of all systems, fabrication of First Plasma hardware, and financial contributions for IO operations during construction. The estimated total project cost range is $4,700,000,000 to $6,500,000,000.

The U.S. In-kind contribution represents 9.09 percent (1/11th) of the overall ITER project, but will allow access to 100 percent of the science and engineering associated with what will be the largest magnetically confined burning plasma experiment ever created. Recent advances in validated theory indicate that ITER will outperform its currently stated performance, including higher fusion power gain, longer plasma duration, demonstration of advanced operating scenarios, and improvements in divertor power handling. The U.S. involvement in ITER will help to advance the promise of carbon-free, inherently safe, and abundant fusion energy for America.

[a] https://www.nap.edu/read/24939/chapter/1

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Construction	**$257,000**	**$226,000**	**-$31,000**
20-SC-61, Matter in Extreme Conditions (MEC) Petawatt Upgrade, SLAC	$15,000	$5,000	-$10,000
The Enacted budget supports design activities, preparation for developing a project baseline, and long-lead procurements for an upgrade to MEC.		The Request will support design activities, preparation for developing a project baseline, and long-lead procurements for an upgrade to MEC.	Funding will support critical activities required to develop a cost, schedule, and scope baseline for the MEC upgrade project.
14-SC-60, U.S. Contributions to ITER	$242,000	$221,000	-$21,000
The Enacted budget supports continued design and fabrication of In-kind hardware systems for the First Plasma subproject (SP-1).		The Request will support continued design and fabrication of In-kind hardware systems for the SP-1.	Funding will continue to focus on SP-1 activities.

Fusion Energy Sciences
Capital Summary

(dollars in thousands)

	Total	Prior Years	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Capital Operating Expenses						
Capital Equipment	N/A	N/A	21,760	27,020	27,000	-20
Minor Construction Activities						
General Plant Projects	N/A	N/A	6,350	2,000	1,500	-500
Total, Capital Operating Expenses	**N/A**	**N/A**	**28,110**	**29,020**	**28,500**	**-520**

Capital Equipment

(dollars in thousands)

	Total	Prior Years	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Capital Equipment						
Major Items of Equipment						
Burning Plasma Science: Long Pulse						
Materials Plasma Exposure eXperiment (MPEX)	108,575	11,575	21,000	21,000	25,000	+4,000
Total, MIEs	N/A	N/A	21,000	21,000	25,000	+4,000
Total, Non-MIE Capital Equipment	N/A	N/A	760	6,020	2,000	-4,020
Total, Capital Equipment	**N/A**	**N/A**	**21,760**	**27,020**	**27,000**	**-20**

Note: The Capital Equipment table includes MIEs located at a DOE facility with a Total Estimated Cost (TEC) > $5M and MIEs not located at a DOE facility with a TEC >$2M.

Fusion Energy Sciences
Minor Construction Activities

(dollars in thousands)

	Total	Prior Years	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
General Plant Projects (GPP)						
Total GPPs less than $5M	N/A	N/A	6,350	2,000	1,500	-500
Total, General Plant Projects (GPP)	**N/A**	**N/A**	**6,350**	**2,000**	**1,500**	**-500**
Total, Minor Construction Activities	**N/A**	**N/A**	**6,350**	**2,000**	**1,500**	**-500**

Note: GPP activities less than $5M include design and construction for additions and/or improvements to land, buildings, replacements or addition to roads, and general area improvements. AIP activities less than $5M include minor construction at an existing accelerator facility.

Fusion Energy Sciences
Major Items of Equipment Description(s)

<u>Burning Plasma Science: Long Pulse MIEs:</u>
Materials Plasma Exposure eXperiment (MPEX)
FES is developing a first-of-a-kind, world-leading experimental capability to explore solutions to the plasma-materials interactions challenge. This device, known as MPEX, will be located at ORNL and will enable dedicated studies of reactor-relevant plasma-material interactions at a scale not previously accessible to the fusion program. The overall motivation of this project is to gain entry into a new class of fusion materials science wherein the combined effects of fusion-relevant heat, particle, and neutron fluxes can be studied for the first time anywhere in the world. The project is currently expected to be baselined in FY 2022. The proposed funding in FY 2022 will allow for the project to proceed with the highest-priority activities of baseline approval and continuation of long-lead procurements. The preliminary cost range is $86,000,000–$175,000,000.

Fusion Energy Sciences
Construction Projects Summary

(dollars in thousands)

	Total	Prior Years	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
20-SC-61, Matter in Extreme Conditions Petawatt Upgrade, SLAC						
Total Estimated Cost (TEC)	362,000	–	15,000	15,000	5,000	-10,000
Other Project Cost (OPC)	10,000	1,600	4,500	2,000	–	-2,000
Total Project Cost (TPC)	**372,000**	**1,600**	**19,500**	**17,000**	**5,000**	**-12,000**
14-SC-60, U.S. Contributions to ITER						
Total Estimated Cost (TEC)	3,587,698	1,371,617	242,000	242,000	221,000	-21,000
Other Project Cost (OPC)	70,302	70,302	–	–	–	–
Total Project Cost (TPC)	**3,658,000**	**1,441,919**	**242,000**	**242,000**	**221,000**	**-21,000**
Total, Construction						
Total Estimated Cost (TEC)	**N/A**	**N/A**	**257,000**	**257,000**	**226,000**	**-31,000**
Other Project Cost (OPC)	**N/A**	**N/A**	**4,500**	**2,000**	**–**	**-2,000**
Total Project Cost (TPC)	**N/A**	**N/A**	**261,500**	**259,000**	**226,000**	**-33,000**

Fusion Energy Sciences
Funding Summary

(dollars in thousands)

	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Research	253,000	260,149	297,230	+37,081
Facility Operations	128,500	129,211	125,270	-3,941
Projects				
Line Item Construction (LIC)	261,500	259,000	226,000	-33,000
Major Items of Equipment (MIE)	21,000	21,000	25,000	+4,000
Total, Projects	**282,500**	**280,000**	**251,000**	**-29,000**
Other	7,000	2,640	1,500	-1,140
Total, Fusion Energy Sciences	**671,000**	**672,000**	**675,000**	**+3,000**

Fusion Energy Sciences
Scientific User Facility Operations

The treatment of user facilities is distinguished between two types: TYPE A facilities that offer users resources dependent on a single, large-scale machine; TYPE B facilities that offer users a suite of resources that is not dependent on a single, large-scale machine.

Definitions for TYPE A facilities:

Achieved Operating Hours – The amount of time (in hours) the facility was available for users.

Planned Operating Hours –

- For Past Fiscal Year (PY), the amount of time (in hours) the facility was planned to be available for users.
- For Current Fiscal Year (CY), the amount of time (in hours) the facility is planned to be available for users.
- For the Budget Fiscal Year (BY), based on the proposed Budget Request the amount of time (in hours) the facility is anticipated to be available for users.

Optimal Hours – The amount of time (in hours) a facility would be available to satisfy the needs of the user community if unconstrained by funding levels.

Percent of Optimal Hours – An indication of utilization effectiveness in the context of available funding; it is not a direct indication of scientific or facility productivity.

Unscheduled Downtime Hours – The amount of time (in hours) the facility was unavailable to users due to unscheduled events. NOTE: For type "A" facilities, zero Unscheduled Downtime Hours indicates Achieved Operating Hours equals Planned Operating Hours.

(dollars in thousands)

	FY 2020 Enacted	FY 2020 Current	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Scientific User Facilities - Type A					
DIII-D National Fusion Facility	**116,500**	**114,459**	**121,000**	**120,390**	**-610**
Number of Users	718	830	830	830	–
Achieved Operating Hours	–	194	–	–	–
Planned Operating Hours	800	194	720	800	+80
Optimal Hours	960	960	960	880	-80
Percent of Optimal Hours	83.3%	20.0%	75.0%	90.0%	+15.0%
National Spherical Torus Experiment-Upgrade	**98,000**	**96,579**	**101,331**	**98,000**	**-3,331**
Number of Users	326	312	372	372	–
Total, Facilities	**214,500**	**211,038**	**222,331**	**218,390**	**-3,941**
Number of Users	1,044	1,142	1,202	1,202	–
Achieved Operating Hours	–	194	–	–	–
Planned Operating Hours	800	194	720	800	+80
Optimal Hours	960	960	960	880	-80

Note: Achieved Operating Hours and Unscheduled Downtime Hours will only be reflected in the Congressional budget cycle which provides actuals.

Fusion Energy Sciences
Scientific Employment

	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Number of Permanent Ph.Ds (FTEs)	859	846	891	+45
Number of Postdoctoral Associates (FTEs)	106	104	111	+7
Number of Graduate Students (FTEs)	287	282	297	+15
Number of Other Scientific Employment (FTEs)	1,284	1,261	1,331	+70

Note: Other Scientific Employment (FTEs) includes technicians, engineers, computer professionals and other support staff.

20-SC-61, Matter in Extreme Conditions (MEC) Petawatt Upgrade, SLAC
SLAC National Accelerator Laboratory
Project is for Design and Construction

1. Summary, Significant Changes, and Schedule and Cost History

Summary

The FY 2022 Request for the Matter in Extreme Conditions (MEC) Petawatt Upgrade project is $5,000,000. The project has a preliminary estimated Total Project Cost (TPC) range of $234,000,000 to $372,000,000. Currently, this cost range encompasses the most feasible preliminary alternatives.

The future MEC Petawatt user facility will be a premier research facility to conduct experiments in the field of High Energy Density Plasmas utilizing the Linac Coherent Light Source (LCLS) X-Ray Free-Electron Laser (XFEL) beam at SLAC to probe and characterize plasmas and extreme states of matter in pursuit of Fusion Energy as a viable unlimited, carbon-free power source.

Significant Changes

The MEC Petawatt Upgrade project was initiated in FY 2020. The project achieved Critical Decision-0 (CD-0), "Approve Mission Need," on January 4, 2019. Other Project Costs (OPC) funding in FY 2020 supported conceptual design of the civil infrastructure and technical hardware. When the project achieves CD-1, "Approve Alternative Selection and Cost Range," which is planned for 4Q FY 2021, the project will initiate the TEC-funded preliminary design phase.

A level-3 Federal Project Director has been assigned to the MEC Petawatt Upgrade project.

Critical Milestone History

Fiscal Year	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	D&D Complete	CD-4
FY 2020	1/4/19	3Q FY 2019	1Q FY 2020	TBD	TBD	TBD	TBD	TBD
FY 2021	1/4/19	4Q FY 2020	4Q FY 2020	3Q FY 2022	4Q FY 2021	3Q FY 2023	FY 2040	1Q FY 2028
FY 2022	1/4/19	3Q FY 2021	4Q FY 2021	2Q FY 2023	2Q FY 2023	3Q FY 2023	TBD	1Q FY 2028

CD-0 – Approve Mission Need for a construction project with a conceptual scope and cost range
Conceptual Design Complete – Actual date the conceptual design was completed (if applicable)
CD-1 – Approve Alternative Selection and Cost Range
CD-2 – Approve Performance Baseline
Final Design Complete – Estimated/Actual date the project design will be/was complete(d)
CD-3 – Approve Start of Construction
D&D Complete – Completion of D&D work
CD-4 – Approve Start of Operations or Project Closeout

Project Cost History

(dollars in thousands)

Fiscal Year	TEC, Design	TEC, Construction	TEC, Total	OPC, Except D&D	OPC, D&D	OPC, Total	TPC
FY 2020	1,000	—	1,000	1,600	—	1,600	2,600
FY 2021	20,000	170,400	190,400	9,600	—	9,600	200,000
FY 2022	20,000	342,000	362,000	10,000	—	10,000	372,000[a]

2. Project Scope and Justification

Scope

The scope of the MEC Petawatt Upgrade project includes the development of a user facility that couples long-pulse (1 Kilojoule or higher) and short-pulse (1 petawatt or higher) drive lasers to an X-ray source, as well as a second chamber that will accommodate laser-only fusion and material science experiments. The lasers will be placed in a dedicated MEC experimental hall (located at the end of the LCLS-II Far Experimental hall), comprised of a new access tunnel with a range of 100 to 500 feet in length, a new cavern with 10,000 to 19,000 square feet, and associated safety systems and infrastructure.

Justification

The FES mission is to build the scientific foundations needed to develop a fusion energy source and to expand the fundamental understanding of matter at very high temperatures and densities. To meet this mission, there is a scientific need for a petawatt or greater laser facility that is currently not available in the U.S. The National Academies of Science, Engineering, and Medicine (NASEM) 2017 study titled "Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light[b]" found that about 80 percent to 90 percent of the high-intensity laser systems are overseas, and all of the highest-power lasers currently in construction or already built are overseas as well. The report noted that the U.S. is losing ground in a second laser revolution of high-intensity, ultrafast lasers, which have broad applications in manufacturing, medicine, and national security. The report made five recommendations that would improve the nation's position in the field, including a recommendation for DOE to plan for at least one large-scale, open-access, high-intensity laser facility that leverages other major science infrastructures in the DOE complex.

The NASEM report focuses on high-intensity, pulsed petawatt-class lasers (1 petawatt is 10^{15} watts). Such laser beams can drive nuclear reactions, heat matter to mimic conditions found in stars, and create electron-positron plasmas. In addition to discovery-driven science, petawatt-class lasers can generate particle beams with potential applications in medicine, intense neutron and gamma ray beams for homeland security applications, directed energy for defense applications, and radiation for extreme ultraviolet lithography.

Co-location of high-intensity lasers with existing infrastructure such as particle accelerators has been recognized as a key advantage of the U.S. laboratories over the Extreme Light Infrastructure concept in Europe. A laser facility with high-power, high-intensity beam parameters that is co-located with hard X-ray laser probing capabilities (i.e., with an X-ray wavelength that allows atomic resolution) will provide the required diagnostic capabilities for fusion discovery science and related fields. This co-location enables novel pump-probe experiments with the potential to dramatically improve understanding of the ultrafast response of materials in extreme conditions, e.g., found in the environment of fusion plasmas, astrophysical objects, and highly stressed engineering materials. Recent research on ultrafast pump-probe experiments using the LCLS at the SLAC National Accelerator Laboratory has demonstrated exquisite ultrafast measurements of the material structural response to radiation. Higher flux sources of deuterons, neutrons, and gamma rays are needed, however, to properly emulate the environment and physics processes that occur in materials next to fusion plasmas. The upgrade includes the

[a] This project is pre-CD-2; therefore, funding and schedule estimates are preliminary.
[b] https://www.nap.edu/catalog/24939/opportunities-in-intense-ultrafast-lasers-reaching-for-the-brightest-light

petawatt laser beam and the long pulse laser beam. The latter is required to compress matter to densities relevant to planetary science and fusion plasmas.

FES is seeking to develop a new world-class petawatt laser capability to meet the FES mission and the recommendations from the NASEM report.

The project will be generally conducted utilizing the project management principles described in DOE O 413.3B*, Program and Project Management for the Acquisition of Capital Assets*.

Key Performance Parameters (KPPs)

The KPPs are preliminary and may change during design phase as the project continues towards CD-2. At CD-2 approval, the KPPs will be baselined. The Threshold KPPs represent the minimum acceptable performance that the project must achieve. The Objective KPPs represent the desired project performance. Achievement of the Threshold KPPs will be a prerequisite for approval of CD-4, Project Completion. The project is in the conceptual design phase, and the KPPs reflect the types of parameters being considered and are notional at this stage; the preliminary KPPs will be developed in coordination with FES and proposed for Project Management Executive (PME) consideration and approval at CD-1.

Performance Measure	Threshold	Objective
Optical Laser Systems		
▪ High repetition rate short pulse laser	▪ 30 Joules of energy ▪ 300 fs pulse length 1 Hz frequency	▪ 150 Joules of energy ▪ 150 fs pulse length 10 Hz frequency
▪ High energy long pulse laser	▪ 200 Joules of energy on target ▪ 10 ns pulse length 1 shot per 60 minutes.	▪ 1000 Joules of energy on target ▪ 10 ns pulse length 1 shot per 30 minutes.
X-ray Beam Delivery		
▪ Photon energy	▪ 5-25 KeV energy delivered to target center	▪ 5-45 KeV of energy delivered to target center
Experimental Systems		
▪ Re-entrant diagnostic inserters	▪ 4 inserters	▪ 9 inserters

3. **Financial Schedule**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Estimated Cost (TEC)			
Design (TEC)			
FY 2020	15,000	–	–
FY 2021	5,000	–	–
FY 2022	–	20,000	20,000
Total, Design (TEC)	**20,000**	**20,000**	**20,000**
Construction (TEC)			
FY 2021	10,000	–	–
FY 2022	5,000	15,000	15,000
Outyears	327,000	327,000	327,000
Total, Construction (TEC)	**342,000**	**342,000**	**342,000**
Total Estimated Cost (TEC)			
FY 2020	15,000	–	–
FY 2021	15,000	–	–
FY 2022	5,000	35,000	35,000
Outyears	327,000	327,000	327,000
Total, TEC	**362,000**	**362,000**	**362,000**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Other Project Cost (OPC)			
FY 2019	1,600	1,600	280
FY 2020	4,500	4,500	3,808
FY 2021	2,000	2,000	2,000
FY 2022	–	–	2,012
Outyears	1,900	1,900	1,900
Total, OPC	**10,000**	**10,000**	**10,000**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Project Cost (TPC)			
FY 2019	1,600	1,600	280
FY 2020	19,500	4,500	3,808
FY 2021	17,000	2,000	2,000
FY 2022	5,000	35,000	37,012
Outyears	328,900	328,900	328,900
Total, TPC	**372,000**	**372,000**	**372,000**

Note: This project is pre-CD-2; therefore, funding and schedule estimates are preliminary.

4. Details of Project Cost Estimate

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design	17,000	17,000	**N/A**
Design - Contingency	3,000	3,000	**N/A**
Total, Design (TEC)	**20,000**	**20,000**	**N/A**
Construction	161,798	70,000	**N/A**
Equipment	115,191	60,800	**N/A**
Construction - Contingency	68,111	39,600	**N/A**
Total, Construction (TEC)	**345,100**	**170,400**	**N/A**
Total, TEC	**365,100**	**190,400**	**N/A**
Contingency, TEC	*71,111*	*42,600*	***N/A***
Other Project Cost (OPC)			
R&D	350	350	**N/A**
Conceptual Planning	850	850	**N/A**
Conceptual Design	1,900	1,900	**N/A**
Other OPC Costs	2,400	3,500	**N/A**
OPC - Contingency	1,400	3,000	**N/A**
Total, Except D&D (OPC)	**6,900**	**9,600**	**N/A**
Total, OPC	**6,900**	**9,600**	**N/A**
Contingency, OPC	*1,400*	*3,000*	***N/A***
Total, TPC	**372,000**	**200,000**	**N/A**
Total, Contingency (TEC+OPC)	***72,511***	***45,600***	***N/A***

5. Schedule of Appropriations Requests

(dollars in thousands)

Request Year	Type	Prior Years	FY 2020	FY 2021	FY 2022	Outyears	Total
FY 2020	TEC	—	1,000	—	—	TBD	TBD
	OPC	1,600	—	—	—	TBD	TBD
	TPC	1,600	1,000	—	—	TBD	TBD
FY 2021	TEC	—	15,000	5,000	—	170,400	190,400
	OPC	1,600	4,500	—	—	3,500	9,600
	TPC	1,600	19,500	5,000	—	173,900	200,000
FY 2022	TEC	—	15,000	15,000	5,000	327,000	362,000
	OPC	1,600	4,500	2,000	—	1,900	10,000
	TPC	1,600	19,500	17,000	5,000	328,900	372,000[a]

6. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy	1Q FY 2028
Expected Useful Life	TBD
Expected Future Start of D&D of this capital asset	TBD

Related Funding Requirements
(dollars in thousands)

	Annual Costs		Life Cycle Costs	
	Previous Total Estimate	Current Total Estimate	Previous Total Estimate	Current Total Estimate
Operations, Maintenance and Repair	N/A	21,200	N/A	931,000

7. D&D Information

The new area being constructed for this project is under analysis at this time.

	Square Feet
New area being constructed by this project at SLAC National Accelerator Laboratory	TBD
Area of D&D in this project at SLAC National Accelerator Laboratory	TBD
Area at SLAC National Accelerator Laboratory to be transferred, sold, and/or D&D outside the project, including area previously "banked"	TBD
Area of D&D in this project at other sites	TBD
Area at other sites to be transferred, sold, and/or D&D outside the project, including area previously "banked"	TBD
Total area eliminated	TBD

[a] This project is pre-CD-2; therefore, funding and schedule estimates are preliminary.

8. Acquisition Approach

The FES is proposing that the MEC-U Project be acquired by Stanford University under the SLAC Management and Operations (M&O) Contract (DE-AC02-76-SF00515) for DOE. The acquisition of large research facilities is within the scope of the DOE contract for the management and operations of SLAC and consistent with the general expectation of the responsibilities of DOE M&O contractors.

SLAC does not currently possess all the necessary core competencies to design, procure and build the laser systems. To address this, SLAC will collaborate with Lawrence Livermore National Laboratory (LLNL) and University of Rochester Laboratory for Laser Energetics (LLE) as partners through signed Memorandum of Agreements to perform significant portions of the MEC-U laser systems scope of work. Memorandum Purchase Orders will be used to define work scopes and budgets with LLNL as funds become available. Any work accomplished through LLE will be completed using the standard DOE format university agreements. Procurements authorized by the partner institutions will utilize the approved DOE purchasing systems.

14-SC-60, U.S. Contributions to ITER
Project is for Design and Construction

1. Summary, Significant Changes, and Schedule and Cost History

Summary

The FY 2022 Request for the U.S. ITER project is $221,000,000. The approved Total Project Cost (TPC) for the U.S. Contributions to ITER Subproject–1 (SP-1) is $1,267,422,000. Sections of this Construction Project Data Sheet (CPDS) have been tailored accordingly to reflect the unique nature of the U.S. ITER project.

Significant Changes

The FY 2022 Request of $221,000,000 will support the continued design and fabrication of "in-kind" hardware systems and cash contributions. This includes continued fabrication of the Central Solenoid (CS) magnet system, which consists of seven superconducting magnet modules, structural components, and assembly tooling. In FY 2021, the U.S. will deliver the first CS magnet module to the ITER site, as well as continue design and fabrication efforts associated with other "In-kind" hardware systems. The U.S. ITER project has obligated more than $1.3 billion through the end of FY 2020, of which more than 80 percent has gone to U.S. industry, universities, and DOE laboratories.

ITER was initiated in FY 2006. The ITER SP-1 achieved both Critical Decision (CD)–2, "Approve Performance Baseline," and CD-3, "Approve Start of Construction," on January 13, 2017. CD-4, "Project Completion," for SP–1 is planned for December 2028.

A Federal Project Director with certification level 3 has been assigned to this Project.

Critical Milestone History

Fiscal Year	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	D&D Complete	CD-4
FY 2006	7/5/05	-	TBD	TBD	-	TBD	N/A	TBD
FY 2007	7/5/05	-	TBD	TBD	-	TBD	N/A	2017
FY 2008	7/5/05	-	1/25/08	4Q FY 2008	-	TBD	N/A	2017
FY 2009	7/5/05	9/30/09	1/25/08	4Q FY 2010	-	TBD	N/A	2018
FY 2010	7/5/05	7/27/10	1/25/08	4Q FY 2011	-	TBD	N/A	2019
FY 2011	7/5/05	5/30/11	1/25/08	4Q FY 2011	4/12/11	TBD	N/A	2024
FY 2012	7/5/05	7/10/12	1/25/08	3Q FY 2012	5/2/12	TBD	N/A	2028
FY 2013	7/5/05	12/11/12	1/25/08	TBD	4/10/13	TBD	N/A	2033
FY 2014	7/5/05	-	1/25/08	TBD	12/10/13	TBD	N/A	2034
FY 2015	7/5/05	-	1/25/08	TBD	-	TBD	N/A	2036
FY 2016	7/5/05	-	1/25/08	TBD	-	TBD	N/A	TBD
FY 2017	7/5/05	-	1/25/08	1/13/17	-	1/13/17	N/A	TBD
FY 2018	7/5/05	-	1/25/08	1/13/17	-	1/13/17	N/A	1Q FY 2027
FY 2019	7/5/05	-	1/25/08	1/13/17	-	1/13/17	N/A	1Q FY 2027
FY 2020	7/5/05	-	1/25/08	1/13/17	-	1/13/17	N/A	1Q FY 2027
FY 2021	7/5/05	-	1/25/08	1/13/17	-	1/13/17	N/A	1Q FY 2028
FY 2022	7/5/05	-	1/25/08	1/13/17	-	1/13/17	N/A	1Q FY 2028

CD-0 – Approve Mission Need for a construction project with a conceptual scope and cost range

Conceptual Design Complete – Actual date the conceptual design was completed (if applicable)

CD-1 – Approve Alternative Selection and Cost Range

CD-2 – Approve Performance Baseline

Final Design Complete – Estimated/Actual date the project design will be/was complete(d)

CD-3 – Approve Start of Construction

D&D Complete – Completion of D&D work

CD-4 – Approve Start of Operations or Project Closeout

Fiscal Year	CD-1 Cost Range Update	CD-3B
FY 2018	1/13/17	1/13/17
FY 2019	1/13/17	1/13/17
FY 2021	1/13/17	1/13/17
FY 2022	1/13/17	1/13/17

Note on multiple dates in Conceptual and Final Design columns for each piece of equipment: Electron Cyclotron Heating (ECH) Transmission lines (TL) (06/22/2009); Tokamak Cooling Water System (07/21/2009); CS Modules, Structures, and Assembly Tooling (AT) (09/30/2009); Ion Cyclotron Heating Transmission Lines (ICH) (10/14/2009); Tokamak Exhaust Processing (TEP) (05/17/2010); Diagnostics: Residual Gas Analyzer (RGA) (07/14/2010), Upper Visible Infrared Cameras (VIR) (07/27/2010); Vacuum Auxiliary System (VAS) – Main Piping (12/13/2010); Diagnostics Low-Field-Side Reflectometer (LFS) (05/30/2011); Cooling Water Drain Tanks (04/12/2011); Diagnostics: Upper Port (10/03/2011), Electron Cyclotron Emission (ECE) (12/06/2011), Equatorial Port E-9 and Toroidal Interferometer Polarimeter (TIP) (01/02/2012), Equatorial Port E-3 (07/10/2012); Steady State Electrical Network (05/02/2012); VAS Supply (11/13/2012); Disruption Mitigation (12/11/2012); Pellet Injection (04/29/2013); Diagnostics: Motional Stark Effect Polarimeter (MSE) (05/29/2013), Core Imaging X-ray Spectrometer (CIXS) (06/01/2013); The CD-2 date will be determined upon acceptable resolution of issues related to development of a high-confidence ITER Project Schedule and establishment of an approved funding profile; RGA Divertor Sampling Tube (07/28/14); CS AT, Early Items (09/17/14); CS Modules and Structures (11/18/2013); VAS Main Piping B-2, L-1, L-2 (12/10/2013); CS AT Remaining Items (12/02/2015); Roughing Pumps (03/2017); VAS 03 Supply (07/2017); Roughing Pumps I&C (04/2017); VAS 03 Supply I&C (07/2017); CS AT Bus Bar Alignment and Coaxial Heater (04/2017); VAS Main Piping L3/L4 (03/2017); VAS 02 CGVS (&C Part 1 (06/2017); VAS 02 Supply Part 1 (05/2018); ICH RF Building and I&C (11/2017); TCWS Captive Piping and First Plasma (11/2017); ICH RF components supporting INDA/IO testing (01/2018).

Project Cost History

At the time of CD-1 approval in January 2008, the preliminary cost range was $1.45 billion to $2.2 billion. Until 2016, however, it was not possible to confidently baseline the project due to prior delays in the international ITER construction schedule. Various factors (e.g., schedule delays, design and scope changes, funding constraints, regulatory requirements, risk mitigation, and inadequate project management and leadership issues in the ITER Organization (IO) at that time) affected the project cost and schedule. Shortly after the current Director General's appointment in March 2015, the ITER Project was baselined for cost and schedule.

In response to a 2013 Congressional request, a DOE SC Independent Project Review (IPR) Committee assessed the project and determined that the existing cost range estimate of $4.0 billion to $6.5 billion would likely encompass the final total TPC. This range, recommended in 2013, was included in subsequent President's Budget Requests. In May 2016, the DOE Secretary provided a "Report on the Continued U.S. Participation in the ITER Project" to Congress, which stated that the First Plasma part of the U.S. ITER project would be baselined in FY 2017. In preparation for baselining SP-1, based on the results of the Integrated Project Review, the acting Director for the Office of Science updated the lower end of this range to reflect updated cost estimates, resulting in the current approved CD-1R range of $4.7 billion to $6.5 billion. This updated CD-1R range incorporates increases in the project's hardware estimate that have occurred since August 2013. The SP-1 TPC is now baselined at $2.5 billion.

Subproject 1 (First Plasma Hardware for U.S. ITER)[a]
(dollars in thousands)

Fiscal Year	TEC, Design	TEC, Construction	TEC, Total	OPC, Except D&D	OPC, D&D	OPC, Total	TPC
FY 2017[b]	696,025	1,723,334	2,419,359	80,641	N/A	80,641	2,500,000
FY 2018	696,025	1,723,334	2,419,359	80,641	N/A	80,641	2,500,000
FY 2019	696,025	1,723,334	2,419,359	80,641	N/A	80,641	2,500,000
FY 2020	696,025	1,733,673	2,429,698	70,302	N/A	70,302	2,500,000
FY 2021	696,025	1,733,673	2,429,698	70,302	N/A	70,302	2,500,000
FY 2022	503,262	1,926,436	2,429,698	70,302	N/A	70,302	2,500,000

2. Project Scope and Justification

ITER, currently the largest science experiment in the world, is a major fusion research facility being constructed in St. Paul-lez-Durance, France by an international partnership of seven Members or Domestic Agencies, specifically, the U.S., China, the European Union, India, the Republic of Korea, Japan, and the Russian Federation. ITER is co-owned and co-governed by the seven Members, including the U.S. The Energy Policy Act of 2005 (EPAct 2005), Section 972(c)(5)(C), authorized U.S. participation in ITER. The Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project (Joint Implementation Agreement or JIA), signed on November 21, 2006, provides the legal framework for the four phases of the program: construction, operation, deactivation, and decommissioning. The JIA is a Congressional-Executive Hybrid Agreement that is considered "treaty-like". The other six members entered the agreement by treaty. Through participation in the JIA, the European Union, as the Host, bears five-elevenths (45.45 percent) of the ITER facility's construction cost, while the other six Members, including the U.S., each support one-eleventh (9.09 percent) of the ITER facility's construction cost. The IO is an international legal entity located in France.

As outlined in the May 2016 Secretary of Energy's Report to Congress, DOE was to baseline the "First Plasma" portion of the U.S. ITER project. As such, DOE divided the U.S. ITER project hardware scope into two distinct subprojects, which represent the two phases of the project: the First Plasma (FP) subproject (SP-1), and the Post-FP subproject (SP-2). SP-1 completes all design, delivers the Steady State Electrical Network, Toroidal Field Conductor, Central Solenoid Magnet, and portions of other systems described in Table 1, SP-1 In-Kind Hardware Description. SP-2 is the second element of the U.S. ITER project, and includes the remainder of U.S. hardware contributions for Post-FP operations leading up to Deuterium-Tritium Operations. SP-2 is planned for baselining in the future.

The financial contributions to the IO operational costs during construction are shared among the seven Members, pursuant to the ITER JIA, and is the third element of the U.S. ITER Total Project Cost. These funds are used by the IO to provide design integration, nuclear licensing, regulatory engagement, assembly and installation of in-kind components, and overall project management.

Scope

U.S. Contributions to ITER – Construction Project Scope

The overall U.S. ITER project includes three major elements:

- Hardware components, built under the responsibility of the U.S., and then shipped to the ITER site for IO assembly, installation, and operation. Included in this element is cash provided in-lieu of U.S. in-kind component contributions to adjust for certain reallocations of hardware contributions between the U.S. and the IO.

[a] Funding shown is for Subproject-1 and does not include cash contributions.
[b] Prior to FY2017 the TPC for U.S. ITER was reported as "TBD"; estimates reported beginning in FY 2017 represent the validated baseline values for Subproject 1 First Plasma Hardware. These values for the SP-1 baseline have not been updated to reflect impacts from FY 2017 and FY 2018 funding reductions and allocations.

- Funding to the IO to support common expenses, including ITER research and development (R&D), design and construction integration, overall project management, nuclear licensing, IO staff and infrastructure, IO-provided hardware, on-site assembly/installation/testing of all ITER components, installation, safety, quality control and operation.
- Other project costs, including R&D (other than mentioned above) and conceptual design-related activities.

The U.S. is to contribute the agreed-upon hardware to ITER, the technical components of which are split between SP-1 (FP) and SP-2 (Post-FP). The description of the component systems and the percentage to be delivered in SP-1 are indicated in the table below:

Table 1. SP-1 In-Kind Hardware Description

System/Subsystem	Threshold
Central Solenoid Magnet System	Provide seven (including spare) independent coil packs made of superconducting niobium-tin providing 13 Tesla at 45 kilo Amps (kA), the vertical pre- compression structure, and assembly tooling. (100 percent in SP-1)
Toroidal Field Magnet Conductor	Provide 15 percent of the overall ITER requirements which includes 9 active lengths (~765m), one dummy length (~765m) for winding trials and two active lengths (~100m each) for superconducting qualification. (100 percent in SP-1)
Steady State Electrical Network	Provide 75 percent of the overall ITER requirement which includes components for a large AC power distribution system (transformers, switches, circuit breakers, etc.) at high-voltage (400kV) and medium-voltage (22kV) levels. (100 percent in SP-1)
Tokamak Cooling Water System	Provide Final Designs for major industrial components (heat exchangers, pumps, valves, pressurizers, etc.) capable of removing 1 gigawatt (GW) of heat. Among those components, also fabricate and deliver certain IO-designated items. (58 percent in SP-1)
Diagnostics	Provide Final Designs for four diagnostic port plugs and seven instrumentation systems (Core Imaging X-ray Spectrometer, Electron Cyclotron Emission Radiometer, Low Field Side Reflectometer, Motional Stark Effect Polarimeter, Residual Gas Analyzer, Toroidal Interferometer/Polarimeter, and Upper IR/Visible Cameras). Among those components, also fabricate and deliver certain IO-designated items. (6 percent in SP-1)
Electron Cyclotron Heating Transmission Lines	Provide Final Designs for approximately 4 kilometers (km) of aluminum waveguide lines (24 lines) capable of transmitting up to 1.5 megawatts (MW) per line. Among those components, also fabricate and deliver certain IO-designated items. (55 percent in SP-1)
Ion Cyclotron Heating Transmission Lines	Provide Final Designs for approximately 1.5 km of coaxial transmission lines (8 lines) capable of transmitting up to 6 MW per line. Among those components, also fabricate and deliver certain IO-designated items. (15 percent in SP-1)
Pellet Injection System	Provide Final Designs for injector system capable of delivering deuterium/tritium fuel pellets up to 16 times per second. Among those components, also fabricate and deliver certain IO-designated items. (55 percent in SP-1)
Vacuum Roughing Pumps	Provide Final Designs for a matrix of pump trains consisting of approximately 400 vacuum pumps. Among those components, also fabricate and deliver certain IO-designated items. (65 percent in SP-1)

Table 1. SP-1 In-Kind Hardware Description

System/Subsystem	Threshold
Vacuum Auxiliary Systems	Provide Final Designs for vacuum system components (valves, pipe manifolds, auxiliary pumps, etc.) and approximately 6 km of vacuum piping. Among those components, also fabricate and deliver certain IO-designated items. (85 percent in SP-1)
Tokamak Exhaust Processing System	Provide Final Designs for an exhaust separation system for hydrogen isotopes and non-hydrogen gases. (100 percent of design in SP-1)
Disruption Mitigation System	Provide design, and research and development (R&D) (up to a limit of $25,000,000[a]) for a system to mitigate plasma disruptions that could cause damage to the tokamak inner walls and components. (100 percent of design in SP-1)

Justification

The purpose of ITER is to investigate and conduct research in the "burning plasma" regime—a performance region that exists beyond the current experimental state of the art. Creating a self-sustaining burning plasma will provide essential scientific knowledge necessary for practical fusion power. There are two parts of this need that will be achieved by ITER. The first part is to investigate the fusion process in the form of a "burning plasma," in which the heat generated by the fusion process exceeds that supplied from external sources (i.e., self-heating). The second part of this need is to sustain the burning plasma for a long duration (e.g., several hundred to a few thousand seconds), during which time equilibrium conditions can be achieved within the plasma and adjacent structures. ITER is the necessary next step toward developing a fusion pilot plant.

Although not classified as a Capital Asset, the U.S. ITER project is being conducted in accordance with the project management principles of DOE Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets,* to the greatest extent possible.

Key Performance Parameters (KPPs)

The U.S. ITER project will not deliver an integrated operating facility, but rather In-kind hardware contributions, which represent a portion of the subsystems for the international ITER facility. Therefore, typical KPPs are not practical for this type of project. The U.S. ITER project defines project completion as delivery and IO acceptance of the U.S. in-kind hardware. For SP-1, in some cases (e.g., Tokamak Exhaust Processing and Disruption Mitigation), only the completion of the design is required, which requires IO approval of the final designs (see Table 1 on previous page for more detail).

[a] Any additional costs would be funded by the ITER organization.

3. Financial Schedule

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Estimated Cost (TEC)			
Design (TEC)			
FY 2006	13,754	13,754	6,169
FY 2007	33,702	33,702	21,352
FY 2008	22,371	22,371	22,992
FY 2009	45,574	45,574	26,278
FY 2010	36,218	36,218	46,052
FY 2011	39,143	39,143	67,919
FY 2012	54,151	54,151	54,151
FY 2013	49,124	49,124	49,124
FY 2014	42,811	42,811	42,811
FY 2015	55,399	55,399	55,399
FY 2016	46,996	46,996	46,996
FY 2022	43,883	43,883	43,883
Outyears	20,136	20,136	20,136
Total, Design (TEC)	**503,262**	**503,262**	**503,262**
Construction (TEC)			
FY 2007	2,886	2,886	2,886
FY 2008	1,129	1,129	1,129
FY 2009	39,827	39,827	–
FY 2010	49,048	49,048	–
FY 2011	24,732	24,732	16,402
FY 2012	37,302	37,290	45,098
FY 2013	58,511	58,545	60,950
FY 2014	123,794	123,794	111,184
FY 2015	78,644	78,644	58,730
FY 2016	68,004	68,004	59,523
FY 2017	50,000	50,000	123,117
FY 2018	122,000	122,000	98,185
FY 2019	102,000	102,000	126,726
FY 2020	157,000	157,000	75,338
FY 2021	182,000	182,000	182,000
FY 2022	136,117	136,117	136,117
Outyears	693,442	693,420	829,051
Total, Construction (TEC)	**1,926,436**	**1,926,436**	**1,926,436**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Cash Contributions (TEC)			
FY 2006	2,112	2,112	2,112
FY 2007	7,412	7,412	7,412
FY 2008	2,644	2,644	2,644
FY 2009	23,599	23,599	23,599
FY 2010	29,734	29,734	29,734
FY 2011	3,125	3,125	3,125
FY 2012	13,214	13,214	13,214
FY 2013	13,805	13,805	13,805
FY 2014	32,895	32,895	32,895
FY 2015	15,957	15,957	15,957
FY 2019	30,000	30,000	30,000
FY 2020	85,000	85,000	85,000
FY 2021	60,000	60,000	60,000
FY 2022	41,000	41,000	41,000
Outyears	797,503	797,503	797,503
Total, Cash Contributions (TEC)	**1,158,000**	**1,158,000**	**1,158,000**
Total Estimated Cost (TEC)			
FY 2006	15,866	15,866	8,281
FY 2007	44,000	44,000	31,650
FY 2008	26,144	26,144	26,765
FY 2009	109,000	109,000	49,877
FY 2010	115,000	115,000	75,786
FY 2011	67,000	67,000	87,446
FY 2012	104,667	104,655	112,463
FY 2013	121,440	121,474	123,879
FY 2014	199,500	199,500	186,890
FY 2015	150,000	150,000	130,086
FY 2016	115,000	115,000	106,519
FY 2017	50,000	50,000	123,117
FY 2018	122,000	122,000	98,185
FY 2019	132,000	132,000	156,726
FY 2020	242,000	242,000	160,338
FY 2021	242,000	242,000	242,000
FY 2022	221,000	221,000	221,000
Outyears	1,511,081	1,511,059	1,646,690
Total, TEC	**3,587,698**	**3,587,698**	**3,587,698**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Other Project Cost (OPC)			
FY 2006	3,449	3,449	3,449
FY 2007	16,000	16,000	16,000
FY 2008	-74	-74	-74
FY 2009	15,000	15,000	15,000
FY 2010	20,000	20,000	20,000
FY 2011	13,000	13,000	13,000
FY 2012	333	333	333
FY 2013	2,560	2,560	2,560
FY 2016	34	34	34
Total, OPC	**70,302**	**70,302**	**70,302**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Project Cost (TPC)			
FY 2006	19,315	19,315	11,730
FY 2007	60,000	60,000	47,650
FY 2008	26,070	26,070	26,691
FY 2009	124,000	124,000	64,877
FY 2010	135,000	135,000	95,786
FY 2011	80,000	80,000	100,446
FY 2012	105,000	104,988	112,796
FY 2013	124,000	124,034	126,439
FY 2014	199,500	199,500	186,890
FY 2015	150,000	150,000	130,086
FY 2016	115,034	115,034	106,553
FY 2017	50,000	50,000	123,117
FY 2018	122,000	122,000	98,185
FY 2019	132,000	132,000	156,726
FY 2020	242,000	242,000	160,338
FY 2021	242,000	242,000	242,000
FY 2022	221,000	221,000	221,000
Outyears	1,511,081	1,511,059	1,646,690
Total, TPC	**3,658,000**	**3,658,000**	**3,658,000**

Note:

- *TEC: Costs through FY 2020 reflect actual costs; costs for FY 2021 and the outyears are estimates.*
- *FY 2012: Prior actuals adjusted to incorporate project funds utilized at PPPL and DOE. Obligation adjusted to reflect year-end PPPL settlement funding.*

- *FY 2014: Appropriations prior to FY 2014 reflect major item of equipment funding. Starting in FY 2014, this project is funded as a Congressional control point.*
- *FY 2016 funding for taxes and tax support is included in the FY 2017 Hardware funding amount.*
- *Cash Contributions includes cash payments, secondees, taxes and tax support and are considered separate from the SP-1 TPC.*
- *Appropriations for the U.S. Contributions to ITER project include both funding for SP-1 and funding for Cash Contributions.*

4. Details of Project Cost Estimate

The overall U.S. Contributions to ITER project has an approved updated CD-1 Cost Range. DOE has chosen to divide the project hardware scope into two distinct subprojects (FP SP-1, and Post-FP SP-2). The baseline for SP-1 was approved in January 2017. Baselining of SP-2 will be done at a future point; SP-2 design work is underway. An Independent Project Review (IPR) of U.S. Contributions to ITER was conducted on November 14–17, 2016, to consider the project's readiness for CD-2 (Approve Performance Baseline) and CD-3 (Approve Start of Construction [Fabrication]) for SP-1, as well as for the proposed updated CD-1 Cost Range. Outcomes from the IPR indicated that the project was ready for approval of SP-1 CD-2/3, following a reassessment of contingency to account for risk in the areas of escalation and currency exchange. This recommendation has been addressed. In addition, the IPR committee found no compelling reason to deviate from the cost-range identified in the May 2016 Report to Congress ($4,000,000,000 to $6,500,000,000) and recommended that this range be adopted and approved as the Updated CD-1 cost-range. However, as noted above, in preparation for baselining SP-1 and based on the outcome of the IPR, a decision was made to update the lower end of this range to reflect updated cost estimates, resulting in the current approved CD-1R range of $4,700,000,000 to $6,500,000,000.

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design	503,262	573,660	573,660
Design - Contingency	N/A	122,365	122,365
Total, Design (TEC)	**503,262**	**696,025**	**696,025**
Construction	1,696,355	N/A	**N/A**
Equipment	N/A	1,362,521	1,362,521
Construction - Contingency	230,081	371,152	371,152
Total, Construction (TEC)	**1,926,436**	**1,733,673**	**1,733,673**
Total, TEC	**2,429,698**	**2,429,698**	**2,429,698**
Contingency, TEC	*230,081*	*493,517*	*493,517*
Other Project Cost (OPC)			
OPC, Except D&D	70,302	N/A	70,302
Other OPC Costs	N/A	70,302	**N/A**
Total, Except D&D (OPC)	**70,302**	**70,302**	**70,302**
Total, OPC	**70,302**	**70,302**	**70,302**
Contingency, OPC	***N/A***	*N/A*	***N/A***
Total, TPC	**2,500,000**	**2,500,000**	**2,500,000**
Total, Contingency (TEC+OPC)	***230,081***	***493,517***	***493,517***

Note:
- *Funding shown is for Subproject-1 and does not include cash contributions.*

5. Schedule of Appropriations Requests

(dollars in thousands)

Request Year	Type	Prior Years	FY 2020	FY 2021	FY 2022	Outyears	Total
FY 2006	TEC	1,038,000	—	—	—	—	1,038,000
	OPC	84,000	—	—	—	—	84,000
	TPC	1,122,000	—	—	—	—	1,122,000
FY 2007	TEC	1,077,051	—	—	—	—	1,077,051
	OPC	44,949	—	—	—	—	44,949
	TPC	1,122,000	—	—	—	—	1,122,000
FY 2008	TEC	1,078,230	—	—	—	—	1,078,230
	OPC	43,770	—	—	—	—	43,770
	TPC	1,122,000	—	—	—	—	1,122,000
FY 2009[a]	TEC	266,366	—	—	—	—	TBD
	OPC	38,075	—	—	—	—	TBD
	TPC	304,441	—	—	—	—	TBD
FY 2010	TEC	294,366	—	—	—	—	TBD
	OPC	70,019	—	—	—	—	TBD
	TPC	364,385	—	—	—	—	TBD
FY 2011	TEC	379,366	—	—	—	—	TBD
	OPC	65,019	—	—	—	—	TBD
	TPC	444,385	—	—	—	—	TBD
FY 2012[b]	TEC	394,366	—	—	—	—	TBD
	OPC	75,019	—	—	—	—	TBD
	TPC	469,385	—	—	—	—	TBD
FY 2013[c]	TEC	617,261	—	—	—	—	TBD
	OPC	82,124	—	—	—	—	TBD
	TPC	699,385	—	—	—	—	TBD
FY 2014[d]	TEC	806,868	—	—	—	—	TBD
	OPC	73,159	—	—	—	—	TBD
	TPC	880,027	—	—	—	—	TBD
FY 2015	TEC	942,578	—	—	—	—	TBD
	OPC	80,341	—	—	—	—	TBD
	TPC	1,022,919	—	—	—	—	TBD
FY 2016	TEC	1,092,544	—	—	—	—	TBD
	OPC	80,341	—	—	—	—	TBD
	TPC	1,172,885	—	—	—	—	TBD
FY 2017	TEC	1,182,578	—	—	—	—	TBD
	OPC	80,341	—	—	—	—	TBD
	TPC	1,262,919	—	—	—	—	TBD

[a] The Prior Years column for FY 2009 through FY 2012 reflects the total of appropriations and funding requests only through the year of that row. Thus, for example, in the FY 2010 row, it reflects only funding from FY 2006 to FY 2012.
[b] The FY 2012 request was submitted before a full-year appropriation for FY 2011 was in place, and so FY 2011 was TBD at that time. Hence, the Prior Years column for FY 2012 reflects appropriations for FY 2006 through FY 2010 plus the FY 2012 request.
[c] The FY 2013 amount shown in the FY 2014 request reflected a short-term continuing resolution level annualized to a full year and based on the FY 2012 funding level for ITER.
[d] Prior to FY 2015, the requests were for a major item of equipment broken out by TEC, OPC, and TPC.

(dollars in thousands)

Request Year	Type	Prior Years	FY 2020	FY 2021	FY 2022	Outyears	Total
FY 2018	TEC	1,170,244	—	—	—	—	TBD
	OPC	80,641	—	—	—	—	TBD
	TPC	1,250,885	—	—	—	—	TBD
FY 2019	TEC	1,245,244	—	—	—	—	TBD
	OPC	80,641	—	—	—	—	TBD
	TPC	1,325,885	—	—	—	—	TBD
FY 2020	TEC	1,371,617	107,000	—	—	—	TBD
	OPC	70,302	—	—	—	—	TBD
	TPC	1,441,919	107,000	—	—	—	TBD
FY 2021	TEC	1,371,617	242,000	107,000	—	—	TBD
	OPC	70,302	—	—	—	—	TBD
	TPC	1,441,919	242,000	107,000	—	—	TBD
FY 2022	TEC	1,371,617	242,000	242,000	221,000	—	TBD
	OPC	70,302	—	—	—	—	TBD
	TPC	1,441,919	242,000	242,000	221,000	—	TBD

6. Related Operations and Maintenance Funding Requirements

The U.S. Contributions to ITER operations phase is to begin with initial integrated commissioning activities and assumed to continue for a period of 15 to 25 years. The fiscal year in which commissioning activities begin depends on the international ITER project schedule, which currently indicates 2025.

Start of Operation or Beneficial Occupancy	12/2025
Expected Useful Life	15–25 years
Expected Future Start of D&D of this capital asset	TBD

7. D&D Information

Since ITER is being constructed in France by a coalition of countries and will not be a DOE asset, the "one-for-one" requirement is not applicable to this project.

The U.S. Contributions to ITER decommissioning phase is assumed to begin no earlier than 20 years after the start of operations. The deactivation phase is also assumed to begin no earlier than 20 years after operations begin and will continue for a period of 5 years. The U.S. is responsible for 13 percent of the total decommissioning and deactivation cost; the fund will be collected and escrowed out of research operations funding.

8. Acquisition Approach

The U.S. ITER Project Office (USIPO) at Oak Ridge National Laboratory, with its two partner laboratories (Princeton Plasma Physics Laboratory and Savannah River National Laboratory), will procure and deliver In-kind hardware in accordance with the Procurement Arrangements established with the international IO. The USIPO will subcontract with a variety of research and industry sources for design and fabrication of its ITER components, ensuring that designs are developed that permit fabrication, to the maximum extent possible, under fixed-price subcontracts (or fixed-price arrangement documents with the IO) based on performance specifications, or more rarely, on build-to-print designs. USIPO will use cost-reimbursement type subcontracts only when the work scope precludes accurate and reasonable cost contingencies being gauged and established beforehand. USIPO will utilize best value, competitive source-selection procedures to the maximum extent possible, including foreign firms on the tender/bid list where appropriate. Such procedures shall allow for cost and technical trade-offs during source selection. For the large-dollar-value subcontracts (and critical path subcontracts as appropriate), USIPO will utilize unique subcontract provisions to incentivize cost control and schedule performance. In addition, where it is cost effective and it reduces risk, the USIPO will participate in common procurements led by the IO or request the IO to perform activities that are the responsibility of the U.S.