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. To achieve its mission, FES strives to develop a well-trained STEM workforce, guided by the principles of diversity, equity, and inclusion.

Importantly, high-temperature laboratory fusion plasmas at hundreds of millions of degrees are being exploited to become the basis for a future clean energy source. Once developed, fusion will provide a clean energy source well-suited for on-demand, dispatchable electricity production, supplementing intermittent renewables and fission. Energy from fusion will be carbon-free, inherently safe, with a virtually limitless fuel supply, and without the production of long-lived radioactive waste. Developing fusion energy is the motivation for the FES subprograms focused on study of the “burning plasma” state of matter, for which self-heating from fusion reactions exceeds external heating and leads to net energy production.

The frontier area of high-power, long-pulse 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. The DIII-D National Fusion Facility and the National Spherical Torus Experiment-Upgrade (NSTX-U) are world-leading Office of Science (SC) user facilities for experimental research, used by scientists from national laboratories, universities, and industry research groups, to optimize magnetic confinement regimes. Partnerships with the emerging fusion private sector could potentially shorten the time for developing fusion energy by combining efforts to resolve common scientific and technological challenges; along with the Innovation Network for Fusion Energy (INFUSE) voucher program, FES will initiate a milestone-based cost-share fusion enterprise program. In addition, FES will initiate an inertial fusion energy science and technology program.

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. FES supports several Scientific Discovery through Advanced Computing (SciDAC) centers, in partnership with the Advanced Scientific Computing Research (ASCR) program. U.S. scientists use international partnerships to conduct research on overseas tokamaks and stellarators with unique capabilities. The development of novel materials that can withstand enormous heat and neutron exposure is important for fusion and the design basis for a fusion pilot plant (FPP).

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. Plasma science is wide-ranging, with various types of plasma comprising 99 percent of the visible universe. Practical applications of plasmas are found in microelectronics fabrication, nanomaterial synthesis, and space weather forecasting. 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 economic and societal impact.

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 advanced computing.

Decisions about the direction of the FES program and its activities are informed by the recent strategic plan “Powering the Future: Fusion and Plasmas”[ff] from the Fusion Energy Sciences Advisory Committee (FESAC), as well as reports from the National Academies of Sciences, Engineering, and Medicine (NASEM) and community workshops. Specific projects are selected through rigorous peer review and the application of validated standards.

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

Highlights of the FY 2023 Request

The FY 2023 Request is $723.2 million. The Request is aligned with recommendations in the recent FESAC Long-Range Plan (LRP), including addressing science and technology needs for the design basis of an FPP. Key elements in the FY 2023 Request include:

<u>Research</u>

- DIII-D research: Evaluate negative triangularity as an integrated reactor scenario, mitigate drift effects in small angle slot divertor, map the operational space of the ITER Baseline Scenario, and validate plasma stability limits in high beta discharges.
- NSTX-U research: Support focused efforts on plasma startup and initial machine commissioning, along with collaborative research at other facilities for addressing program priorities.
- Partnerships with private fusion efforts: Expand public-private partnerships in critical fusion research areas by establishing a new milestone-based cost-share program and continuing the INFUSE program.
- Inertial fusion energy: Establish a new program to develop the scientific foundation and technologies that could facilitate the transition from laboratory inertial confinement fusion experiments to inertial fusion energy.
- Enabling technology, fusion nuclear science, and materials: Support research on high-temperature superconductors, materials, blanket/fuel cycle research, and advanced manufacturing.
- Scientific Discovery through Advanced Computing: Continue development of an integrated simulation capability, expanding it from whole-device to whole-facility modeling, in partnership with the ASCR program under SciDAC.
- 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 and AI/ML: Support the National Quantum Initiative, including the SC National QIS Research Centers (NQISRCs), along with a core research portfolio to advance developments in QIS and related technology. Enhance support of AI/ML activities for fusion and discovery plasma science.
- ITER research: Continue support for a national team for ITER research to ensure the U.S. fusion community takes full advantage of ITER research operations.
- Future Facilities Studies: Enhance the future facilities studies activity to address one of the highest-priority recommendations in the FESAC LRP for the design of an FPP.
- Reaching a New Energy Sciences Workforce (RENEW): Enhance support for 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.
- Funding for Accelerated, Inclusive Research (FAIR): The FAIR initiative will provide focused investment on enhancing research on clean energy, climate, and related topics at minority serving institutions (MSIs), including attention to underserved and environmental justice regions. The activities will improve the capability of MSIs to perform and propose competitive research and will build beneficial relationships between MSIs and DOE national laboratories and facilities.
- Accelerate Innovations in Emerging Technologies (Accelerate): The Accelerate initiative will support scientific research to accelerate the transition of science advances to energy technologies. The goal is to drive scientific discovery to sustainable production of new technologies across the innovation continuum, to provide experiences in working across this continuum for the workforce needed for industries of the future, and to meet the nation's needs for abundant clean energy, a sustainable environment, and national security.

<u>Facility Operations</u>

- DIII-D operations: Support 22 weeks of facility operations, representing 90 percent of the optimal run time, and complete ongoing machine and infrastructure refurbishments and improvements.
- NSTX-U recovery and operations: Continue the recovery and repair activities. NSTX-U Operations will support machine assembly and hardware commissioning.

Projects

- U.S. hardware development and delivery to ITER: Support the continued design, fabrication, and delivery of U.S. in-kind hardware systems, including the continued fabrication and delivery of the Central Solenoid magnet system. Other U.S. contributed hardware systems include tokamak cooling water, tokamak exhaust processing, electron and ion heating transmission lines, diagnostics, tokamak fueling, disruption mitigation, vacuum auxiliary, and roughing pumps.
- Petawatt laser facility upgrade for HEDLP science: Support design activities for a world-leading upgrade to the Matter in Extreme Conditions (MEC) instrument on the Linac Coherent Light Source-II (LCLS-II) facility at SLAC. MEC-U scope includes a new underground experimental facility, two experimental target chambers, petawatt and kilo-joule lasers, facility access tunnel, and support building with control room.
- Major Item of Equipment (MIE) project for plasma-material interaction research: Continue to support the Material Plasma Exposure eXperiment (MPEX) MIE project in executing the approved performance baseline and continuation of approved long-lead procurements. MPEX scope includes the design, fabrication, installation, and commissioning of the MPEX linear plasma device, and associated facility modification and reconfiguration.

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 2023 Research Initiatives.

(dollars in thousands)

	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Accelerate Innovations in Emerging Technologies	–	–	6,000	+6,000
Advanced Computing	–	–	2,000	+2,000
Artificial Intelligence and Machine Learning	7,000	7,000	11,000	+4,000
Fundamental Science to Transform Advanced Manufacturing	–	–	3,000	+3,000
Funding for Accelerated, Inclusive Research (FAIR)	–	–	2,000	+2,000
Microelectronics	5,000	5,000	5,000	–
Quantum Information Science	9,520	10,000	10,000	+480
Reaching a New Energy Sciences Workforce (RENEW)	–	–	6,000	+6,000
Total, Research Initiatives	**21,520**	**22,000**	**45,000**	**+23,480**

Fusion Energy Sciences
Funding

(dollars in thousands)

	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Fusion Energy Sciences				
Advanced Tokamak	127,038	127,868	127,122	+84
Spherical Tokamak	104,331	104,331	101,100	-3,231
Theory & Simulation	42,000	49,000	51,000	+9,000
GPP/GPE Infrastructure	2,640	2,640	1,500	-1,140
Public-Private Partnerships	5,000	6,000	32,000	+27,000
Artificial Intelligence and Machine Learning	7,000	7,000	11,000	+4,000
Inertial Fusion Energy (IFE)	–	–	3,000	+3,000
Total, Burning Plasma Science: Foundations	**288,009**	**296,839**	**326,722**	**+38,713**
Long Pulse: Tokamak	15,000	15,000	15,000	–
Long Pulse: Stellarators	8,500	8,500	7,500	-1,000
Materials & Fusion Nuclear Science	49,000	57,410	54,500	+5,500
Future Facilities Studies	–	3,000	4,000	+4,000
Total, Burning Plasma Science: Long Pulse	**72,500**	**83,910**	**81,000**	**+8,500**
ITER Research	–	2,000	2,000	+2,000
Total, Burning Plasma Science: High Power	**–**	**2,000**	**2,000**	**+2,000**

(dollars in thousands)

	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Plasma Science and Technology	32,700	40,000	37,000	+4,300
Measurement Innovation	3,000	3,000	3,000	–
Quantum Information Science (QIS)	9,520	10,000	10,000	+480
Advanced Microelectronics	5,000	5,000	5,000	–
Other FES Research	4,271	5,251	3,500	-771
Reaching a New Energy Sciences Workforce	–	–	6,000	+6,000
FES-Funding for Accelerated, Inclusive Research (FAIR)	–	–	2,000	+2,000
FES-Accelerate Innovations in Emerging Technologies	–	–	6,000	+6,000
Total, Discovery Plasma Science	**54,491**	**63,251**	**72,500**	**+18,009**
Subtotal, Fusion Energy Sciences	**415,000**	**446,000**	**482,222**	**+67,222**
Construction				
20-SC-61, Matter in Extreme Conditions (MEC) Petawatt Upgrade, SLAC	15,000	5,000	1,000	-14,000
14-SC-60, U.S. Contributions to ITER	242,000	221,000	240,000	-2,000
Subtotal, Construction	**257,000**	**226,000**	**241,000**	**-16,000**
Total, Fusion Energy Sciences	**672,000**	**672,000**	**723,222**	**+51,222**

SBIR/STTR funding:

- FY 2021 Enacted: SBIR $12,352,000 and STTR $1,740,000
- FY 2022 Annualized CR: SBIR $13,216,000 and STTR $1,863,000
- FY 2023 Request: SBIR $14,487,000 and STTR $2,036,000

Fusion Energy Sciences
Explanation of Major Changes

	(dollars in thousands) FY 2023 Request vs FY 2021 Enacted
Burning Plasma Science: Foundations The Request for DIII-D will support 22 weeks of research operations which is 90 percent of the optimal run time, as well as completion of facility enhancements to maintain the world-leading status of the facility. Funding for the NSTX-U program will support the recovery activities and maintain collaborative research at other facilities to support NSTX-U research program priorities. A new milestone-based cost-share program with private fusion industry will be initiated, as well as a new research program in inertial fusion energy science and technology. SciDAC will maintain emphasis on whole-facility modeling. 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.	**+38,713**
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 also blanket and fuel cycle research. The Request supports construction activities for the MPEX MIE project and continues long-lead procurements; the reduction in funding is consistent with the MPEX project CD-1 approved cost range. The Request continues support for a Future Facilities Studies program to address one of the highest recommendations in the FESAC LRP for the design of an FPP.	**+8,500**
Burning Plasma Science: High Power The Request will continue support for establishing an ITER Research program to prepare the U.S. fusion community to take full advantage of ITER research operations.	**+$2,000**

	(dollars in thousands)
	FY 2023 Request vs FY 2021 Enacted
Discovery Plasma Science For General Plasma Science, the Request will emphasize 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, 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 National QIS Research Centers (NQISRCs) established in FY 2020 and the core research portfolio stewarded by FES. Support for the SC initiative on advanced microelectronics will continue. The RENEW initiative will increase to provide undergraduate and graduate training opportunities for students and academic institutions under-represented in the U.S. S&T ecosystem, in alignment with a recommendation in the FESAC LRP. This subprogram will also support the FAIR initiative to enhance research on clean energy, climate, and related topics at Minority Serving Institutions, including attention to underserved and environmental justice communities; and the Accelerate initiative to support scientific research to accelerate the transition of science advances to energy technologies.	**+18,009**
Construction FES will continue to support design activities for a world-leading upgrade to the MEC facility. The U.S. Contributions to ITER project will continue design, fabrication, and delivery of First Plasma hardware, including continued fabrication and delivery of the central solenoid superconducting magnet modules. The Request supports funding for construction financial contributions to the ITER Organization.	**-16,000**
Total, Fusion Energy Sciences	**+51,222**

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 manages a joint program with NNSA in HEDLP physics and continues to support awards under joint solicitations with the Advanced Research Projects Agency-Energy (ARPA-E). 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
Disruption and runaway electron mitigation techniques advanced through coupled experiment and theory collaborations.
U.S. researchers are developing new control methods to ensure safe operation of tokamaks. One method deployed on the DIII-D National Fusion Facility uses boron-filled diamond shell pellets to quickly cool, or quench, the plasma. Quenching is often done by injecting a large quantity of a gas or a cryogenically frozen solid into the plasma, cooling it from the outside and releasing the confined heat outward. The new approach reverses the process by cooling the inner plasma first, so that the released heat is still trapped by the outer plasma regions as it is converted to light. New simulations that reproduce DIII-D results show that under the right conditions the outer edge of the magnetized plasma continues to confine heat until nearly all the heat in the plasma core is converted, thereby protecting the outer wall. A second method studied on DIII-D and the Joint European torus in the U.K. involves injection of cryogenically frozen deuterium into high energy runaway electron beams, triggering a plasma instability that reduces confinement of the electrons and allows benign plasma termination. New data from DIII-D and JET are being used to explore whether this approach can potentially solve one of the major issues of future reactors based on the tokamak.

U.S. researchers are keeping it cool.
One challenge facing tokamaks is how to keep the plasma core hot enough that fusion can occur while maintaining low edge temperatures, so the tokamak walls do not melt. For the first time, impurity radiation was used in DIII-D’s new small angle slot divertor to reduce exhaust heat, a process known as divertor detachment. Researchers performed the first simultaneous observation of plasma cooling without degrading plasma performance. In related work, the same advanced divertor control algorithm was used to sustain plasmas with excellent core confinement by integrating divertor detachment with an additional internal transport barrier further inside the plasma. When the injected radiative gases dissipate heat and cool the edge plasma, this tends to further reduce turbulence, and isolation the high-temperature core from the walls. This internal transport barrier is created by tailoring the shape of the plasma current in a way that is known to reduce plasma turbulence.

Gain in the fast lane: fast-ion confinement improved in advanced tokamak scenarios.
A key ingredient to any fusion reactor is the ability to keep energetic ions in the plasma, since these particles undergo fusion reactions more readily and also keep the plasma hot. However, too many fast ions in the core of the plasma can trigger instabilities that cause fast ions to move out from the core, similar to how a sandpile cannot become too steep. In DIII-D, advanced tokamak experiments have utilized the upgraded neutral beam injection (NBI) system to double the amount of NBI power that can be injected off-axis. This distributes the fast-ions more evenly across the plasma, enabling improved fast-ion confinement and plasma performance. New experiments using the combination of off-axis beam power and an electron cyclotron current drive resulted in increased measured neutron counts from approximately 70 percent of the classically predicted rates with on-axis NBI to 95 percent using off-axis NBI. This demonstrates improved fast-ion confinement and shows that it is possible to use flexible control tools to optimize the advanced tokamak scenarios envisioned for compact fusion power plants and ITER’s peak performance goals.

High-performance computing and AI/ML help develop a predictive formulation for the heat-flux width in tokamaks.
Predicting the width of the narrow channel through which the power produced in the core plasma is exhausted to the material surfaces is a critical issue for ITER and future fusion reactors. The heat-flux width determines whether the plasma

facing components (PFCs), including the divertor plates, can survive the extreme heat fluxes anticipated in reactor-grade plasmas which can be comparable to the heat fluxes in rocket nozzles and spacecrafts during reentry. While several formulas for the heat-flux width exist, they predict very narrow widths for ITER raising concerns about whether the PFCs would fail prematurely. Large-scale simulations performed by a PPPL-led multi-institutional SciDAC team on the SC leadership computing facilities showed that when turbulence effects are properly considered, the resulting heat-flux width is much larger, relaxing the constraints on the PFCs. However, these extreme-scale simulations are computationally expensive. The SciDAC researchers used AI/ML techniques and large datasets from their first-principles simulations to develop a physics-informed surrogate formula that reproduces the heat-flux widths observed in the present tokamaks and the predicted heat-flux width on ITER. This capability will be invaluable for ITER and for the design of future fusion reactors, including the FPP.

SNAP Machine Learning Interatomic Potential Reproduces Key Hydrogen Surface Interactions.
Researchers at Sandia National Laboratories, University of Tennessee, and Los Alamos National Laboratory have developed new a machine-learned interatomic potential for studying plasma interactions with fusion reactor materials using atomistic modeling. Previously, spectral neighbor analysis potentials (SNAP) have been successfully developed to study beryllium interactions with tungsten surfaces. This work has now been extended to hydrogen, which makes up most of the plasma impinging on the divertor surface. The new potential was trained to handle a range of surface environments and reproduces the adsorption energies and surface diffusion barriers, as compared to density functional theory for low energy crystallographic orientations. Understanding both the microstructural changes caused by hydrogen and the retention of hydrogen in the divertor is critical for designing future divertor materials and machine learning methods are an enabling technology to accelerate atomistic simulations of these processes.

Super-X divertors in spherical tokamaks can really take the heat.
For the first time, a Super-X divertor has been experimentally realized in the Mega Ampere Spherical Tokamak-Upgrade (MAST-U) at the Culham Centre for Fusion Energy in the UK. The idea for this technology originated with U.S. scientists at the University of Texas - Austin, where theorists showed that specially shaped magnetic fields can expand the area that hot plasma exhaust strikes, thereby reducing the heat absorbed by the surrounding materials. In fusion, where the generated internal plasma temperatures are hotter than the core of the sun, reducing the exhausted heat in a way that does not vaporize the surrounding materials of the reactor is essential. These initial MAST-U results showed that a Super-X divertor can reduce this material heat loading by more than a factor of ten, which may prove sufficient for future fusion power plant designs.

Continuous Cryogenic Pellet-Fueling System for Wendelstein 7-X Shows Promise.
Continuous injection of cryogenic deuterium-hydrogen pellets is required on the German stellarator, Wendelstein 7-X (W7-X), to maintain reactor-like plasma densities and enhanced confinement in long-pulse operation. W7-X is designed to sustain high-performance plasmas for up to 30 minutes. Exploratory experiments on W7-X demonstrated that the injection of 50, 2-mm hydrogen pellets at a velocity of 200 m/s could sustain a high-density plasma heated with 5 MW of microwave power with electrons and ions at temperatures of about 3 keV for about a second. Physics analysis shows that these pellet-fueled plasmas have reduced turbulent transport, which improves the plasma energy confinement. A U.S- led international team is now constructing a continuous, high-speed pellet system to fuel W7-X plasmas in quasi steady-state conditions with plasma experiments starting in 2022.

The Material Plasma Exposure eXperiment (MPEX) Project receives approval to begin Long-Lead Procurements.
The scientific demonstration of magnetic fusion energy as an environmentally sustainable and economically competitive energy source will require mastering of materials science issues associated with the plasma-material interface. The MPEX Project will deliver a world leading capability enabling the testing of plasma-facing materials and components under reactor-relevant plasma loading conditions. As part of the tailoring strategy, the MPEX project is utilizing long-lead procurements which are necessary to ensure the timely, cost-effective delivery of the MPEX work scope while minimizing overall project risk. These long-lead procurements include six superconducting and one resistive magnet subsystems, two gyrotrons, a high voltage power supply, and facility reconfiguration and enhancements, totaling $44.6M in cost. The MPEX project received formal Approval of Long-Lead Procurements (CD-3A) on October 29th, 2020, a major milestone for the project.

FES and ARPA-E collaboration on Fusion Technology R&D
The Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) and FES oversaw the issuance of a joint solicitation aimed at supporting innovative R&D on a range of fusion enabling technologies. The program, known as Galvanizing Advances in Market-aligned fusion for an Overabundance of Watts (GAMOW) prioritized R&D in 1) technologies and subsystems between the fusion plasma and balance of plant, 2) cost-effective, high-efficiency, high-duty-cycle driver technologies, and 3) cross-cutting areas such as novel fusion materials and advanced and additive manufacturing for fusion-relevant materials and components. The program was aimed at bridging the gap in traditional mission spaces of FES and ARPA-E, where applicants were encouraged to leverage and build on foundational SC-FES research programs while ensuring that market-aware techno-economic analyses informed project goals consistent with ARPA-E directives. The joint program made 14 awards with an execution period over the next three years and a total funding of $30M, equally shared between the two programs.

Researchers offer a new definitive test to explain auroras.
The shimmering displays of the aurora borealis have always fascinated humankind, but a demonstration of how auroral electrons are accelerated down towards the Earth where collisions with molecules in the thin upper atmosphere cause the emission of auroral light has remained elusive. According to theory, Alfvén waves accelerate electrons toward Earth, causing them to precipitate and produce auroras. Although space-based measurements provide strong support of this theory, limitations inherent to spacecraft and rocket measurements have prevented a definitive test. For the first time, using laboratory experiments on the Large Plasma Device at UCLA's Basic Plasma Science Facility, researchers from the University of Iowa, Wheaton College, and UCLA have discovered a direct link between energy transfer from Alfvén waves to electrons that causes auroras. The electrons were shown to "surf" on the electric field of the Alfvén wave, a phenomenon known as Landau damping, in which the energy of the wave is transferred to the accelerated electrons, analogous to a surfer catching a wave and being continually accelerated as the surfer moves along with the wave.

LaserNetUS: Tomographic Imaging with an intense laser-driven multi-MeV Photon Source.
Scientists from Los Alamos National Laboratory in collaboration with Colorado State University successfully demonstrated multi-MeV Photon radiography with intense lasers. Photon sources with energy >1 MeV are of significant interest for imaging and radiography of dense objects in inertial fusion energy, stockpile stewardship, industry, and homeland security applications. This work was enabled by LaserNetUS, a consortium of ten institutions, including both academic and national laboratories, funded by FES to advance laser-driven discovery science and translational research that produces societal benefit.

U.S. hardware development and delivery to ITER.
Increased design and fabrication continued for all systems within the U.S. responsibility. Two of the seven ITER Central Solenoid magnet modules were successfully delivered to the international ITER site in France.

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.
- Support for public-private partnerships through the INFUSE activity and the establishment of a new cost-share milestone-based partnership program.
- Research on inertial fusion energy science and technology.
- Research on small-scale magnetic confinement experiments.
- 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, such as high-temperature superconducting (HTS) magnets, needed to support continued improvement and capabilities of the experimental program and current and future facilities.
- Infrastructure improvements at PPPL and other DOE laboratories where fusion research is ongoing.
- Research on AI/ML relevant to fusion and plasma science.

Research in the Burning Plasma Science: Foundations area in FY 2023 will focus on high-priority scientific issues in alignment with the recommendations in the recent FESAC LRP, including addressing key science and technology needs in the design basis for an FPP.

<u>Advanced Tokamak</u>

The Advanced Tokamak (AT) element is a major pillar of the FES research portfolio, supporting a broad range of activities focused on closing gaps in the scientific and technical basis for the tokamak approach to fusion energy. The advanced tokamak is an integrated fusion energy system that simultaneously achieves a stationary plasma state characterized by high plasma pressure, high fractions of self-generated (bootstrap) plasma current, adequate heat and particle confinement, and levels of heat and particle exhaust that are compatible with plasma-facing surfaces. Generating and sustaining such states requires optimization of the configuration via experimental and theoretical studies, as well as multifaceted control algorithms that rely on efficient actuators and validated plasma models. The AT activity comprises several research lines to support the accompanying R&D in these areas, including the DIII-D National Fusion Facility, Enabling Research and Development, and Small-scale AT research.

The DIII-D user facility at General Atomics 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. The current DIII-D five-year plan aims to deliver three major goals: (1) enable a successful ITER research program; (2) develop the physics basis for and validation of the Advanced Tokamak path to a U.S. fusion pilot plant; and (3) advance the physics understanding of fusion science across a broad front, developing validated predictive capabilities to project solutions to future devices and maintaining U.S. world leadership in fusion science. The DIII-D program has the long-term objective to establish the physics basis for an integrated core-edge solution in a fusion power plant.

Enabling Research and Development (R&D) is aimed at advancing the plasma-supporting technologies required for the realization of fusion energy. Magnets are an integral feature of magnetic fusion configurations, and a primary focus of this element is to support R&D aimed at the development of magnets with higher fields, operating temperatures, and reliability, opening the way towards a FPP. In addition, this element supports the development of heating and current drive technologies, which need substantial advancement in order to meet performance, efficiency, and lifetime goals for an FPP. Enabling R&D also supports the development of plasma fueling and disruption mitigation systems, which are required to enable high-power, steady-state plasma discharges.

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. Recent efforts are focused on improving fusion plasma control physics for advanced tokamaks.

Spherical Tokamak

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 pilot plant than other plasma confinement geometries. In FY 2023, 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, high-reward, 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 Advanced Computing.

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 in partnership with ASCR. The new portfolio will build upon the SciDAC-4 portfolio that was focused on integration and whole-device modeling and expand its scope to whole-facility modeling, addressing recommendations in the FESAC long-range plan and also providing a consistent set of high-fidelity tools for design and performance assessment of FPP concepts.

The Advanced Computing for Fusion element supports efforts that address the growing data needs of fusion research, resulting from both experimental and large-scale simulation efforts, by investing in enhanced data infrastructure capabilities. This element also aims to integrate fusion-relevant capabilities developed under the Exascale Computing Project into the FES program.

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

INFUSE provides private-sector fusion companies with access to the expertise and facilities of DOE's national laboratories and other supported institutions to overcome critical scientific and technological hurdles in pursuing development of fusion energy systems. 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 Fusion Enterprise Cost Share Program is a new milestone-based program with 50/50 cost-share between DOE and the private sector. It aims at accelerating the closing of technological gaps for multiple fusion pilot plant concepts by working closely with the private sector.

Artificial Intelligence and Machine Learning

The objective is to support research on the development and application of AI/ML techniques that can have a transformative impact on FES mission areas. Research addresses recommendations from the 2018 FESAC report on "Transformative Enabling Capabilities for Efficient Advance toward Fusion Energy,"[gg] is informed by the findings of the joint 2019 FES-ASCR workshop on "Advancing Fusion with Machine Learning,"[hh] 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; plasma diagnostics; extraction of models from experimental and simulation data; and extreme data algorithms. Supported activities encompass multiple FES areas, including magnetic fusion, materials science, and discovery plasma science, and contribute to the development of FPP design tools.

Strategic Accelerator Technology

The objective is to leverage expertise across SC to maximize research and development progress in high-temperature superconducting (HTS) magnets for future fusion facilities. A key aspect is the support of the High Field Vertical Magnet Test Stand at Fermi National Laboratory, which is being funded jointly with High Energy Physics (HEP). This test stand will be a world-leading capability for testing conductors.

Inertial Fusion Energy

This activity supports development of the scientific foundation and technologies for inertial fusion energy. Improved knowledge of driver-target physics, understanding of physical limits on design parameters applicable across drivers, advanced concepts for increasing gain, and high-repetition-rate drivers and targets are all critical to advancing IFE concepts.

[gg] https://science.osti.gov/-/media/fes/fesac/pdf/2018/TEC_Report_15Feb2018.pdf
[hh] 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 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Burning Plasma Science: Foundations	**$288,009**	**$326,722**	**+$38,713**
Advanced Tokamak	$127,038	$127,122	+$84
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 22 weeks of operations at the DIII-D facility, which is 90 percent of optimal. Research will continue to exploit innovative current drive systems to assess their potential as actuators for a fusion pilot plant and to optimize plasma performance. Upgrades include increasing electron cyclotron power, completing the installation of the high-field-side lower hybrid current drive system and commencing experiments, and increasing the power of the neutral beam injection system. The Request will continue supporting research in high-temperature superconducting magnet technology, plasma heating and current drive, plasma fueling, and other enabling technologies for fusion. The Request will continue support for small-scale AT experiments.	The increase will support DIII-D operations, research aligned with the FESAC Long-Range Plan, and upgrades.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Spherical Tokamak $104,331	$101,100	-$3,231
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 support the remaining NSTX-U Recovery fabrication and machine reassembly activities, and begins to support the commissioning of auxiliary heating systems in preparation for plasma operations. Research efforts will focus on studies utilizing a variety of domestic and international spherical tokamak facilities; these studies are aligned with the mission of the NSTX-U program, which contributes to the development of the design basis for a next-step FPP. The Request will continue to support small-scale ST studies dedicated to simplifying and reducing the capital cost of future fusion facilities.	Operations funding will support the continuation of the NSTX-U Recovery activities. Research funding will focus on the highest-priority scientific objectives, which are aligned with the FESAC Long-Range Plan.
Theory & Simulation $42,000	$51,000	+$9,000
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 efforts at universities, national laboratories, and private industry focused on the fundamental theory of magnetically confined plasmas and the development of a predictive capability for magnetic fusion. The Request will continue to support the SciDAC portfolio with emphasis on whole-facility modeling, in alignment with the Long-Range Plan recommendations, and also provide a consistent set of high-fidelity tools for design and performance assessment of FPP concepts. The Request will also support Advanced Computing, including investments in enhanced data infrastructure capabilities to address the growing data needs of fusion research.	Research efforts will focus on the highest-priority activities, including continuing support of the SciDAC portfolio.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 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 continue to support infrastructure improvements, repair, maintenance, and environmental monitoring at PPPL and other DOE laboratories.	The funding will continue to support infrastructure improvements.
Public-Private Partnerships $5,000	$32,000	+$27,000
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 continue to support the INFUSE program, providing the private-sector with access to DOE developed capabilities at both national laboratories and universities. The Request also initiates a cost-share milestone-based program for private fusion companies.	The funding increase will support the new cost-share milestone-based public-private partnership program.
Artificial Intelligence and Machine Learning $7,000	$11,000	+$4,000
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 a competitive solicitation to identify multi-institutional collaborations focused on deploying AI/ML applications across FES program elements.	The level of effort will be strengthened to support distributed data capabilities and the development of FPP design tools.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Inertial Fusion Energy $ —	$3,000	+$3,000
No funding in FY 2021.	The Request will establish a new IFE program to support the priority research opportunities in scientific foundations and technologies that will be identified in the planned FY 2022 Basic Research Needs Workshop for IFE.	The funding will initiate a new program in IFE.

Note:

- *Funding for the subprogram above, includes 3.65 percent 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 unique capabilities to accelerate our scientific understanding of how to control and operate a burning plasma and contribute to the design of a fusion pilot plant (FPP). This subprogram includes long-pulse international tokamak and stellarator research, 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. Collaborative research on international facilities with capabilities not available in the U.S. aims at building the science and technology required to control, sustain, and predict a burning plasma, as described in the FESAC LRP.[ii] Multidisciplinary teams work together to close key gaps in the design basis for an FPP, 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-like scenarios and mature diagnostic suites.

Long Pulse: Stellarators
This activity supports research on stellarators, which offer the potential of steady-state confinement regimes without transient events such as 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 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 formal partnership status for the U.S. Accordingly, the U.S. is participating fully in W7-X research and has full 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 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 FPP, as recommended by the FESAC LRP. 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 FPP. The SC initiative on Fundamental

[ii] https://usfusionandplasmas.org/

Science to Transform Advanced 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. 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, e.g., an FPP, as recommended by the FESAC LRP.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Burning Plasma Science: Long Pulse $72,500	**$81,000**	**+$8,500**
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 the second budget period for U.S. teams conducting research on international facilities, which will help close key gaps in the design basis for an FPP.	No change.
Long Pulse: Stellarators $8,500	$7,500	-$1,000
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.	In the next W7-X experimental campaign, the Request will support research on turbulent transport, stability and edge physics, and boundary and scrape-off-layer physics. The Request will continue to support experiments on domestic stellarators in regimes relevant to the mainline stellarator magnetic confinement efforts.	Research efforts will emphasize the highest-priority topics.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Materials & Fusion Nuclear Science $49,000	$54,500	+$5,500
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 continue to support research activities in these areas, consistent with the recommendations of the FESAC Long-Range Plan. This includes continued development of critical technologies for an FPP, such as plasma-facing components, structural and functional materials, and breeding-blanket and tritium-handling systems. The Request will also continue to support research into advanced manufacturing technologies consistent with the SC initiative in this area. Finally, the Request will continue to support the MPEX MIE project, with efforts focused on construction following the combined baselining and approval of construction in FY 2022.	The Request will increase support for the materials and fusion nuclear science research programs and advanced manufacturing technologies. Funding for the MPEX project will decrease, consistent with the planned funding profile.
Future Facilities Studies $ —	$4,000	+$4,000
No funding in FY 2021.	The Request will support the Future Facilities Studies activity to conduct design studies for an integrated fusion plant, e.g., an FPP, consistent with the FESAC Long-Range Plan recommendation.	Funding will enhance the level of effort of this activity.

Note:

- *Funding for the subprogram above, includes 3.65 percent 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.

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 of Q = 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 EU, India, Japan, South Korea, and Russia. More information about the U.S. Contributions to the ITER project is provided in the FES Construction section.

ITER Research
To ensure that 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 FESAC LRP. A Basic Research Needs workshop is being held in FY 2022 to identify the highest-priority research and engagement opportunities for the U.S. in order to maximize the benefit of its participation in ITER.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Burning Plasma Science: High Power **$ —**	**$2,000**	**+$2,000**
ITER Research $ —	$2,000	+$2,000
No Funding in FY 2021.	The Request will support the highest-priority research and engagement opportunities identified in the Basic Research Needs workshop that is being held in FY 2022.	Funding will support highest-priority research.

Note:

- *Funding for the subprogram above, includes 3.65 percent 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 the following activities:

Plasma Science and Technology

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 Lab Plasmas (HEDLP): Research directed at exploring the behavior of plasmas at extreme conditions of temperature, density, and pressure, including relativistic high energy density (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.

Measurement Innovation

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[jj] 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 quantum simulation capabilities for fusion and plasma science, quantum sensing for plasma diagnostics, HEDLP techniques to form novel quantum materials, and plasma science tools to simulate and control quantum systems. FES also participates in supporting the SC-wide crosscutting QIS research centers.

Advanced Microelectronics

The Advanced Microelectronics activity supports discovery 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 is informed by the recent Long-Range Plan developed by FESAC, the NASEM Plasma 2020 decadal survey report, and a planned FY 2022 workshop on plasma science for microelectronics fabrication.

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 (USBPO); 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 under-represented in the U.S. S&T ecosystem and aligns with a recommendation in the FESAC LRP.

Funding for Accelerated, Inclusive Research (FAIR)

This activity supports the Funding for Accelerated, Inclusive Research (FAIR) initiative which will provide focused investment on enhancing research on clean energy, climate, and related topics at Minority Serving Institutions (MSIs), including attention to underserved and environmental justice regions.

Accelerate Innovations in Emerging Technologies (Accelerate)

This activity supports the Accelerate initiative, which will support scientific research to accelerate the transition of science advances to energy technologies.

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

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Discovery Plasma Science	**$54,491**	**$72,500**	**+$18,009**
Plasma Science and Technology	$32,700	$37,000	+$4,300
General Plasma Science	*$15,000*	*$19,000*	*+$4,000*
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.		The Request will support core research at the frontiers of basic and low temperature plasma science, as well as operations of and user-led experiments on collaborative research facilities.	Funding will support core research at universities and national laboratories.
High Energy Density Lab Plasmas	*$15,700*	*$18,000*	*+$2,300*
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 basic and translational science, MEC and LaserNetUS operations and user support, and the SC-NNSA joint program.	Funding will support core research at universities and national laboratories.
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 innovative and transformative diagnostics.	No change.
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 priority research opportunities identified in the 2018 Roundtable Workshop Report. It will also continue to support the SC QIS Research Centers.	Funding will continue to support priority research.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 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 support high priority research and the continuation of laboratory awards made through a competitive lab call and review in FY 2021.	No change.
Other FES Research $4,271	$3,500	-$771
Funding supports U.S. Burning Plasma Organization (USBPO) activities, peer reviews for solicitations, outreach programs, and FESAC.	The Request will continue to support programmatic activities such as the FES Postdoctoral Research Program, the FES Fusion and Plasma Science Outreach programs, USBPO, peer reviews for FES solicitations and project activities, and FESAC.	Funding supports highest-priority activities.
Reaching a New Energy Sciences Workforce (RENEW) $ —	$6,000	+$6,000
No funding in FY 2021.	The Request will support the RENEW initiative to provide undergraduate and graduate training opportunities for students and academic institutions under-represented in the U.S. S&T ecosystem and aligns with a recommendation in the FESAC Long-Range Plan.	The funding will enhance support of the RENEW activities.
Funding for Accelerated, Inclusive Research (FAIR) $ —	$2,000	+$2,000
No funding in FY 2021.	This activity supports the Funding for Accelerated, Inclusive Research (FAIR) initiative, which will provide focused investment on enhancing research on clean energy, climate, and related topics at Minority Serving Institutions, including attention to underserved and environmental justice communities.	The funding supports the FAIR initiative.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Accelerate Innovations in Emerging Technologies $ —	$6,000	+$6,000
No funding in FY 2021.	This activity supports the Accelerate initiative, which will support scientific research to accelerate the transition of science advances to energy technologies.	The funding supports the Accelerate initiative.

Note:

- *Funding for the subprogram above, includes 3.65 percent 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"[kk] 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-1 (CD-1), "Approve Alternative Selection and Cost Range," on October 4, 2021. The FY 2023 Request of $1,000,000 will support preliminary design activities. The estimated total project cost range is $264,000,000 to $461,000,000.

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 to 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 carbon-free fusion energy pilot plant that will keep the U.S. competitive internationally. Construction of ITER is a collaboration among the U.S., European Union, Russia, Japan, India, Republic of Korea, and China, governed under 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 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 2023 Request of $240,000,000 will support the continued systems design, fabrication of First Plasma hardware, and financial contributions for IO operations. The estimated total project cost range is $4,700,000,000 to $6,500,000,000, which includes all U.S. in-kind hardware and financial construction contributions through the completion of ITER.

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. The U.S. involvement in ITER will help to advance the promise of carbon-free, inherently safe, and abundant fusion energy.

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

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Construction	**$257,000**	**$241,000**	**-$16,000**
20-SC-61, Matter in Extreme Conditions (MEC) Petawatt Upgrade, SLAC	$15,000	$1,000	-$14,000
The Enacted budget supports design activities, preparation for developing a project baseline, and long-lead procurements for an upgrade to MEC.		The Request will continue to support design activities and preparation for developing a project performance baseline.	Funding will support critical preparation activities for baseline.
14-SC-60, U.S. Contributions to ITER	$242,000	$240,000	-$2,000
The Enacted budget supports continued design and fabrication of In-kind hardware systems for the First Plasma subproject (SP-1).		The Request will continue to support continued design and fabrication of In-kind hardware systems for the SP-1 and requested construction financial contributions.	Funding will support in-kind and financial contributions.

Fusion Energy Sciences
Capital Summary

(dollars in thousands)

	Total	Prior Years	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Capital Operating Expenses						
Capital Equipment	N/A	N/A	27,020	31,020	22,000	-5,020
Minor Construction Activities						
General Plant Projects	N/A	N/A	2,000	2,000	1,500	-500
Total, Capital Operating Expenses	**N/A**	**N/A**	**29,020**	**33,020**	**23,500**	**-5,520**

Capital Equipment

(dollars in thousands)

	Total	Prior Years	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Capital Equipment						
Major Items of Equipment						
Burning Plasma Science: Long Pulse						
Material Plasma Exposure eXperiment (MPEX)	100,579	33,084	21,000	25,000	14,000	-7,000
Total, MIEs	N/A	N/A	21,000	25,000	14,000	-7,000
Total, Non-MIE Capital Equipment	N/A	N/A	6,020	6,020	8,000	+1,980
Total, Capital Equipment	**N/A**	**N/A**	**27,020**	**31,020**	**22,000**	**-5,020**

Notes:
- *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.*
- *In FY 2021, additional funding of $7,996,000 above the Enacted level was provided for the MPEX MIE. The adjusted TEC Total is $108,575,000.*

Fusion Energy Sciences
Minor Construction Activities

(dollars in thousands)

	Total	Prior Years	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
General Plant Projects (GPP)						
Total GPPs less than $5M	N/A	N/A	2,000	2,000	1,500	-500
Total, General Plant Projects (GPP)	**N/A**	**N/A**	**2,000**	**2,000**	**1,500**	**-500**
Total, Minor Construction Activities	**N/A**	**N/A**	**2,000**	**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)

Burning Plasma Science: Long Pulse MIEs:

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 FY 2023 Request will allow the project to execute the approved performance baseline and continuation of approved long-lead procurements. MPEX scope includes the design, fabrication, installation, and commissioning of the MPEX linear plasma device, and associated facility and infrastructure modifications and reconfiguration. The CD-1 was approved on February 3, 2020, with a TPC cost range of $86,000,000–$175,000,000.

Fusion Energy Sciences
Construction Projects Summary

(dollars in thousands)

	Total	Prior Years	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
20-SC-61, Matter in Extreme Conditions (MEC) Upgrade						
Total Estimated Cost (TEC)	448,700	8,487	15,000	5,000	1,000	-14,000
Other Project Cost (OPC)	13,500	6,100	2,000	–	–	-2,000
Total Project Cost (TPC)	**462,200**	**14,587**	**17,000**	**5,000**	**1,000**	**-16,000**
14-SC-60, U.S. Contributions to ITER						
Total Estimated Cost (TEC)	3,330,198	1,613,617	242,000	221,000	240,000	-2,000
Other Project Cost (OPC)	70,302	70,302	–	–	–	–
Total Project Cost (TPC)	**3,400,500**	**1,683,919**	**242,000**	**221,000**	**240,000**	**-2,000**
Total, Construction						
Total Estimated Cost (TEC)	**N/A**	**N/A**	**257,000**	**226,000**	**241,000**	**-16,000**
Other Project Cost (OPC)	**N/A**	**N/A**	**2,000**	**–**	**–**	**-2,000**
Total Project Cost (TPC)	**N/A**	**N/A**	**259,000**	**226,000**	**241,000**	**-18,000**

Note:
- *In FY 2021, funding was reduced to $800,000,000 for MEC OPC. The adjusted TPC with FY 2021 Current funding is $461,000,000.*

Fusion Energy Sciences
Funding Summary

(dollars in thousands)

	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Research	260,149	289,149	337,722	+77,573
Facility Operations	129,211	129,211	129,000	-211
Projects				
Line Item Construction (LIC)	259,000	226,000	241,000	-18,000
Major Items of Equipment (MIE)	21,000	25,000	14,000	-7,000
Total, Projects	**280,000**	**251,000**	**255,000**	**-25,000**
Other	2,640	2,640	1,500	-1,140
Total, Fusion Energy Sciences	**672,000**	**672,000**	**723,222**	**+51,222**

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 2021 Enacted	FY 2021 Current	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Scientific User Facilities - Type A					
DIII-D National Fusion Facility	**121,000**	**114,971**	**121,000**	**123,000**	**+2,000**
Number of Users	830	429	515	515	-315
Achieved Operating Hours	–	748	–	–	–
Planned Operating Hours	720	720	800	864	+144
Optimal Hours	960	960	880	960	–
Percent of Optimal Hours	75.0%	77.9%	90.0%	90.0%	+15.0%
Unscheduled Down Time Hours	–	102	–	–	–
National Spherical Torus Experiment-Upgrade	**101,331**	**95,092**	**101,331**	**98,100**	**-3,231**
Number of Users	372	358	372	373	+1
Total, Facilities	**222,331**	**210,063**	**222,331**	**221,100**	**-1,231**
Number of Users	1,202	787	887	888	-314
Achieved Operating Hours	–	748	–	–	–
Planned Operating Hours	720	720	800	864	+144
Optimal Hours	960	960	880	960	–
Unscheduled Down Time Hours	–	102	–	–	–

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 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Number of Permanent Ph.Ds (FTEs)	846	888	964	+118
Number of Postdoctoral Associates (FTEs)	104	109	120	+16
Number of Graduate Students (FTEs)	282	296	322	+40
Number of Other Scientific Employment (FTEs)	1,261	1,322	1,441	+180
Total Scientific Employment (FTEs)	**2,493**	**2,615**	**2,847**	**+354**

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 2023 Request for the Matter in Extreme Conditions (MEC) Petawatt Upgrade project is $1,000,000. The project has a preliminary estimated Total Project Cost (TPC) range of $264,000,000 to $461,000,000. 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. It will utilize 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.

Significant Changes

The MEC Petawatt Upgrade project was initiated in FY 2019. 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. The project achieved CD-1, "Approve Alternative Selection and Cost Range," on October 4, 2021, and will initiate the TEC-funded preliminary design phase.

The upper-end of the cost range increased from $372,000,000 to $461,000,000 and from a CD-4 date of 1Q FY 2028 to 4Q FY 2029. The increases in cost and schedule were implemented in order to address the uncertainty associated with budget requests and future appropriations.

A Level III 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	TBD	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
FY 2023	1/4/19	3/9/21	10/4/21	3Q FY 2024	3Q FY 2024	3Q FY 2024	TBD	4Q FY 2029

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, 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
FY 2023	23,487	425,213	448,700	12,300	12,300	461,000

Note:
- *This project has not received CD-2 approval; therefore, funding estimates are preliminary.*
- *Increase from FY 2022 due to funding uncertainty which increased cost contingency amounts.*

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 target 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), composed of an access tunnel, an experimental hall with 12,000 to 17,000 square feet, a stand-alone control room, 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 Sciences, Engineering, and Medicine (NASEM) 2017 study titled "Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light[ll]" found that about 80 percent to 90 percent of the high-intensity laser systems are overseas, and all the highest-power lasers currently under 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

[ll] https://www.nap.edu/catalog/24939/opportunities-in-intense-ultrafast-lasers-reaching-for-the-brightest-light

the SLAC National Accelerator Laboratory has demonstrated exquisite ultrafast measurements of the material structural response to radiation. The upgrade includes the 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 address 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*.

<u>Key Performance Parameters (KPPs)</u>
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.

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	8,487	–	–
FY 2021	15,000	23,487	–
FY 2022	–	–	23,487
Total, Design (TEC)	**23,487**	**23,487**	**23,487**
Construction (TEC)			
FY 2022	5,000	5,000	5,000
FY 2023	1,000	1,000	1,000
Outyears	419,213	419,213	419,213
Total, Construction (TEC)	**425,213**	**425,213**	**425,213**
Total Estimated Cost (TEC)			
FY 2020	8,487	–	–
FY 2021	15,000	23,487	–
FY 2022	5,000	5,000	28,487
FY 2023	1,000	1,000	1,000
Outyears	419,213	419,213	419,213
Total, TEC	**448,700**	**448,700**	**448,700**

(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	800	800	2,782
FY 2022	–	–	30
Outyears	5,400	5,400	5,400
Total, OPC	**12,300**	**12,300**	**12,300**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Project Cost (TPC)			
FY 2019	1,600	1,600	280
FY 2020	12,987	4,500	3,808
FY 2021	15,800	24,287	2,782
FY 2022	5,000	5,000	28,517
FY 2023	1,000	1,000	1,000
Outyears	424,613	424,613	424,613
Total, TPC	**461,000**	**461,000**	**461,000**

Note:

- *This project has not received CD-2 approval; therefore, funding 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	14,787	17,000	**N/A**
Design - Contingency	8,700	3,000	**N/A**
Total, Design (TEC)	**23,487**	**20,000**	**N/A**
Construction	129,093	161,798	**N/A**
Equipment	138,076	115,191	**N/A**
Construction - Contingency	158,044	68,111	**N/A**
Total, Construction (TEC)	**425,213**	**345,100**	**N/A**
Total, TEC	**448,700**	**365,100**	**N/A**
Contingency, TEC	*166,744*	*71,111*	***N/A***
Other Project Cost (OPC)			
R&D	350	350	**N/A**
Conceptual Planning	4,650	850	**N/A**
Conceptual Design	1,900	1,900	**N/A**
Other OPC Costs	3,800	2,400	**N/A**
OPC - Contingency	1,600	1,400	**N/A**
Total, Except D&D (OPC)	**12,300**	**6,900**	**N/A**
Total, OPC	**12,300**	**6,900**	**N/A**
Contingency, OPC	*1,600*	*1,400*	***N/A***
Total, TPC	**461,000**	**372,000**	**N/A**
Total, Contingency (TEC+OPC)	***168,344***	***72,511***	***N/A***

5. Schedule of Appropriations Requests

(dollars in thousands)

Fiscal Year	Type	Prior Years	FY 2021	FY 2022	FY 2023	Outyears	Total
FY 2020	TEC	1,000	—	—	—	—	1,000
	OPC	1,600	—	—	—	—	1,600
	TPC	2,600	—	—	—	—	2,600
FY 2021	TEC	15,000	5,000	—	—	170,400	190,400
	OPC	6,100	—	—	—	3,500	9,600
	TPC	21,100	5,000	—	—	173,900	200,000
FY 2022	TEC	15,000	15,000	5,000	—	327,000	362,000
	OPC	6,100	2,000	—	—	1,900	10,000
	TPC	21,100	17,000	5,000	—	328,900	372,000
FY 2023	TEC	8,487	15,000	5,000	1,000	419,213	448,700
	OPC	6,100	800	—	—	5,400	12,300
	TPC	14,587	15,800	5,000	1,000	424,613	461,000

Note:

- *This project has not received CD-2 approval; therefore, funding estimates are preliminary.*

6. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy	4Q FY 2029
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	21,200	21,200	931,000	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

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 2023 Request for the U.S. ITER project is $240,000,000 of Total Estimated Cost (TEC) funding. The Total Project Cost (TPC) for the U.S. Contributions to ITER (U.S. ITER) project is $3,400,500,000, including $2,500,000,000 for Subproject-1 (SP-1), First Plasma Hardware for U.S. ITER and $900,500,000 estimated for cash contributions. Sections of this Construction Project Data Sheet (CPDS) have been tailored accordingly to reflect the unique nature of the U.S. ITER project. Research results from the ITER project, if successful, are expected to contribute to the development of a fusion pilot plant. Fusion energy could provide a carbon-free, inherently safe energy source that will be a significant contributor to ameliorating climate change.

As outlined in the May 2016 Secretary of Energy's Report to Congress, DOE expected 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 FY 2023.

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

Significant Changes

The FY 2023 Request of $240,000,000 will support the continued design and fabrication of "in-kind" hardware systems and construction financial contributions to the ITER Organization. This includes continued fabrication and delivery of the Central Solenoid (CS) magnet system, which consists of seven superconducting magnet modules. In FY 2022, the U.S. is scheduled to ship the second and third CS magnet modules and continue the design and fabrication efforts associated with other "In-kind" hardware systems. The U.S. ITER project will have obligated more than $1,500,000,000 through the end of FY 2022, of which more than 80 percent is to U.S. industry, universities, and DOE laboratories.

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

A Federal Project Director with a level-I certification has been assigned to this Project, and is currently pursuing higher-level certification.

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
FY 2023	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
FY 2023	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);*
- *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).*

<u>Project Cost History</u>

At the time of CD-1 approval in January 2008, the preliminary cost range was $1,450,000,000 to $2,200,000,000. Until 2016, however, it was not possible to confidently baseline the project due to delays early on 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 $4,000,000,000 to $6,500,000,000 would likely encompass the final TPC. This range, recommended in 2013, was included in subsequent President's Budget Requests. In May 2016, the Secretary of Energy 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 an Independent 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-1 Revised (CD-1R) range of $4,700,000,000 to $6,500,000,000. 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 $2,500,000,000. Starting in FY 2022, the table below includes both SP-1 and cash contributions.

Subproject 1 (First Plasma Hardware for U.S. ITER) and Cash Contributions

(dollars in thousands)

Fiscal Year	TEC, Design	TEC, Construction	TEC, Cash Contributions	TEC, Total	OPC, Except D&D	OPC, Total	TPC
FY 2006	—	1,038,000	—	1,038,000	84,000	84,000	1,122,000
FY 2007	—	1,077,051	—	1,077,051	44,949	44,949	1,122,000
FY 2008	—	1,078,230	—	1,078,230	43,770	43,770	1,122,000
FY 2009	—	266,366	—	266,366	38,075	38,075	304,441
FY 2010	—	294,366	—	294,366	70,019	70,019	364,385
FY 2011	—	379,366	—	379,366	65,019	65,019	444,385
FY 2012	—	394,366	—	394,366	75,019	75,019	469,385
FY 2013	—	617,261	—	617,261	82,124	82,124	699,385
FY 2014	—	806,868	—	806,868	73,159	73,159	880,027
FY 2015	—	942,578	—	942,578	80,341	80,341	1,022,919
FY 2016	—	1,092,544	—	1,092,544	80,341	80,341	1,172,885
FY 2017	696,025	1,723,334	—	2,419,359	80,641	80,641	2,500,000
FY 2018	696,025	1,723,334	—	2,419,359	80,641	80,641	2,500,000
FY 2019	696,025	1,723,334	—	2,419,359	80,641	80,641	2,500,000
FY 2020	696,025	1,733,673	—	2,429,698	70,302	70,302	2,500,000
FY 2021	696,025	1,733,673	—	2,429,698	70,302	70,302	2,500,000
FY 2022	503,262	1,926,436	1,158,000	3,587,698	70,302	70,302	3,658,000
FY 2023	483,126	1,946,572	900,500	3,330,198	70,302	70,302	3,400,500

Notes:

- *From FY 2006 through FY 2014, ITER was a MIE.*
- *From FY 2009 to FY 2016, the TPC for U.S. ITER was not reported.*
- *Starting in FY 2017, TPC estimates 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.*

2. Project Scope and Justification

ITER, currently the largest science experiment in the world, is a major fusion research facility under construction in St. Paul-lez-Durance, France by an international partnership of seven Members or domestic agencies, specifically, the U.S., China, the EU, India, the Republic of Korea, Japan, and the Russian Federation. ITER is co-owned and co-governed by the seven Members. 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 Member entered the project 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 contribute one-eleventh (9.09 percent) of the ITER facility’s construction cost. The IO is a designated international legal entity located in France.

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.
- 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 currently 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)
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[mm]) 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)

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

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 planned experimental outcomes expected from ITER: The first 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 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 following 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. Contributions to the ITER Project will not deliver an integrated operating facility, but rather In-kind hardware contributions, which represent a portion of 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 needed, which requires IO approval of the final designs (see Table 1 on previous page for more detail).

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
Total, Design (TEC)	**483,126**	**483,126**	**483,126**
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	41,527
FY 2022	136,117	136,117	136,117
FY 2023	170,000	170,000	170,000
Outyears	543,578	543,628	819,732
Total, Construction (TEC)	**1,946,572**	**1,946,644**	**1,946,644**

(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
FY 2023	70,000	70,000	70,000
Outyears	470,003	470,003	470,003
Total, Cash Contributions (TEC)	**900,500**	**900,500**	**900,500**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
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	101,527
FY 2022	221,000	221,000	221,000
FY 2023	240,000	240,000	240,000
Outyears	1,013,581	1,013,631	1,289,735
Total, TEC	**3,330,198**	**3,330,270**	**3,330,270**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Other Project Cost (OPC)			
FY 2006	3,449	3,449	1,110
FY 2007	16,000	16,000	7,607
FY 2008	-74	-74	7,513
FY 2009	15,000	15,000	5,072
FY 2010	20,000	20,000	7,754
FY 2011	13,000	13,000	10,032
FY 2012	333	311	22,302
FY 2013	2,560	2,560	5,984
FY 2014	–	–	2,090
FY 2015	–	–	600
FY 2016	34	34	–
FY 2017	–	-50	58
FY 2018	–	–	2
FY 2019	–	–	106
Total, OPC	**70,302**	**70,230**	**70,230**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Project Cost (TPC)			
FY 2006	19,315	19,315	9,391
FY 2007	60,000	60,000	39,257
FY 2008	26,070	26,070	34,278
FY 2009	124,000	124,000	54,949
FY 2010	135,000	135,000	83,540
FY 2011	80,000	80,000	97,478
FY 2012	105,000	104,966	134,765
FY 2013	124,000	124,034	129,863
FY 2014	199,500	199,500	188,980
FY 2015	150,000	150,000	130,686
FY 2016	115,034	115,034	106,519
FY 2017	50,000	49,950	123,175
FY 2018	122,000	122,000	98,187
FY 2019	132,000	132,000	156,832
FY 2020	242,000	242,000	160,338
FY 2021	242,000	242,000	101,527
FY 2022	221,000	221,000	221,000
FY 2023	240,000	240,000	240,000
Outyears	1,013,581	1,013,631	1,289,735
Total, TPC	**3,400,500**	**3,400,500**	**3,400,500**

Notes:

- *The total project cost (TPC) shown above is only for SP-1 In-kind and cash contributions through the completion of SP-1. SP-2 is expected to be baselined in FY 2023 and when combined with SP-1 and cash contributions, will bring the entire project TPC to within the CD-1 (R) cost range of $4,700,000,000–$6,500,000,000.*
- *In FY 2012, prior year actuals were adjusted to incorporate project funds used at PPPL and DOE. Obligation adjustments reflect year-end PPPL settlement funding.*
- *Starting in FY 2014, this project is funded as a Congressional control point. Appropriations prior to FY 2014 reflect major item of equipment funding.*
- *FY 2016 funding for taxes and tax support is included in the FY 2017 Hardware funding amount.*
- *All Appropriations for the U.S. Contributions to ITER project include both funding for SP-1 and funding for Cash Contributions.*
- *Cash Contributions includes cash payments, secondees, taxes and tax support and are considered separate from the SP-1 TPC.*
- *TEC: Obligations and costs through FY 2021 reflect actuals; obligations and costs for FY 2022 and the outyears are estimates.*

4. Details of Project Cost Estimate

The overall U.S. Contributions to ITER project has an approved revised CD-1 Cost Range (CD-1R). DOE chose to divide the project hardware scope into two distinct subprojects (FP SP-1, and Post-FP or SP-2) so that an initial portion of the project that was mature enough to baseline could be accomplished. The baseline for SP-1 ($2,500,000,000) was approved in January 2017. Baselining of SP-2 is expected in FY 2023; SP-2 design work is underway which is included in SP-1 scope. An Independent Project Review (IPR) of U.S. 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. 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	483,126	503,262	573,660
Design - Contingency	N/A	N/A	122,365
Total, Design (TEC)	**483,126**	**503,262**	**696,025**
Construction	1,696,355	1,696,355	**N/A**
Equipment	N/A	N/A	1,362,521
Construction - Contingency	250,217	230,081	371,152
Total, Construction (TEC)	**1,946,572**	**1,926,436**	**1,733,673**
Cash Contributions	900,500	N/A	**N/A**
Total, Cash Contributions (TEC)	**900,500**	**N/A**	**N/A**
Total, TEC	**3,330,198**	**2,429,698**	**2,429,698**
Contingency, TEC	*250,217*	*230,081*	*493,517*
Other Project Cost (OPC)			
OPC, Except D&D	70,302	70,302	70,302
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	**3,400,500**	**2,500,000**	**2,500,000**
Total, Contingency (TEC+OPC)	***250,217***	***230,081***	***493,517***

Notes:

- *In the table above, the current total estimate includes cash contributions estimate to align with the TPC budget request. The Baseline information represents only the SP-1 project.*
- *Current total estimated design reflects work done prior to CD-2/3. When determining how best to incorporate design work after CD-2/3, DOE treated the remaining design work the same as all other scope to be accomplished under SP-1.*

5. **Schedule of Appropriations Requests**

(dollars in thousands)

Fiscal Year	Type	Prior Years	FY 2021	FY 2022	FY 2023	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	TEC	266,366	—	—	—	—	266,366
	OPC	38,075	—	—	—	—	38,075
	TPC	304,441	—	—	—	—	304,441
FY 2010	TEC	294,366	—	—	—	—	294,366
	OPC	70,019	—	—	—	—	70,019
	TPC	364,385	—	—	—	—	364,385
FY 2011	TEC	379,366	—	—	—	—	379,366
	OPC	65,019	—	—	—	—	65,019
	TPC	444,385	—	—	—	—	444,385
FY 2012	TEC	394,366	—	—	—	—	394,366
	OPC	75,019	—	—	—	—	75,019
	TPC	469,385	—	—	—	—	469,385
FY 2013	TEC	617,261	—	—	—	—	617,261
	OPC	82,124	—	—	—	—	82,124
	TPC	699,385	—	—	—	—	699,385
FY 2014	TEC	806,868	—	—	—	—	806,868
	OPC	73,159	—	—	—	—	73,159
	TPC	880,027	—	—	—	—	880,027
FY 2015	TEC	942,578	—	—	—	—	942,578
	OPC	80,341	—	—	—	—	80,341
	TPC	1,022,919	—	—	—	—	1,022,919
FY 2016	TEC	1,092,544	—	—	—	—	1,092,544
	OPC	80,341	—	—	—	—	80,341
	TPC	1,172,885	—	—	—	—	1,172,885

(dollars in thousands)

Fiscal Year	Type	Prior Years	FY 2021	FY 2022	FY 2023	Outyears	Total
FY 2017	TEC	1,182,244	—	—	—	1,237,115	2,419,359
	OPC	80,641	—	—	—	—	80,641
	TPC	1,262,885	—	—	—	1,237,115	2,500,000
FY 2018	TEC	1,170,244	—	—	—	1,249,115	2,419,359
	OPC	80,641	—	—	—	—	80,641
	TPC	1,250,885	—	—	—	1,249,115	2,500,000
FY 2019	TEC	1,245,244	—	—	—	1,174,115	2,419,359
	OPC	80,641	—	—	—	—	80,641
	TPC	1,325,885	—	—	—	1,174,115	2,500,000
FY 2020	TEC	1,478,617	—	—	—	951,081	2,429,698
	OPC	70,302	—	—	—	—	70,302
	TPC	1,548,919	—	—	—	951,081	2,500,000
FY 2021	TEC	1,613,617	107,000	—	—	709,081	2,429,698
	OPC	70,302	—	—	—	—	70,302
	TPC	1,683,919	107,000	—	—	709,081	2,500,000
FY 2022	TEC	1,613,617	242,000	221,000	—	1,511,081	3,587,698
	OPC	70,302	—	—	—	—	70,302
	TPC	1,683,919	242,000	221,000	—	1,511,081	3,658,000
FY 2023	TEC	1,613,617	242,000	221,000	240,000	1,013,581	3,330,198
	OPC	70,302	—	—	—	—	70,302
	TPC	1,683,919	242,000	221,000	240,000	1,013,581	3,400,500

Notes:
- *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.*
- *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.*
- *Prior to FY 2015, the requests were for a major item of equipment broken out by TEC, OPC, and TPC.*
- *Starting in FY 2022, the table above includes both SP-1 and cash contributions.*

6. Related Operations and Maintenance Funding Requirements

The U.S. Contributions to ITER operations phase is to begin with initial integrated commissioning activities with an assumed useful life of 20 to 25 years. The fiscal year in which commissioning activities begin depends on the international ITER project schedule, which currently indicates 2025. As a result of COVID-19 and other known delays, the overall ITER project is being re-baselined to update cost and schedule estimates.

Start of Operation or Beneficial Occupancy	12/2025
Expected Useful Life	30–35 years
Expected Future Start of D&D of this capital asset	2058-2063

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 five 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 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, to use 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 use best value, competitive source-selection procedures to the maximum extent possible, including foreign firms on the tender/bid list when necessary. 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.