High Energy Physics

Overview

The mission of the High Energy Physics (HEP) program is to understand how the universe works at its most fundamental level by discovering the elementary constituents of matter and energy, probing the interactions between them, and exploring the basic nature of space and time. HEP accomplishes its mission through excellence in scientific discovery in particle physics, and through stewardship of world-class scientific user facilities that enable cutting-edge research and development. HEP continues to deliver major construction projects on time and on budget, and provide reliable availability and support to users for operating facilities.

Our current understanding of the elementary constituents of matter and energy and the forces that govern them is described by the Standard Model of particle physics. However, experimental measurements suggest that the Standard Model is incomplete and that new physics may be discovered by future experiments. The May 2014 report of the Particle Physics Project Prioritization Panel (P5), "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context"[a] was unanimously approved by the High Energy Physics Advisory Panel (HEPAP) to serve the DOE and National Science Foundation (NSF) as the ten-year strategic plan for U.S. high energy physics in the context of a 20-year global vision. The P5 report identified five intertwined science drivers of particle physics that provide compelling lines of inquiry with great promise to discover what lies beyond the Standard Model:

- Use the Higgs boson as a new tool for discovery;
- Pursue the physics associated with neutrino mass;
- Identify the new physics of dark matter;
- Understand cosmic acceleration: dark energy and inflation; and
- Explore the unknown: new particles, interactions, and physical principles.

The HEP program enables scientific discovery and supports cutting edge research and development (R&D):

- Energy Frontier Experimental Physics, where researchers accelerate particles to the highest energies ever made by humanity and collide them to produce and study the fundamental constituents of matter.
- Intensity Frontier Experimental Physics, where researchers use a combination of intense particle beams and highly sensitive detectors to make extremely precise measurements of particle properties, to study some of the rarest interactions predicted by the Standard Model, and to search for new physics.
- Cosmic Frontier Experimental Physics, where researchers use naturally occurring cosmic particles and phenomena to reveal the nature of dark matter, understand the cosmic acceleration caused by dark energy and inflation, infer certain neutrino properties, and explore the unknown.
- Theoretical, Computational, and Interdisciplinary Physics provides the framework to explain experimental observations and gain a deeper understanding of nature.
- The Advanced Technology R&D subprogram fosters fundamental research into particle acceleration and detection techniques and instrumentation.

Innovative research methods and enabling technologies that emerge from R&D into accelerators, instrumentation, quantum information science (QIS), and artificial intelligence (AI) and machine learning (ML) will advance scientific knowledge in high energy physics and in a broad range of related fields, advancing DOE's strategic goals for science. Many of the advanced technologies, research tools, and analysis techniques originally developed for high energy physics have proved widely applicable to other scientific disciplines as well as for health services, national security, and the private sector.

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[a] High Energy Physics Advisory Panel, Department of Energy. Report of the Particle Physics Project Prioritization Panel (P5). Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context. May 2014. https://science.osti.gov/~/media/hep/hepap/pdf/May-2014/FINAL_P5_Report_053014.pdf

Highlights of the FY 2022 Request

The FY 2022 Request for $1,061.0 million focuses resources toward the highest priorities in fundamental research, operation and maintenance of scientific user facilities, facility upgrades, and projects identified in the P5 report.

The Accelerator Stewardship subprogram moves to the Accelerator R&D and Production (ARDAP) program in the FY 2022 Request.

Key elements in the FY 2022 Request include:

Research

The Request provides continued support for university and laboratory researchers carrying on critical core competencies, enabling high priority theoretical and experimental activities in pursuit of discovery science. The Request provides support to foster a diverse, highly skilled, American workforce, and to build R&D capacity and conduct world-leading R&D:

- Accelerator Science and Technology Initiative: In coordination with the ARDAP program, HEP will continue and increase support for mid- to long-term R&D to maintain a leading position in key accelerator technologies that define SC's competitive advantage.
- AI/ML: Research to tackle the challenges of managing increasingly high volumes and complexity of HEP experimental and simulated data, and to address cross-cutting challenges across the HEP program in coordination with DOE investments in exascale computing and associated AI efforts.
- Integrated Computational and Data Infrastructure for Scientific Discovery: In coordination with SC, HEP will support development of data storage capabilities to handle tens of exabytes of data from future experiments; cross-cutting efforts in AI/ML and edge computing to seek solutions for real-time and extremely high data rate environments; and investments in software development to improve the interface with SC infrastructure and ASCR-supported middleware.
- Microelectronics: HEP will work together with Advanced Scientific Computing Research (ASCR), Basic Energy Sciences (BES), and Fusion Energy Sciences (FES) programs to support multi-disciplinary microelectronics research, including 5G, to accelerate the advancement of microelectronic technologies.
- QIS: R&D to accelerate discovery in particle physics while advancing the national effort. HEP QIS promotes the co-development of quantum information, theory, and technology with the science drivers and opens prospects for new capabilities in sensing, simulation, and computing.
- QIS Research Centers: HEP, in partnership with other SC programs, will continue support for multi-disciplinary QIS Research Centers initiated in FY 2020 to accelerate the advancement of QIS through vertical integration between systems and theory, and hardware and software. QIS Research Center scope includes work relating to sensors, quantum computing, emulators/simulators, and enabling technologies that will pave the path to accelerate and exploit QIS-associated technologies in the longer term.
- Reaching a New Energy Sciences Workforce (RENEW): The Office of Science is fully committed to advancing a diverse, equitable, and inclusive research community. This commitment is key to providing the scientific and technical expertise for U.S. leadership in high energy physics. Toward that goal, HEP will participate in the SC-wide RENEW initiative that leverages SC's unique national laboratories, user facilities, and other research infrastructures to provide undergraduate and graduate training opportunities for students and academic institutions not currently well represented in the U.S. S&T ecosystem. This includes Minority Serving Institutions and individuals from groups historically underrepresented in STEM, but also includes students from communities with environmental justice impacts and the EPSCoR jurisdictions. The hands-on experiences gained through the RENEW initiative will open new career avenues for the participants, forming a nucleus for a future pool of talented young scientists, engineers, and technicians with the critical skills and expertise needed for the full breadth of SC research activities, including DOE national laboratory staffing.

Facility Operations

HEP supports two Scientific User Facilities. The Fermilab Accelerator Complex and the Facility for Advanced Accelerator Experimental Tests II (FACET-II) will continue operations at 90 percent of optimal. HEP supports laboratory-based accelerator and detector test facilities, and supports the maintenance and operations of large-scale experiments and facilities that are not based at a national laboratory, including the U.S. Large Hadron Collider (LHC) at CERN in Geneva, Switzerland; Sanford Underground Research Facility (SURF) in Lead, South Dakota; Vera C. Rubin Observatory in Chile; Dark Energy Spectroscopic Instrument (DESI) at the Mayall telescope in Arizona; Large Underground Xenon (LUX)-ZonED Proportional Scintillation in Liquid Noble gases (Zeplin) (LUX-ZEPLIN) (LZ) dark matter experiment at SURF; the Super

Cryogenic Dark Matter Search at Sudbury Neutrino Observatory Laboratory (SuperCDMS-SNOLAB) experiment in the Creighton Mine near Sudbury, Ontario, Canada; and the Belle II experiment at the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan.

Projects

The Request provides continued support for the Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE), Proton Improvement Plan II (PIP-II), and Muon to Electron Conversion Experiment (Mu2e) projects. The FY 2022 Request also continues four Major Item of Equipment (MIE) projects: Cosmic Microwave Background Stage 4 (CMB-S4), High-Luminosity (HL-LHC) Accelerator Upgrade Project, and the HL-LHC ATLAS and CMS Detector Upgrade Projects. The FY 2022 Request includes one new MIE start, the Accelerator Controls Operations Research Network (ACORN).

High Energy Physics
FY 2022 Research Initiatives

High Energy Physics supports the following FY 2022 Research Initiatives.

(dollars in thousands)

	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Accelerator Science and Technology Initiative	–	6,411	17,432	+11,021
Artificial Intelligence and Machine Learning	15,000	33,488	35,806	+2,318
Integrated Computational & Data Infrastructure	–	–	4,146	+4,146
Microelectronics	–	5,000	7,000	+2,000
Quantum Information Science	38,500	45,072	51,566	+6,494
Reaching a New Energy Sciences Workforce (RENEW)	–	–	4,000	+4,000
Total, Research Initiatives	**53,500**	**89,971**	**119,950**	**+29,979**

High Energy Physics
Funding

	(dollars in thousands)			
	FY 2020 Enacted	**FY 2021 Enacted**	**FY 2022 Request**	**FY 2022 Request vs FY 2021 Enacted**
High Energy Physics				
Energy Frontier, Research	71,125	68,000	71,833	+3,833
Energy Frontier, Facility Operations and Experimental Support	52,650	53,650	49,850	-3,800
Energy Frontier, Projects	100,000	72,500	40,000	-32,500
Energy Frontier, SBIR/STTR	4,663	–	–	–
Total, Energy Frontier Experimental Physics	**228,438**	**194,150**	**161,683**	**-32,467**
Intensity Frontier, Research	58,871	63,082	65,994	+2,912
Intensity Frontier, Facility Operations and Experimental Support	177,122	166,785	176,845	+10,060
Intensity Frontier, Projects	5,494	3,000	8,000	+5,000
Intensity Frontier, SBIR/STTR	8,747	–	–	–
Total, Intensity Frontier Experimental Physics	**250,234**	**232,867**	**250,839**	**+17,972**
Cosmic Frontier, Research	48,072	47,091	49,012	+1,921
Cosmic Frontier, Facility Operations and Experimental Support	41,358	44,500	42,500	-2,000
Cosmic Frontier, Projects	2,000	6,000	5,000	-1,000
Cosmic Frontier, SBIR/STTR	3,471	–	–	–
Total, Cosmic Frontier Experimental Physics	**94,901**	**97,591**	**96,512**	**-1,079**
Theoretical, Computational, and Interdisciplinary Physics, Research	111,434	136,362	157,422	+21,060
Theoretical, Computational, and Interdisciplinary Physics, SBIR/STTR	4,093	–	–	–
Total, Theoretical, Computational, and Interdisciplinary Physics	**115,527**	**136,362**	**157,422**	**+21,060**

(dollars in thousands)

	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Advanced Technology R&D, Research	64,391	72,833	75,344	+2,511
Advanced Technology R&D, Facility Operations and Experimental Support	39,232	43,262	40,200	-3,062
Advanced Technology R&D, SBIR/STTR	3,783	–	–	–
Total, Advanced Technology R&D	**107,406**	**116,095**	**115,544**	**-551**
HEP Accelerator Stewardship, Research	10,788	10,835	–	-10,835
HEP Accelerator Stewardship, Facility Operations and Experimental Support	6,067	6,100	–	-6,100
HEP Accelerator Stewardship, SBIR/STTR	639	–	–	–
Total, HEP Accelerator Stewardship	**17,494**	**16,935**	**–**	**-16,935**
Subtotal, High Energy Physics	**814,000**	**794,000**	**782,000**	**-12,000**
Construction				
18-SC-42, Proton Improvement Plan II (PIP-II), FNAL	60,000	79,000	90,000	+11,000
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment	171,000	171,000	176,000	+5,000
11-SC-41, Muon to Electron Conversion Experiment, FNAL	–	2,000	13,000	+11,000
Subtotal, Construction	**231,000**	**252,000**	**279,000**	**+27,000**
Total, High Energy Physics	**1,045,000**	**1,046,000**	**1,061,000**	**+15,000**

SBIR/STTR funding:

- FY 2020 Enacted: SBIR $22,265,000 and STTR $3,131,000
- FY 2021 Enacted: SBIR $22,325,000 and STTR $3,140,000
- FY 2022 Request: SBIR $22,618,000 and STTR $3,181,000

High Energy Physics
Explanation of Major Changes

	(dollars in thousands) FY 2022 Request vs FY 2021 Enacted
Energy Frontier Experimental Physics The Request will support data analysis activities during the next LHC run that are prioritized through a competitive peer review process and are based on highest scientific merit and potential impact. Efforts associated with the HL-LHC ATLAS and HL-LHC CMS Detector upgrade activities will continue. An increase in funding to support additional U.S.-based computing infrastructure will be offset by a decrease in funding due to the completion of the installation and commissioning of U.S.-built detector components for the ATLAS and CMS detector upgrades. Support will focus on critical path items to best maintain synchronization with the international LHC and HL-LHC schedules as well as prototyping and fabrication efforts necessary to continue the HL-LHC ATLAS and CMS Detector Upgrade Projects.	**-32,467**
Intensity Frontier Experimental Physics The Request will increase research to support data collection and analysis on the Short-Baseline Neutrino (SBN) program. Support for research on lower priority small- to mid-scale neutrino experiments will ramp down. The Request will increase the Fermilab Accelerator Complex from 81 to 90 percent of optimal operations. Support for General Plant Project (GPP) funding increases to fund the Target Systems Integration Building construction. Funding will support increased excavation support costs at SURF for LBNF/DUNE construction, and increased ACORN MIE OPC for system design and other related engineering activities.	**+17,972**
Cosmic Frontier Experimental Physics The Request will increase support for research efforts for data collection and analysis on new experiments, efforts on CMB-S4, and scientific planning for future experiments, while support for completed experiments will ramp down. Support will continue for commissioning and pre-operations activities of Vera C. Rubin Observatory and the Dark Energy Science Collaboration (DESC) and the commissioning of SuperCDMS-SNOLAB will complete. The Request will prioritize design activities for CMB-S4.	**-1,079**
Theoretical, Computational, and Interdisciplinary Physics The Request will increase to support the new integrated computational and data infrastructure initiative, and the highest-impact theoretical research as determined by competitive peer review. Funding increases to support innovation and new opportunities in building algorithms that learn about complex data to solve big-data computing hardware and infrastructure challenges; embedding AI into sensors and experimental design in extreme environments; and developing operations and controls AI/ML techniques. The Request increases to support the multi-laboratory HEP Computational Center for Excellence to develop portable parallelization solutions, data transfer and storage challenges, and event generation and complex workflows. Funding increases to support quantum simulation, physics beyond the Standard Model experiments using HEP and QIS expertise and techniques, and lab research technology including quantum networks and communications testbeds. This subprogram also supports the RENEW initiative to provide undergraduate and graduate training opportunities for students and academic institutions not currently well represented in the U.S. S&T ecosystem.	**+21,060**

	(dollars in thousands) FY 2022 Request vs FY 2021 Enacted
Advanced Technology R&D The Request will capitalize on the science opportunities at the newly completed FACET-II facility and the second beamline at Berkeley Lab Laser Accelerator (BELLA); continue the Traineeship Program; increase support for the Accelerator Science and Technology Initiative; and increase support for microelectronics R&D activities. Ongoing Detector R&D will prioritize support for collaborative opportunities at universities and national laboratories that enable new directions in HEP discovery science programs and strengthen new technology developments and capabilities that address priorities identified in the FY 2020 Basic Research Needs Workshop on High Energy Physics Detector Research and Development.[a] Funding will decrease for the FACET-II operations, reducing support from 100 percent to 90 percent optimal in FY 2022.	**-551**
HEP Accelerator Stewardship Funding for the Accelerator Stewardship subprogram moves to the Accelerator R&D and Production program.	**-16,935**
Construction The Request will continue support for the completion of the design phase for PIP-II, construction of the Early Conventional Facilities subproject, and fabrication of prototypes for the linear accelerator. Approval of CD-3 in FY 2022 will allow the start of construction on the full project. The Request also will continue support for LBNF/DUNE for the excavation of detector caverns at the Far Site, and the ramp-up of design effort on the Near Site facilities and the detectors. Additional funding is also requested for Mu2e to respond to cost increases resulting from schedule delays caused by pandemic response at FNAL and at collaborating universities, and by delayed delivery of two superconducting magnets caused by poor vendor performance.	**+27,000**
Total, High Energy Physics	**+15,000**

[a] https://science.osti.gov/hep/Community-Resources/Reports

Basic and Applied R&D Coordination

The HEP General Accelerator R&D (GARD) research activity within the Advanced Technology R&D subprogram provides the fundamental building blocks of accelerator technology needed for the High Energy Physics mission. The GARD activity is based on input from the community, including high-level advice on long term facility goals from HEPAP and P5, and more detailed technical advice developed through a series of Roadmap Workshops. The GARD activity is coordinated with other Offices of Science (especially Basic Energy Sciences, Fusion Energy Sciences, Nuclear Physics, and Accelerator R&D and Production programs) and other federal agencies to optimize synergy and foster strong U.S capability in this key technology area.

The HEP QIS research program has coordinated partnerships with the Department of Defense Office of Basic Research as well as the Air Force's Office of Scientific Research on synergistic research connecting foundational theory research with quantum error correction and control systems for sensors, and a partnership with the Department of Commerce's National Institute of Standards and Technology on quantum metrology and quantum sensor development for experimental discovery along HEP science drivers and for better understanding of fundamental constants. Furthermore, the SC QIS Research Center effort is a partnership across all SC programs and engages industry to inform use-inspired research and connect to applied and development activities. These interdisciplinary QIS efforts are aligned with the National Quantum Initiative and SC QIS priorities.

Program Accomplishments

LHC data enables sensitive studies of the Higgs boson and searches for the dark matter particle production (Energy Frontier Experimental Physics).

Scientists from the ATLAS and CMS collaborations continued their studies of Higgs boson interactions and searched for signs of dark matter being created in high energy particle collisions. Using AI/ML techniques to enhance their sensitivity, the ATLAS and CMS collaborations used the Higgs boson as a tool for discovery by searching for evidence of it decaying to pairs of muons. While this challenging decay channel is predicted by the standard model at a low rate and thereby considered rare, the analysis suggests that an observation will be possible with additional data acquired at the LHC or during the future era of the HL-LHC. A different search by the ATLAS and CMS collaborations probes the possibility for the Higgs boson to serve as a portal to dark matter particles based on the fact that the Higgs boson couples to mass, allowing potentially massive dark matter particles to interact with it. Using the full dataset acquired from the 2015-2018 run, each LHC experiment has placed stringent constraints that bound the phase space for the Higgs boson decaying to dark matter. These analyses demonstrate the potential for discovery as the LHC will resume operations in 2022.

A team of international physicists join forces in hunt for sterile neutrinos (Intensity Frontier Experimental Physics).

An international group of more than 260 scientists have produced one of the most stringent tests for the existence of sterile neutrinos to date. The close collaboration of scientists from two major international neutrino experimental groups: MINOS+, which studies the disappearance of muon neutrinos produced by the Fermilab Accelerator Complex and propagating to an underground detector in northern Minnesota 735 kilometers away; and Daya Bay, which uses eight identically designed detectors to precisely measure how electron neutrinos emitted by six nuclear reactors in China "disappear" as they morph into other types; enabled the combination of two complementary world-leading constraints on muon neutrinos and electron antineutrinos disappearing into sterile neutrinos. The combined analysis reported by Daya Bay and MINOS+ not only ruled out the specific kind of sterile neutrino oscillation that would explain the anomalous results from earlier single-detector neutrino experiments, but also looked for other sterile neutrino signatures with never-before-achieved sensitivity, yielding some of the most stringent limits on the existence of these elusive particles to date.

Double advances for Cosmic Frontier dark energy experiments (Cosmic Frontier Experimental Physics).

The extended Baryon Oscillation Spectroscopic Survey (eBOSS) completed its five-year survey, mapping of an uncharted five billion years of cosmic history. The expansion of our universe is accelerating, not slowing down under gravity, which is one of the central mysteries of physics; one explanation for this phenomenon is a new form of energy—dark energy—with "antigravity" properties. eBOSS measured both the expansion and the growth rate of large-scale structure through a spectroscopic survey of distant galaxies, quasars, and hydrogen gas. The final eBOSS results in July 2020 constrained dark energy and other cosmological parameters a total of 50 times better than the previous generation of experiments. Meanwhile, the Dark Energy Spectroscopic Instrument (DESI) is the first of the next generation, precision dark energy surveys. DESI, the world's most advanced multi-object spectrograph, successfully completed commissioning in March 2020 and had project completion approved in May 2020, fully meeting all technical design requirements. DESI operations restarted in mid-December 2020 and has collected over 1.8 million spectra of distant galaxies midway through its survey validation phase. The 5-year science survey is planned to start in May 2021.

High energy experiment undergoes successful on-orbit repair on the International Space Station (Cosmic Frontier Experimental Physics).
The Massachusetts Institute of Technology-led Alpha Magnetic Spectrometer (AMS) international collaboration, developed with National Aeronautics and Space Administration (NASA), supported a plan of action to replace the failed cooling system on the AMS experiment that resides on the International Space Station (ISS). In a series of spacewalks in the fall of 2019, NASA astronauts on the ISS installed the AMS replacement cooling system. NASA engineers regard this repair as the most complex on-orbit repair ever attempted. From early 2020, the new AMS cooling system has been performing flawlessly and AMS is once again taking data for study of cosmic rays, antimatter in space, and the cosmos.

Physicists publish worldwide consensus of muon magnetic moment calculation (Theoretical, Computational, and Interdisciplinary Physics).
The U.S. Lattice Quantum Chromodynamics (USQCD) community used Leadership Class Computing facilities and cluster hardware to calculate a precise new theoretical value of the muon's anomalous magnetic moment, g-2, which accounts for the way muons rotate in magnetic fields. Because the quantum vacuum is composed of an almost infinite number of short-lived particle oscillations which can couple to the muon, the muon g-2 is a sensitive test for new physics beyond the Standard Model, but a precise theoretical calculation is very difficult. USQCD collaborated with the global theoretical physics community to publish a consensus Standard Model prediction for muon g-2 before the publication of the recently announced initial FNAL muon g-2 experimental result. Since the Standard Model theoretical calculation still differs from the experimental measurement with high significance, physicists may be one step closer to determining whether the muon's magnetic interactions are hinting at particles or forces that have yet to be discovered.

FNAL has achieved breakthrough success in demonstrating unprecedented coherence times of seconds (Theoretical, Computational, and Interdisciplinary Physics).
Viable quantum computing technology relies on the development of quantum bits, or qubits, that can maintain quantum information for periods of time longer than one second. The coherence time is a function of the system's quality (Q) factor. HEP Quantum Information Science Enabled Discovery (QuantISED) funded research at FNAL has enabled the transformation of superconducting radiofrequency (SRF) cavities to full quantum regimes of ultralow temperatures and single photon field levels. Drawing on the laboratory's decades of world-leading expertise in superconducting technology, and exploiting existing infrastructure, FNAL scientists and engineers have designed superconducting resonators that routinely achieve a Q more than 1,000 times better than existing resonators used in quantum computing.

World record magnetic field strength achieved for a superconducting accelerator magnet (Advanced Technology R&D).
In high-energy circular colliders, strong magnetic fields are needed to steer particle beams so they can be brought into collision at the interaction points. Future particle colliders will require stronger magnets in order to push the frontiers of discovery science. Stronger magnets reduce the collider size needed for a given particle energy or enable higher energies within the same sized machine. In 2020, scientists at FNAL announced the achievement of the highest magnetic field strength ever recorded for an accelerator magnet. The world record field strength of 14.5 Tesla was achieved with the advanced superconducting material niobium-tin at a magnet temperature of 1.9 Kelvin (minus 456 degrees Fahrenheit). Efforts are underway to push the performance of the accelerator magnet to even higher fields.

High Energy Physics
Energy Frontier Experimental Physics

Description

The Energy Frontier Experimental Physics subprogram's focus is to support the U.S. researchers participating in the Large Hadron Collider (LHC) program. The LHC hosts two large multi-purpose particle detectors, ATLAS and CMS, which are partially supported by DOE and NSF and are used by large international collaborations of scientists. U.S. researchers participating in the LHC program account for approximately 20 percent and 25 percent of the ATLAS and CMS collaborations, respectively, and play critical leadership roles in all aspects of each experiment. Data collected by ATLAS and CMS are used to address three of the five science drivers as explained below:

- *Use the Higgs boson as a new tool for discovery.*
  In the Standard Model of particle physics, the Higgs boson is a key ingredient responsible for generating the mass for fundamental particles. Experiments at the LHC continue to actively measure the Higgs's properties to establish its exact character and to discover if there are additional effects that are the result of new physics beyond the Standard Model.
- *Explore the unknown: new particles, interactions, and physical principles.*
  Researchers at the LHC probe for evidence of what lies beyond the Standard Model or significantly constrain postulated modifications to it, such as supersymmetry, mechanisms for black hole production, extra dimensions, and other exotic phenomena. The upgraded LHC detectors will be increasingly more sensitive to potential deviations from the Standard Model that may be exposed by the highest energy collisions in the world.
- *Identify the new physics of dark matter.*
  If dark matter particles are light enough, they may be produced in LHC collisions and their general properties may be inferred through the behavior of the accompanying normal matter. This "indirect" detection of dark matter is complementary to, and a powerful cross-check on, the ultra-sensitive direct detection experiments in the Cosmic Frontier and Intensity Frontier Experimental Physics subprograms.

Research

The Energy Frontier Experimental Physics subprogram's Research activity supports groups at U.S. academic and research institutions and physicists from national laboratories. These groups, as part of the ATLAS and CMS collaborations, typically have a broad portfolio of responsibilities and leadership roles in support of R&D, experimental design, fabrication, commissioning, operations, and maintenance, and they perform scientific simulations and physics data analyses. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. In FY 2018, HEPAP evaluated the currently operating portfolio of experiments in the Energy Frontier and assessed the priority of their science output in the context of the HEP science drivers. The findings from this review[a], in combination with input on strategic directions from regular, open community workshops will inform funding decisions in subsequent years. The activity also supports long-term development to efficiently analyze large datasets anticipated during future LHC operations. The next external peer review of the Energy Frontier laboratory research groups is planned for FY 2022.

Facility Operations and Experimental Support

U.S. LHC Detector Operations supports the maintenance of U.S.-supplied detector systems for the ATLAS and CMS detectors in the LHC at CERN, and the U.S.-based computer infrastructure used by U.S. physicists to analyze LHC data, including the Tier 1 computing centers at BNL and FNAL. The Tier 1 centers provide around-the-clock support for the worldwide LHC Computing Grid; are responsible for storing a portion of raw and processed data; perform large-scale data reprocessing; and store the corresponding output.

[a] The "HEP Portfolio Review of Operating Experiments" report can be found at: https://science.osti.gov/-/media/hep/hepap/pdf/Reports

Projects

CERN is implementing a major upgrade to the LHC machine to increase the particle collision rate by a factor of at least five to explore new physics beyond its current reach. Through the HL-LHC Accelerator Upgrade Project, HEP will contribute to this upgrade by constructing and delivering the next-generation of superconducting accelerator components, where U.S. scientists have critical expertise. After the upgrade, the HL-LHC collisions will lead to very challenging conditions in which the ATLAS and CMS detectors must operate. As a result, the HL-LHC ATLAS and HL-LHC CMS Detector Upgrades are critical investments to enable the experiments to operate for an additional decade and collect more data by at least a factor of ten.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Energy Frontier Experimental Physics	**$194,150**	**$161,683**	**-$32,467**
Research	$68,000	$71,833	+$3,833
Funding continues to support U.S. leadership roles in all aspects of the ATLAS and CMS experimental programs, completing analysis of the large datasets collected during the previous LHC run that ended in FY 2019, and preparing for the next LHC run, which begins in FY 2022.		The Request will support U.S. scientists leading high profile analysis topics using the large datasets during the next LHC run, which will begin in FY 2022.	Funding will support data analysis activities during the next LHC run that are prioritized through a competitive peer review process and based on highest scientific merit and potential impact. Efforts associated with the HL-LHC ATLAS and HL-LHC CMS Detector upgrade activities will continue.
Facility Operations and Experimental Support	$53,650	$49,850	-$3,800
Funding supports ATLAS and CMS detector maintenance and operations at CERN, and completing the installation and commissioning of U.S.-built detector components for the initial ATLAS and CMS detector upgrades in preparation for the next LHC run.		The Request will support critical ATLAS and CMS detector maintenance activities at CERN and the U.S.-based computing infrastructure and resources used by U.S. scientists to store and analyze the large volume of LHC data that will be acquired during the next LHC run starting in FY 2022.	An increase in funding to support additional U.S.-based computing infrastructure will be offset by a decrease in funding due to the completion of the installation and commissioning of U.S.-built detector components for the ATLAS and CMS detector upgrades.
Projects	$72,500	$40,000	-$32,500
Funding continues to support the critical path items in the production of quadrupole magnets and crab cavities for the HL-LHC Accelerator Upgrade, and continues critical path items and procurements for the Detector upgrades.		The Request will support the production of quadrupole magnets and crab cavities for the HL-LHC Accelerator Upgrade, and continue support to critical path items and procurements for the HL-LHC ATLAS and CMS Detector Upgrade Projects.	Support will focus on critical path items to best maintain synchronization with the international LHC and HL-LHC schedules as well as prototyping and fabrication efforts necessary to continue the HL-LHC ATLAS and CMS Detector Upgrade Projects.

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

High Energy Physics
Intensity Frontier Experimental Physics

Description

The Intensity Frontier Experimental Physics subprogram supports the investigation of some of the rarest processes in nature, including unusual interactions of fundamental particles or subtle effects requiring large data sets to observe and measure. This HEP subprogram focuses on using high-power particle beams or other intense particle sources to make precision measurements of fundamental particle properties. These measurements in turn probe for new phenomena that are not directly observable at the Energy Frontier, either because they occur at much higher energies and their effects may only be seen indirectly, or because their interactions are too weak for detection in high-background conditions at the LHC. Data collected from Intensity Frontier experiments are used to address three of the five science drivers as explained below:

- *Pursue the physics associated with neutrino mass*
  Of all known particles, neutrinos are perhaps the most enigmatic and certainly the most elusive. HEP researchers working at U.S. facilities discovered all of the three known varieties of neutrinos. HEP supports research into fundamental neutrino properties that may reveal important clues about the unification of forces and the very early history of the universe. The Intensity Frontier-supported portfolio of neutrino experiments will advance neutrino physics while serving as an international platform for the R&D activities necessary to establish the U.S.-hosted international LBNF/DUNE.
- *Explore the unknown: new particles, interactions, and physical principles*
  A number of observed phenomena are not described by the Standard Model, including the imbalance of matter and antimatter in the universe today. Precision measurements of the properties of known particles may reveal information about what new particles and forces might explain these discrepancies and whether the known forces unify at energies beyond the reach of the LHC.
- *Identify the new physics of dark matter*
  The lack of experimental evidence from current generation dark matter detectors has led to proposed theoretical models with new particles and forces that rarely interact with normal matter. These theoretical particles and forces are effectively invisible to conventional experiments, but may connect to the cosmic dark matter. Experiments use intense accelerator beams at national laboratories outfitted with highly efficient high-rate detectors to explore these theoretical models.

Research

The Intensity Frontier Experimental Physics subprogram's Research activity supports groups at U.S. academic and research institutions and national laboratories. These groups, as part of scientific collaborations, typically have a broad portfolio of responsibilities and leadership roles in support of R&D, experimental design, fabrication, commissioning, operations, and maintenance, as well as performing scientific simulations and physics data analyses on the experiments. DOE selects research efforts with the highest scientific merit and potential impact based on a competitive peer review process. HEP conducted an external peer review of the Intensity Frontier laboratory research groups in FY 2018; the next review is planned for FY 2023. In FY 2018, HEPAP evaluated the currently operating portfolio of experiments on the Intensity Frontier[a] and assessed the priority of their science output in the context of the science drivers. In early FY 2019, HEP conducted a Basic Research Needs (BRN)[b] workshop to assess the science landscape and new opportunities for dark matter particle searches and identified three priority research directions beyond the current HEP program's sensitivity. The findings from the reviews and BRN workshop, in combination with input on strategic directions from regular, open, community studies, will inform funding decisions in subsequent years.

The largest component of the Intensity Frontier subprogram is the support for research in accelerator-based neutrino physics centered at FNAL with multiple experiments running concurrently in two separate neutrino beams with different beam energies. The Neutrinos at the Main Injector (NuMI) beam is used by the NuMI Off-Axis ν_e Appearance (NOvA) experiment. The Booster Neutrino Beam is used by the Short-Baseline Neutrino (SBN) program, which includes a near

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[a] The "HEP Portfolio Review of Operating Experiments" report can be found at: https://science.osti.gov/hep/hepap/Reports
[b] The "Basic Research Needs for Dark Matter Small Projects New Initiatives" report can be found at: https://science.osti.gov/hep/Community-Resources/Reports

detector and a far detector separated by about 1,600 feet to definitively address hints of additional neutrinos types beyond the three currently described in the Standard Model. LBNF/DUNE will be the centerpiece of a U.S.-hosted world-leading neutrino research facility, using the world's most intense neutrino beam and large, sensitive underground detectors to make transformative discoveries.

The Research activity includes efforts at FNAL and at other international facilities, including experiments in Japan, to search for rare processes to detect physics beyond the reach of the LHC. The Muon g-2 experiment at FNAL, with four times better precision than previously achieved, is following up on hints of new physics from an earlier experiment. The Mu2e experiment will search for extremely rare muon decays that, if detected, will provide clear evidence of new physics. The Tokai-to-Kamioka (T2K) long-baseline neutrino experiment in Japan is complementary to NOvA, and a combined measurement from these two experiments will offer the best available information on neutrino oscillations prior to LBNF/DUNE. At the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan, the Belle II experiment searches for new physics produced in electron-positron collisions at the SuperKEKB accelerator.

Recent theoretical studies have underscored that current dark matter particle search candidates are special cases of a broader theoretical framework that have many of the same attractive features. Along with technology advancements, this provides strong motivation for new opportunities to search for dark matter in previously unexplored areas. Two R&D efforts, aligned with the Basic Research Needs workshop priority research directions, are carrying out technology and concept studies that have the potential for future small, projects to address these new opportunities.

Facility Operations and Experimental Support

The Intensity Frontier Experimental Physics subprogram supports several distinct facility operations and experimental activities, the largest of which is the Fermilab Accelerator Complex User Facility. This activity includes the operations of all accelerators and beamlines at FNAL, the operation of the detectors that use those accelerators, and the computing support needed by both the accelerators and detectors. General Plant Project (GPP) and Accelerator Improvement Project (AIP) funding supports improvements to FNAL facilities.

HEP has a cooperative agreement with the South Dakota Science and Technology Authority (SDSTA), a quasi-state agency created by the State of South Dakota for the operation of the SURF. Experiments supported by DOE, NSF, and private entities are conducted there, including the Nuclear Physics-supported Majorana Demonstrator and the HEP-supported LZ experiment. SURF will be the home of the DUNE far site detectors being built by the LBNF/DUNE project. All costs associated with LBNF and DUNE at SURF are supported by the project and not the cooperative agreement supporting SURF.

Projects

In support of LBNF/DUNE, a lease with SDSTA provides the framework for DOE and FNAL to construct federally funded buildings and facilities on non-federal land and to establish a long-term (multi-decade) arrangement for DOE and FNAL to use SDSTA space to host the DUNE neutrino detector. Other Project Costs (OPC) have been identified by the LBNF/DUNE project and DOE for the cost of SURF services used by LBNF/DUNE.

FNAL will upgrade its dated accelerator control system with a modern system, which is maintainable, sustainable, and capable of utilizing advances in Artificial Intelligence and Machine Learning to create a high-performance accelerator for the future. The Accelerator Controls Operations Research Network (ACORN) MIE upgrade project is critical as the control system of the Fermilab Accelerator Complex initiates particle beam production; controls beam energy and intensity; steers particle beams to their ultimate destination; measures beam parameters; and monitors beam transport through the complex to ensure safe, reliable and effective operations.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Intensity Frontier Experimental Physics	**$232,867**	**$250,839**	**+$17,972**
Research	$63,082	$65,994	+$2,912
Funding supports world-leading research efforts on short- and long-baseline neutrino experiments, muon and rare physics processes experiments, and technology studies and science planning for Mu2e and LBNF/DUNE. The SBN program will move into initial operations with the far detector installed and commissioned. The funding also supports analyses on physics data sets collected by the neutrino experiments that have completed operations.		The Request will support core research efforts in all phases of experiments. Researchers will continue data collection and analysis on NOvA, Muon g-2, T2K, and Belle II, and begin physics data taking with SBN. Researchers will support pre-operations activities for Mu2e, and continue science planning for LBNF/DUNE. HEP will sponsor modeling and design studies for ultra-efficient muon pre-conceptual modular systems in collaboration with Advanced Research Projects Agency-Energy (ARPA-E) to accelerate research for utilizing muon catalyzed fusion as a new source of carbon-free electricity generation.	Funding increase will support initial data collection and analysis on the SBN program, and a new muon-catalyzed fusion clean-energy effort with ARPA-E. Support for research on lower priority small- to mid-scale neutrino experiments, as determined by the FY 2018 HEPAP portfolio review, will ramp down.
Facility Operations and Experimental Support	$166,785	$176,845	+$10,060
Funding supports the Fermilab Accelerator Complex and the neutrino and muon experiments at 81 percent of optimal operations; modernization efforts to mitigate the risk of slowing down programs and projects; design and planning for the Target Systems Integration Building GPP; and SURF operations and investments to enhance SURF infrastructure.		The Request will support the Fermilab Accelerator Complex and the neutrino and muon experiments at 90 percent of optimal operations; construction of the Target Systems Integration Building GPP; continue modernization efforts; and SURF operations and investments to enhance SURF infrastructure.	Funding increase will support the delivery of particle beams at peak power and provide detector and computing operations for the SBN program. Overall operations of the Fermilab Accelerator Complex will increase from 81 to 90 percent of optimal. Support for GPP funding increases to fund the Target Systems Integration Building construction.

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request		Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Projects	$3,000		$8,000	+$5,000
Funding supports OPC for execution support costs including electrical power at SURF for LBNF/DUNE construction and OPC for the Fermilab Accelerator Controls Operations Research Network (ACORN) MIE to develop a work breakdown structure, hire a project team, and begin preliminary system design.		The Request will continue support of OPC execution support costs at SURF for LBNF/DUNE construction. The Fermilab Accelerator Controls Operations Research Network (ACORN) MIE will continue OPC and begin TEC and will fund system design and other related engineering activities.		Funding will support increased execution support costs at SURF for LBNF/DUNE construction, and increase support for the ACORN MIE and begin TEC funding.

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

High Energy Physics
Cosmic Frontier Experimental Physics

Description

The Cosmic Frontier Experimental Physics subprogram uses measurements of naturally occurring cosmic particles and observations of the universe to probe fundamental physics questions and offer new insight about the nature of dark matter, cosmic acceleration in the forms of dark energy and inflation, neutrino properties, and other phenomena. The activities in this subprogram use diverse tools and technologies, from ground-based observatories and space-based missions, to large detectors deep underground to address four of the five science drivers as explained below:

- *Identify the new physics of dark matter*
  Experimental evidence reveals that dark matter accounts for five times as much matter in the universe as ordinary matter. Direct-detection experiments provide the primary method to search for the elusive dark matter particles' rare interactions with ordinary matter, while indirect-detection experiments search for the products of dark matter annihilation. A staged series of direct-detection experiments search for the leading theoretical candidate particles using multiple technologies to cover a wide range in mass with increasing sensitivity. Accelerator-based dark matter searches performed in the Intensity Frontier and the Energy Frontier subprograms are complementary to these experiments.
- *Understand cosmic acceleration: dark energy and inflation*
  The nature of dark energy, which drives the accelerating expansion of the universe, continues as one of the most perplexing questions in science. Together, dark energy and dark matter comprise 95 percent of the matter and energy in the universe. The cosmic microwave background (CMB), the oldest observable light in the universe, informs researchers about the era of inflation, the rapid expansion in the early universe shortly after the Big Bang. Researchers use measurements of ancient light from the early universe and light from distant galaxies to map the acceleration of the universe over time and to unravel the nature of dark energy and inflation.
- *Pursue the physics associated with neutrino mass*
  The study of the largest physical structures in the Universe may reveal the properties of particles with the smallest known cross section, the neutrinos. Experiments studying dark energy and the CMB will put constraints on the number of neutrino species and their masses. The properties of neutrinos affected the evolution of matter distribution in the universe, leading to changes in the CMB observables when measured in different directions. These measurements are complementary to, and a powerful cross check of, the ultra-sensitive measurements made in the Intensity Frontier.
- *Explore the unknown: new particles, interactions, and physical principles*
  High-energy cosmic rays and gamma rays probe energy scales well beyond what may be produced with man-made particle accelerators, albeit not in a controlled experimental setting. Searches for new phenomena and indirect signals of dark matter in these surveys may yield surprising discoveries about the fundamental nature of the universe.

Research

The Cosmic Frontier Experimental Physics subprogram's Research activity supports groups at U.S. academic and research institutions and national laboratories who perform experiments using instruments on the surface, deep underground, and in space. These groups, as part of scientific collaborations, typically have a broad portfolio of responsibilities and leadership roles in support of R&D, experimental design, fabrication, commissioning, operations, and maintenance, as well as perform scientific simulations and physics data analyses on the experiments in the subprogram. DOE selects research efforts with the highest scientific merit and potential impact based on a competitive peer-review process. HEP conducted an external peer review of the Cosmic Frontier laboratory research groups in FY 2016; the next review is scheduled for FY 2021. In FY 2018, HEPAP evaluated the currently operating portfolio of experiments in the Cosmic Frontier[a] and assessed the priority of their science output in the context of the science drivers. In early FY 2019, HEP conducted a Basic Research Needs (BRN)[b] workshop to assess the science landscape and new opportunities for dark matter particle searches made possible by recent technology and theoretical advancements and identified three priority research directions beyond the current HEP program's sensitivity. The findings from the reviews and BRN workshop, in combination with input on strategic directions from regular, open community studies, inform funding decisions in subsequent years.

[a] The "HEP Portfolio Review of Operating Experiments" report can be found at: https://science.osti.gov/-/media/hep/hepap/pdf/Reports

[b] The "Basic Research Needs for Dark Matter Small Projects New Initiatives" report can be found at: https://science.osti.gov/hep/Community-Resources/Reports

Two complementary next-generation, dark energy “Stage 4” experiments will provide increased precision in measuring the history of the expansion of the universe. The Vera C. Rubin Observatory will carry out a 10-year wide-field, ground-based optical and near-infrared imaging Legacy Survey of Space and Time (LSST) that will be used by the Dark Energy Science Collaboration (DESC). The Dark Energy Spectrographic Instrument (DESI) collaboration is carrying out a five-year survey to make light-spectrum measurements of 30 million galaxies and quasars that span over two-thirds of the history of the universe. Together the data sets will enable studies on whether acceleration of the expansion of the universe is due to an unknown force, a cosmological constant, or if Einstein’s General Theory of Relativity breaks down at large distances.

The next-generation Cosmic Microwave Background Stage 4 (CMB-S4) experiment will have unprecedented sensitivity and precision in measurements of the temperature fluctuations of the early universe. CMB-S4 will enable researchers to peer directly into the inflationary era in the early moments of the universe, at a time scale unreachable by other types of experiments. CMB-S4 and the dark energy experiments will also provide information on neutrino properties and searches for relic particles from the early universe.

Two complementary next-generation, dark matter particle search experiments will use complementary technologies to search for weakly interacting massive particles (WIMP) over a wide range of masses, with LZ searching for heavier WIMPs and SuperCDMS-SNOLAB sensitive to lighter WIMPs. The Axion Dark-Matter eXperiment Generation 2 (ADMX-G2) searches for another candidate, the axion. Recent theoretical studies have underscored that current dark matter particle search candidates are special cases of a broader theoretical framework that have many of the same attractive features. Along with technology advancements, this provides strong motivation for new opportunities to search for dark matter in previously unexplored areas. R&D efforts, aligned with the BRN workshop priority research directions, are conducting technology and concept studies that have the potential for future, small projects to address these new opportunities.

Facility Operations and Experimental Support

This activity supports the DOE share of expenses necessary to carry out the successful operating phase of Cosmic Frontier experiments, including instrumentation maintenance, data collection, and data processing and serving. These experiments are typically not sited at national laboratories, but at ground-based observatories and facilities, in space, or deep underground. Support is provided for the experiments currently operating and for pre-operations activities for the next-generation experiments in the design or fabrication phase. HEP conducts planning reviews to ensure readiness as each experiment transitions from project fabrication to science operations, and periodic reviews during the operations phase.

The DESI instrumentation is mounted and operating on the NSF’s Mayall Telescope at Kitt Peak National Observatory with both the instrumentation and telescope operations supported by DOE. The Vera C. Rubin Observatory, which includes the DOE-provided 3-billion pixel camera, is being commissioned in Chile. DOE and NSF are full partners in the Vera C. Rubin Observatory operations with planning and pre-operations activities in process. SLAC manages the Observatory’s U.S. Data Facility as part of DOE’s responsibilities during the operations phase. The DESC continues its pre-operations activities to prepare for the initiation of the 10-year LSST survey.

The LZ dark matter detector is operating underground in the Sanford Underground Research Facility (SURF) in Lead, South Dakota, and the SuperCDMS-SNOLAB dark matter detector, to be located at the Sudbury Neutrino Observatory in Sudbury, Canada, is carrying out planning and pre-operations activities. The ADMX-G2 experiment continues operations at the University of Washington to carry out its ultra-sensitive searches for axion dark matter particles.

Projects

The next-generation CMB-S4 experiment is a planned partnership with NSF with the distribution of scope determined in FY 2022. The project will consist of an array of small and large telescopes working in concert at two locations: the NSF Amundsen-Scott South Pole Station and the Atacama high desert in Chile. The focal planes will include 500,000 ultra-sensitive sensors and associated readout systems. Lawrence Berkeley National Laboratory (LBNL) was selected in August 2020 to lead the efforts in providing the DOE scope for the project.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request		Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Cosmic Frontier Experimental Physics	**$97,591**		**$96,512**	**-$1,079**
Research	$47,091		$49,012	+$1,921
Funding supports core research efforts in all phases of experiments. ADMX-G2 collaboration is completing the primary data analyses on Run 1C. Researchers are participating in data collection for LZ and DESI. Researchers are participating in commissioning and pre-operations planning for SuperCDMS-SNOLAB and the Vera C. Rubin Observatory, with the associated DESC planning for the subsequent LSST. Research efforts on CMB-S4 and planning for future Dark Matter and Dark Energy opportunities are increasing.		The Request will support core research efforts in all phases of experiments. Researchers will continue data collection and analysis for ADMX-G2 Run2, LZ, and DESI, and data planning and for SuperCDMS-SNOLAB. Researchers will continue supporting commissioning and pre-operations activities of Vera C. Rubin Observatory and the DESC will continue planning for the subsequent LSST. Research efforts on CMB-S4 will support the preliminary design along with data simulations and analysis planning.		Funding increase will support data collection and analysis on new experiments, research efforts on CMB-S4 project, and scientific planning for future experiments in the Cosmic Frontier. Research on completed and lower priority experiments will ramp down.
Facility Operations and Experimental Support	$44,500		$42,500	-$2,000
Funding supports continued science operations on DESI, LZ, and ADMX-G2 run 1C and 1D, and commissioning and pre-operations efforts on the Vera C. Rubin Observatory and SuperCDMS-SNOLAB.		The Request will support continued operations, with DESI and LZ moving into their second year of data-taking, and ADMX completing Run 1C, starting Run 1D, and preparing for Run 2A. The Vera C. Rubin Observatory and SuperCDMS-SNOLAB continue commissioning and pre-operations efforts.		The net decrease in funding includes an increase to support commissioning and pre-operations activities of Vera C. Rubin Observatory and the DESC, offset by a decrease due to the completed commissioning of SuperCDMS-SNOLAB, and the planned conclusion of operations for other Cosmic Frontier experiments.

(dollars in thousands)

FY 2021 Enacted	FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Projects $6,000	$5,000	-$1,000
CMB-S4 OPC funding supports continuing project development, R&D and conceptual design leading to planning for CD-1. TEC Funding supports a new MIE start for CMB-S4 when it moves forward with preliminary project engineering design.	The Request will support completion of the CMB-S4 conceptual design OPC activities for CD-1, as well as TEC-design activities and long lead procurements for sensors and cryostats	Support will prioritize project engineering design activities for CMB-S4.

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

High Energy Physics
Theoretical, Computational, and Interdisciplinary Physics

Description

The Theoretical, Computational, and Interdisciplinary Physics subprogram provides the mathematical, phenomenological, computational, and technological framework to understand and extend our knowledge of the dynamics of particles and fields, and the nature of space and time. This research is essential for proper interpretation and understanding of the experimental research activities described in other HEP subprograms, and cuts across all five science drivers and the Energy, Intensity, Cosmic Frontier Experimental Physics, and Advanced Technology R&D subprograms.

Theory

The HEP theory activity supports world-leading research groups at U.S. academic and research institutions and national laboratories. Both university and laboratory research groups play important roles in addressing the leading research areas discussed above. Laboratory groups are typically more focused on data-driven theoretical investigations and precise calculations of experimentally observable quantities. University groups usually focus on building models of physics beyond the Standard Model and studying their phenomenology, as well as on formal and mathematical theory. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. HEP conducted an external peer review of the Theory laboratory research groups in FY 2018; the next review is planned for FY 2022. The findings from this review, in combination with input on strategic directions from regular, open, community studies as well as a planned, future Basic Research Needs workshop, will inform funding decisions in subsequent years.

The HEP theory activity supports an integrated computational and data infrastructure initiative to create more seamless use of clouds, with SC computing, community software, and storage resources for experimental and observational data analysis, and enable new scientific workflows for scientific discovery. HEP's strategic focus is in the development of data storage capabilities to manage petabytes of data from future experiments; cross-cutting efforts in AI/ML and edge computing to seek solutions for real-time and ultra-high data rates towards terabits per second; and investments in software development to improve the interface with SC infrastructure and ASCR-supported middleware.

The HEP theory activity will support the Reaching a New Energy Sciences Workforce (RENEW) initiative to provide undergraduate and graduate training opportunities for students and academic institutions not currently well represented in the U.S. S&T ecosystem.

Computational HEP

The Computational HEP activity supports advanced simulations and computational science that extends the boundaries of scientific discovery to regions not directly accessible by experiments, observations, or traditional theory. Computation is necessary at all stages of HEP experiments—from planning and constructing accelerators and detectors, to theoretical modeling, to supporting computationally intensive experimental research and large-scale data analysis for scientific discovery in HEP. The multi-laboratory HEP Center for Computational Excellence (CCE) is supported to advance HEP computing by exploiting the latest architectures in current and future high performance computing platforms and exascale systems. Computational HEP partners with ASCR, including via the Scientific Discovery through Advanced Computing (SciDAC) activity, to optimize the HEP computing ecosystem for the near and long term future. The re-competition of HEP-ASCR SciDAC partnerships is planned for FY 2022.

Quantum Information Science

The HEP QIS activity supports the 'science first' goal of the national QIS strategic plan and advances both HEP and QIS research. Key sub topics include: foundational research on connections between physics of the cosmos and qubit systems, quantum computing for foundational theory as well as for HEP experiments, development of precision quantum sensors and QIS based experiments that may yield information on fundamental physics beyond the Standard Model, and applications of HEP research to advance QIS including specialized quantum controls and communication protocols. QIS Research Centers, jointly supported across SC programs, apply concepts and technology from the relevant foundational core research in the corresponding programs and foster partnerships in support of the SC mission. The HEP QIS research activity is part of a broader SC initiative that is conducted in coordination with SC programs, other federal agencies, and the private sector where relevant.

Artificial Intelligence and Machine Learning

The HEP AI/ML activity supports research to tackle the challenges of managing increasingly high volumes and complexity of experimental and simulated data across the HEP experimental frontiers, theory, and technology thrusts. This activity also addresses cross-cutting challenges across the HEP program in coordination with DOE investments in exascale computing and associated AI efforts. Priorities include advancing AI/ML capabilities to provide more efficient processing of large data sets, modeling and mitigation of systematic uncertainties, high-throughput data selection, real-time data classification, and improved operations of particle accelerators and detectors. The activity routinely seeks input on key strategic directions in HEP AI/ML best aligned to support programmatic priorities from open community workshops and relevant federal advisory committees. The HEP AI/ML research activity is conducted in coordination with DOE and SC programs, other federal agencies, and the private sector, where relevant.

High Energy Physics
Theoretical, Computational, and Interdisciplinary Physics

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Theoretical, Computational, and Interdisciplinary Physics	**$136,362**	**$157,422**	**+$21,060**
Research	$136,362	$157,422	+$21,060
Theory	*$46,284*	*$55,050*	*+$8,766*
Funding supports world-leading research that addresses the interactions of neutrinos with matter, the interpretation of experimental results, the development of new ideas for future projects, and innovative ideas to advance the theoretical understanding of nature.		The Request will continue support for world-leading theoretical particle physics research and will support the new integrated computational and data infrastructure initiative. The Request will also support the Reaching a New Energy Sciences Workforce (RENEW) initiative to provide undergraduate and graduate training opportunities for students and academic institutions not currently well represented in the U.S. S&T ecosystem.	Funding increases to support the new integrated computational and data infrastructure initiative, the RENEW initiative and the highest-impact theoretical research as determined by competitive peer review.
Computational HEP	*$11,518*	*$15,000*	*+$3,482*
Funding supports transformative computational science, high performance computing, and SciDAC 4 activities; cross-cut computational science tools for HEP science and computational science driven discovery; and exploratory research on portable parallelization techniques, storage solutions, and complex workflows and optimizing use of exascale architectures.		The Request will support the multi-laboratory HEP Computational Center for Excellence (CCE) to develop portable parallelization solutions, data transfer and storage challenges, and event generation and complex workflows. The HEP-ASCR SciDAC partnerships will re-compete. The Request will support a new Traineeship Program in High Performance Scientific Computing to address critical HEP workforce needs.	Funding increase will support the HEP CCE and the new Traineeship Program.

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Quantum Information Science	*$45,072*	*$51,566*	*+$6,494*
Funding supports interdisciplinary HEP-QIS consortia and lab programs for focused research on foundational research at the intersection of HEP and QIS, including novel experiments, quantum computing, communications, sensors, and research technology. Funding also continues and enhances support for QIS Research Centers in partnership with other SC program offices.		The Request will support and enhance interdisciplinary HEP-QIS consortia and lab programs for focused research on foundational research at the intersection of HEP and QIS, including novel experiments, quantum computing, communications, sensors, and research technology. The Request will continue support for QIS Research Centers in partnership with other SC program offices.	Funding will support increases in quantum simulation, physics beyond the Standard Model experiments using HEP and QIS expertise and techniques, and lab research technology including quantum networks and communications testbeds.
Artificial Intelligence and Machine Learning	*$33,488*	*$35,806*	*+$2,318*
Funding supports AI/ML research to tackle challenges across the HEP program, including new techniques to support the analysis of the large datasets that will be produced in the next LHC run; further enhancements to the science output of data-intensive experiments through improved pattern recognition, anomaly detection, and background rejection; increased operations automation of large detectors and accelerators; and more sophisticated production of large simulated data sets to reduce steeply growing computational demands.		The Request will continue to support AI/ML research and development to improve physics measurements and searches, and build an AI/ML community around cross-cutting challenges to fulfill the HEP mission. A new Funding Opportunity for specific AI/ML applications in HEP is planned.	Funding will support increases in innovation and new opportunities in building algorithms that learn about complex data to solve big-data computing hardware and infrastructure challenges; embedding AI into sensors and experimental design in extreme environments; and developing operations and controls AI/ML techniques.

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

High Energy Physics
Advanced Technology R&D

Description

The Advanced Technology Research and Development (R&D) subprogram fosters cutting-edge research in the physics of particle beams, accelerator R&D, and R&D for particle and radiation detection—all of which are necessary for continued progress in high energy physics. Long-term multi-purpose accelerator research, applicable to fields beyond HEP, is carried out under the Accelerator Stewardship subprogram, which will reside in the Accelerator R&D and Production program beginning in FY 2022.

General Accelerator R&D

The HEP General Accelerator R&D (GARD) activity supports the science underlying the technologies used in particle accelerators and storage rings, as well as the fundamental physics of charged particle beams. Long-term research goals include developing technologies to enable breakthroughs in particle accelerator size, cost, beam intensity, and control. The GARD activity supports groups at U.S. academic and research institutions and national laboratories performing research activity categorized into five thrust areas: accelerator and beam physics; advanced acceleration concepts; particle sources and targetry; radio-frequency acceleration technology; and superconducting magnet and materials. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. HEP conducted an external peer review of the GARD laboratory research groups in FY 2018; the next review is planned for FY 2022. The findings from this review, in combination with input on strategic directions from regular, open, community studies as well as future Basic Research Needs workshops, will inform funding decisions in subsequent years. The 2016 U.S. Magnet Development Program Plan[a], a strategic plan with research roadmap for the GARD superconducting magnet and materials thrust, was refreshed in FY 2020. An HEP program review and collaboration workshop was held to assess progress in the program and to update the research roadmap[b] for this GARD thrust.

The state-of-the-art SC facilities attract the world's leading researchers, bringing knowledge and ideas that enhance U.S. science and create high technology jobs. As competing accelerator-based facilities are built abroad, they are beginning to draw away scientific and technical talent. Sustaining world-class accelerator-based SC facilities requires continued, transformative advances in accelerator science and technology, and a workforce capable of performing leading accelerator research for future application. In coordination with the Office of Accelerator R&D and Production, the SC Accelerator Science and Technology Initiative (ASTI) will address these needs by reinforcing high-risk, high-reward accelerator R&D that will invest in SC facilities to stay at the global forefront, and develop a world-leading workforce to build and operate future generations of facilities. As a part of ASTI, ASCR, BES, FES, HEP, and NP will enhance coordination and jointly pursue accelerator R&D topics that will have a strong impact on the scientific capabilities of SC facilities.

The GARD activity supports the successful U.S. Particle Accelerator School (USPAS). HEP conducted a review of the USPAS Program in late FY 2020. The USPAS had to postpone its Summer 2020 session due to COVID-19. The Winter 2021 session was successfully accomplished via online instructions. GARD also supports the Traineeship Program for Accelerator Science and Technology to revitalize education, training, and innovation in the physics of particle accelerators for the benefit of HEP and other SC programs that rely on these enabling technologies. The Traineeship Program is aimed at university and national laboratory consortia to provide the academic training and research experience needed to meet DOE's anticipated workforce needs. HEP holds a competition for traineeship awards for graduate level students to increase workforce development in areas of critical need. These traineeships leverage existing GARD research activities as well as the capabilities and assets of DOE laboratories.

Detector R&D

The Detector R&D activity supports the development of the next generation instrumentation and particle and radiation detectors necessary to maintain U.S. scientific leadership in a worldwide experimental endeavor that is broadening into new research areas. To meet this challenge, HEP aims to foster an appropriate balance between evolutionary, near-term, low-risk detector R&D and revolutionary, long-term, high-risk detector R&D, while training the next generation of experts.

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[a] https://www2.lbl.gov/LBL-Programs/atap/MagnetDevelopmentProgramPlan.pdf
[b] https://science.osti.gov/-/media/hep/pdf/Reports/2020/USMDP-2020-Plan-Update-web.pdf

The Detector R&D activity consists of groups at U.S. academic and research institutions and national laboratories performing research into the fundamental physics underlying the interactions of particles and radiation in detector materials. This activity also supports technology development that turns these insights into working detectors. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. HEP conducted an external peer review of the Detector R&D laboratory research groups in FY 2016; the next review is planned for FY 2022. In FY 2020, HEP conducted a Basic Research Needs workshop to assess the science landscape and new opportunities for potentially transformative detector technologies, and to identify which R&D areas would be most suitable for new investments in the HEP program. The findings from this workshop[a], in combination with input on strategic directions from regular, open community workshops will inform funding decisions in subsequent years.

The Detector R&D activity supports the Traineeship Program for HEP Instrumentation to address critical, targeted workforce development in fields of interest to the DOE mission. The program is aimed at university and national laboratory consortia to provide the academic training and research experience needed to meet DOE's anticipated workforce needs. HEP holds a competition for traineeship awards for graduate level students to revitalize education, training, and innovation in the physics of particle detectors and next generation instrumentation for the benefit of HEP and other SC and DOE programs that rely on these enabling technologies. These traineeships leverage existing Detector R&D research activities as well as the capabilities and assets of DOE laboratories.

SC is in a unique position to both play a critical role in the advancement of microelectronic technologies over the coming decades, and also to benefit from the resultant capabilities in detection, computing, and communications. Five SC programs—ASCR, BES, FES, HEP, and NP—will work together to advance microelectronics technologies. This activity is intentionally focused on establishing the foundational knowledge base for future microelectronics technologies for sensing, communication, and computing that are complementary to quantum computing. Radiation and particle detection specifically will benefit from detector materials R&D, device R&D, advances in front-end electronics, and integrated sensor/processor architectures.

Facility Operations and Experimental Support

This activity supports GARD laboratory experimental and test facilities: Berkeley Lab Laser Accelerator (BELLA), the laser-driven plasma wakefield acceleration facility at Lawrence Berkeley National Laboratory (LBNL); FACET-II, the beam-driven plasma wakefield acceleration facility at SLAC National Accelerator Laboratory (SLAC); and superconducting radio-frequency accelerator and magnet facilities at FNAL. This activity also supports the test beam at FNAL, and detector test and fabrication facilities such as the Microsystems Laboratory at LBNL and the Silicon Detector Facility at FNAL. Accelerator Improvement Projects (AIP) support improvements to GARD facilities.

[a] https://science.osti.gov/-/media/hep/pdf/Reports/2020/DOE_Basic_Research_Needs_Study_on_High_Energy_Physics.pdf

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Advanced Technology R&D	**$116,095**	**$115,544**	**-$551**
Research	$72,833	$75,344	+$2,511
General Accelerator R&D	*$49,574*	*$51,814*	*+$2,240*
Funding supports world-leading research activities in the areas of accelerator and beam physics, advanced acceleration concepts, particle sources and targetry, radio-frequency acceleration technology and superconducting magnet and materials. This activity is augmented by new funding for the Accelerator Science and Technology Initiative (ASTI) to support critical capabilities and maintain U.S. competitiveness. Funding also supports the Traineeship Program for Accelerator Science and Technology.		The Request will continue to support world-leading, innovative advanced accelerator R&D, provide increased support for ASTI, and continue support for the Traineeship Program for Accelerator Science and Technology.	Funding will support capitalization on the science opportunities at the newly completed FACET-II facility and the second beamline at BELLA; increases to ASTI efforts in superconducting magnet development and upgrades to SRF facilities; and co-fund a multi-SC program R&D initiative in superconducting materials.
Detector R&D	*$23,259*	*$23,530*	*+$271*
Funding supports world-leading Detector R&D activities at universities and national laboratories, with increased emphasis on long-term, high-risk, and high potential impact R&D efforts, informed by the findings of the FY 2020 Basic Research Needs workshop on HEP Detector R&D. HEP collaborates with ASCR, BES, FES, and NP to advance microelectronics technologies. The Traineeship Program for HEP Instrumentation has been initiated.		The Request will continue to support world-leading, innovative Detector R&D, provide increased support to advance microelectronics technologies, and continue support for the Traineeship Program in HEP Instrumentation.	Funding will increase support toward the microelectronics activities, while ongoing Detector R&D support will prioritize collaborative opportunities at universities and national laboratories that enable new directions in HEP discovery science programs and strengthen new technology developments and capabilities that address priorities identified in the FY 2020 Basic Research Needs workshop.

(dollars in thousands)

FY 2021 Enacted	FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Facility Operations and Experimental Support $43,262	$40,200	-$3,062
Funding supports the operation of accelerator, test beam, and detector facilities at FNAL, LBNL, and SLAC, and improvements to superconducting radio-frequency and magnet test facilities. Funding also supports 3,720 hours (100 percent of optimal) facility operations for FACET-II.	The Request will support the operation of accelerator, test beam, and detector facilities at ANL, FNAL, LBNL, and SLAC, and improvements to superconducting radio-frequency and magnet test facilities. The Request will provide support for 2,700 hours (90 percent of optimal) of facility operations for FACET-II. Due to the COVID-19 pandemic, the FACET-II experiments will start at least six months later than planned.	Funding will support beam time for experiments but not all capability improvements to the facilities at ANL, FNAL, LBNL, and SLAC. Priority will be guided by recent comparative reviews of the laboratory programs.

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

High Energy Physics
HEP Accelerator Stewardship

Description

In FY 2020, the Office of Science (SC) initiated a reorganization, creating a new Office of Accelerator R&D and Production (ARDAP) that facilitates coordination of accelerator R&D needed for all Office of Science research programs and matures accelerator technologies needed for future SC facilities and by other agencies of the U.S. government. As part of this reorganization, the Accelerator Stewardship subprogram moved to ARDAP and continues to provide support in three principal activities: facilitating access to unique state-of-the-art SC accelerator R&D infrastructure for the private sector and other users; supporting innovative early-stage applied research to deploy accelerator technology for medical, industrial, environmental cleanup, security, and defense applications; and driving a limited number of specific accelerator applications towards practical, testable prototypes in a five to seven year timeframe. The budget request and further details concerning the Accelerator Stewardship subprogram may be found in the ARDAP program budget narrative.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request		Explanation of Changes FY 2022 Request vs FY 2021 Enacted	
HEP Accelerator Stewardship	**$16,935**		**$ —**		**-$16,935**
Research	$10,835		$ —		-$10,835
Funding supports new research activities at laboratories, universities, and in the private sector for technology R&D areas such as accelerator technology for industrial, medical and security uses, and advanced laser technology R&D.		N/A		Funding for FY 2022 is requested in the Accelerator R&D and Production program.	
Facility Operations and Experimental Support	$6,100		$ —		-$6,100
Funding supports operation of the BNL ATF at 100 percent of optimal levels.		N/A		Funding for FY 2022 is requested in the Accelerator R&D and Production program.	

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

Description
This subprogram supports all line-item construction for the entire HEP program. All Total Estimated Costs (TEC) are funded in this subprogram, including engineering, design, and construction.

<u>18-SC-42, Proton Improvement Plan II (PIP-II), FNAL</u>
The PIP-II project will enhance the Fermilab Accelerator Complex to enable it to deliver higher-power proton beams to the neutrino-generating target for groundbreaking discovery in neutrino physics. The project will design and construct an 800 megaelectronvolt (MeV) superconducting radio-frequency (SRF) proton linear accelerator and beam transfer line. The PIP-II project also will modify the existing FNAL Booster, Recycler, and Main Injector synchrotrons downstream from the new linear accelerator to accept the increased beam intensity. Some of the new components and the cryoplant will be provided through international, in-kind contributions.

The most recent DOE Order 413.3B approved Critical Decision (CD) is CD-3A (Approve Long-lead Procurement), approved March 16, 2021; it followed three months after CD-2 (Approve Performance Baseline), approved on December 14, 2020, with a Total Project Cost (TPC) of $978,000,000. The funding profile supports the approved TPC of $978,000,000. The CD-4 milestone date is 1Q FY 2033.

The PIP-II project is inclusive of a subproject, Early Conventional Facilities (ECF) for PIP-II, that received Critical Decision CD-2/3 (Approval of Subproject Baseline and Start of Construction) on July 17, 2020. The TPC for the ECF subproject is $36,000,000 which will be funded out of the same line-item appropriation as the PIP-II project.

<u>11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment, FNAL</u>
The LBNF/DUNE construction project is a federal, state, private, and international partnership developing and implementing the technologies of particle accelerators and detectors to enable world-leading research into the fundamental physics of neutrinos, which are the most ubiquitous particles in the universe while at the same time among the most mysterious. LBNF/DUNE will study the transformations of muon neutrinos that occur as they travel from FNAL, where they are produced in a high-energy proton beam, to a large detector in South Dakota, 800 miles away from FNAL. The experiment will analyze the rare, flavor-changing transformations of neutrinos in flight, from one lepton flavor to another, which are expected to help explain the fundamental physics of neutrinos and the puzzling imbalance of matter and antimatter that enables our existence in a matter-dominated universe.

The LBNF/DUNE project is a national flagship particle physics initiative and will be the first-ever large-scale, international science facility hosted by the U.S. The LBNF/DUNE project consists of two multinational collaborative efforts. LBNF is responsible for the beamline at FNAL and other experimental and civil infrastructure at FNAL and at the SURF in South Dakota. DUNE is an international scientific collaboration responsible for defining the scientific goals and technical requirements for the beam and detectors, as well as the design, construction and commissioning of the detectors and subsequent research.

DOE's High Energy Physics program manages both activities as a single, line-item construction project—LBNF/DUNE. LBNF, with DOE/FNAL leadership and minority participation by a small number of international partners including CERN, will construct a megawatt-class neutrino source and related facilities at FNAL (the "Near Site"), as well as underground caverns and cryogenic facilities in South Dakota (the "Far Site") needed to house the DUNE detectors. DUNE has international leadership and participation by over 1,100 scientists and engineers from over 200 institutions in over 30 countries. DOE will fund less than one-third of DUNE.

The most recent approved DOE Order 413.3B Critical Decision is CD-3A, approval for Initial Far Site Construction. This approval initiated excavation and construction for the LBNF Far Site conventional facilities in order to mitigate risks and minimize delays for providing a facility ready to accept detectors for installation. The preliminary Total Project Cost (TPC) range is $1,260,000,000 to $1,860,000,000, as approved on September 1, 2016, with a preliminary CD-4 date of Q4 FY 2030.

Updated planning and analysis has the TPC point estimate for LBNF/DUNE at $2,600,000,000. Scope reductions are being considered to refine the scope by FY 2022 for the baseline.

<u>11-SC-41, Muon to Electron Conversion Experiment, FNAL</u>
Mu2e, under construction at FNAL, will search for evidence that a muon can undergo direct (neutrinoless) conversion into an electron, a process that would violate lepton flavor conservation and probe new physics at energy scales beyond the collision energy of the Large Hadron Collider. If observed, this major discovery would signal the existence of new particles or new forces beyond the Standard Model. The Mu2e project completed its technical design phase (CD-3) on July 14, 2016 and moved into full construction at that time. Civil construction of the underground detector housing and the surface building for the experiment were completed in 2017.

The most recent approved DOE Order 413.3B Critical Decision is CD-3, Approve Start of Construction approved on July 14, 2016. The funding profile through FY 2019 supported the current TPC of $273,677,000 and the currently approved CD-4 milestone date of 1Q FY 2023.

However, it became apparent the approved baseline schedule could no longer be met as a result of the COVID-19 pandemic that resulted in unplanned work shutdowns and inefficiencies at the participating universities and laboratories in FY 2020, and because of delayed delivery of two superconducting magnets resulting from poor schedule and technical performance by the vendor. A baseline change was recommended by an Independent Project Review in February 2021; the Baseline Change Proposal (BCP) is in process but not yet submitted, reviewed, or approved. In anticipation of approval of the BCP, $2,000,000 of TEC funding was appropriated in FY 2021 and $13,000,000 of TEC funding is requested in FY 2022. None of these additional funds will be available to spend until the BCP approval and the project is re-baselined.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
Construction	**$252,000**	**$279,000**	**+$27,000**
18-SC-42, Proton Improvement Plan II (PIP-II), FNAL	$79,000	$90,000	+$11,000
Funding supports completion of civil engineering design for the conventional facilities, technical design and prototyping for the accelerator components, and initiation of Early Conventional Facilities (ECF) subproject construction, as well as long-lead procurement and procurement for technical systems when design is final and construction is authorized by CD-3.		The Request will support completion of procurement for the Early Conventional Facilities (ECF) subproject and initiation of civil engineering design for the rest of the linear accelerator facilities, as well as technical design and prototyping for the accelerator components and initiation of procurement and construction for technical systems when design is final and construction is authorized by CD-3.	Funding increase will support the completion of the design phase of PIP-II, the Early Conventional Facilities subproject for the cryogenic plant, and fabrication of prototypes for the linear accelerator. The construction phase will fully begin with CD-3 in FY 2022.
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment, FNAL	$171,000	$176,000	+$5,000
Funding supports completion of the Far Site civil construction activities for pre-excavation and the beginning of excavation activities for the underground equipment caverns and connecting drifts (tunnels), as well as design and procurement activities for Far Site cryogenics systems. Funding also supports Near Site (FNAL) beamline and conventional facilities design and continuation of a site-preparation construction subcontract at the Near Site for relocation of existing service roads and utilities. Funding supports the continuation of construction and fabrication for technical systems including contributions to the DUNE detectors, when design is final and construction authorized by CD-3.		The Request will support continuation of the Far Site civil construction activities, as well as continuing design and procurement activities for Far Site cryogenics systems. The Request will also support procurement activities for the Near Site (FNAL) beamline and conventional facilities. The Request will support the continuation of construction and fabrication for technical systems, including contributions to the DUNE detectors, when design is final and construction is authorized by CD-3.	Funding will support continuation for excavation at the Far Site and the ramp-up of design effort on the Near Site facilities and the detectors.

(dollars in thousands)

FY 2021 Enacted	FY 2022 Request	Explanation of Changes FY 2022 Request vs FY 2021 Enacted
11-SC-41, Muon to Electron Conversion Experiment, FNAL $2,000	$13,000	+$11,000
Funding will support initial mitigation of increased costs due to schedule delays caused by pandemic response at FNAL and collaborating universities. These funds were not part of the originally approved project baseline, although a BCP is in process.	The Request will support continuing mitigation of increased costs due to schedule delays caused by pandemic response at FNAL and collaborating universities, and by delayed delivery of two superconducting magnets due to vendor's poor technical and schedule performance. These funds were not part of the originally approved project baseline, although a BCP is in process.	Funding will support increased costs from COVID-19 impacts and vendor performance.

High Energy Physics
Capital Summary

(dollars in thousands)

	Total	Prior Years	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Capital Operating Expenses						
Capital Equipment	N/A	N/A	105,350	91,830	52,180	-39,650
Minor Construction Activities						
General Plant Projects	N/A	N/A	10,900	1,500	14,000	+12,500
Total, Capital Operating Expenses	**N/A**	**N/A**	**116,250**	**93,330**	**66,180**	**-27,150**

Capital Equipment

(dollars in thousands)

	Total	Prior Years	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Capital Equipment						
Major Items of Equipment						
Energy Frontier Experimental Physics						
High Luminosity Large Hadron Collider Accelerator Upgrade Project	236,672	71,572	52,025	43,000	20,000	-23,000
High Luminosity Large Hadron Collider ATLAS Upgrade Project	136,000	27,500	24,500	16,000	10,000	-6,000
High Luminosity Large Hadron Collider CMS Upgrade Project	121,800	13,750	23,475	13,500	10,000	-3,500
Intensity Frontier Experimental Physics						
Accelerator Controls Operations Research Network	136,900	–	–	–	2,000	+2,000
Cosmic Frontier Experimental Physics						
Cosmic Microwave Background - Stage 4	375,600	–	–	1,000	2,000	+1,000
Total, MIEs	N/A	N/A	100,000	73,500	44,000	-29,500
Total, Non-MIE Capital Equipment	N/A	N/A	5,350	18,330	8,180	-10,150
Total, Capital Equipment	**N/A**	**N/A**	**105,350**	**91,830**	**52,180**	**-39,650**

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

Minor Construction Activities

	(dollars in thousands)					
	Total	**Prior Years**	**FY 2020 Enacted**	**FY 2021 Enacted**	**FY 2022 Request**	**FY 2022 Request vs FY 2021 Enacted**
General Plant Projects (GPP)						
GPPs (greater than or equal to $5M and less than $20M)						
Kautz Road Sub-Station	7,500	–	7,500	–	–	–
Target Systems Integration Building	15,500	–	–	1,500	14,000	+12,500
Total GPPs (greater than or equal to $5M and less than $20M)	N/A	N/A	7,500	1,500	14,000	+12,500
Total GPPs less than $5M	N/A	N/A	3,400	–	–	–
Total, General Plant Projects (GPP)	**N/A**	**N/A**	**10,900**	**1,500**	**14,000**	**+12,500**
Total, Minor Construction Activities	**N/A**	**N/A**	**10,900**	**1,500**	**14,000**	**+12,500**

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..

High Energy Physics
Major Items of Equipment Description(s)

Energy Frontier Experimental Physics MIEs:

High-Luminosity Large Hadron Collider Accelerator Upgrade Project (HL-LHC Accelerator Upgrade Project)

The HL-LHC Accelerator Upgrade Project received CD-2/3b approval on February 11, 2019, with a TPC of $242,720,000. CD-3 was approved on December 21, 2020 to complete the production of the remaining accelerator components for the upgrade. Following the major upgrade, the CERN LHC machine will further increase the particle collision rate by at least a factor of five to explore new physics beyond its current reach. This project will deliver components for which U.S. scientists have critical expertise: interaction region focusing quadrupole magnets, and special superconducting radiofrequency crab cavities that are capable of generating transverse electric fields. The magnets will be assembled at LBNL, BNL, and FNAL, exploiting special expertise and unique capabilities at each laboratory. The FY 2022 Request for TEC funding of $20,000,000 will continue to focus support on critical path items in the production of quadrupole magnets and crab cavities to best maintain international schedule synchronization.

High-Luminosity Large Hadron Collider ATLAS Detector Upgrade Project (HL-LHC ATLAS)

The HL-LHC ATLAS project received CD-1 approval on September 21, 2018, with an estimated cost range of $149,000,000 to $181,000,000, and received CD-3a approval on October 16, 2019. CD-2 is planned for FY 2022. The ATLAS detector will integrate a higher amount of data per run by at least a factor of ten compared to the period prior to the HL-LHC upgrades, making the physical conditions in which the detectors run very challenging. To operate for an additional decade in these new conditions, the ATLAS detector will require upgrades to the silicon pixel and strip tracker detectors, the muon detector systems, the calorimeter detectors and associated electronics, and the trigger and data acquisition systems. The National Science Foundation (NSF) approved support for a Major Research Equipment and Facility Construction (MREFC) project in FY 2020 to provide different scope to the HL-LHC ATLAS detector upgrade. DOE and NSF are coordinating their contributions to avoid duplication. The FY 2022 Request for TEC funding of $10,000,000 will focus support on critical path items to best maintain international schedule synchronization for the project.

High-Luminosity Large Hadron Collider CMS Detector Upgrade Project (HL-LHC CMS)

The HL-LHC CMS project received CD-1 approval on December 19, 2019, with an estimated cost range of $144,100,000 to $183,000,000, and received CD-3a approval on June 8, 2020. CD-2 is planned for FY 2022. The CMS detector will integrate a higher amount of data per run by at least a factor of ten compared to the period prior to the HL-LHC upgrades, making the physical conditions in which the detectors run very challenging. To operate for an additional decade in these new conditions, the CMS detector will require upgrades to the silicon pixel tracker detectors, outer tracker detector, the muon detector systems, the calorimeter detectors and associated electronics, the trigger and data acquisition systems, and the addition of a novel timing detector. NSF approved support for a MREFC Project in FY 2020 to provide different scope to the HL-LHC CMS detector upgrade. DOE and NSF are coordinating their contributions to avoid duplication. The FY 2022 Request for TEC funding of $10,000,000 will focus support on critical path items to best maintain international schedule synchronization for the project.

Intensity Frontier Experimental Physics MIE:

Accelerator Controls Operations Research Network (ACORN)

The ACORN project received CD-0 approval on August 28, 2020, with an estimated cost range of $100,000,000 to $142,000,000. This project will replace FNAL's dated accelerator control system with a modern system which is maintainable, sustainable, and capable of utilizing advances in Artificial Intelligence and Machine Learning to create a high-performance accelerator for the future. The control system of the Fermilab Accelerator Complex initiates particle beam production; controls beam energy and intensity; steers particle beams to their ultimate destination; measures beam parameters; and monitors beam transport through the complex to ensure safe, reliable, and effective operations. ACORN will provide FNAL with an accelerator control system that will be compatible with PIP-II. FNAL plans to collaborate with other national labs that have experience with accelerator control systems. This project is expected to receive CD-1 approval in Q4 FY 2021 and CD-2 approval in FY 2022. The FY 2022 Request for TEC funding of $2,000,000 will initiate a new start for MIE and will fund system design and other related engineering activities.

Cosmic Frontier Experimental Physics MIE:

Cosmic Microwave Background Stage 4 (CMB-S4)

The CMB-S4 project received CD-0 approval on July 25, 2019, with an estimated cost range of $320,000,000 to $395,000,000. The project is expected to be carried out as a partnership with NSF, with DOE as the lead agency and a distribution of scope determined by FY 2022. The project consists of fabricating an array of small and large telescopes at two locations: the NSF Amundsen-Scott South Pole Station and the Atacama high desert in Chile. It will include a focal plane of 500,000 ultra-sensitive sensors with associated readout systems. LBNL was selected in August 2020 to lead the efforts in providing the DOE scope for the project. The project is expected to obtain CD-1 approval in FY 2022, along with CD-3a approval of long lead procurements at the same time. In FY 2022, plans for the sensors and readout systems as well as the conceptual design will be completed and the preliminary design and pre-production efforts will start. The FY 2022 Request for TEC funding of $2,000,000 will enable long lead procurement for sensor production and testing, as well as associated systems and infrastructure.

General Plant Projects $5 Million to less than $20 Million

Target Systems Integration Building
General Plant Project Details

Project Name:	Target Systems Integration Building
Location/Site:	Fermilab Accelerator Complex
Type:	GPP
Total Estimated Cost:	$15,500,000
Construction Design:	$1,500,000
Project Description:	The proposed building will provide facilities to produce and integrate hardware for the future activities of LBNF, and High Power Targetry R&D, as well as continuing target facilities (NuMI, BNB, g-2 Target Station, and Mu2e). Existing activities occur at the Main Injector (MI)-8 building, so the new building will expand off of MI-8. The present building has inadequate crane capacity and floor space for future activities.

High Energy Physics
Construction Projects Summary

(dollars in thousands)

	Total	Prior Years	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
18-SC-42, Proton Improvement Plan II, FNAL						
Total Estimated Cost (TEC)	891,200	21,000	60,000	79,000	90,000	+11,000
Other Project Cost (OPC)	86,800	73,100	494	–	–	–
Total Project Cost (TPC)	**978,000**	**94,100**	**60,494**	**79,000**	**90,000**	**+11,000**
11-SC-40, Long Baseline Neutrino Facility / Deep Underground Neutrino Experiment						
Total Estimated Cost (TEC)	2,390,000	336,781	171,000	171,000	176,000	+5,000
Other Project Cost (OPC)	210,000	87,625	4,000	2,000	4,000	+2,000
Total Project Cost (TPC)	**2,600,000**	**424,406**	**175,000**	**173,000**	**180,000**	**+7,000**
11-SC-41, Muon to Electron Conversion Experiment						
Total Estimated Cost (TEC)	265,000	250,000	–	2,000	13,000	+11,000
Other Project Cost (OPC)	23,677	23,677	–	–	–	–
Total Project Cost (TPC)	**288,677**	**273,677**	**–**	**2,000**	**13,000**	**+11,000**
Total, Construction						
Total Estimated Cost (TEC)	**N/A**	**N/A**	**231,000**	**252,000**	**279,000**	**+27,000**
Other Project Cost (OPC)	**N/A**	**N/A**	**4,494**	**2,000**	**4,000**	**+2,000**
Total Project Cost (TPC)	**N/A**	**N/A**	**235,494**	**254,000**	**283,000**	**+29,000**

Note for Mu2e: In anticipation of approval of the Baseline Change Proposal (BCP), $2,000,000 of TEC funding was appropriated in FY 2021 and $13,000,000 of TEC funding is requested in FY 2022. These additional funds cannot be spent until the BCP approval and the project is re-baselined.

High Energy Physics
Funding Summary

(dollars in thousands)

	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Research	390,077	398,203	419,605	+21,402
Facility Operations	316,429	314,297	309,395	-4,902
Projects				
Line Item Construction (LIC)	235,494	254,000	283,000	+29,000
Major Items of Equipment (MIE)	103,000	79,500	49,000	-30,500
Total, Projects	**338,494**	**333,500**	**332,000**	**-1,500**
Total, High Energy Physics	**1,045,000**	**1,046,000**	**1,061,000**	**+15,000**

High Energy Physics
Scientific User Facility Operations

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

Definitions for TYPE A facilities:

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

Planned Operating Hours –

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

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

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

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

(dollars in thousands)

	FY 2020 Enacted	FY 2020 Current	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Scientific User Facilities - Type A					
Fermilab Accelerator Complex	**141,520**	**142,755**	**130,900**	**143,000**	**+12,100**
Number of Users	2,450	2,014	2,050	2,340	+290
Achieved Operating Hours	–	2,604	–	–	–
Planned Operating Hours	4,900	4,340	3,640	5,180	+1,540
Optimal Hours	5,740	5,740	4,480	5,740	+1,260
Percent of Optimal Hours	85.4%	45.4%	81.3%	90.2%	+8.9%
Unscheduled Down Time Hours	–	1,736	–	–	–

(dollars in thousands)

	FY 2020 Enacted	FY 2020 Current	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Accelerator Test Facility	**6,067**	**5,310**	**6,100**	**–**	**-6,100**
Number of Users	127	106	105	–	-105
Achieved Operating Hours	–	2,341	–	–	–
Planned Operating Hours	2,500	2,500	2,250	–	-2,250
Optimal Hours	2,500	2,500	2,500	–	-2,500
Percent of Optimal Hours	100.0%	93.6%	90.0%	–	-90.0%
Unscheduled Down Time Hours	–	165	–	–	–
Facility for Advanced Accelerator Experimental Tests II (FACET II)	**6,000**	**6,000**	**16,000**	**13,000**	**-3,000**
Number of Users	200	94	250	225	-25
Planned Operating Hours	1,500	1,500	3,720	2,700	-1,020
Optimal Hours	3,000	3,000	3,720	3,000	-720
Percent of Optimal Hours	50.0%	–	100.0%	90.0%	-10.0%
Total, Facilities	**153,587**	**154,065**	**153,000**	**156,000**	**+3,000**
Number of Users	2,777	2,214	2,405	2,565	+160
Achieved Operating Hours	–	4,945	–	–	–
Planned Operating Hours	8,900	8,340	9,610	7,880	-1,730
Optimal Hours	11,240	11,240	10,700	8,740	-1,960
Unscheduled Down Time Hours	–	1,901	–	–	–

Note: Achieved Operating Hours and Unscheduled Downtime Hours will only be reflected in the Congressional budget cycle which provides actuals.
Note: Funding for the Accelerator Test Facility is funded in the Accelerator R&D and Production program in FY 2022.

High Energy Physics
Scientific Employment

	FY 2020 Enacted	FY 2021 Enacted	FY 2022 Request	FY 2022 Request vs FY 2021 Enacted
Number of Permanent Ph.Ds (FTEs)	788	780	791	+11
Number of Postdoctoral Associates (FTEs)	361	370	374	+4
Number of Graduate Students (FTEs)	486	485	486	+1
Number of Other Scientific Employment (FTEs)	1,625	1,585	1,632	+47

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

18-SC-42, Proton Improvement Plan II (PIP-II), FNAL
Fermi National Accelerator Laboratory
Project is for Design and Construction

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

Summary

The FY 2022 Request for the Proton Improvement Project II (PIP-II) is $90,000,000 of Total Estimated Cost (TEC) funding. The project has an approved Total Project Cost (TPC) of $978,000,000.

The PIP-II project will enhance the Fermilab Accelerator Complex to enable it to deliver higher-power proton beams to the neutrino-generating target for groundbreaking discovery in neutrino physics. The project will design and construct an 800 megaelectronvolt (MeV) superconducting radio frequency (SRF) proton linear accelerator and beam transfer line. The PIP-II project also will modify the existing Fermi National Accelerator Laboratory (FNAL) Booster, Recycler, and Main Injector synchrotrons downstream from the new linear accelerator to accept the increased beam intensity. Some of the new components and the cryoplant will be provided through international, in-kind contributions.

Significant Changes

This project was initiated in FY 2018. The most recent DOE Order 413.3B approved Critical Decision (CD) is CD-3A (Approve Long-lead Procurement), approved March 16, 2021; it followed three months after CD-2 (Approve Performance Baseline), approved on December 14, 2020, with a Total Project Cost (TPC) of $978,000,000. The PIP-II project was restructured in FY 2020 with a subproject, "Early Conventional Facilities (ECF)," that received Critical Decision CD-2/3 (Approve Subproject Performance Baseline and Start of Construction) on July 17, 2020. The ECF subproject is a subsidiary subset of the PIP-II project, with TPC of $36,000,000. ECF will be funded out of the same line-item appropriation as the PIP-II project. All financial information for PIP-II is inclusive of ECF. Approve Start of Construction, CD-3, is anticipated in late FY 2021, and the preliminary date for CD-4, Project Completion, is FY 2033.

Continued design and development work in FY 2020 improved the maturity of the civil engineering and technical system designs, cost estimates, risk assessment and contingency plans, as well as the planning of technical prototypes for risk mitigation of the project. Outcomes included net reduction of the estimated cost for the civil construction and net increase of the estimated cost for the technical equipment. Assumptions were refined for the level of in-kind contributions from the international partner laboratories; and the project team now includes a new international partner, Poland's Wroclaw University of Science and Technology (WUST). Estimates were updated for indirect costs and for schedule impacts to date due to the COVID-19 pandemic.

Due to the reassessment of delivery schedules for international in-kind contributions, the planned CD-4 critical milestone date is delayed by three years to FY 2033. The planned CD-3 milestone date for starting construction has not changed because of the intentional strategy of prioritizing civil construction ahead of design completion for the accelerator's technical systems. Design of the technical components will be completed when needed for fabrication.

FY 2021 funds support initiation of construction for the cryogenic plant building and, to the extent possible, civil engineering and site work for the other PIP-II conventional facilities as well as technical design, prototyping and initiation of procurement for PIP-II technical systems when designs are final and construction is authorized by CD-3.

The FY 2022 Request will support completion of construction for the cryogenic plant building and continuation of civil engineering and site work for the other PIP-II conventional facilities as well as continue technical design, prototyping and procurement for PIP-II technical systems when designs. The Office of Science is evaluating cost and schedule impacts due to the COVID-19 pandemic.

A Federal Project Director (FPD) has been assigned to this project and has approved this CPDS. The FPD completed Level 3 certification in FY 2018, and Level 4 certification is in process.

Critical Milestone History

Fiscal Year	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	CD-4
FY 2020	11/12/15	7/23/18	7/23/18	3Q FY 2020	4Q FY 2021	4Q FY 2021	1Q FY 2030
FY 2021	11/12/15	7/23/18	7/23/18	3Q FY 2020	4Q FY 2025	4Q FY 2021	1Q FY 2030
FY 2022	11/12/15	7/23/18	7/23/18	12/14/20	4Q FY 2022	4Q FY 2022	1Q FY 2033

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	Performance Baseline Validation	CD-3A
FY 2020	2Q FY 2020	3Q FY 2020
FY 2021	2Q FY 2020	3Q FY 2020
FY 2022	12/14/20	3/16/21

CD-3A – Approve long-lead procurement of niobium for superconducting radio frequency (SRF) cavities and other long lead components for SRF cryomodules

Project Cost History

(dollars in thousands)

Fiscal Year	TEC, Design	TEC, Construction	TEC, Total	OPC, Except D&D	OPC, D&D	OPC, Total	TPC
FY 2020	91,000	547,965	638,965	82,035	N/A	82,035	721,000
FY 2021	184,000	617,200	801,200	86,800	N/A	86,800	888,000
FY 2022	177,000	714,200	891,200	86,800	N/A	86,800	978,000

2. Project Scope and Justification

Scope

Specific scope elements of the PIP-II project include construction of (a) the superconducting radio frequency (SRF) Linac, (b) cryoplant to support SRF operation, (c) beam transfer line, (d) modifications to the Booster, Recycler and Main Injector synchrotrons, and (e) conventional facilities:

a) 800-MeV Superconducting H^- Linac consisting of a 2.1 MeV warm (normal-conducting) front-end injector and five types of SRF cryomodules that are continuous wave capable but operating initially in pulsed mode. The cryomodules include Half Wave Resonator cavities (HWR) at 162.5 MHz, two types of Single Spoke Resonator cavities (SSR1 and SSR2) at 325 MHz, Low-Beta and High-Beta elliptical cavities at 650 MHz (LB-650 and HB-650).

The warm front-end injector consists of an H^- ion source, Low Energy Beam Transport (LEBT), Radiofrequency Quadrupole (RFQ) and Medium Energy Beam Transport (MEBT) that prepare the beam for injection into the SRF cryomodules. The scope includes the associated electronic power sources, instrumentation and controls to support Linac operation.

The PIP-II Injector Test Facility at FNAL is an R&D prototype for the low-energy proton injector at the front-end of the Linac, consisting of H^- ion source, LEBT, RFQ, MEBT, HWR, and one SSR1 cryomodule. It is being developed to reduce technical risks for the project, with participation and in-kind contributions from the India Department of Atomic Energy (DAE) Labs.

b) Cryoplant with storage and distribution system to support SRF Linac operation. The cryoplant is an in-kind contribution by the India DAE Labs that is similar to the cryoplant being designed and constructed for a high-intensity superconducting proton accelerator project in India.[a]

c) Beam Transfer Line from the Linac to the Booster Synchrotron, including accommodation of a beam dump and future delivery of beam to the FNAL Muon Campus.

d) Modification of the Booster, Recycler and Main Injector synchrotrons to accommodate a 50 percent increase in beam intensity and construction of a new injection area in the Booster to accommodate 800-megaelectronvolt (MeV) injection.

e) Civil construction of conventional facilities, including housings, service buildings, roads, access points and utilities with the special capabilities required for the linac and beam transport line. The linac housing will be constructed with adequate length to accommodate the possibility of a future extension of the linac for beam energy up to 1 GeV. A portion of the civil construction scope comprises the ECF subproject. That subproject scope includes the cryogenics plant building and site work. ECF subproject total estimated cost is $36,000,000; $8,000,000 in FY 2020, $22,000,000 in FY 2021 and $6,000,000 in FY 2022. (See footnotes in the Financial Schedule, Section 3 below.) If the ECF subproject completes less than budget, DOE may authorize redistribution of those funds to remaining PIP-II project scope.

Significant pieces of the Linac and cryogenic scope (a and b above) will be delivered as in-kind international contributions not funded by DOE. These include assembly and/or fabrication of Linac SRF components and the cryoplant. The rationale or motivation behind these contributions are institutional and/or industrial technical capability, and interest in SRF technology. The construction phase scope of in-kind contributions is divided between U.S. DOE Labs, India Department of Atomic Energy (DAE) Labs, Italy National Institute for Nuclear Physics (INFN) Labs, French Atomic Energy Commission (CEA) and National Center for Scientific Research (CNRS)-National Institute of Nuclear and Particle Physics (IN2P3) Labs, UK Science & Technology Facilities Council (STFC) Labs, and Poland Wroclaw University of Science and Technology, tentatively as indicated in the following table of Scope Responsibilities for PIP-II.[a]

Construction-phase Scope Responsibilities for PIP-II Linac RF Components

Components	Quan-tity	Freq. (MHz)	SRF Cavities	Responsibility for Cavity Fabrication	Responsibility for Module Assembly	Responsibility for RF Amplifiers	Cryogenic Cooling Source and Distribution System
RFQ	1	162.5	N/A	N/A	U.S. DOE (LBNL)	U.S. DOE (FNAL)	N/A
HWR Cryomodule	1	162.5	8	U.S. DOE (ANL)	U.S. DOE (ANL)	U.S. DOE (FNAL)	India DAE Labs, Poland WUST
SSR1 Cryomodule	2	325	16	U.S. DOE (FNAL), India DAE Labs	U.S. DOE (FNAL)	India DAE Labs	India DAE Labs, Poland WUST
SSR2 Cryomodule	7	325	35	France CNRS (IN2P3 Lab)	U.S. DOE (FNAL)	India DAE Labs	India DAE Labs, Poland WUST
LB-650 Cryomodule	9	650	36	Italy INFN (LASA)	France CEA (Saclay Lab)	India DAE Labs	India DAE Labs, Poland WUST
HB-650 Cryomodule	4	650	24	UK STFC Labs	UK STFC Labs, U.S. DOE (FNAL)	India DAE Labs	India DAE Labs, Poland WUST

[a] See Section 8.

Justification

The PIP-II project will enhance the Fermilab Accelerator Complex by providing the capability to deliver higher-power proton beams to the neutrino-generating target that serves the LBNF/DUNE program[a] for groundbreaking discovery in neutrino physics, a major field of fundamental research in high energy particle physics. Increasing the neutrino beam intensity requires increasing the proton beam power on target. The higher proton beam power will come from a 1.2-megawatt (MW) beam on target over an energy range of 60-120 GeV, a significant increase of beam power beyond the current proton beam capability. The PIP-II project will provide more flexibility for future science-driven upgrades to the entire accelerator complex and increase the system's overall reliability by addressing some of the accelerator complex's elements that are far beyond their design life.

PIP-II was identified as one of the highest priorities in the 10-year strategic plan for U.S. High Energy Physics developed by the High Energy Physics Program Prioritization Panel (P5) and unanimously approved by the High Energy Physics Advisory Panel (HEPAP), advising DOE and NSF, in 2014.[b]

The project is being conducted in accordance with the project management requirements in DOE Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets*.

Key Performance Parameters (KPPs)

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.

Performance Measure	Threshold	Objective
Linac Beam Energy	H- beam will be accelerated to 600 MeV.	H- beam will be accelerated to 700 MeV. Linac systems required for 800 MeV will be installed and tested.
Linac Beam Intensity	H- beam will be delivered to the beam absorber at the end of the linac.	H- beam with intensity of 1.3×10^{12} particles per pulse at 20 Hz pulse-repetition rate will be delivered to the Beam Transfer Line absorber.
Booster, Recycler and Main Injector Synchrotron Upgrades	Upgrades of the Booster, Recycler and Main Injector Synchrotrons, required to support delivery of 1.2 MW onto the LBNF target, will be installed and tested without beam.	Linac beam will be injected into and circulated in the Booster.

[a] LBNF/DUNE is the DOE Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment.
[b] "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context," HEPAP, 2014.

3. Financial Schedule

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Estimated Cost (TEC)			
Design (TEC)			
FY 2018	1,000	1,000	–
FY 2019	20,000	20,000	17,812
FY 2020	51,000	51,000	37,770
FY 2021	53,000	53,000	53,000
FY 2022	40,000	40,000	40,000
Outyears	12,000	12,000	28,418
Total, Design (TEC)	**177,000**	**177,000**	**177,000**
Construction (TEC)			
FY 2020	9,000	9,000	123
FY 2021	26,000	26,000	26,000
FY 2022	50,000	50,000	50,000
Outyears	629,200	629,200	638,077
Total, Construction (TEC)	**714,200**	**714,200**	**714,200**
Total Estimated Cost (TEC)			
FY 2018	1,000	1,000	–
FY 2019	20,000	20,000	17,812
FY 2020	60,000	60,000	37,893
FY 2021	79,000	79,000	79,000
FY 2022	90,000	90,000	90,000
Outyears	641,200	641,200	666,495
Total, TEC	**891,200**	**891,200**	**891,200**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Other Project Cost (OPC)			
FY 2016	18,715	18,715	12,724
FY 2017	16,285	15,220	17,494
FY 2018	23,100	24,165	22,214
FY 2019	15,000	15,000	19,112
FY 2020	494	494	1,845
FY 2021	–	–	205
Outyears	13,206	13,206	13,206
Total, OPC	**86,800**	**86,800**	**86,800**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Project Cost (TPC)			
FY 2016	18,715	18,715	12,724
FY 2017	16,285	15,220	17,494
FY 2018	24,100	25,165	22,214
FY 2019	35,000	35,000	36,924
FY 2020	60,494	60,494	39,738
FY 2021	79,000	79,000	79,205
FY 2022	90,000	90,000	90,000
Outyears	654,406	654,406	679,701
Total, TPC	**978,000**	**978,000**	**978,000**

Notes:

- *Costs through FY 2020 reflect actual costs; costs for FY 2021 and outyears are estimates.*
- *FY 2017 Budget Authority includes recategorization of pre-conceptual design activities to Other Project Costs that occurred in FY 2018.*
- *The ECF subproject, funded by TEC, is a total of $36M; with $8M in FY 2020, $22M in FY 2021 and $6M in FY 2022.*

4. Details of Project Cost Estimate

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design	149,314	170,000	149,314
Design - Contingency	27,686	14,000	27,686
Total, Design (TEC)	**177,000**	**184,000**	**177,000**
Construction	124,009	145,000	124,009
Site Preparation	12,783	18,000	12,783
Equipment	378,705	245,000	378,705
Construction - Contingency	198,703	209,200	198,703
Total, Construction (TEC)	**714,200**	**617,200**	**714,200**
Total, TEC	**891,200**	**801,200**	**891,200**
Contingency, TEC	*226,389*	*223,200*	*226,389*
Other Project Cost (OPC)			
R&D	67,117	67,700	67,117
Conceptual Planning	8,324	9,000	8,324
Conceptual Design	2,855	4,000	2,855
OPC - Contingency	8,504	6,100	8,504
Total, Except D&D (OPC)	**86,800**	**86,800**	**86,800**
Total, OPC	**86,800**	**86,800**	**86,800**
Contingency, OPC	*8,504*	*6,100*	*8,504*
Total, TPC	**978,000**	**888,000**	**978,000**
Total, Contingency (TEC+OPC)	***234,893***	***229,300***	***234,893***

5. Schedule of Appropriations Requests

(dollars in thousands)

Request Year	Type	Prior Years	FY 2020	FY 2021	FY 2022	Outyears	Total
FY 2020	TEC	21,000	20,000	—	—	597,965	638,965
	OPC	72,035	5,000	—	—	5,000	82,035
	TPC	93,035	25,000	—	—	602,965	721,000
FY 2021	TEC	21,000	60,000	20,000	—	700,200	801,200
	OPC	72,035	494	2,000	—	12,271	86,800
	TPC	93,035	60,494	22,000	—	712,471	888,000
FY 2022	TEC	21,000	60,000	79,000	90,000	641,200	891,200
	OPC	73,100	494	—	—	13,206	86,800
	TPC	94,100	60,494	79,000	90,000	654,406	978,000

6. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy	FY 2033
Expected Useful Life	20 years
Expected Future Start of D&D of this capital asset	FY 2053

FNAL will operate the PIP-II Linac as an integral part of the entire Fermilab Accelerator Complex. Related funding estimates for operations, utilities, maintenance and repairs are incremental to the balance of the FNAL accelerator complex for which the present cost of operation, utilities, maintenance and repairs is approximately $100,000,000 annually.

Related Funding Requirements
(dollars in thousands)

	Annual Costs		Life Cycle Costs	
	Previous Total Estimate	**Current Total Estimate**	**Previous Total Estimate**	**Current Total Estimate**
Operations	4,000	4,000	80,000	80,000
Utilities	3,000	3,000	60,000	60,000
Maintenance and Repair	2,000	2,000	40,000	40,000
Total, Operations and Maintenance	9,000	9,000	180,000	180,000

7. D&D Information

The new area being constructed in this project is not replacing existing facilities.

	Square Feet
New area being constructed by this project at FNAL	127,676
Area of D&D in this project at FNAL	—
Area at FNAL to be transferred, sold, and/or D&D outside the project, including area previously "banked"	—
Area of D&D in this project at other sites	—
Area at other sites to be transferred, sold, and/or D&D outside the project, including area previously "banked"	127,676
Total area eliminated	—

The one-for-one replacement will be met through banked space. A waiver from the one-for-one requirement to eliminate excess space at FNAL to offset PIP-II and other projects was approved by DOE Headquarters on November 12, 2009. The waiver identified and transferred to FNAL 575,104 square feet of excess space to accommodate new facilities including Mu2e, LBNF, DUNE, and other facilities, as-yet unbuilt, from space that was banked at other DOE facilities. The PIP-II Project is following all current DOE procedures for tracking and reporting space utilization.

8. Acquisition Approach

DOE is acquiring the PIP-II project through Fermi Research Alliance (FRA), the Management and Operating (M&O) contractor responsible for FNAL, rather than have the DOE compete a contract for fabrication to a third party. FRA has a strong relationship with the high energy physics community and its leadership, including many FNAL scientists and engineers. This arrangement will facilitate close cooperation and coordination for PIP-II with an experienced team of project leaders managed by FRA, which will have primary responsibility for oversight of all subcontracts required to execute the project. The arrangement is expected to include subcontracts for the purchase of components from third party vendors as well as delivery of in-kind contributions from non-DOE partners.

Project partners will deliver significant pieces of scope as in-kind international contributions, not funded by U.S. DOE. The rationale or motivation behind these contributions are institutional and/or industrial technical capability, long-standing collaborations in the physics programs at FNAL that PIP-II will support, and interest in SRF technology. Scientific institutions from several countries, tabulated below, are engaged in discussion of potential PIP-II scope contributions within the framework of international, government-to-government science and technology agreements.

Scientific Agencies and Institutions Discussing Potential Contributions of Scope for PIP-II

Country	Funding Agency	Institutions
U.S.	Department of Energy	Fermi National Accelerator Laboratory; Lawrence Berkeley National Laboratory; Argonne National Laboratory
India	Department of Atomic Energy	Bhabha Atomic Research Centre, Mumbai; Inter University Accelerator Centre, New Delhi; Raja Ramanna Centre for Advanced Technology, Indore; Variable Energy Cyclotron Centre, Kolkata
Italy	National Institute for Nuclear Physics	Laboratory for Accelerators and Applied Superconductivity, Milan
France	Atomic Energy Commission National Center for Scientific Research	Saclay Nuclear Research Center; National Institute of Nuclear & Particle Physics, Paris
UK	Science & Technology Facilities Council	Daresbury Laboratory
Poland	Wroclaw University of Science and Technology	Wroclaw University of Science and Technology

For example, joint participation by U.S. DOE and the India DAE in the development and construction of high intensity superconducting proton accelerator projects at FNAL and in India is codified in Annex I to the “Implementing Agreement between DOE and Indian Department of Atomic Energy in the Area of Accelerator and Particle Detector Research and Development for Discovery Science for High Intensity Proton Accelerators,” signed in January 2015 by the U.S. Secretary of Energy and the India Chairman of DAE. FNAL and DAE Labs subsequently developed a “Joint R&D Document” outlining the specific roles and goals of the collaborators during the R&D phase of the PIP-II project. This R&D agreement is expected to lead to a similar agreement for the construction phase, describing roles and in-kind contributions. DOE and FNAL are developing similar agreements with Italy, France, and the UK for PIP-II.

SC is putting mechanisms into place to facilitate joint consultation between the partnering funding agencies, such that coordinated oversight and actions will ensure the success of the overall program. SC is successfully employing similar mechanisms for international partnering for the DOE LBNF/DUNE project and for DOE participation in LHC-related projects hosted by CERN.

Domestic engineering and construction subcontractors will perform the civil construction at FNAL. FNAL is utilizing a firm fixed-price contract for architectural-engineering services to complete all remaining designs for conventional facilities with an option for construction support. The general construction subcontract will be placed on a firm-fixed-price basis.

All subcontracts will be competitively bid and awarded based on best value to the government. Fermi Site Office provides contract oversight for FRA’s plans and performance. Project performance metrics for FRA are included in the M&O contractor’s annual performance evaluation and measurement plan.

11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment, FNAL
Fermi National Accelerator Laboratory
Project is for Design and Construction

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

<u>**Summary**</u>

The FY 2022 Request for Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE) is $176,000,000 of Total Estimated Cost (TEC) funding and $4,000,000 in Other Project Cost (OPC) funding. Currently, the project has a preliminary Total Project Cost (TPC) range of $1,260,000,000 to $1,860,000,000, which includes the full cost of the DOE contribution to the LBNF host facility and the DUNE experimental apparatus excluding foreign contributions. This cost range encompasses the most feasible preliminary alternatives at this time. The preliminary TPC estimate for DOE's share of this project is $2,600,000,000 which exceeds by 40 percent the top of the cost range of $1,260,000,000 to $1,860,000,000 that was approved for CD-1(R) on November 5, 2015. An Independent Project Review conducted by DOE in January 2021 recommended the cost range be reevaluated with a planned review of new range in 1Q FY 2022. According to DOE policy, if the top end of the original approved CD-1 cost range grows by more than 50 percent as the project proceeds toward CD-2 then the Program, in coordination with the Project Management Executive, must reassess the alternative selection process.[a]

<u>**Significant Changes**</u>

This project was initiated in FY 2012. The most recent approved DOE Order 413.3B critical decision is CD-3A, approval for Initial Far Site Construction: initiating excavation and construction for the LBNF Far Site conventional facilities in order to mitigate risks and minimize delays for providing a facility ready to accept detectors for installation.

Updated planning and analysis in FY 2019-2020 increased the TPC point estimate for the LBNF/DUNE project to $2,600,000,000. The cost estimate increased for three reasons. The first is due to the cost of the excavation. The excavation Construction Manager is now on site and has identified deficiencies in the greater than 100-year-old mining infrastructure that will need to be repaired to support the large volume of rock removal. In addition, the time required to complete the excavation was underestimated. The independent cost estimator employed by the project and the design firm verified these findings. The second reason for the increased cost is that contributions from international partners have been lower than expected. DOE and the laboratory are continuing engagement with potential partners. The third reason is due to significantly higher installation costs, determined when the detailed installation plan was developed in FY 2020. Scope reductions are being considered to refine the scope by FY 2022 for the baseline.

The Office of Science (SC) processed a reduction to the approved scope within the authorized expenditures related to work previously approved by CD-3A. This action was triggered by higher cost estimates for the scope approved by CD-3A. The change transferred some of the scope that had been approved by CD-3A to a later authorization decision. CD-3, Approve Start of Construction, is anticipated in FY 2022, and the preliminary date for CD-4, Project Completion, is early FY 2034.

In FY 2020, the project refined its plan and cost estimate for technical integration of the DUNE experimental equipment for neutrino detection, with the civil and cryogenic facility infrastructure. Prototype liquid-argon neutrino detectors and cryostats were constructed and operated by the DUNE scientific collaboration, at reduced scale, at FNAL and CERN in FY 2018-2020, reducing the project's technical risk. The refined plan and cost estimate addressed explicitly the Other Project Costs (OPC) and laboratory operating organization needed to support technical coordination. The details of the project's current total estimate now include the "Other OPC Costs" for execution support including the cost of electrical power for construction and installation, which previously had been estimated as construction costs.

[a]Per DOE Order 413.3B, Appendix A-6, 11/29/2010.

FY 2020 funding supported the pre-excavation, the reliability projects, the design of the near site conventional facilities, the cryogenic systems, and the detectors. The project was evaluated by Independent Project Reviews in January 2020, July 2020, and January 2021. The reviews saw evidence of progress but saw the need for more work before baselining. The project plans to establish a technical, cost, and schedule baseline in FY 2022. FY 2021 funding supports the completion of the pre-excavation, which was accomplished in March 2021, and work on final design needed for CD-3.

The FY 2022 Request will support continuation of the Far Site civil construction activities for excavation of the underground equipment caverns and connecting drifts (tunnels), as well as continuing design and procurement activities for Far Site cryogenics systems. The Request will also support Near Site (FNAL) beamline and conventional facilities construction procurement activities. Near Site preparation continues in FY 2022, including relocation of utilities at FNAL and staging of beamline shielding blocks to assess their useability for the project and mitigate the need to procure new steel shielding. Shielding blocks are sourced by recovering surplus material buried on-site and by obtaining off-site recycled material. The Request will support design and prototyping of technical systems, including contributions to the DUNE detectors. When design is final and construction is authorized by CD-3, fabrication will begin. SC is evaluating cost and schedule impacts due to the COVID-19 pandemic.

A Federal Project Director with a certification level 4 has been assigned to this project and has approved this CPDS.

Critical Milestone History

Fiscal Year	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	CD-4
FY 2011	1/8/10	-	1Q FY 2011	-	4Q FY 2013	-	-
FY 2012	1/8/10	-	2Q FY 2012	-	2Q FY 2015	-	-
FY 2016	1/8/10	12/10/12	12/10/12	4Q FY 2017	4Q FY 2019	4Q FY 2019	4Q FY 2027
FY 2017	1/8/10	11/5/15	11/5/15	4Q FY 2017	4Q FY 2019	4Q FY 2019	4Q FY 2030
FY 2018	1/8/10	11/5/15	11/5/15	1Q FY 2021	1Q FY 2022	1Q FY 2022	4Q FY 2030
FY 2019	1/8/10	11/5/15	11/5/15	1Q FY 2021	1Q FY 2022	1Q FY 2022	4Q FY 2030
FY 2020	1/8/10	11/5/15	11/5/15	1Q FY 2021	1Q FY 2022	1Q FY 2022	4Q FY 2030
FY 2021	1/8/10	11/5/15	11/5/15	1Q FY 2021	4Q FY 2023	4Q FY 2023	4Q FY 2033
FY 2022	1/8/10	11/5/15	11/5/15	1Q FY 2022	4Q FY 2022	4Q FY 2022	4Q FY 2034

Note:

- *No CPDS was submitted for FY 2013, FY 2014 or FY 2015 because no TEC funds were requested; however, TEC funds for design activities were provided in each year's appropriation. FY 2016 was the initial CPDS for design and construction.*

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	Performance Baseline Validation	CD-1R	CD-3A	CD-3B	CD-3C
FY 2017	1Q FY 2020	11/5/15	2Q FY 2016	3Q FY 2018	1Q FY 2020
FY 2018	1Q FY 2021	11/5/15	9/1/16	1Q FY 2021	1Q FY 2022
FY 2019	1Q FY 2021	11/5/15	9/1/16	1Q FY 2021	1Q FY 2022
FY 2020	1Q FY 2021	11/5/15	9/1/16	1Q FY 2021	1Q FY 2022
FY 2021	1Q FY 2021	11/5/15	9/1/16	1Q FY 2021	4Q FY 2023
FY 2022	1Q FY 2022	11/5/15	9/1/16	2Q FY 2022	4Q FY 2022

CD-1R – Refresh of CD-1 approval for the new Conceptual Design.
CD-3A – Approve Initial Far Site Construction: initiating excavation and construction for the LBNF Far Site conventional facilities in order to mitigate risks and minimize delays for providing a facility ready to accept detectors for installation.
CD-3B – Approve Start of Far Site Construction: procurement of the remaining Far Site scope for conventional facilities and selected long-lead procurements.
CD-3C – Approve Start of Near Site Construction: procurement of Near Site scope and any remaining LBNF/DUNE scope.

Project Cost History

(dollars in thousands)

Fiscal Year	TEC, Design	TEC, Construction	TEC, Total	OPC, Except D&D	OPC, D&D	OPC, Total	TPC
FY 2011	102,000	TBD	TBD	22,180	TBD	TBD	TBD
FY 2012	133,000	TBD	TBD	42,621	TBD	TBD	TBD
FY 2016	127,781	655,612	783,393	89,539	N/A	89,539	872,932
FY 2017	123,781	1,290,680	1,414,461	89,539	N/A	85,539	1,500,000
FY 2018	234,375	1,199,000	1,433,375	102,625	N/A	102,625	1,536,000
FY 2019	231,000	1,234,000	1,465,000	95,000	N/A	95,000	1,560,000
FY 2020	259,000	1,496,000	1,755,000	95,000	N/A	95,000	1,850,000
FY 2021	300,000	2,176,375	2,476,375	123,625	—	123,625	2,600,000
FY 2022	445,934	1,944,066	2,390,000	210,000	—	210,000	2,600,000

Note:
- *No CPDS was submitted for FY 2013, FY 2014 or FY 2015 because no TEC funds were requested; however, TEC funds for design activities were provided in each year's appropriation.*
- *The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 was $1,260,000,000 to $1,860,000,000. The TPC point estimate has increased to $2,600,000,000 and was reviewed by Independent Project Review (IPR) in FY 2020.*
- *No construction, other than site preparation and approved civil construction or long-lead procurement, will be performed prior to validation of the Performance Baseline and approval of CD-3.*

2. Project Scope and Justification

Scope
LBNF/DUNE will be composed of a neutrino beam created by new construction as well as modifications to the existing Fermilab Accelerator Complex, massive neutrino detectors (at least 40,000 tons in total) and associated cryogenics infrastructure located in one or more large underground caverns to be excavated at least 800 miles "downstream" from the neutrino source, and a much smaller neutrino detector at FNAL for monitoring the neutrino beam near its source. A primary beam of protons will produce a neutrino beam directed into a target for converting the protons into a secondary beam of

particles (pions and muons) that decay into neutrinos, followed by a decay tunnel hundreds of meters long where the decay neutrinos will emerge and travel through the earth to the massive detector. The Neutrinos at the Main Injector (NuMI) beam at FNAL is an existing example of this type of configuration for a neutrino beam facility. The new LBNF beam line will provide a neutrino beam of lower energy and greater intensity than the NuMI beam and would point to a far detector at a greater distance than is used with NuMI experiments.[a]

For the LBNF/DUNE project, FNAL will be responsible for design, construction and operation of the major components of LBNF including: the primary proton beam, neutrino production target, focusing structures, decay pipe, absorbers and corresponding beam instrumentation; the conventional facilities and experiment infrastructure on the FNAL site required for the near detector; and the conventional facilities and experiment infrastructure at SURF for the large detectors including the cryostats and cryogenics systems.

Justification

Recent international progress in neutrino physics, celebrated by the Nobel Prizes for Physics in 1988, 1995, 2002, and 2015, provides the basis for further discovery opportunities. Determining relative masses and mass ordering of the three known neutrinos will give guidance and constraints to theories beyond the Standard Model of particle physics. The study and observation of the different behavior of neutrinos and antineutrinos will offer insight into the dominance of matter over antimatter in our universe and, therefore, the very structure of our universe. The only other source of the matter-antimatter asymmetry, in the quark sector, is too small to account for the observed matter dominance.

The LBNF/DUNE construction project is a federal, state, private, and international partnership developing and implementing the technologies of particle accelerators and detectors to enable world-leading research into the fundamental physics of neutrinos, which are the most ubiquitous particles in the universe while at the same time among the most mysterious. Neutrinos are intimately involved in nuclear decay processes and high energy nuclear reactions. LBNF/DUNE will study the transformations of muon neutrinos that occur as they travel to a large detector in South Dakota, 800 miles away from FNAL, where they are produced in a high-energy beam. The experiment will analyze the rare, flavor-changing transformations of neutrinos in flight, from one lepton flavor to another, which are expected to help explain the fundamental physics of neutrinos and the puzzling matter-antimatter asymmetry that enables our existence in a matter-dominated universe.

The LBNF/DUNE project comprises a national flagship particle physics initiative. LBNF/DUNE will be the first-ever large-scale international science facility hosted by the United States. As part of implementation of High Energy Physics Advisory Panel (HEPAP)-Particle Physics Project Prioritization Panel (P5) recommendations, the LBNF/DUNE project consists of two multinational collaborative efforts:

- LBNF is responsible for the beamline and other experimental and civil infrastructure at FNAL and at the Sanford Underground Research Facility (SURF) in South Dakota. It is currently operated by the South Dakota Science and Technology Authority (SDSTA), an agency of the State of South Dakota, and hosts experiments supported by DOE, the National Science Foundation, and major research universities.

- DUNE is an international scientific collaboration responsible for defining the scientific goals and technical requirements for the beam and detectors, as well as the design, construction and commissioning of the detectors and subsequent research program.

DOE's High Energy Physics program manages both activities as a single, line-item construction project—LBNF/DUNE. LBNF, with DOE/FNAL leadership and minority participation by a small number of international partners including CERN, will construct a megawatt-class neutrino source and related facilities at FNAL (the "Near Site"), as well as underground caverns and cryogenic facilities in South Dakota (the "Far Site") needed to house the DUNE detectors. DUNE has international leadership and participation of over 1,100 scientists and engineers from over 200 institutions in over 30 countries. DOE will

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[a] Detailed analyses of alternatives compared the NuMI beam to a new, lower-energy neutrino beam directed toward SURF in South Dakota, and also compared different neutrino detection technologies for the DUNE detector.

fund less than a third of DUNE. DOE continues to refine the development of the design and cost estimates as the U.S. DOE contributions to the multinational effort are now defined. FNAL continues to identify and incorporate additional design activities and prototypes into the project design.

FNAL and DOE have confirmed contributions to LBNF documented in international agreements from CERN, the UK, India, Poland, and Brazil. Discussions are ongoing with several other countries for additional contributions. For the DUNE detectors, the collaboration put in place a process to complete a technical design of the detectors and divide the work of building the detectors between the collaborating institutions. The review of the detector design with a complete set of funding responsibilities by the Long Baseline Neutrino Committee began in 2019, and development of the set of funding responsibilities has made significant progress and continues to advance. SC will manage all DOE contributions to the facility and the detectors according to DOE Order 413.3B, and FNAL will provide unified project management reporting.

The project is being conducted in accordance with the project management requirements in DOE Order 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 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.

Performance Measure	Threshold	Objective
Primary Beam to produce neutrinos directed to the far detector site	Beamline hardware commissioning complete and demonstration of protons delivered to the target	In addition to Threshold KPPs, system enhancements to maximize neutrino flux, enable tunability in neutrino energy spectrum or to improve neutrino beam capability
Far Site-Conventional Facilities	Caverns excavated for 40 kiloton fiducial detector mass[a]; beneficial occupancy granted for cavern space to house 20 kiloton fiducial detector mass[a]	In addition to Threshold KPPs, Beneficial Occupancy granted for remaining cavern space
Detector Cryogenic Infrastructure	DOE-provided components for cryogenic subsystems installed and pressure tested for 20 kiloton fiducial detector mass	In addition to Threshold KPPs, additional DOE contributions to cryogenic subsystems installed and pressure tested for additional 20 kiloton fiducial detector mass; DOE contributions to cryostats
Long-Baseline Distance between neutrino source and far detector	1,000 km to 1,500 km	1,000 km to 1,500 km
Far Detector	DOE-provided components installed in cryostats to support 20 kiloton fiducial detector mass, with cosmic ray interactions detected in each detector module	In addition to Threshold KPPs, additional DOE contributions to support up to 40 kiloton fiducial detector mass

[a] Fiducial detector mass pertains to the mass of the interior volume of the detection medium (liquid argon) that excludes the external portion of the detection medium where most background events would occur.

3. Financial Schedule

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Estimated Cost (TEC)			
Design (TEC)			
FY 2012	4,000	4,000	–
FY 2013	3,781	3,781	801
FY 2014	16,000	16,000	7,109
FY 2015	12,000	12,000	15,791
FY 2016	26,000	26,000	26,436
FY 2017	48,585	48,585	36,924
FY 2018	25,000	25,000	44,749
FY 2019	70,000	70,000	53,841
FY 2020	78,568	78,568	71,104
FY 2021	81,000	81,000	81,000
FY 2022	81,000	81,000	108,179
Total, Design (TEC)	**445,934**	**445,934**	**445,934**
Construction (TEC)			
FY 2017	1,415	1,415	333
FY 2018	70,000	70,000	1,427
FY 2019	60,000	60,000	25,865
FY 2020	92,432	92,432	75,605
FY 2021	90,000	90,000	90,000
FY 2022	95,000	95,000	95,000
Outyears	1,535,219	1,535,219	1,655,836
Total, Construction (TEC)	**1,944,066**	**1,944,066**	**1,944,066**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Estimated Cost (TEC)			
FY 2012	4,000	4,000	–
FY 2013	3,781	3,781	801
FY 2014	16,000	16,000	7,109
FY 2015	12,000	12,000	15,791
FY 2016	26,000	26,000	26,436
FY 2017	50,000	50,000	37,257
FY 2018	95,000	95,000	46,176
FY 2019	130,000	130,000	79,706
FY 2020	171,000	171,000	146,709
FY 2021	171,000	171,000	171,000
FY 2022	176,000	176,000	203,179
Outyears	1,535,219	1,535,219	1,655,836
Total, TEC	**2,390,000**	**2,390,000**	**2,390,000**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Other Project Cost (OPC)			
FY 2009	12,486	12,486	–
FY 2010	14,178	14,178	11,032
FY 2011	7,768	7,750	18,554
FY 2012	17,000	17,018	18,497
FY 2013	14,107	14,107	13,389
FY 2014	10,000	10,000	11,348
FY 2015	10,000	10,000	10,079
FY 2016	86	86	2,284
FY 2017	–	–	120
FY 2018	1,000	1,000	86
FY 2019	1,000	1,000	347
FY 2020	4,000	4,000	4,006
FY 2021	2,000	2,000	2,000
FY 2022	4,000	4,000	4,000
Outyears	112,375	112,375	114,258
Total, OPC	**210,000**	**210,000**	**210,000**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Project Cost (TPC)			
FY 2009	12,486	12,486	–
FY 2010	14,178	14,178	11,032
FY 2011	7,768	7,750	18,554
FY 2012	21,000	21,018	18,497
FY 2013	17,888	17,888	14,190
FY 2014	26,000	26,000	18,457
FY 2015	22,000	22,000	25,870
FY 2016	26,086	26,086	28,720
FY 2017	50,000	50,000	37,377
FY 2018	96,000	96,000	46,262
FY 2019	131,000	131,000	80,053
FY 2020	175,000	175,000	150,715
FY 2021	173,000	173,000	173,000
FY 2022	180,000	180,000	207,179
Outyears	1,647,594	1,647,594	1,770,094
Total, TPC	**2,600,000**	**2,600,000**	**2,600,000**

Note:
- *Costs through FY 2020 reflect actual costs; costs for FY 2021 and outyears are estimates.*
- *In FY 2012, $1,078,000 of design funding was erroneously costed to this project, the accounting records were adjusted in early FY 2013.*
- *In FY 2012, $18,000 of FY 2011 funding was attributed towards the Other Projects Costs activities.*
- *In FY 2019, $13,000,000 of Other Project Cost for Recovery Act funding was originally planned for the conceptual design, although $12,486,000 was attributed to the project from recategorization for pre-conceptual design activities ($511,000) and closeout of expired funds ($3,000) in subsequent years.*

4. Details of Project Cost Estimate

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design	397,568	270,000	**N/A**
Design - Contingency	48,366	30,000	**N/A**
Total, Design (TEC)	**445,934**	**300,000**	**N/A**
Construction	1,134,000	1,146,000	**N/A**
Equipment	375,000	381,000	**N/A**
Construction - Contingency	435,066	649,375	**N/A**
Total, Construction (TEC)	**1,944,066**	**2,176,375**	**N/A**
Total, TEC	**2,390,000**	**2,476,375**	**N/A**
Contingency, TEC	*483,432*	*679,375*	***N/A***
Other Project Cost (OPC)			
R&D	20,625	20,625	**N/A**
Conceptual Planning	30,000	30,000	**N/A**
Conceptual Design	35,000	35,000	**N/A**
Other OPC Costs	100,000	38,000	**N/A**
OPC - Contingency	24,375	N/A	**N/A**
Total, Except D&D (OPC)	**210,000**	**123,625**	**N/A**
Total, OPC	**210,000**	**123,625**	**N/A**
Contingency, OPC	*24,375*	*N/A*	***N/A***
Total, TPC	**2,600,000**	**2,600,000**	**N/A**
Total, Contingency (TEC+OPC)	***507,807***	***679,375***	***N/A***

Note:

- *The validated baseline does not occur until CD-2. That column is the only place where N/As are acceptable.*
- *Construction involves excavation of caverns at SURF, 4850 ft. below the surface, for technical equipment including particle detectors and cryogenic systems and construction of the housing for the neutrino-production beam line and the near detector.*
- *Technical equipment in the DOE scope, estimated here, will be supplemented by in-kind contributions of additional technical equipment, for the accelerator beam and particle detectors, from non-DOE partners as described in Section 1.*
- *"Other OPC Costs" include execution support costs including electrical power for construction and equipment installation.*

5. Schedule of Appropriations Requests

(dollars in thousands)

Request Year	Type	Prior Years	FY 2020	FY 2021	FY 2022	Outyears	Total
FY 2011	TEC	102,000	—	—	—	—	102,000
	OPC	22,180	—	—	—	—	22,180
	TPC	124,180	—	—	—	—	124,180
FY 2012	TEC	133,000	—	—	—	—	133,000
	OPC	42,621	—	—	—	—	42,621
	TPC	175,621	—	—	—	—	175,621
FY 2016	TEC	51,781	—	—	—	731,612	783,393
	OPC	89,539	—	—	—	—	89,539
	TPC	141,320	—	—	—	731,612	872,932
FY 2017	TEC	106,802	—	—	—	1,307,659	1,414,461
	OPC	85,539	—	—	—	—	85,539
	TPC	192,341	—	—	—	1,307,659	1,500,000
FY 2018	TEC	166,681	—	—	—	1,266,694	1,433,375
	OPC	85,725	—	—	—	16,900	102,625
	TPC	252,406	—	—	—	1,283,594	1,536,000
FY 2019	TEC	279,681	—	—	—	1,185,319	1,465,000
	OPC	86,725	—	—	—	8,275	95,000
	TPC	366,406	—	—	—	1,193,594	1,560,000
FY 2020	TEC	336,781	100,000	—	—	1,318,219	1,755,000
	OPC	87,625	4,000	—	—	3,375	95,000
	TPC	424,406	104,000	—	—	1,321,594	1,850,000
FY 2021	TEC	336,781	171,000	100,500	—	1,868,094	2,476,375
	OPC	87,625	4,000	1,000	—	31,000	123,625
	TPC	424,406	175,000	101,500	—	1,899,094	2,600,000
FY 2022	TEC	336,781	171,000	171,000	176,000	1,535,219	2,390,000
	OPC	87,625	4,000	2,000	4,000	112,375	210,000
	TPC	424,406	175,000	173,000	180,000	1,647,594	2,600,000

Note:
- *All estimates are preliminary. For the first column of Request Year, the outyears represent the time period beyond that specific requested Budget Year.*

6. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy	FY 2034
Expected Useful Life	20 years
Expected Future Start of D&D of this capital asset	FY 2054

Operations and maintenance funding of this experiment will become part of the existing Fermilab Accelerator Complex. Annual related funding estimates include the incremental cost of 20 years of full operation, utilities, maintenance, and repairs with the accelerator beam on. The estimates also include operations and maintenance for the remote site of the large detector.

Related Funding Requirements
(dollars in thousands)

	Annual Costs		Life Cycle Costs	
	Previous Total Estimate	**Current Total Estimate**	**Previous Total Estimate**	**Current Total Estimate**
Operations	9,000	9,000	180,000	180,000
Utilities	8,000	8,000	160,000	160,000
Maintenance and Repair	1,000	1,000	20,000	20,000
Total, Operations and Maintenance	18,000	18,000	360,000	360,000

7. D&D Information

The new area being constructed in this project is replacing existing facilities.

	Square Feet
New area being constructed by this project at Fermi National Accelerator Laboratory...................	48,200
New area being constructed by this project at Sanford Underground Research Facility (SURF).......	93,800
Area of D&D in this project at Fermi National Accelerator Laboratory..	—
Area at Fermi National Accelerator Laboratory to be transferred, sold, and/or D&D outside the project, including area previously "banked"	48,200
Area of D&D in this project at other sites	—
Area at other sites to be transferred, sold, and/or D&D outside the project, including area previously "banked"	93,800
Total area eliminated	—

The one-for-one replacement has been met through banked space. A waiver from the one-for-one requirement to eliminate excess space at FNAL to offset the LBNF/DUNE project was approved by DOE Headquarters on November 12, 2009. The waiver identified and transferred to FNAL 575,104 square feet of excess space to accommodate the new LBNF/DUNE facilities and other as yet unbuilt facilities from space that was banked at other DOE facilities.

8. Acquisition Approach

The Acquisition Strategy, approved as part of CD-1, documents the acquisition approach. DOE is acquiring design, construction, fabrication, and operation of LBNF through the M&O contractor responsible for FNAL, Fermi Research Alliance (FRA). FRA and FNAL, through the LBNF Project based at FNAL, is responsible to DOE to manage and complete construction of LBNF at both the near and remote site locations. FRA and FNAL are assigned oversight and management responsibility for execution of the international DUNE project, to include management of the DOE contributions to DUNE. The basis for this choice and strategy is that:

- FNAL is the site of the only existing neutrino beam facility in the U.S. and, in addition to these facilities, provides a source of existing staff and expertise to be utilized for beamline and detector construction.
- FNAL can best ensure that the design, construction, and installation of key LBNF and DUNE components are coordinated effectively and efficiently with other research activities at FNAL.
- FNAL has a DOE-approved procurement system with established processes and acquisition expertise needed to obtain the necessary components and services to build the scientific hardware, equipment and conventional facilities for the accelerator beamline, and detectors for LBNF and DUNE.
- FNAL has extensive experience in managing complex construction, fabrication, and installation projects involving multiple national laboratories, universities, and other partner institutions, building facilities both on-site and at remote off-site locations.

- FNAL, through the LBNF Project, has established a close working relationship with SURF and the SDSTA, organizations that manage and operate the remote site for the far detector in Lead, SD.
- FNAL has extensive experience with management and participation in international projects and international collaborations, including most recently the LHC and CMS projects at CERN, as well as in the increasingly international neutrino experiments and program.

The LBNF/DUNE construction project is a federal, state, private and international partnership. Leading the LBNF/DUNE Project, FNAL will collaborate and work with many institutions, including other DOE national laboratories (e.g. BNL, LBNL and SLAC), dozens of universities, foreign research institutions, and the SDSTA. FNAL will be responsible for overall project management, Near Site conventional facilities, and the beamline. FNAL will work with SDSTA to complete the conventional facilities construction at the remote site needed to house and outfit the DUNE far detector. With the DUNE collaboration, FNAL is also responsible for technical and resource coordination to support the DUNE far and near detector design and construction. DOE will be providing in-kind contributions to the DUNE collaboration for detector systems, as agreed upon with the international DUNE collaboration.

International participation in the design, construction, and operation of LBNF and DUNE will be of essential importance because the field of High Energy Physics is international by nature; necessary talent and expertise are globally distributed, and DOE does not have the procurement or technical resources to self-perform all of the required construction and fabrication work. Contributions from other nations will be predominantly through the delivery of components built in their own countries by their own researchers. DOE will negotiate agreements in cooperation with the Department of State on a bilateral basis with all contributing nations to specify their expected contributions and the working relationships during the construction and operation of the experiment.

DOE will provide funding for the LBNF/DUNE Project directly to FNAL and collaborating DOE national laboratories via approved financial plans, and under management control of the LBNF/DUNE-U.S. Project Office at FNAL, which will also manage and control DOE funding to the combination of university subcontracts and direct fixed-price vendor procurements that are anticipated for the design, fabrication and installation of LBNF and DUNE technical components. All actions will perform in accordance with DOE approved procurement policies and procedures.

FNAL staff, or by subcontract, temporary staff working directly with FNAL personnel will perform much of the neutrino beamline component design, fabrication, assembly, and installation. The acquisition approach includes both new procurements based on existing designs, and re-purposed equipment from the Fermilab Accelerator Complex. For some highly specialized components, FNAL will have the Rutherford Appleton Laboratory (RAL) in the United Kingdom design and fabricate the components. RAL is a long-standing FNAL collaborator who has proven experience with such components.

FNAL has chosen the Construction Manager/General Contractor (CM/GC) model to execute the delivery of LBNF conventional facilities at the SURF Far Site. The Laboratory is contracting with an architect/engineer (A/E) firm for design of LBNF Far Site conventional facilities at SURF and with a CM/GC subcontractor to manage the construction of LBNF Far Site facilities. FNAL selected this strategy to reduce risk, enhance quality and safety performance, provide a more collaborative approach to construction, and offer the opportunity for reduced cost and shortened construction schedules, via options for the CM/GC to self-perform or competitively bid subcontract award packages. FNAL determined that excavation scope should be openly competed as provided by the subcontract. The cost reconciliation process provided valuable insight into understanding the scope, schedule, and various approaches to the work. An excavation proposal with a favorable schedule was received that is within the project's current budget.

For the LBNF Near Site conventional facilities at FNAL, the laboratory will subcontract with an A/E firm for design and has initially planned for a CM/GC subcontractor to manage construction of LBNF Near Site facilities. The Laboratory re-evaluated this strategy based on a gap that developed between when Near Site conventional facilities design would be completed and construction could start based on funding constraints. This resulted in selection of a design-bid-build traditional construction method supported by additional procurements for preconstruction and construction phase services.

For the LBNF Far Site conventional facilities at SURF, DOE entered into a land lease with SDSTA on May 20, 2016 covering the area on which the DOE-funded facilities housing and supporting the LBNF and DUNE detector will be built. The lease and related realty actions provides the framework for DOE and FNAL to construct federally-funded buildings and facilities on non-federal land, and to establish a long-term (multi-decade) arrangement for DOE and FNAL to use SDSTA space to host the DUNE experiment. Modifications, repairs, and improvements to the SDSTA infrastructure to support the LBNF/DUNE project are costed to the project. Repairs and improvements for the overall facility are costed to the cooperative agreement between HEP and SDSTA for operation of the facility. Protections for DOE's real property interests in these infrastructure tasks are acquired through the lease with SDSTA, contracts and other agreements such as easements. DOE plans for FNAL to have responsibility for managing and operating the LBNF and DUNE far detector and facilities for a useful lifetime of 20 years and may contract with SDSTA for day-to-day management and maintenance services. At the end of useful life, federal regulations permit transfer of ownership to SDSTA, which is willing to accept ownership as a condition for the lease. FNAL developed an appropriate decommissioning plan prior to lease signing.

11-SC-41, Muon to Electron Conversion Experiment, FNAL
Fermi National Accelerator Laboratory
Project is for Design and Construction

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

Summary
The FY 2022 Request for the Muon to Electron Conversion Experiment (Mu2e) is $13,000,000 of Total Estimated Cost (TEC) funding to support the approved baseline funding profile for the construction project.

The Mu2e project provides the accelerator beam and experimental apparatus to unambiguously identify neutrinoless muon-to-electron conversion events. The conversion of a muon to an electron in the field of a nucleus would probe new physics for discovery at mass scales far beyond the reach of any existing or proposed experiment.

Significant Changes
This project was initiated in FY 2012. The most recent DOE Order 413.3B approved Critical Decision (CD) is CD-3 (Approve Start of Construction), concurrent with completion of the final design, approved on July 14, 2016. Total Project Cost was approved at $273,677,000. The approved funding profile supported this TPC. The CD-4 milestone was set at 1Q FY 2023.

Construction progressed according to plan through FY 2019, the final year of approved funding. FY 2019 funding supported continuing procurement and fabrication activities for the accelerator, beamline, superconducting magnets and particle detectors. Civil construction of the building and underground housing for the experiment was completed in April 2017. This civil facility has special capabilities required to house the primary beam target and transport systems for producing the muons and stopping them in the detector system.

The approved baseline schedule cannot be met as a result of work restrictions at most of the participating institutions in FY 2020 due to the COVID-19 pandemic and because of delayed delivery of two superconducting magnets resulting from poor schedule performance by the vendor. An Independent Project Review recommended a baseline change in February 2021. The Baseline Change Proposal (BCP) is in process, but not yet submitted, reviewed, or approved. In anticipation of approval of the BCP, $2,000,000 of TEC funding was appropriated in FY 2021 and $13,000,000 of TEC funding is requested in FY 2022. The additional funds cannot be spent until the BCP approval and the project is re-baselined.

A Federal Project Director with Certification Level 3 has been assigned to this project and has approved this CPDS.

Critical Milestone History

Fiscal Year	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	CD-4
FY 2011	11/24/09	-	4Q FY 2010	-	4Q FY 2012	-	-
FY 2012	11/24/09	-	4Q FY 2011	-	4Q FY 2013	-	-
FY 2013	11/24/09	-	4Q FY 2012	4Q FY 2013	4Q FY 2014	4Q FY 2014	4Q FY 2018
FY 2014	11/24/09	-	7/11/12	2Q FY 2014	2Q FY 2015	4Q FY 2015	2Q FY 2021
FY 2015	11/24/09	-	7/11/12	4Q FY 2014	2Q FY 2015	4Q FY 2014	2Q FY 2021
FY 2016	11/24/09	7/11/12	7/11/12	2Q FY 2015	3Q FY 2016	3Q FY 2016	1Q FY 2023
FY 2017	11/24/09	7/11/12	7/11/12	3/4/15	3Q FY 2016	3Q FY 2016	1Q FY 2023

Fiscal Year	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	CD-4
FY 2018	11/24/09	7/11/12	7/11/12	3/4/15	7/14/16	7/14/16	1Q FY 2023
FY 2019	11/24/09	7/11/12	7/11/12	3/4/15	7/14/16	7/14/16	1Q FY 2023
FY 2022	11/24/09	7/11/12	7/11/12	3/4/15	7/14/16	7/14/16	1Q FY 2023

Note:
- *Congress approved an FY 2013 reprogramming for the Mu2e construction project following the submission of the FY 2014 budget. The Critical Milestones were consistent with the FY 2014 Request.*

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	Performance Baseline Validation	CD-3A	CD-3B	CD-3C
FY 2014	-	3Q FY 2013	-	-
FY 2015	-	3Q FY 2014	-	-
FY 2016	2Q FY 2015	7/10/14	2Q FY 2015	3Q FY 2016
FY 2017	3/4/15	7/10/14	3/4/15	3Q FY 2016
FY 2018	3/4/15	7/10/14	3/4/15	7/14/16
FY 2019	3/4/15	7/10/14	3/4/15	7/14/16
FY 2022	3/4/15	7/10/14	3/4/15	7/14/16

Note:
- *Congress approved an FY 2013 reprogramming for the Mu2e construction project following the submission of the FY 2014 budget. The Critical Milestones were consistent with the FY 2014 Request.*

CD-3A – Approve Long-Lead Procurements: advanced the procurement, prior to CD-2, for superconducting cable needed for solenoid fabrication, which reduced schedule risk and cost risk to optimize cost and schedule savings in the project baseline.
CD-3B – Approve Long-Lead Procurements: advanced the start of civil construction of the detector hall, which allowed for a shorter and more cost-effective transition from civil engineering design to construction. CD-3B also advanced procurement of superconducting magnet modules for the Transport Solenoid. Advancing these CD-3B procurements reduced the project's schedule and cost risk.
CD-3C – Approve All Construction and Fabrication (same as CD-3)

<u>Project Cost History</u>

(dollars in thousands)

Fiscal Year	TEC, Design	TEC, Construction	TEC, Total	OPC, Except D&D	OPC, D&D	OPC, Total	TPC
FY 2011	35,000	TBD	TBD	10,000	TBD	TBD	TBD
FY 2012	36,500	TBD	TBD	18,777	TBD	TBD	TBD
FY 2013	44,000	N/A	N/A	24,177	–	24,177	68,177

(dollars in thousands)

Fiscal Year	TEC, Design	TEC, Construction	TEC, Total	OPC, Except D&D	OPC, D&D	OPC, Total	TPC
FY 2014	61,000	162,000	223,000	26,177	–	26,177	249,177
FY 2013 Reprogramming	49,000	162,000	211,000	23,677	–	23,677	234,677
FY 2015	47,000	162,900	209,900	23,677	–	23,677	233,577
FY 2016	57,000	193,000	250,000	23,677	N/A	23,677	273,677
FY 2017	57,000	193,000	250,000	23,677	N/A	23,677	273,677[a]
FY 2018	60,598[b]	189,402	250,000	23,677	N/A	23,677	273,677
FY 2019	60,598	189,402	250,000	23,677	N/A	23,677	273,677
FY 2022	60,598	204,402	265,000	23,677	N/A	23,677	288,677

Note for FY 2022:

- *In anticipation of approval of the Baseline Change Proposal (BCP), $2,000,000 of TEC funding was appropriated in FY 2021 and $13,000,000 of TEC funding is requested in FY 2022. These funds cannot be spent until the BCP approval and the project is re-baselined.*

2. Project Scope and Justification

Scope

The Mu2e project includes accelerator modifications, fabrication of superconducting magnets and particle detector systems, and construction of a civil facility with the special capabilities necessary for the experiment. The scope of work in the Project Data Sheet has not changed. The muon beam for the Mu2e experiment will be produced by an intense 8-GeV proton beam, extracted from the Fermilab Booster accelerator, striking a tungsten target. The Mu2e project is modifying the existing Fermilab accelerator complex (Booster, Recycler, and Debuncher Rings) to deliver the primary proton beam to a muon production target, and will efficiently collect and transport the produced muons to a stopping target. The stopping target is surrounded by the Mu2e detector system that can identify muon-to-electron conversions and reject background contamination from muon decays, which produce neutrinos, in contrast to muon conversions which are neutrinoless.

The project has designed and is constructing the detector system (consisting of a tracker, calorimeter, cosmic ray veto, and data acquisition subsystem), a new beam line to the detector system from the former Debuncher Ring, and three superconducting solenoid magnets (a Production Solenoid, Transport Solenoid and Detector Solenoid) that will serve as the beam transport channel for collecting the muons and transporting them into the detector system.

The project designed and completed construction of a 25,000 square foot civil facility with the special capabilities required to house the primary beam target and transport systems for producing the muons and stopping them in the detector system. The civil construction consists of an underground detector enclosure and a surface building for containing the necessary equipment and infrastructure that can be accessed while the multikilowatt proton beam is being delivered to the experiment. The building includes radiation shielding and design features for safe operation of the beam line and experimental apparatus.

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[a] No construction, other than approved long-lead procurement and detector hall civil construction, was performed prior CD-3 approval.

[b] Increased final design development work in FY 2016 reduced the estimated construction cost with modest delay of final design completion and Critical Decision CD-3.

Justification

The conversion of a muon to an electron in the Coulomb field of an atomic nucleus provides a unique experimental signature for discovery of charged-lepton flavor-symmetry violation (CLFV), which may be accessible to this experiment of unprecedented sensitivity and would allow access to new physics at very high mass scales beyond the reach of the LHC. In 2008, the Particle Physics Project Prioritization Panel (P5), a subpanel of the High Energy Physics Advisory Panel (HEPAP), recommended: "Development of a muon-to-electron conversion experiment should be strongly encouraged under all budget scenarios considered by the panel."[a] Again, in 2014, the most recent P5 Subpanel emphasized the priority of the current "Mu2e" experimental construction project in its new report to HEPAP, saying the Mu2e project is an "immediate target of opportunity in the drive to search for new physics and will help inform future choices of direction." "The scientific case is undiminished relative to its earlier prioritization."[b]

Key Performance Parameters (KPPs)

The Threshold KPPs, represent the minimum acceptable performance that the project must achieve. Achievement of the Threshold KPPs will be a prerequisite for approval of CD-4, Project Completion. The Objective KPPs represent the desired project performance.

Performance Measure	Threshold	Objective
Accelerator	Accelerator components are acceptance tested at nominal voltages and currents. Components necessary for single-turn extraction installed. Shielding designed for 1.5 kW operation delivered to Fermilab and ready for installation. All target station components are complete, delivered to Fermilab and tested. Heat and Radiation Shield is installed in Production Solenoid. Other components are ready to be installed after field mapping.	Protons are delivered to the diagnostic absorber in the M4 beamline. Shielding designed for 8 kW operation delivered to Fermilab and ready for installation.
Superconducting Solenoid Magnets	The Production, Transport and Detector Solenoids have been cooled and powered to the settings necessary to take physics data.	The Production, Transport and Detector Solenoids have been cooled and powered to their nominal field settings.
Detector Components	Cosmic Ray Tracks are observed in the Tracker, Calorimeter and a subset of the Cosmic Ray Veto and acquired by the Data Acquisition System after they are installed in the garage position behind the Detector Solenoid. The balance of the Cosmic Ray Veto counters are at Fermilab and ready for installation.	The cosmic ray data in the detectors is acquired by the Data Acquisition System, reconstructed in the online processors, visualized in the event display and stored on disk.

[a] "US Particle Physics: Scientific Opportunities, A Strategic Plan for the Next 10 Years," Report of the Particle Physics Project Prioritization Panel (May 2008).

[b] "Building for Discovery, Strategic Plan for U.S. Particle Physics in the Global Context," Report of the Particle Physics Project Prioritization Panel (May 2014).

3. Financial Schedule

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Estimated Cost (TEC)			
Design (TEC)			
FY 2012	24,000	24,000	–
FY 2013	8,000	8,000	14,653
FY 2014	15,000	15,000	15,404
FY 2015	10,000	10,000	16,892
FY 2016	3,598	3,598	13,649
Total, Design (TEC)	**60,598**	**60,598**	**60,598**
Construction (TEC)			
FY 2014	20,000	20,000	–
FY 2015	15,000	15,000	9,907
FY 2016	36,502	36,502	24,300
FY 2017	43,500	43,500	26,868
FY 2018	44,400	44,400	29,364
FY 2019	30,000	30,000	28,632
FY 2020	–	–	18,360
FY 2021	2,000	2,000	18,000
FY 2022	13,000	13,000	13,000
Outyears	–	–	35,971
Total, Construction (TEC)	**204,402**	**204,402**	**204,402**
Total Estimated Cost (TEC)			
FY 2012	24,000	24,000	–
FY 2013	8,000	8,000	14,653
FY 2014	35,000	35,000	15,404
FY 2015	25,000	25,000	26,799
FY 2016	40,100	40,100	37,949
FY 2017	43,500	43,500	26,868
FY 2018	44,400	44,400	29,364
FY 2019	30,000	30,000	28,632
FY 2020	–	–	18,360
FY 2021	2,000	2,000	18,000
FY 2022	13,000	13,000	13,000
Outyears	–	–	35,971
Total, TEC	**265,000**	**265,000**	**265,000**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Other Project Cost (OPC)			
FY 2010	4,777	4,777	3,769
FY 2011	8,400	8,400	8,940
FY 2012	8,000	8,000	6,740
FY 2013	2,500	2,500	1,020
FY 2014	–	–	2,136
FY 2015	–	–	159
FY 2016	–	–	252
FY 2017	–	–	11
FY 2018	–	–	5
FY 2022	–	–	645
Total, OPC	**23,677**	**23,677**	**23,677**

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Project Cost (TPC)			
FY 2010	4,777	4,777	3,769
FY 2011	8,400	8,400	8,940
FY 2012	32,000	32,000	6,740
FY 2013	10,500	10,500	15,673
FY 2014	35,000	35,000	17,540
FY 2015	25,000	25,000	26,958
FY 2016	40,100	40,100	38,201
FY 2017	43,500	43,500	26,879
FY 2018	44,400	44,400	29,369
FY 2019	30,000	30,000	28,632
FY 2020	–	–	18,360
FY 2021	2,000	2,000	18,000
FY 2022	13,000	13,000	13,645
Outyears	–	–	35,971
Total, TPC	**288,677**	**288,677**	**288,677**

Note:

- *Costs through FY 2020 reflect actual costs; costs for FY 2021 and outyears are estimates.*
- *In anticipation of approval of the Baseline Change Proposal (BCP), $2,000,000 of TEC funding was appropriated in FY 2021 and $13,000,000 of TEC funding is requested in FY 2022. These funds cannot be spent until the BCP approval and the project is re-baselined.*

4. Details of Project Cost Estimate

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design	60,598	60,598	49,000
Design - Contingency	N/A	N/A	8,000
Total, Design (TEC)	**60,598**	**60,598**	**57,000**
Construction	17,336	18,477	13,000
Site Preparation	1,390	1,390	2,000
Equipment	180,346	133,535	133,000
Construction - Contingency	5,330	36,000	45,000
Total, Construction (TEC)	**204,402**	**189,402**	**193,000**
Total, TEC	**265,000**	**250,000**	**250,000**
Contingency, TEC	*5,330*	*36,000*	*53,000*
Other Project Cost (OPC)			
R&D	7,555	8,200	8,200
Conceptual Planning	2,300	2,300	2,300
Conceptual Design	13,177	13,177	13,177
OPC - Contingency	645	N/A	**N/A**
Total, Except D&D (OPC)	**23,677**	**23,677**	**23,677**
Total, OPC	**23,677**	**23,677**	**23,677**
Contingency, OPC	*645*	*N/A*	***N/A***
Total, TPC	**288,677**	**273,677**	**273,677**
Total, Contingency (TEC+OPC)	***5,975***	***36,000***	***53,000***

Note:

- *In anticipation of approval of the Baseline Change Proposal (BCP), $2,000,000 of TEC funding was appropriated in FY 2021 and $13,000,000 of TEC funding is requested in FY 2022. These funds cannot be spent until the BCP approval and the project is re-baselined.*

5. Schedule of Appropriations Requests

(dollars in thousands)

Request Year	Type	Prior Years	FY 2020	FY 2021	FY 2022	Outyears	Total
FY 2011	TEC	35,000	—	—	—	—	35,000
	OPC	10,000	—	—	—	—	10,000
	TPC	45,000	—	—	—	—	45,000
FY 2012	TEC	36,500	—	—	—	—	36,500
	OPC	18,777	—	—	—	—	18,777
	TPC	55,277	—	—	—	—	55,277
FY 2013	TEC	44,000	—	—	—	—	44,000
	OPC	24,177	—	—	—	—	24,177
	TPC	68,177	—	—	—	—	68,177
FY 2014	TEC	223,000	—	—	—	—	223,000
	OPC	26,177	—	—	—	—	26,177
	TPC	249,177	—	—	—	—	249,177
FY 2013 Reprogramming	TEC	211,000	—	—	—	—	211,000
	OPC	23,677	—	—	—	—	23,677
	TPC	234,677	—	—	—	—	234,677
FY 2015	TEC	209,900	—	—	—	—	209,900
	OPC	23,677	—	—	—	—	23,677
	TPC	233,577	—	—	—	—	233,577
FY 2016	TEC	250,000	—	—	—	—	250,000
	OPC	23,677	—	—	—	—	23,677
	TPC	273,677	—	—	—	—	273,677
FY 2017	TEC	250,000	—	—	—	—	250,000
	OPC	23,677	—	—	—	—	23,677
	TPC	273,677	—	—	—	—	273,677
FY 2018	TEC	250,000	—	—	—	—	250,000
	OPC	23,677	—	—	—	—	23,677
	TPC	273,677	—	—	—	—	273,677
FY 2019	TEC	250,000	—	—	—	—	250,000
	OPC	23,677	—	—	—	—	23,677
	TPC	273,677	—	—	—	—	273,677
FY 2022	TEC	250,000	—	2,000	13,000	—	265,000
	OPC	23,677	—	—	—	—	23,677
	TPC	273,677	—	2,000	13,000	—	288,677

Note:

- *In anticipation of approval of the Baseline Change Proposal (BCP), $2,000,000 of TEC funding was appropriated in FY 2021 and $13,000,000 of TEC funding is requested in FY 2022. These funds cannot be spent until the BCP approval and the project is re-baselined.*

6. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy	FY 2023
Expected Useful Life	10 years
Expected Future Start of D&D of this capital asset	FY 2033

Operations and maintenance of this experiment will become part of the existing Fermilab accelerator facility. Annual related funding estimates are for the incremental cost of five years of full operation, utilities, maintenance and repairs with the accelerator beam on. Five subsequent years are planned for further analysis of the data while the detector and beam line are maintained in a minimal maintenance state (with annual cost of approximately 3% of full operations) to preserve availability for future usage with much smaller annual cost.

Related Funding Requirements
(dollars in thousands)

	Annual Costs		**Life Cycle Costs**	
	Previous Total Estimate	**Current Total Estimate**	**Previous Total Estimate**	**Current Total Estimate**
Operations	3,100	3,100	16,000	16,000
Utilities	2,400	2,400	12,400	12,400
Maintenance and Repair	100	100	600	600
Total, Operations and Maintenance	5,600	5,600	29,000	29,000

7. D&D Information

The new area being constructed in this project is not replacing existing facilities.

	Square Feet
New area being constructed by this project at Fermi National Accelerator Laboratory..................	~25,000
Area of D&D in this project at FNAL	0
Area at FNAL to be transferred, sold, and/or D&D outside the project, including area previously "banked"	0
Area of D&D in this project at other sites	0
Area at other sites to be transferred, sold, and/or D&D outside the project, including area previously "banked" "	~25,000
Total area eliminated	0

The one-for-one replacement has been met through banked space. A waiver from the one-for-one requirement to eliminate excess space at Fermilab to offset the Mu2e project was approved by DOE Headquarters on November 12, 2009. The waiver identified and transferred to Fermilab 575,104 square feet of excess space to accommodate the new Mu2e facilities and other as yet unbuilt facilities from space that was banked at other DOE facilities.

8. Acquisition Approach

The acquisition approach is fully documented in the Acquisition Strategy approved as part of CD-1. This is a high-level summary of material from that document.

DOE awarded the prime contract for the Mu2e project to the Fermi Research Alliance (FRA), the Fermilab Management and Operating (M&O) contractor, rather than have the DOE compete a contract for fabrication to a third party. FRA has a strong relationship with the high energy physics community and its leadership, including many Fermilab scientists and engineers. This arrangement will facilitate close cooperation and coordination between the Mu2e scientific collaboration and an experienced team of project leaders managed by FRA, which will have primary responsibility for oversight of all subcontracts required to execute the project. These subcontracts are expected to include the purchase of components from third party vendors as well as subcontracts with university groups to fabricate detector subsystems.

The largest procurements are the magnet systems and the civil construction. The superconducting solenoid magnets are divided into three systems that could be procured independently but which must ultimately perform as a single integrated magnetic system. Two of the systems are similar to systems that have been successfully built in private industry, so the engineering design and fabrication for two of the solenoids was subcontracted to a third party vendor after a study of industrial vendor capabilities confirmed that the technical risks were acceptable. The third solenoid is unique because of its rather large size and unusual configuration, and no good industrial analog exists. This solenoid was designed at Fermilab and is being fabricated by a third-party vendor in multiple modular components, each of which is well matched to existing industrial capabilities.

There were two major subcontracts for the civil construction. An architectural and engineering contract was placed on a firm-fixed-price basis for Preliminary (Title I) Design, and Final (Title II) Design with an option for construction support (Title III). The general construction subcontract was placed on a firm-fixed-price basis and was completed successfully.

All subcontracts have been competitively bid and awarded based on best value to the government. Fermi Site Office provides contract oversight for FRA's plans and performance. Project performance metrics for FRA are included in the M&O contractor's annual performance evaluation and measurement plan.