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 provides reliable availability and support to users for operating facilities. HEP's work allows the U.S. to remain a global leader in international particle physics research and collaboration.

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 2023 Request

The FY 2023 Request for $1,122.0 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.

Key elements in the FY 2023 Request include:

<u>Research</u>

The Request will provide 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 will provide support to foster a diverse, highly skilled, American workforce, and to build R&D capacity and conduct world-leading R&D in the following initiatives:

- Accelerator Science and Technology Initiative (ASTI): In coordination with the Accelerator R&D and Production (ARDAP) program, HEP will continue support for mid- to long-term R&D to maintain a leading position in key accelerator technologies that define SC's competitive advantage.
- Advanced Computing: This initiative will maximize the Nation's investment in Exascale Computing to ensure that researchers will have the ability to intuitively meld and orchestrate AI-enabled advanced computing, instruments, and data to accelerate discovery and innovation. HEP, along with the other SC programs, will work with the national laboratories to ensure broad access to exascale computing resources. This effort will create an integrated system of scientific user facilities, connected via advanced networks and enabling software, accessible to U.S. researchers via the internet and remote virtual platforms, to join as equal partners in DOE's team science model to solve the Nation's biggest challenges.
- AI/ML: HEP leads cutting edge research to tackle the challenges of extracting signals of signature particle physics from HEP experimental and simulated data with increasingly high volumes and complexity; to seek solutions for operating accelerators and detectors in real-time and extremely high data rate environments; and to address cross-cutting challenges across the HEP program in coordination with DOE investments in AI/ML efforts.
- Microelectronics: HEP will work together with other SC programs to support multi-disciplinary research to accelerate the advancement of sensor materials, devices, and front-end electronics that will be vital to future progress in high energy physics.
- QIS: 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. HEP is the lead program supporting the Superconducting Quantum Materials and Systems (SQMS) Center involving 20 institutions and led by the Fermi National Accelerator Laboratory (FNAL). SQMS has a particular focus on extending the coherence lifetime of quantum states to reduce error rates in quantum computing and improve the sensitivity of quantum sensors for dark matter candidates and other precision measurements.
- Reaching a New Energy Sciences Workforce (RENEW): HEP will support 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 diverse students and academic institutions not currently well represented in the U.S. Science & Technology ecosystem.
- Funding for Accelerated, Inclusive Research (FAIR): HEP will support the SC-wide FAIR initiative that provides focused investment on enhancing research on clean energy, climate, and related topics at minority serving institutions (MSI), including attention to underserved and environmental justice communities. The activities will improve the capability of MSIs to perform and propose competitive research and will build beneficial relationships between MSIs and DOE national laboratories and facilities.
- Accelerate Innovations in Emerging Technologies: HEP will support the SC-wide Accelerate initiative that promotes scientific research to accelerate the transition of science advances to energy technologies. The goal is to drive scientific discovery to sustainable production of new technologies across the innovation continuum, to provide experiences in working across this continuum for the workforce needed for industries of the future, and to meet the nation's needs for abundant clean energy, a sustainable environment, and national security.

Facility Operations

HEP supports two Scientific User Facilities, the Fermilab Accelerator Complex and the Facility for Advanced Accelerator Experimental Tests II (FACET-II). These facilities will increase operations to 87 and 91 percent, respectively, of optimal. HEP also 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 DOE National Laboratory, including the ATLAS and CMS detectors at the 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 will continue 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 Request will also continue five Major Item of Equipment (MIE) projects: 1) Accelerator Controls Operations Research Network (ACORN); 2) Cosmic Microwave Background Stage 4 (CMB-S4); 3) High-Luminosity (HL-LHC) Accelerator Upgrade Project; 4) HL-LHC ATLAS Detector Upgrade; and 5) HL-LHC CMS Detector Upgrade Projects.

High Energy Physics
FY 2023 Research Initiatives

High Energy Physics supports the following FY 2023 Research Initiatives.

(dollars in thousands)

	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Accelerate Innovations in Emerging Technologies	–	–	4,000	+4,000
Accelerator Science and Technology Initiative	6,411	6,411	10,000	+3,589
Advanced Computing	–	–	5,146	+5,146
Artificial Intelligence and Machine Learning	33,488	33,488	40,000	+6,512
Funding for Accelerated, Inclusive Research (FAIR)	–	–	2,000	+2,000
Microelectronics	5,000	5,000	7,000	+2,000
Quantum Information Science	45,072	45,072	50,566	+5,494
Reaching a New Energy Sciences Workforce (RENEW)	–	–	8,000	+8,000
Total, Research Initiatives	**89,971**	**89,971**	**126,712**	**+36,741**

High Energy Physics
Funding

	(dollars in thousands)			
	FY 2021 Enacted	**FY 2022 Annualized CR**	**FY 2023 Request**	**FY 2023 Request vs FY 2021 Enacted**
High Energy Physics				
Energy Frontier, Research	68,000	68,438	70,833	+2,833
Energy Frontier, Facility Operations and Experimental Support	53,650	50,642	48,787	-4,863
Energy Frontier, Projects	72,500	72,500	85,000	+12,500
Total, Energy Frontier Experimental Physics	**194,150**	**191,580**	**204,620**	**+10,470**
Intensity Frontier, Research	63,082	62,382	67,644	+4,562
Intensity Frontier, Facility Operations and Experimental Support	166,785	159,500	172,261	+5,476
Intensity Frontier, Projects	3,000	5,000	6,000	+3,000
Total, Intensity Frontier Experimental Physics	**232,867**	**226,882**	**245,905**	**+13,038**
Cosmic Frontier, Research	47,091	44,353	48,512	+1,421
Cosmic Frontier, Facility Operations and Experimental Support	44,500	42,500	47,590	+3,090
Cosmic Frontier, Projects	6,000	4,000	1,000	-5,000
Total, Cosmic Frontier Experimental Physics	**97,591**	**90,853**	**97,102**	**-489**
Theoretical, Computational, and Interdisciplinary Physics, Research	136,362	133,862	163,746	+27,384
Total, Theoretical, Computational, and Interdisciplinary Physics	**136,362**	**133,862**	**163,746**	**+27,384**

(dollars in thousands)

	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Advanced Technology R&D, Research	72,833	64,333	67,911	-4,922
Advanced Technology R&D, Facility Operations and Experimental Support	43,262	42,555	44,736	+1,474
Total, Advanced Technology R&D	**116,095**	**106,888**	**112,647**	**-3,448**
HEP Accelerator Stewardship, Research	10,835	–	–	-10,835
HEP Accelerator Stewardship, Facility Operations and Experimental Support	6,100	–	–	-6,100
Total, HEP Accelerator Stewardship	**16,935**	**–**	**–**	**-16,935**
Subtotal, High Energy Physics	**794,000**	**750,065**	**824,020**	**+30,020**
Construction				
18-SC-42, Proton Improvement Plan II (PIP-II), FNAL	79,000	90,000	120,000	+41,000
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment	171,000	176,000	176,000	+5,000
11-SC-41, Muon to Electron Conversion Experiment, FNAL	2,000	13,000	2,000	–
Subtotal, Construction	**252,000**	**279,000**	**298,000**	**+46,000**
Total, High Energy Physics	**1,046,000**	**1,029,065**	**1,122,020**	**+76,020**

SBIR/STTR funding:

- FY 2021 Enacted: SBIR $22,325,000 and STTR $3,140,000
- FY 2022 Annualized CR: SBIR $21,080,000 and STTR $2,964,000
- FY 2023 Request: SBIR $22,769,000 and STTR $3,202,000

Note:

- *The Accelerator Stewardship subprogram moved to the Accelerator R&D and Production (ARDAP) program starting with the FY 2022 Request.*

High Energy Physics
Explanation of Major Changes

	(dollars in thousands) FY 2023 Request vs FY 2021 Enacted
Energy Frontier Experimental Physics	**+10,470**
The Request will increase support for research in Advanced Computing efforts to manage very large LHC data sets on exascale computers. Research efforts associated with the HL-LHC ATLAS and HL-LHC CMS Detector upgrade activities will continue. Support will focus on maintaining the U.S.-based computing infrastructure needed during the ongoing LHC run, while funding decreases due to the completion of maintenance and consolidation activities of U.S.-built detector components during the scheduled LHC technical stop that ends in FY 2022. Funding will increase to ramp up fabrication activities for the HL-LHC ATLAS and CMS Detector Upgrades.	
Intensity Frontier Experimental Physics	**+13,038**
The Request will increase support for research in Advanced Computing efforts to manage very large neutrino data sets on exascale computers, and for a feasibility study for a muon-catalyzed fusion experiment at FNAL. Operations at the Fermilab Accelerator Complex will increase to 87 percent of optimal. Funding will increase support for General Plant Projects (GPP) funding and Special Process Spares. Funding will increase for the ACORN MIE and LBNF/DUNE OPC. Infrastructure improvements at SURF have been slow to get started and therefore funding will be temporarily reduced.	
Cosmic Frontier Experimental Physics	**-489**
The Request will provide reduced funding for the CMB-S4 MIE, focusing support on engineering design activities. Funding will increase support for operations of the Vera C. Rubin Observatory and for research efforts for data collection and analysis on ongoing and new dark matter and dark energy experiments.	
Theoretical, Computational, and Interdisciplinary Physics	**+27,384**
The Request will provide new support for the Advanced Computing, RENEW, and FAIR initiatives. Funding will increase support 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. Funding will increase support for innovation and new opportunities in AI/ML.	

	(dollars in thousands) FY 2023 Request vs FY 2021 Enacted
Advanced Technology R&D The Request will provide new support for the Accelerate initiative. Funding will increase support for Microelectronics and for HEP Traineeships in Accelerators and Instrumentation. Funding will focus on ASTI efforts in superconducting magnet development and upgrades to superconducting radio-frequency (SRF) test facilities, and co-fund multi-SC program R&D in superconducting materials. Funding will support increased cryogenic, magnet, and SRF testing at FNAL and new two-beam laser wakefield acceleration experiments at LBNL. Operations at FACET-II will increase to 91 percent optimal.	**-3,448**
HEP Accelerator Stewardship Funding for the Accelerator Stewardship subprogram moves to the Accelerator R&D and Production program.	**-16,935**
Construction The Request will increase support for the civil construction and fabrication of technical components for the PIP-II project.	**+46,000**
Total, High Energy Physics	**+76,020**

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

First results from Muon g-2 experiment strengthen evidence of new physics (Intensity Frontier Experimental Physics).

The Muon g-2 collaboration published its first physics result in 2021. The result exceeded all prior results in its statistical and systematic precision. The results from the FNAL-based experiment confirm a prior experiment that took data at Brookhaven National Laboratory (BNL) and strengthen the evidence that our understanding of fundamental physics is incomplete. When combined with BNL, the FNAL experimental determination of the muon's anomalous magnetic moment is in tension with the theoretical expectation. There is less than a 1 in 40,000 chance that the difference is merely a statistical fluke. Either there is an additional 18th fundamental particle that has not yet been directly discovered, or there is something amiss with our understanding of the forces governing the known 17. These astounding implications generated the most excitement for the field of particle physics in the mainstream public since the discovery of the Higgs boson in 2013 at CERN. The Muon g-2 experiment uses an intense, energetic beam of subatomic particles called muons that are generated by the powerful Fermilab Accelerator Complex. The muons are circulated in a magnetic storage ring that was transported in one piece from BNL in 2013. Scientists measure how the muon interacts with the ring's magnetic field to better understand its properties and get a glimpse into the quantum world, where particles of all varieties continually blink in and out of existence as they spontaneously generate from the vacuum surrounding the muon. The results published in 2021 were based on a total of 6 percent of the expected total data sample that will be collected by the experiment. The experiment has already collected ten times the data that was used for the first result. The next publication is expected in 2023 and will shrink the experimental uncertainty by another factor of two, with a factor of four expected by the end of the experiment.

LHC data enables sensitive studies of the Higgs boson and searches for exotic particle decays to probe the existence of new physics (Energy Frontier Experimental Physics).

Scientists at the LHC continued their studies of Higgs boson interactions and searched for exotic particles being created in high energy particle collisions. Using AI/ML techniques to enhance their sensitivity, the ATLAS collaboration used the Higgs boson as a tool for discovery by searching for evidence of decays of the Higgs boson where a pair of oppositely charged muons or electrons accompany the photon decay from the Higgs. While this challenging decay channel is predicted by the standard model at a very 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 CMS collaboration probes the possibility of the Higgs boson serving as a portal for the existence of new particles that have not yet been observed but can provide hints of new physics. The presence of such new and exotic particles can be long-lived and thereby travel longer distances before creating observable signatures in the CMS detector. Using the full dataset acquired from the 2015–2018 run, the CMS experiment has placed stringent constraints that bound the phase space for the signal-like evidence of long-lived particles. These analyses demonstrate the potential for discovery as LHC data taking operations continue in FY 2023.

Double advances for Cosmic Frontier dark energy experiments (Cosmic Frontier Experimental Physics).
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, started its full 5-year scientific survey in May 2021. DESI will carry out a spectroscopic survey of roughly 30 million distant galaxies and quasars, which is ten times more than the previous generation of spectroscopic surveys. With the three-dimensional map derived from these data, DESI will measure the expansion history of the last 8 billion years to better than 0.3 percent precision. These distance measurements will allow the tightest constraints to date on the nature of the dark energy that is responsible for the accelerated expansion of the Universe. In addition to the expansion history, DESI will place the most precise limits on the sum of neutrino masses, provide new tests of inflationary models, and measure the growth rate of large-scale structure in the universe to test models of dark energy. Meanwhile, the Legacy Survey of Space and Time (LSST) Camera (LSSTCam), fabricated for the next generation Vera C. Rubin Observatory, a joint DOE and NSF partnership, completed its MIE funded construction phase in 2021. The LSSTCam will complete testing at SLAC before shipment to Chile for integration on the telescope, followed by commissioning of the entire system. DOE and NSF will also partner for the operations phase, to carry out the ten-year LSST imaging survey which is expected to start in 2024.

Emerging Technologies: Superconducting Quantum Materials and Systems (SQMS) Center (Theoretical, Computational, and Interdisciplinary Physics).
The FNAL-led SQMS Center established a multidisciplinary collaboration comprised of more than 250 experts from twenty partner institutions, spanning from U.S. national labs, academia and industry. The Center has successfully accomplished more than 65 new hires, and new fellowships and internship programs have been created and executed, with emphasis on training a new generation of diverse quantum workforce.

- High Coherence Quantum Devices: 3D superconducting radio-frequency (SRF) cavities and 2D qubits from Rigetti computing have been integrated for the first time, demonstrating a record coherence time of the integrated qubit system approximately 40 times above the state of the art. The combined system has now successfully demonstrated quantum operation and constitutes the first important milestone for a 3D SRF-based quantum computer. A round robin testing program is executed, where qubits are traveling from Rigetti to NIST to FNAL to underground facilities in Italy, for the first large scale systematic benchmarking study of qubit performance.
- Physics and Sensing: New schemes for axion and dark matter detection based on the unique SRF high coherence devices have been proposed. Several tests have been carried out to understand the feasibility of such schemes, and for the first time Nb3Sn cavities have shown to remain superconducting in high magnetic fields, offering an important pathway to improve the sensitivity reach of several dark matter search experiments. The DarkSRF experiment has established a record sensitivity in the search of dark photons and progress has been made in commissioning this experiment in a dilution fridge.
- Algorithms: Quantum simulation of high energy physics has been a key area of research for SQMS. Principal investigators tackled the simulation of dihedral gauge theories on digital quantum computers, which represents a new multi-institution collaboration (FNAL, NASA, Rigetti). In co-design with the SRF based systems under development at the SQMS Center, recent results demonstrate a theoretical approach to studying field theories using a qubit-based simulator.

Construction crews start lowering equipment a mile underground for excavation for Long-Baseline Neutrino Facility (Construction)
The FNAL-hosted Deep Underground Neutrino Experiment (DUNE) is an enormous international scientific effort. More than 1,300 collaborators from over 200 institutions in 33 countries plus CERN aim to shed light on elusive subatomic particles known as neutrinos—and possibly the nature of matter itself. DUNE is also going to be physically enormous. The experiment will send the world's most intense high-energy neutrino beam from the near site in Batavia, Illinois to huge particle detectors 800 miles away at SURF in Lead, South Dakota. Each of the two neutrino detector modules will be four-stories high and over 200 feet long. Construction crews will excavate almost 800,000 tons of rock to create the gigantic caverns of the Long-Baseline Neutrino Facility (LBNF) that will house these detectors. Two years of pre-excavation work was completed, building the necessary systems to move excavated rock from a mile underground to the surface, crush it and then transport it on a 4,200-foot conveyor system for deposit in the Lead Open Cut, in accordance with the wishes of local Native American tribes. On April 5, 2021, Thyssen Mining, the company contracted to carry out the excavation, received the green light to start underground work. Everything required to excavate the LBNF caverns in South Dakota, and build the

future particle detectors, must be lowered a mile below the surface of the Earth through a 13- by 5-foot shaft compartment and then assembled underground, like a ship in a bottle. Thyssen conducted the first underground blast in June. The main cavern excavation work began in August 2021 and will continue for two-and-a-half years.

Successful tests pave the way for FNAL's next-generation particle accelerator; FNAL's new Accelerator Science Program to Increase Representation in Engineering (ASPIRE) fellowship for underrepresented students aims to develop the next generation of accelerator engineers (Construction)
The Proton Improvement Plan II (PIP-II) project includes building a new superconducting proton accelerator to replace the aging linac that serves as the frontend of the Fermilab Accelerator Complex. Once complete, PIP-II will be one of the highest-power linear accelerators in the world. It is the first accelerator project in the U.S. with significant international contributions, with partner institutions in France, India, Italy, Poland, and the United Kingdom. The project successfully completed the operation of the PIP-II Integration Test Facility in 2021. The purpose of the facility was to demonstrate the functionality of the normal conducting frontend of PIP-II by accelerating a proton beam through the frontend and into two prototype superconducting cyromodules. The prototype cryomodules performed as predicted by simulations validating the cryomodules' designs. The facility will now be converted to a cryomodule test-stand where the bulk of the PIP-II cryomodules will be tested with high voltage before being installed into the accelerator.

PIP-II led the development of the ASPIRE fellowship to provide immersive learning experiences at FNAL for undergraduate and masters-level engineering students who are underrepresented in accelerator engineering fields, including Black, LatinX and Indigenous identities, and women. ASPIRE is a partnership between FNAL and colleges and universities. The ASPIRE Fellows participate in the design, development, and construction of world-leading particle accelerators, initially on the PIP-II project. A primary goal of the ASPIRE program is to develop participants into competitive candidates for full-time employment in particle accelerator and related fields upon fellowship completion.

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 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.*
  LHC collisions may possibly produce dark matter particles, and their general properties may be inferred through the behavior of the accompanying normal matter. This "indirect" detection of dark matter is complementary to 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 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 performing scientific simulations and data analyses. This activity also supports Advanced Computing to ensure broad access to exascale computing resources for HEP researchers. DOE selects research efforts with the highest scientific merit and potential impact based on a competitive peer-review process. In FY 2022, HEP plans to conduct an external peer review of the Energy Frontier laboratory research groups. The findings from the reviews in combination with input on strategic directions from regular, open, community workshops will inform funding decisions of the Energy Frontier subprogram in subsequent years.

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.

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 is contributing 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 at least a factor of ten more data.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Energy Frontier Experimental Physics	**$194,150**	**$204,620**	**+$10,470**
Research	$68,000	$70,833	+$2,833
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 the Advanced Computing initiative and will continue support for U.S. leadership roles in all aspects of the ATLAS and CMS experimental programs. This includes the analyses of the large physics datasets collected during the LHC run, as well as scientific personnel support for the HL-LHC ATLAS and CMS Detector upgrade activities.	Funding will focus on support for the Advanced Computing initiative and will continue support for data analysis activities during the present LHC run that will be prioritized through a competitive peer review process 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	$48,787	-$4,863
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 continue supporting ATLAS and CMS detector maintenance and operations activities at CERN and the U.S.-based computing infrastructure and resources required to collect, store, and analyze the large volume of LHC data from the LHC run.	Funding will focus on maintaining the U.S.-based computing infrastructure. Funding will decrease due to the completion of maintenance and consolidation activities of U.S.-built detector components.

(dollars in thousands)

FY 2021 Enacted		FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Projects	$72,500	$85,000	+$12,500
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 continue supporting the production of quadrupole magnets and crab cavities for the HL-LHC Accelerator Upgrade, and ramp-up of fabrication activities for the HL-LHC ATLAS and CMS Detector Upgrades.	Funding will increase to ramp up fabrication activities for the HL-LHC ATLAS and CMS Detector Upgrades. The HL-LHC Accelerator Upgrade Project will continue fabrication efforts.

Note:

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

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 rare 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 such as reactors 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 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 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*
  Several 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.

<u>Research</u>

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, and they perform scientific simulations and physics data analyses. This activity also supports Advanced Computing to ensure broad access to exascale computing resources for HEP researchers. DOE selects research efforts with the highest scientific merit and potential impact based on a competitive peer review process. In FY 2018, HEP conducted an external peer review of the Intensity Frontier laboratory research groups; the next review is planned for FY 2023. In 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 across the Intensity and Cosmic Frontiers that are beyond the current HEP program's sensitivity. The findings from the reviews and BRN workshop in combination with input on strategic directions from regular and open community workshops will inform funding decisions of the Intensity Frontier subprogram 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 near (SBND) and far (ICARUS) detectors to definitively address measurements of additional neutrino types beyond the three currently

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[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

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. Oak Ridge National Laboratory hosts two HEP experimental efforts to measure neutrino properties and to search for new physics. The experiments leverage the Spallation Neutron Source and High Flux Isotope Reactor facilities, via the byproducts of neutron production, which are muon-type neutrinos and electron-type anti-neutrinos, respectively.

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 HEP-supported LZ experiment. SURF will be the home of the DUNE far site detectors being built by the LBNF/DUNE project. The SURF cooperative agreement provides basic services to LBNF/DUNE, and other experiments located at the site.

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 beyond the basic operational support covered by the SURF cooperative agreement mentioned above.

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 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Intensity Frontier Experimental Physics	**$232,867**	**$245,905**	**+$13,038**
Research	$63,082	$67,644	+$4,562
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 continue support for core research efforts in all phases of experiments: data collection, analysis, and dissemination; pre-operations activities for Mu2e, and science planning and development for LBNF/DUNE. Funding will support the Advancing Computing initiative to support new software and networking technologies, which will be developed to transport and analyze very large neutrino data sets on exascale computers. Support will enhance muon beam facilities at FNAL to host a joint muon catalyzed fusion experiment.	Funding increase will support advanced software and computing efforts to manage large neutrino data sets on exascale computers, and a feasibility study for a muon catalyzed fusion experiment at FNAL.
Facility Operations and Experimental Support	$166,785	$172,261	+$5,476
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 SURF operations, and the continued fabrication and installation of the SBND experiment and operations of ICARUS as part of the SBN program. The Fermilab Accelerator Complex will run at 87 percent of optimal and includes funding for a minor General Plant Project. Support for Special Process Spares are needed for efficient recovery from unexpected downtime.	Funding increase will support the delivery of particle beams at peak power and provide detector and computing operations at 87 percent of optimal. Support for GPP and Special Process Spares will increase. Infrastructure improvements at SURF have been slow to get started and therefore funding is temporarily reduced until the backlog is cleared.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Projects $3,000	$6,000	+$3,000
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 increase support for the ACORN MIE system design and other related engineering activities, and OPC execution support costs at SURF for LBNF/DUNE such as electric power for excavation and construction.	Funding increase will support the ACORN MIE system design activities and the LBNF/DUNE OPC support costs at SURF.

Note:

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

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 described 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. 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 this ancient CMB light 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, as the properties of neutrinos lead to changes in these other measurements. These measurements are complementary to 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. In addition, they perform scientific simulations and 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. In FY 2021, HEP conducted an external peer review of the Cosmic Frontier laboratory research groups. In early FY 2019, HEP conducted a Basic Research Needs (BRN)[c] workshop to assess the science landscape and new opportunities for dark matter particle searches made possible by recent technology and theoretical advancements. The scientists identified three priority research directions across the Intensity and Cosmic Frontiers that are 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.

Two complementary next-generation, dark energy "Stage 4" experiments will provide increased precision in measuring the history of the expansion of the universe. 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. The Vera C. Rubin Observatory will carry out a ten-year wide-field, ground-based optical and near-

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

infrared imaging Legacy Survey of Space and Time (LSST) that will be used by the Dark Energy Science Collaboration (DESC). 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, and 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. Research activities support the design and science optimization of the planned experiment.

Two complementary next-generation, dark matter particle search experiments 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. A third next-generation experiment, ADMX-G2, searches for axions, another type of possible dark matter particles. To address the priority research directions aligned with the BRN study, technology studies and planning efforts are being carried out for four potential small dark matter search projects in the Cosmic Frontier.

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.

DOE's DESI instrumentation is mounted and started its five-year science survey in May 2021 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, using the DOE-provided three billion-pixel LSST camera (LSSTCam), is being commissioned in Chile. DOE and NSF are full partners in the Observatory's operations phase to carry out the ten-year LSST survey, planned to start in late FY 2024. SLAC manages the Observatory's U.S. Data Facility as part of DOE's responsibilities during the operations phase.

The LZ dark matter detector began science operations underground in the Sanford Underground Research Facility (SURF) in Lead, South Dakota in December 2021.

The SuperCDMS-SNOLAB dark matter detector, located at the Sudbury Neutrino Observatory in Sudbury, Canada, is finishing pre-operations activities and is expected to start full science operations in late 2023.

Projects

The next-generation CMB-S4 experiment is a planned partnership with NSF. LBNL leads the efforts for the DOE scope of the CMB-S4 project, which 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. Both arrays are required to reach the full science capabilities.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Cosmic Frontier Experimental Physics	**$97,591**	**$97,102**	**-$489**
Research	$47,091	$48,512	+$1,421
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 continued research activities on the ADMX-G2, DESI, LZ, and SuperCDMS-SNOLAB experiments, physics preparation for the Vera C. Rubin Observatory, the associated DESC for LSST, and design and planning for new dark matter concepts.	Funding will support research on the Vera C. Rubin Observatory and its associated DESC, and for while design and planning for new dark matter concepts.
Facility Operations and Experimental Support	$44,500	$47,590	+$3,090
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 of DESI, LZ, ADMX-G2, and the start of operations for SuperCDMS-SNOLAB. Commissioning and pre-operations planning efforts will continue for the Vera C. Rubin Observatory and the DESC planning for the LSST survey.	The increase in funding will support the ramp up in operations funds for the Rubin Observatory and the DESC.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Projects $6,000	$1,000	-$5,000
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 engineering design efforts for the CMB-S4 project.	The decrease in funding for CMB-S4 will prioritize the engineering design activities.

Note:

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

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 merit and potential impact 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 2023. 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.

This activity supports the Advanced Computing initiative (formerly referred to as Integrated Computational and Data Infrastructure) to ensure broad access to exascale computing resources. This activity will also support the Reaching a New Energy Sciences Workforce (RENEW) initiative to provide undergraduate and graduate training opportunities for diverse students and academic institutions not currently well represented in the U.S. science and technology ecosystem and the Funding for Accelerated, Inclusive Research (FAIR) initiative to provide focused investment on enhancing research on clean energy, climate, and related topics at minority serving institutions.

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 developing common software tools and 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.

Quantum Information Science

The HEP QIS activity supports the “science first” goal of the national QIS strategy and advances both HEP and QIS research. Key subtopics 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. National 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. HEP is the lead program supporting the Superconducting Quantum Materials and Systems (SQMS) Center involving 21 institutions and led by the Fermi National Accelerator Laboratory. SQMS has a particular focus on extending the coherence lifetime of quantum states to reduce error rates in quantum computing and improve the sensitivity of quantum sensors for dark matter candidates and other precision measurements. The HEP QIS core research and Centers activity is part of a broader SC initiative that is conducted in coordination with SC programs, other federal agencies, and the private sector.

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 technological progression. 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.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Theoretical, Computational, and Interdisciplinary Physics	**$136,362**	**$163,746**	**+$27,384**
Research	$136,362	$163,746	+$27,384
Theory	*$46,284*	*$59,050*	*+$12,766*
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 support world-leading theoretical particle physics research at U.S. universities and national laboratories. The Request will also support RENEW, Advanced Computing, and FAIR.	Funding will increase to support the RENEW, Advanced Computing, and FAIR initiatives.
Computational HEP	*$11,518*	*$14,130*	*+$2,612*
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, which is scheduled to be re-competed in FY 2022, will continue. The Request will continue the Traineeship Program in Computational HEP to address critical HEP workforce needs.	Funding will increase to support HEP CCE and new SciDAC activities.

(dollars in thousands)

FY 2021 Enacted		FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Quantum Information Science	*$45,072*	*$50,566*	*+$5,494*
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 interdisciplinary HEP-QIS consortia and lab programs for focused research at the intersection of HEP and QIS, including novel experiments, foundational theory, quantum computing, communications, sensors, and research technology. The Request will support SQMS as part of the National 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*	*$40,000*	*+$6,512*
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 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, including targeted small demonstration efforts and “seed” awards to explore emerging opportunities.	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 for accelerators.

Note:

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

High Energy Physics
Advanced Technology R&D

Description

The Advanced Technology Research and Development (R&D) subprogram fosters cutting-edge basic research in the physics of particle beams, accelerator R&D, and R&D for particle and radiation detection. These activities are necessary for continued progress in high energy physics. Longer-term multi-purpose accelerator technology development, applicable to fields beyond HEP, is carried out by the Accelerator R&D and Production program.

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 activities categorized into five thrust areas: 1) accelerator and beam physics; 2) advanced acceleration concepts; 3) particle sources and targetry; 4) radio-frequency acceleration technology; and 5) superconducting magnets and materials. A community study aimed at establishing a technology roadmap for the accelerator and beam physics thrust is planned for late FY 2022. Community studies for the other HEP GARD thrusts were completed in the past five years.[d] DOE selects research efforts with the highest scientific merit and potential impact based on a competitive peer-review process. In FY 2018, HEP conducted an external peer review of the GARD laboratory research groups; the next review is planned for FY 2023. 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 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 highly successful U.S. Particle Accelerator School (USPAS). HEP conducted a review of the USPAS Program in late FY 2020 and the review committee found its performance to be excellent. 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.

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

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

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. 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 merit and potential impact based on a competitive peer-review process. In FY 2016, HEP conducted an external peer review of the Detector R&D laboratory research groups; the next review is planned for FY 2022. In FY 2020, HEP conducted a Basic Research Needs workshop[e] 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 reviews and BRN workshop in combination with input on strategic directions from regular, open community studies 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 to benefit from the resultant capabilities in detection, computing, and communications. Five SC programs—ASCR, BES, FES, HEP, and NP—are working together to advance microelectronics technologies. This activity is 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); Argonne Wakefield Accelerator (AWA) in structure-based advanced acceleration concepts; and the Fermilab Integrable Optics Test Accelerator (IOTA), superconducting radio-frequency accelerator and magnet facilities at FNAL. This activity also supports detector test beam and fabrication facilities at FNAL.

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

High Energy Physics
Advanced Technology R&D

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Advanced Technology R&D	**$116,095**	**$112,647**	**-$3,448**
Research	$72,833	$67,911	-$4,922
General Accelerator R&D	*$49,574*	*$43,382*	*-$6,192*
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 support capitalizing on the science opportunities at the newly completed FACET-II facility and the second beamline at BELLA; other accelerator R&D activities at DOE national laboratories and universities, including ASTI efforts in superconducting magnet and SRF; and the Traineeship Program for Accelerator Science and Technology. The Request will also support the Accelerate initiative.	Funding will support the Accelerate initiative and additional awards in traineeship activities. With overall reduced funding, support will focus on efforts in superconducting magnet development and upgrades to SRF test facilities, multi-SC program R&D in superconducting materials.
Detector R&D	*$23,259*	*$24,529*	*+$1,270*
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 support world-leading, innovative Detector R&D, provide support to advance microelectronics technologies, and continue the Traineeship Program in HEP Instrumentation.	Funding will support additional awards in traineeship activities.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Facility Operations and Experimental Support $43,262	$44,736	+$1,474
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 testing and beam time for experiments at the test facilities at ANL, FNAL, LBNL and SLAC. BELLA operations will now include a second beamline. The Request will provide support for 3,000 hours (91 percent of optimal) of facility operations for FACET-II.	Funding increase will support more hours of cryogenic, magnet, and SRF testing at FNAL; new two-beam laser wakefield acceleration experiments at LBNL; and additional hours of operation for FACET-II.

Note:

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

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 SC 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.

High Energy Physics
HEP Accelerator Stewardship

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2023 Request		Explanation of Changes FY 2023 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.		Funding for FY 2023 is requested in the Accelerator R&D and Production (ARDAP) program.		Funding for FY 2023 is requested in the ARDAP program.
Facility Operations and Experimental Support	$6,100		$ —	-$6,100
Funding supports operation of the BNL ATF at 100 percent of optimal levels.		Funding for FY 2023 is requested in the ARDAP program.		Funding for FY 2023 is requested in the ARDAP program.

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

High Energy Physics
Construction

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.

18-SC-42, Proton Improvement Plan II (PIP-II), FNAL

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.

11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment, FNAL

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-US. LBNF, with DOE/FNAL leadership and 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 1,300 scientists and engineers from over 200 institutions in over 30 countries. DOE will fund less than one-third of DUNE under the name DUNE-US.

The most recent approved DOE Order 413.3B Critical Decision is CD-3A, approval for Initial Far Site Construction. Following this approval, excavation and construction for the LBNF Far Site conventional facilities started 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.

The project completed the reliability improvements needed to support excavation in early 2021 and the excavation work began in April 2021 under the CD-3A authorization. Updated planning and analysis led to an increased scope and TPC for LBNF/DUNE of $3,000,000,000, which is being evaluated prior to establishing the project baseline.

The scale of LBNF/DUNE, annual funding levels, and research and development needs have resulted in the major scope elements of the project maturing at different rates. Baselining the entire scope of the project at once introduced too many uncertainties and was no longer viewed as being in the best interest of DOE. Therefore, a subproject tailoring approach in accordance with DOE Order 413.3B is being developed to reorganize the project's scope into several independent subprojects for improved planning and management control. The definition of the subprojects and the approach to managing subprojects will be approved at CD-1RR (reaffirmation and approval of the CD-1 cost range). The first subproject to be baselined will include the completion of cavern excavation at the Far Site.

11-SC-41, Muon to Electron Conversion Experiment, FNAL
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 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, the approved baseline schedule can no longer be met. The COVID-19 pandemic resulted in unplanned work shutdowns and inefficiencies at the participating universities and laboratories in FY 2020-2021. Further schedule delays were incurred because of actions needed to correct performance issues delaying fabrication of the particle tracking detector and two superconducting magnets being fabricated by a vendor. A baseline change was recommended by an Independent Project Review in February 2021. The Baseline Change Proposal (BCP) is being developed but is not yet submitted or approved. In anticipation of approval of the BCP, $2,000,000 of TEC funding was appropriated in FY 2021, $13,000,000 of TEC funding is requested in FY 2022, and $2,000,000 of TEC funding is requested in FY 2023. None of these additional funds will be available to spend until the BCP is approved and the project is re-baselined.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted		FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Construction	**$252,000**	**$298,000**	**+$46,000**
18-SC-42, Proton Improvement Plan II (PIP-II), FNAL	$79,000	$120,000	+$41,000
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 initiation of civil construction for the balance of the linear accelerator facilities as well as fabrication of technical systems when designs are final, and construction is authorized by CD-3.	Funding increase will support the transition from the design phase of PIP-II, from procurement of the Early Conventional Facilities subproject for the cryogenic plant and from site preparation, to initiation of construction for the linear accelerator facilities as well as fabrication of technical components for the accelerator.
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.		Funding will support continuation of the Far Site civil construction activities for excavation of the underground equipment caverns and connecting drifts (tunnels). Design activities will be completed for the far site detectors and cryogenics systems and the beamline design will be finalized.	Funding will increase to support the excavation of the underground equipment caverns and connecting drifts.

(dollars in thousands)

FY 2021 Enacted		FY 2023 Request		Explanation of Changes FY 2023 Request vs FY 2021 Enacted	
11-SC-41, Muon to Electron Conversion Experiment, FNAL	$2,000		$2,000		$ —
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 implementation of corrective actions and increased costs due to schedule delays caused by pandemic response at FNAL and collaborating universities, and by fabrication delays for the tracking detector and two superconducting magnets being fabricated by a vendor.		No change.	

High Energy Physics
Capital Summary

(dollars in thousands)

	Total	Prior Years	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Capital Operating Expenses						
Capital Equipment	N/A	N/A	91,830	86,830	94,500	+2,670
Minor Construction Activities						
General Plant Projects	N/A	N/A	1,500	1,500	4,000	+2,500
Total, Capital Operating Expenses	**N/A**	**N/A**	**93,330**	**88,330**	**98,500**	**+5,170**

High Energy Physics
Capital Equipment

	(dollars in thousands)					
	Total	**Prior Years**	**FY 2021 Enacted**	**FY 2022 Annualized CR**	**FY 2023 Request**	**FY 2023 Request vs FY 2021 Enacted**
Capital Equipment						
Major Items of Equipment						
Energy Frontier Experimental Physics						
High Luminosity Large Hadron Collider Accelerator Upgrade Project	271,952	123,597	43,000	43,000	30,000	-13,000
High Luminosity Large Hadron Collider ATLAS Upgrade Project	150,485	52,000	16,000	16,000	27,500	+11,500
High Luminosity Large Hadron Collider CMS Upgrade Project	140,950	34,738	13,500	13,500	27,500	+14,000
Intensity Frontier Experimental Physics						
Accelerator Controls Operations Research Network	136,400	–	–	–	1,000	+1,000
Cosmic Frontier Experimental Physics						
Cosmic Microwave Background - Stage 4	353,500	–	1,000	1,000	–	-1,000
Total, MIEs	N/A	N/A	73,500	73,500	86,000	+12,500
Total, Non-MIE Capital Equipment	N/A	N/A	18,330	13,330	8,500	-9,830
Total, Capital Equipment	**N/A**	**N/A**	**91,830**	**86,830**	**94,500**	**+2,670**

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.*

High Energy Physics
Minor Construction Activities

(dollars in thousands)

	Total	Prior Years	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
General Plant Projects (GPP)						
GPPs (greater than or equal to $5M and less than $20M)						
Target Systems Integration Building	1,500	–	1,500	–	–	-1,500
Total GPPs (greater than or equal to $5M and less than $20M)	N/A	N/A	1,500	–	–	-1,500
Total GPPs less than $5M	N/A	N/A	–	1,500	4,000	+4,000
Total, General Plant Projects (GPP)	**N/A**	**N/A**	**1,500**	**1,500**	**4,000**	**+2,500**
Total, Minor Construction Activities	**N/A**	**N/A**	**1,500**	**1,500**	**4,000**	**+2,500**

Notes:

- *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.*
- *The Target Systems Integration Building includes $14,000,000 requested in the FY 2022 President's Budget that brings the total project amount to $15,500,000.*

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 can generate transverse electric fields. The magnets will be assembled at LBNL, BNL, and FNAL, exploiting special expertise and unique capabilities at each laboratory. The FY 2023 Request for TEC funding of $30,000,000 will continue to support the production of quadrupole magnets and crab cavities and maintain international schedule synchronization. The project was stalled by shutdowns at the national laboratories due to COVID-19 and has seen increased costs as a result. In all other respects the project is performing well. The Office of Science (SC) plans a rebaseline review in late FY 2022 to evaluate the needs for additional funding.

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 early FY 2023. 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 2023 Request for TEC funding of $27,500,000 will focus on completion of the final design in anticipation of approval of construction (CD-3) and ramp-up of fabrication activities. The project was stalled by shutdowns at the national laboratories due to COVID-19 and has seen increased costs as a result. SC will evaluate the need for additional funding when the project is baselined in early FY 2023.

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 early FY 2023. 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 2023 Request for TEC funding of $27,500,000 will focus on completion of the final design in anticipation of approval of construction (CD-3) and ramp-up of fabrication activities. The project was stalled by shutdowns at the national laboratories due to COVID-19 and has seen increased costs as a result. SC will evaluate the need for additional funding when the project is baselined in early FY 2023.

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 Q2 FY 2023 and CD-2 approval in FY 2024. The FY 2023 Request for TEC funding of $1,000,000 will fund system design and other related engineering activities.

<u>Cosmic Frontier Experimental Physics MIE:</u>

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 planned to be determined by FY 2023. 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. LBNL was selected in August 2020 to lead the efforts in providing the DOE scope for the project. While no TEC funding is requested in the FY 2023 Request, $1,000,000 of OPC funding will enable continued conceptual design and activities needed to inform CD-1 approval as well as planning for the associated systems and infrastructure.

High Energy Physics
Construction Projects Summary

(dollars in thousands)

	Total	Prior Years	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
18-SC-42, Proton Improvement Plan II						
Total Estimated Cost (TEC)	891,200	81,000	79,000	90,000	120,000	+41,000
Other Project Cost (OPC)	86,800	73,594	–	–	–	–
Total Project Cost (TPC)	**978,000**	**154,594**	**79,000**	**90,000**	**120,000**	**+41,000**
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment						
Total Estimated Cost (TEC)	2,866,375	507,781	171,000	176,000	176,000	+5,000
Other Project Cost (OPC)	133,625	91,625	2,000	4,000	4,000	+2,000
Total Project Cost (TPC)	**3,000,000**	**599,406**	**173,000**	**180,000**	**180,000**	**+7,000**
11-SC-41, Muon to Electron Conversion Experiment						
Total Estimated Cost (TEC)	281,000	250,000	2,000	13,000	2,000	–
Other Project Cost (OPC)	23,677	23,677	–	–	–	–
Total Project Cost (TPC)	**304,677**	**273,677**	**2,000**	**13,000**	**2,000**	**–**
Total, Construction						
Total Estimated Cost (TEC)	**N/A**	**N/A**	**252,000**	**279,000**	**298,000**	**+46,000**
Other Project Cost (OPC)	**N/A**	**N/A**	**2,000**	**4,000**	**4,000**	**+2,000**
Total Project Cost (TPC)	**N/A**	**N/A**	**254,000**	**283,000**	**302,000**	**+48,000**

Note for Mu2e:

- *In anticipation of approval of the Baseline Change Proposal (BCP), $2,000,000 of TEC funding was appropriated in FY 2021, $13,000,000 of TEC funding is requested in FY 2022, and $2,000,000 of TEC funding is requested in FY 2023. 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 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Research	398,203	373,368	418,646	+20,443
Facility Operations	314,297	295,197	313,374	-923
Projects				
Line Item Construction (LIC)	254,000	283,000	302,000	+48,000
Major Items of Equipment (MIE)	79,500	77,500	88,000	+8,500
Total, Projects	**333,500**	**360,500**	**390,000**	**+56,500**
Total, High Energy Physics	**1,046,000**	**1,029,065**	**1,122,020**	**+76,020**

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 <u>TYPE A</u> facilities:

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

Planned Operating Hours –

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

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

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

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

(dollars in thousands)

	FY 2021 Enacted	FY 2021 Current	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Scientific User Facilities - Type A					
Fermilab Accelerator Complex	**130,900**	**126,634**	**130,500**	**141,605**	**+10,705**
Number of Users	2,050	1,725	2,250	2,600	+550
Achieved Operating Hours	–	4,230	–	–	–
Planned Operating Hours	3,640	4,200	5,040	4,975	+1,335
Optimal Hours	4,480	4,480	5,740	5,740	+1,260
Percent of Optimal Hours	81.3%	94.4%	87.8%	86.7%	+5.4%
Accelerator Test Facility	**6,100**	**4,950**	**–**	**–**	**-6,100**
Number of Users	105	80	–	–	-105
Achieved Operating Hours	–	2,998	–	–	–
Planned Operating Hours	2,250	2,250	–	–	-2,250
Optimal Hours	2,500	2,500	–	–	-2,500
Percent of Optimal Hours	90.0%	120.9%	–	–	-90.0%
Unscheduled Down Time Hours	–	590	–	–	–

(dollars in thousands)

	FY 2021 Enacted	FY 2021 Current	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Facility for Advanced Accelerator Experimental Tests II (FACET II)	**16,000**	**15,526**	**16,000**	**12,085**	**-3,915**
Number of Users	250	111	250	210	-40
Achieved Operating Hours	–	2,778	–	–	–
Planned Operating Hours	3,720	2,440	3,000	3,000	-720
Optimal Hours	3,720	3,720	3,000	3,300	-420
Percent of Optimal Hours	100.0%	74.7%	100.0%	90.9%	-9.1%
Unscheduled Down Time Hours	–	2,162	–	–	–
Total, Facilities	**153,000**	**147,110**	**146,500**	**153,690**	**+690**
Number of Users	2,405	1,916	2,500	2,810	+405
Achieved Operating Hours	–	10,006	–	–	–
Planned Operating Hours	9,610	8,890	8,040	7,975	-1,635
Optimal Hours	10,700	10,700	8,740	9,040	-1,660
Unscheduled Down Time Hours	–	2,752	–	–	–

Notes:

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

High Energy Physics
Scientific Employment

	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Number of Permanent Ph.Ds (FTEs)	780	746	749	-31
Number of Postdoctoral Associates (FTEs)	370	355	356	-14
Number of Graduate Students (FTEs)	485	470	472	-13
Number of Other Scientific Employment (FTEs)	1,585	1,491	1,668	+83
Total Scientific Employment (FTEs)	**3,220**	**3,062**	**3,245**	**+25**

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 2023 Request for the Proton Improvement Project II (PIP-II) is $120,000,000 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 cryo-plant 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 FY 2022, and the planned date for CD-4, Project Completion, is 1Q FY 2033.

In FY 2021 construction was initiated by the ECF subproject for the building that will house the in-kind contribution of the cryoplant; the building is expected to be completed in calendar year 2022. Also in FY 2021, continued design and development work 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 project risk mitigation. In FY 2021, the civil engineering design for the linear accelerator complex was completed. The PIP-II injector test was completed, a significant R&D program that reduced technical risk for the project. Assumptions were refined for the level of in-kind contributions from the international partner laboratories. Anticipated in-kind technical contributions from international partners total $330,000,000 (equivalent to DOE costing).

Legally binding agreements with all countries but France have been signed to cover the planned work. The legally binding agreement with France has been drafted and signatures are expected in the summer of 2022. Non-binding Project Planning Documents (PPDs) that provide additional technical details beyond those provided in the legally binding agreements are being signed by the international partners; so far PPDs have been signed with Italian, Polish, and UK partner institutions.

The FY 2022 Request of $90,000,000 supports completion of the ECF cryo-plant building and completion of CD-3, approval for site preparation and construction for the linear accelerator complex as well as initiation of preconstruction procurement for the accelerator's technical systems as designs are completed.

The FY 2023 Request of $120,000,000 will support construction of the conventional facilities as well as continuation of procurement and fabrication for the technical systems.

A Federal Project Director (FPD) has been assigned to this project and has approved this CPDS. The FPD has Level-2 certification and is applying for Level-3 certification in FY 2022.

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
FY 2023	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
FY 2023	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, Total	TPC
FY 2020	91,000	547,965	638,965	82,035	82,035	721,000
FY 2021	184,000	617,200	801,200	86,800	86,800	888,000
FY 2022	177,000	714,200	891,200	86,800	86,800	978,000
FY 2023	177,000	714,200	891,200	86,800	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 was developed to reduce technical risks for the project, with participation and in-kind contributions from the India Department of Atomic Energy (DAE) Labs. The Test Facility has successfully completed its program and has been converted to a cryomodule test stand for testing the cryomodules for the project.

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.[f]

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, as well as interest in LBNF/DUNE. 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 Wroclaw University of Science and Technology in Poland, tentatively as indicated in the following table of Scope Responsibilities for PIP-II.[a]

[f] See Section 8.

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

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[g] 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.[h]

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*.

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

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.

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	44,363
FY 2022	40,000	40,000	40,000
FY 2023	7,000	7,000	7,000
Outyears	5,000	5,000	30,055
Total, Design (TEC)	**177,000**	**177,000**	**177,000**
Construction (TEC)			
FY 2020	9,000	9,000	123
FY 2021	26,000	26,000	17,071
FY 2022	50,000	50,000	50,000
FY 2023	113,000	113,000	113,000
Outyears	516,200	516,200	534,006
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	61,434
FY 2022	90,000	90,000	90,000
FY 2023	120,000	120,000	120,000
Outyears	521,200	521,200	564,061
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	–	–	21
Outyears	13,206	13,206	13,390
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	61,455
FY 2022	90,000	90,000	90,000
FY 2023	120,000	120,000	120,000
Outyears	534,406	534,406	577,451
Total, TPC	**978,000**	**978,000**	**978,000**

Notes:
- *Costs through FY 2021 reflect actual costs; costs for FY 2022 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	146,314	149,314	146,314
Design - Contingency	30,686	27,686	30,686
Total, Design (TEC)	**177,000**	**177,000**	**177,000**
Construction	124,009	124,009	124,009
Site Preparation	12,783	12,783	12,783
Equipment	378,705	378,705	378,705
Construction - Contingency	198,703	198,703	198,703
Total, Construction (TEC)	**714,200**	**714,200**	**714,200**
Total, TEC	**891,200**	**891,200**	**891,200**
Contingency, TEC	*229,389*	*226,389*	*229,389*
Other Project Cost (OPC)			
R&D	67,117	67,117	67,117
Conceptual Planning	8,324	8,324	8,324
Conceptual Design	2,855	2,855	2,855
OPC - Contingency	8,504	8,504	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*	*8,504*	*8,504*
Total, TPC	**978,000**	**978,000**	**978,000**
Total, Contingency (TEC+OPC)	***237,893***	***234,893***	***237,893***

5. Schedule of Appropriations Requests

(dollars in thousands)

Fiscal Year	Type	Prior Years	FY 2021	FY 2022	FY 2023	Outyears	Total
FY 2020	TEC	41,000	—	—	—	597,965	638,965
	OPC	77,035	—	—	—	5,000	82,035
	TPC	118,035	—	—	—	602,965	721,000
FY 2021	TEC	81,000	20,000	—	—	700,200	801,200
	OPC	72,529	2,000	—	—	12,271	86,800
	TPC	153,529	22,000	—	—	712,471	888,000
FY 2022	TEC	81,000	79,000	90,000	—	641,200	891,200
	OPC	73,594	—	—	—	13,206	86,800
	TPC	154,594	79,000	90,000	—	654,406	978,000
FY 2023	TEC	81,000	79,000	90,000	120,000	521,200	891,200
	OPC	73,594	—	—	—	13,206	86,800
	TPC	154,594	79,000	90,000	120,000	534,406	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

Summary

The FY 2023 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.

The project has a preliminary Total Project Cost (TPC) range of $1,260,000,000 to $1,860,000,000 approved for CD-1(R) on November 5, 2015. The preliminary TPC excludes foreign contributions. Since then, the preliminary TPC estimate has grown to approximately $3,000,000,000 which exceeds the upper end of the cost range by over 50 percent. According to DOE policy, if the upper 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.[i] An Independent Project Review conducted by DOE in January 2021 recommended the cost range be reevaluated with a planned review of new range in FY 2022. A CD-1 Reaffirmation or 'CD-1RR' is planned in FY 2022 to approve the updated cost range, reaffirm the alternative selection, and approve a new tailoring strategy for baselining the project in multiple subprojects.

Significant Changes

This project was initiated in FY 2012. The most recent approved DOE Order 413.3B critical decision is CD-3A Revision, approval for Initial Far Site Construction: reducing the authorized scope for excavation and construction for the LBNF Far Site conventional facilities. The change transferred some of the scope that had been approved by CD-3A to a later authorization decision.

OPC costs that were previously applied to technical integration of the neutrino detectors have been transferred from "Other OPC Costs" to TEC construction contingency. "Other OPC Costs" now are exclusively execution support costs such as electrical power for construction and equipment installation. DOE and the Laboratory are continuing engagement with potential partners. In June 2021, CERN approved contributing a second cryostat to the project.

HEP and Fermilab have arranged for in-kind contributions from international partners to both the facility (valued at approximately $260,000,000) and the experiment (valued at approximately $400,000,000). These amounts identify the cost if DOE would supply the components.

The scale of LBNF/DUNE and various other factors, including annual funding levels and research and development needs, resulted in the major scope elements of the project maturing at different rates. Baselining the entire scope of the project at once introduced too many uncertainties and was no longer viewed as being in the best interest of DOE. Therefore, a subproject tailoring approach in accordance with DOE Order 413.3B is now being developed in order to reorganize the project's scope into several independent subprojects for improved planning and management control. The definition of the subprojects and the approach to managing subprojects will be approved at CD-1RR during FY 2022. The first subproject to be baselined will authorize the completion of cavern excavation at the Far Site.

FY 2021 funding supported the completion of pre-excavation and reliability projects at the far site which enable full scale excavation to begin. FY 2021 funding also supported the design of the near site conventional facilities, beamline systems, the cryogenic systems, and the detectors. The final design of the Near Site conventional facilities was received by the project at the end of FY 2021.

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

The project was evaluated by Independent Project Reviews in January and June 2021. The reviews noted evidence of progress and supported the approach of phasing with subprojects, but identified additional work needed before CD-1RR and baselining of the subprojects.

The FY 2022 Request supports continued work on the excavation of the detector caverns and completion of design activities and continuation of approved site preparation, as well as preproduction and fabrication activities when approved by CD-3.

The FY 2023 Request will support continuation of the Far Site civil construction activities for excavation of the underground equipment caverns and connecting drifts (tunnels). Design activities will be completed for the Far Site detectors and cryogenics systems and the beam-line design will be finalized.

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
FY 2023	1/8/10	11/5/15	11/5/15	4Q FY 2023	4Q FY 2023	4Q FY 2023	1Q FY 2034

Notes:
- *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.*
- *The critical milestone dates tabulated for the FY 2023 Request are based on project planning in FY 2022 and will be reviewed by IPR and reevaluated for Critical Decision CD-1RR in 4Q FY 2022.*

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
FY 2023	4Q FY 2023	11/5/15	9/1/16	TBD	TBD

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, Total	TPC
FY 2011	102,000	—	102,000	22,180	22,180	124,180
FY 2012	133,000	—	133,000	42,621	42,621	175,621
FY 2016	127,781	655,612	783,393	89,539	89,539	872,932
FY 2017	123,781	1,290,680	1,414,461	85,539	85,539	1,500,000
FY 2018	234,375	1,199,000	1,433,375	102,625	102,625	1,536,000
FY 2019	231,000	1,234,000	1,465,000	95,000	95,000	1,560,000
FY 2020	259,000	1,496,000	1,755,000	95,000	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
FY 2023	455,464	2,410,911	2,866,375	133,625	133,625	3,000,000

Notes:
- *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.*
- *The TPC point estimate tabulated for the FY 2023 Request was increased to $3,000,000,000 in FY 2022 and will be reviewed by Independent Project Review (IPR) and reevaluated by ESAAB in 4Q FY 2022.*
- *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 far detector modules at a greater distance than is used with NuMI experiments.[j]

For the LBNF/DUNE project, FNAL will be responsible for design, construction and operation of the major components of facilities which enable the DUNE research program (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 large detectors 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.

[j] 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.

- 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, fabrication of detector components 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 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 fund approximately one half of the DUNE detectors. This excludes the cryostats that hold the detectors. The cryostats will be provided by CERN. The project continues to refine the development of the design and cost estimates as the U.S. DOE contributions to the multinational effort now are better understood. The cost estimate for DOE contributions will be updated as planning continues in preparation for baselining the various subprojects.

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, including significant additional contributions from CERN that are in the process of being finalized. 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. New commitments for detector contributions are being finalized now. 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*.

Key Performance Parameters (KPPs)

The KPPs are preliminary and will be finalized and approved with each subproject. 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, 120 GeV protons delivered to the absorber and muons observed downstream of the neutrino beamline
Far Site-Conventional Facilities	Caverns excavated for 40 kiloton fiducial detector mass[k]; beneficial occupancy granted for cavern space to house 20 kiloton fiducial detector mass[a]	Same as the Threshold KPP
Detector Cryogenic Infrastructure	DOE-provided components for cryogenic subsystems installed and pressure tested for 20 kiloton fiducial detector mass	In addition to Threshold KPPs, successfully filled first cryostat detector with LAr
Far Detector	DOE-provided components installed in cryostats to support 20 kiloton fiducial detector mass, with continuous readout of the cold electronics and photon detection systems	In addition to Threshold KPPs, observation of cosmic ray tracks in the first detector module

[k] 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	90,530	90,530	72,946
FY 2022	81,000	81,000	108,179
FY 2023	–	–	17,584
Total, Design (TEC)	**455,464**	**455,464**	**455,464**
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	80,470	80,470	69,296
FY 2022	95,000	95,000	95,000
FY 2023	176,000	176,000	176,000
Outyears	1,835,594	1,835,594	1,967,385
Total, Construction (TEC)	**2,410,911**	**2,410,911**	**2,410,911**

(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	142,242
FY 2022	176,000	176,000	203,179
FY 2023	176,000	176,000	193,584
Outyears	1,835,594	1,835,594	1,967,385
Total, TEC	**2,866,375**	**2,866,375**	**2,866,375**

(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	1,954
FY 2022	4,000	4,000	4,000
FY 2023	4,000	4,000	4,000
Outyears	32,000	32,000	33,929
Total, OPC	**133,625**	**133,625**	**133,625**

(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	144,196
FY 2022	180,000	180,000	207,179
FY 2023	180,000	180,000	197,584
Outyears	1,867,594	1,867,594	2,001,314
Total, TPC	**3,000,000**	**3,000,000**	**3,000,000**

Notes:

- *Costs through FY 2021 reflect actual costs; costs for FY 2022 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	397,568	**N/A**
Design - Contingency	57,896	48,366	**N/A**
Total, Design (TEC)	**455,464**	**445,934**	**N/A**
Construction	1,134,000	1,134,000	**N/A**
Equipment	700,000	375,000	**N/A**
Construction - Contingency	576,911	435,066	**N/A**
Total, Construction (TEC)	**2,410,911**	**1,944,066**	**N/A**
Total, TEC	**2,866,375**	**2,390,000**	**N/A**
Contingency, TEC	*634,807*	*483,432*	***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	27,625	100,000	**N/A**
OPC - Contingency	20,375	24,375	**N/A**
Total, Except D&D (OPC)	**133,625**	**210,000**	**N/A**
Total, OPC	**133,625**	**210,000**	**N/A**
Contingency, OPC	*20,375*	*24,375*	***N/A***
Total, TPC	**3,000,000**	**2,600,000**	**N/A**
Total, Contingency (TEC+OPC)	***655,182***	***507,807***	***N/A***

Notes:

- *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)

Fiscal Year	Type	Prior Years	FY 2021	FY 2022	FY 2023	Outyears	Total
FY 2011	TEC	12,000	—	—	—	90,000	102,000
	OPC	22,180	—	—	—	—	22,180
	TPC	34,180	—	—	—	90,000	124,180
FY 2012	TEC	17,000	—	—	—	116,000	133,000
	OPC	42,621	—	—	—	—	42,621
	TPC	59,621	—	—	—	116,000	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	436,781	—	—	—	1,318,219	1,755,000
	OPC	91,625	—	—	—	3,375	95,000
	TPC	528,406	—	—	—	1,321,594	1,850,000
FY 2021	TEC	507,781	100,500	—	—	1,868,094	2,476,375
	OPC	91,625	1,000	—	—	31,000	123,625
	TPC	599,406	101,500	—	—	1,899,094	2,600,000
FY 2022	TEC	507,781	171,000	176,000	—	1,535,219	2,390,000
	OPC	91,625	2,000	4,000	—	112,375	210,000
	TPC	599,406	173,000	180,000	—	1,647,594	2,600,000
FY 2023	TEC	507,781	171,000	176,000	176,000	1,835,594	2,866,375
	OPC	91,625	2,000	4,000	4,000	32,000	133,625
	TPC	599,406	173,000	180,000	180,000	1,867,594	3,000,000

Note:
- *All estimates are preliminary.*

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...................	79,100
New area being constructed by this project at Sanford Underground Research Facility (SURF).......	185,700
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”	79,100
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”	185,700
Total area eliminated	—

The new facility square footage estimates are based on the current design and updating the calculation to be consistent with DOE’s real estate guidance. New facilities information will be identified and reported in accordance with DOE guidance.

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 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 contracted 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. An excavation subcontract was awarded within budget and excavation construction activities began in FY 2021.

For the LBNF Near Site conventional facilities at FNAL, the laboratory will subcontract with an A/E firm for design and plan to utilize a traditional design-bid-build construction method supported by additional procurements for preconstruction and construction phase services from a professional construction management firm.

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 2023 Request for the Muon to Electron Conversion Experiment (Mu2e) is $2,000,000 of Total Estimated Cost (TEC) funding to support the development of a new technical, cost, schedule, and management baseline 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. 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. Technical progress on all aspects of the project has continued through FY 2021. The project is awaiting the new baseline after resolving contract issues for magnet production.

In anticipation of approval of the BCP, $2,000,000 of TEC funding was appropriated in FY 2021, $13,000,000 of TEC funding is requested in FY 2022, and $2,000,000 is requested in FY 2023. 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
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
FY 2023	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
FY 2023	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, Total	TPC
FY 2011	35,000	—	35,000	10,000	10,000	45,000
FY 2012	36,500	—	36,500	18,777	18,777	55,277
FY 2013	44,000	—	44,000	24,177	24,177	68,177
FY 2014	61,000	162,000	223,000	26,177	26,177	249,177
FY 2015	47,000	162,900	209,900	23,677	23,677	233,577
FY 2016	57,000	193,000	250,000	23,677	23,677	273,677
FY 2017	57,000	193,000	250,000	23,677	23,677	273,677
FY 2018	60,598	189,402	250,000	23,677	23,677	273,677
FY 2019	60,598	189,402	250,000	23,677	23,677	273,677
FY 2022	60,598	204,402	265,000	23,677	23,677	288,677
FY 2023	60,598	220,402	281,000	23,677	23,677	304,677

Note:

- *In anticipation of Baseline Change Proposal (BCP) approval, $2,000,000 of TEC funding was appropriated in FY 2021, $13,000,000 is requested in FY 2022, and $2,000,000 is requested in FY 2023 and cannot be spent until the BCP approved and project re-baselined.*

2. Project Scope and Justification

<u>Scope</u>

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.

<u>Justification</u>

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."[l] 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."[m]

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

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.

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

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

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.

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	13,557
FY 2022	13,000	13,000	13,000
FY 2023	2,000	2,000	2,000
Outyears	14,000	14,000	54,414
Total, Construction (TEC)	**220,402**	**220,402**	**220,402**
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	13,557
FY 2022	13,000	13,000	13,000
FY 2023	2,000	2,000	2,000
Outyears	14,000	14,000	54,414
Total, TEC	**281,000**	**281,000**	**281,000**

(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	13,557
FY 2022	13,000	13,000	13,645
FY 2023	2,000	2,000	2,000
Outyears	14,000	14,000	54,414
Total, TPC	**304,677**	**304,677**	**304,677**

Notes:

- *Costs through FY 2021 reflect actual costs; costs for FY 2022 and outyears are estimates.*
- *In anticipation Baseline Change Proposal (BCP) approval, $2,000,000 of TEC funding was appropriated in FY 2021, $13,000,000 is requested in FY 2022, and $2,000,000 is requested in FY 2023 and cannot be spent until the BCP approved and project 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	17,336	13,000
Site Preparation	1,390	1,390	2,000
Equipment	197,976	180,346	133,000
Construction - Contingency	3,700	5,330	45,000
Total, Construction (TEC)	**220,402**	**204,402**	**193,000**
Total, TEC	**281,000**	**265,000**	**250,000**
Contingency, TEC	*3,700*	*5,330*	*53,000*
Other Project Cost (OPC)			
R&D	7,555	7,555	8,200
Conceptual Planning	2,300	2,300	2,300
Conceptual Design	13,177	13,177	13,177
OPC - Contingency	645	645	**N/A**
Total, Except D&D (OPC)	**23,677**	**23,677**	**23,677**
Total, OPC	**23,677**	**23,677**	**23,677**
Contingency, OPC	*645*	*645*	***N/A***
Total, TPC	**304,677**	**288,677**	**273,677**
Total, Contingency (TEC+OPC)	***4,345***	***5,975***	***53,000***

Note:

- *In anticipation of Baseline Change Proposal (BCP) approval, $2,000,000 of TEC funding was appropriated in FY 2021, $13,000,000 is requested in FY 2022, and $2,000,000 is requested in FY 2023 and cannot be spent until BCP approved and the project re-baselined.*

5. Schedule of Appropriations Requests

(dollars in thousands)

Fiscal Year	Type	Prior Years	FY 2021	FY 2022	FY 2023	Outyears	Total
FY 2011	TEC	5,000	—	—	—	30,000	35,000
	OPC	10,000	—	—	—	—	10,000
	TPC	15,000	—	—	—	30,000	45,000
FY 2012	TEC	24,000	—	—	—	12,500	36,500
	OPC	18,777	—	—	—	—	18,777
	TPC	42,777	—	—	—	12,500	55,277
FY 2013	TEC	44,000	—	—	—	—	44,000
	OPC	24,177	—	—	—	—	24,177
	TPC	68,177	—	—	—	—	68,177
FY 2014	TEC	79,000	—	—	—	144,000	223,000
	OPC	26,177	—	—	—	—	26,177
	TPC	105,177	—	—	—	144,000	249,177
FY 2015	TEC	92,000	—	—	—	117,900	209,900
	OPC	23,677	—	—	—	—	23,677
	TPC	115,677	—	—	—	117,900	233,577
FY 2016	TEC	132,100	—	—	—	117,900	250,000
	OPC	23,677	—	—	—	—	23,677
	TPC	155,777	—	—	—	117,900	273,677
FY 2017	TEC	175,600	—	—	—	74,400	250,000
	OPC	23,677	—	—	—	—	23,677
	TPC	199,277	—	—	—	74,400	273,677
FY 2018	TEC	220,000	—	—	—	30,000	250,000
	OPC	23,677	—	—	—	—	23,677
	TPC	243,677	—	—	—	30,000	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
FY 2023	TEC	250,000	2,000	13,000	2,000	14,000	281,000
	OPC	23,677	—	—	—	—	23,677
	TPC	273,677	2,000	13,000	2,000	14,000	304,677

Notes:

- *In anticipation of Baseline Change Proposal (BCP) approval, $2,000,000 of TEC funding was appropriated in FY 2021, $13,000,000 is requested in FY 2022, and $2,000,000 is requested in FY 2023 and cannot be spent until the BCP approved and project re-baselined.*
- *Congress approved an FY 2013 reprogramming for the Mu2e construction project following the submission of the FY 2014 budget with a Total Project Cost of $234,677,000.*

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 percent 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.