High Energy Physics

Overview

The High Energy Physics (HEP) program's mission 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.

Our current understanding of the elementary constituents of matter and energy is captured in what is called the Standard Model of particle physics. It describes the elementary particles that comprise ordinary matter and the forces that govern them with very high precision. However, recent observations that are not explained by the Standard Model suggest that it is incomplete and new physics may be discovered by future experiments. Astronomical observations indicate that ordinary matter makes up only about 5 percent of the universe, the remainder being 70 percent dark energy and 25 percent dark matter, both "dark" because they are either nonluminous or unknown. The observation of very small but non-zero masses of the elementary particles known as neutrinos provides further hints of new physics beyond the Standard Model.

An international enterprise of particle physics research is underway to discover what lies beyond the Standard Model. To guide U.S. investments, the U.S. particle physics community developed a long-term strategic plan through a multi-year process that culminated in 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] The report, which 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, identified five intertwined science drivers of particle physics that provide compelling lines of inquiry with great promise for discovery:

- 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 through three experimental frontiers of particle physics research aligned with three HEP subprograms:

- 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. This requires some of the largest machines ever built. The Large Hadron Collider (LHC) at the European Organization for Nuclear Research, known as CERN, is 17 miles in circumference and accelerates and collides high-energy protons, while sophisticated detectors, some the size of apartment buildings, observe newly produced particles that provide insight into fundamental forces of nature and the conditions of the early universe.
- 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. Measurements of the mass and other properties of neutrinos may have profound consequences for understanding the evolution and ultimate fate of the universe.
- 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. The highest-energy particles ever observed have come from cosmic sources, and the ancient light from the early universe and distant galaxies allows researchers to map the distribution of dark matter and perhaps unravel the nature of dark energy and inflation. Ultra-sensitive detectors deep underground

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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

may glimpse the dark matter passing through Earth. Observations of the cosmic frontier may reveal a universe far stranger than ever thought possible.

HEP's Theoretical, Computational, and Interdisciplinary Physics and Advanced Technology Research and Development (R&D) subprograms formulate and enable scientific discovery. The Theoretical, Computational, and Interdisciplinary Physics subprogram provides the framework to explain experimental observations and gain a deeper understanding of nature. Theoretical physicists take the lead in the interpretation of a broad range of experimental results and synthesize new ideas as they search for deep connections and develop testable models. Computational Physics provides advanced computing tools and simulations that are necessary for designing, operating, and interpreting experiments across the frontiers, and enables discovery research via new techniques in high performance computing. Artificial Intelligence (AI)/Machine Learning (ML) supports research to tackle the challenges of managing the increasingly high volumes and complexity of experimental and simulated data across the HEP experimental frontiers, theory, and technology thrusts, and to address cross-cutting challenges across the HEP program as part of Administration initiative in coordination with DOE investments in exascale computing and associated AI efforts. Quantum Information Science (QIS) is a rapidly-developing, inter-disciplinary field, and HEP QIS efforts are aligned with the National Quantum Initiative and DOE priorities in this area. The HEP QIS research program 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. In support of the National Quantum Initiative, the National QIS Research Centers constitute an interdisciplinary partnership between HEP and other SC programs. This partnership complements a robust core research portfolio that the individual SC programs, including HEP, steward to create the ecosystem across universities, national laboratories, and industry that is needed to advance developments in QIS and related technology.

The Advanced Technology R&D subprogram fosters fundamental research into particle acceleration and detection techniques and instrumentation. These enabling technologies and new research methods advance scientific knowledge in high energy physics and a broad range of related fields, advancing DOE's strategic goals for science.

The Accelerator Stewardship subprogram supports R&D efforts that are synergistic with the HEP mission but also impacts activities outside the traditional HEP boundaries. The activities of the Accelerator Stewardship subprogram include: improving access to SC accelerator R&D infrastructure for the private sector and other users; near-term translational R&D to adapt HEP accelerator technology for potential uses in medical, industrial, security, and defense applications; and long-term R&D for science and technology needed to build future generations of accelerators, with a focus on transformational opportunities.

HEP supports individual investigators and small-scale collaborations, as well as very large international collaborations, chosen for their scientific merit and potential for significant impact. More than 20 HEP-supported physicists have received the Nobel Prize in physics. Moreover, 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.

Highlights of the FY 2021 Request

The FY 2021 Request for $818,131,000 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 2021 Request include:

Research

Support for university and laboratory researchers to preserve critical core competencies, enable high priority theoretical and experimental activities in pursuit of discovery science, explore the potential of QIS and AI/ML, and invest in high-performance computing, including preparations for exascale, as well as world-leading R&D that requires long-term investments. This includes:

- LHC Support: U.S. responsibilities and leadership roles in the A Toroidal LHC Apparatus (ATLAS) and Compact Muon Solenoid (CMS) experiments at the LHC. To prepare for a ramp up to higher particle collision energy, the installation and commissioning of the upgrades to the ATLAS and CMS detectors will continue during the scheduled two-year long LHC technical stop from January 2019 to December 2020;

- Fermi National Accelerator Laboratory: U.S.-hosted, world-leading neutrino and muon physics experiments at Fermi National Accelerator Laboratory (FNAL), consisting of the Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE), the related Short-Baseline Neutrino (SBN) program, the NOvA neutrino oscillation experiment, Muon g-2, and the Muon to Electron Conversion Experiment (Mu2e);
- Cosmic Frontier: U.S. responsibilities and leadership roles in world-leading, next-generation experiments to advance the understanding of the nature of dark energy and cosmic acceleration during inflation in the early universe, and the search for dark matter particles;
- Theoretical Research: Intertwining the physics of the Higgs boson, neutrino masses, the dark universe, and exploring the unknown;
- QIS: R&D to accelerate discovery in particle physics while advancing the national effort;
- QIS Research Centers: HEP, in partnership with other SC programs, will continue support for multi-disciplinary QIS Centers initiated in FY 2020 to accelerate the advancement of QIS through vertical integration between systems and theory, and hardware and software. QIS Center scope includes work relating to sensors, quantum computing, emulators/simulators, and enabling technologies that will pave the path to accelerate and exploit QISassociated technologies in the longer term;
- AI/ML: Research to tackle the challenges of managing increasingly high volumes and complexity of experimental and simulated data across the HEP experimental frontiers, theory, and technology thrusts, and to address cross-cutting challenges across the HEP program in coordination with DOE investments in exascale computing and associated AI efforts;
- Microelectronics: HEP will work together with Advanced Scientific Computing Research (ASCR), Basic Energy Sciences (BES), and Fusion Energy Sciences (FES) programs to support multi-disciplinary microelectronics research to accelerate the advancement of microelectronic technologies;
- Advanced Technology R&D: World-leading Advanced Technology R&D that will enable transformative technology for the next-generation of accelerators and particle detectors and the training of experts who build them. The HEP General Accelerator R&D (GARD) activity will increase support for the Traineeship Program for Accelerator Science and Technology to revitalize graduate level training and innovation in the physics of particle accelerators for the benefit of HEP and other SC programs that rely on these enabling technologies;
- Accelerator Stewardship: Develop the fundamental building blocks of new technological advances in accelerator technology, to empower the private sector to accelerate research discoveries from the laboratory to the marketplace, and to support the mission of other federal agencies; and
- Technology R&D and pre-conceptual design studies: Research support for small projects searching for dark matter in new areas, new concepts for neutrino experiments in the DUNE era, or for next-generation dark energy experiments.

Facility Operations

Funding for the operations of the HEP scientific user facilities and other facility operation costs. Requested funding directs efforts to enable world-class science and the optimization of existing capabilities. This includes:

- Fermilab Accelerator Complex: Operation of the Fermilab Accelerator Complex for 4,580 hours (80 percent of optimal); long-deferred infrastructure maintenance and improvements; the procurement of new computing hardware, software, and storage systems; and the hiring and training of highly-skilled accelerator and instrumentation experts;
- Accelerator Test Facility (ATF): Operation of the Brookhaven National Laboratory (BNL) ATF for 2,150 hours (86 percent of optimal);
- Facility for Advanced Accelerator Experimental Tests II (FACET-II): Commissioning, installation, and 2,500 hours of operation (83 percent of optimal) for FACET-II;
- Sanford Underground Research Facility (SURF): Support services to enable operations of the Large Underground Xenon (LUX)-ZonED Proportional Scintillation in Liquid Noble gases (Zeplin) (LUX-ZEPLIN) (LZ) dark matter experiment, to continue operations of the neutrino-less double beta decay Majorana Demonstrator, and support investments to enhance SURF infrastructure;

- Vera C. Rubin Observatory: Commissioning and facility pre-operations activities for the Vera C. Rubin Observatory in Chile; (formerly known as the Large Synoptic Survey Telescope (LSST) project and facility[a]); and
- Cosmic Frontier Operations: Science operations of the Dark Energy Spectroscopic Instrument (DESI), installed on the Mayall telescope in Arizona, LZ at SURF, and the Super Cryogenic Dark Matter Search at Sudbury Neutrino Observatory Laboratory (SuperCDMS-SNOLAB) dark matter experiment in the Creighton Mine near Sudbury, Ontario, Canada.

Projects

Funding for Construction and Major Items of Equipment (MIEs) includes:

- HL-LHC Projects: Continued investments in the LHC by contributing to the U.S. share of the High-Luminosity (HL-LHC) Accelerator Upgrade Project and the HL-LHC ATLAS and CMS Detector Upgrade Projects to increase the particle collision rate by a factor of three to explore new physics beyond its current reach;
- LBNF/DUNE: Support will enable the Critical Decision (CD)-3B approved scope for the activities: the Far Site excavation of the underground equipment caverns and connecting drifts (tunnels); design and procurement activities for the Far Site cryogenics systems; LBNF Near Site (FNAL) beamline and conventional facilities design; and a site-preparation construction subcontract at the Near Site for relocation of existing service roads and utilities, including communications, power and water systems;
- Proton Improvement Plan II (PIP II): Support will enable engineering design work for conventional facilities and technical systems, continuation of site-preparation activities, initiation of construction for cryogenic plant support systems, and continued fabrication of prototype accelerator system components; and
- Cosmic Microwave Background Stage 4 (CMB-S4): Support for a new start MIE. CMB-S4 is the remaining P5-recommended MIE to commence. Currently operating CMB Stage 3 (CMB-S3) experiments were being built at the time of the P5 report. While these CMB-S3 experiments will provide valuable information on cosmological properties, the sensitivity necessary to directly investigate the inflationary era of the early universe will require designing the next generation project. CMB-S4 will also provide information about the nature of dark energy and neutrino properties.

FY 2021 Research Initiatives

High Energy Physics supports the following FY 2021 Research Initiatives.

	(dollars in thousands)			
	FY 2019 Enacted	**FY 2020 Enacted**	**FY 2021 Request**	**FY 2021 Request vs FY 2020 Enacted**
New Research Initiatives				
Strategic Accelerator Technology Initiative	—	—	6,250	+6,250
Total, New Research Initiatives	**—**	**—**	**6,250**	**+6,250**
Ongoing Research Initiatives				
Artificial Intelligence and Machine Learning	3,750	15,000	34,500	+19,500
Microelectronics Innovation	—	—	5,000	+5,000
Quantum Information Science	27,500	38,500	43,809	+5,309
Total, Ongoing Research Initiatives	**31,250**	**53,500**	**83,309**	**+29,809**

[a] The Vera C. Rubin Observatory Designation Act (H.R. 3196) was signed into law on December 20, 2019.

High Energy Physics
Funding

(dollars in thousands)

	FY 2019 Enacted	FY 2020 Enacted	FY 2021 Request	FY 2021 Request vs FY 2020 Enacted
Energy Frontier Experimental Physics				
Research	76,530	71,125	50,050	-21,075
Facility Operations and Experimental Support	52,000	52,650	48,480	-4,170
Projects	105,000	100,000	78,000	-22,000
SBIR/STTR	5,390	4,663	3,674	-989
Total, Energy Frontier Experimental Physics	**238,920**	**228,438**	**180,204**	**-48,234**
Intensity Frontier Experimental Physics				
Research	61,646	58,871	35,520	-23,351
Facility Operations and Experimental Support	155,035	177,122	157,445	-19,677
Projects	16,000	5,494	4,000	-1,494
SBIR/STTR	8,299	8,747	7,570	-1,177
Total, Intensity Frontier Experimental Physics	**240,980**	**250,234**	**204,535**	**-45,699**
Cosmic Frontier Experimental Physics				
Research	50,741	48,072	29,220	-18,852
Facility Operations and Experimental Support	20,076	41,358	37,400	-3,958
Projects	27,350	2,000	1,000	-1,000
SBIR/STTR	2,869	3,471	2,300	-1,171
Total, Cosmic Frontier Experimental Physics	**101,036**	**94,901**	**69,920**	**-24,981**
Theoretical, Computational, and Interdisciplinary Physics				
Research				
Theory	45,760	48,504	29,480	-19,024
Computational HEP	13,351	9,430	11,440	+2,010
Quantum Information Science	27,500	38,500	43,809	+5,309
Artificial Intelligence and Machine Learning	—	15,000	34,500	+19,500
Total, Research	86,611	111,434	119,229	+7,795
SBIR/STTR	3,223	4,093	3,412	-681
Total, Theoretical, Computational, and Interdisciplinary Physics	**89,834**	**115,527**	**122,641**	**+7,114**

	FY 2019 Enacted	FY 2020 Enacted	FY 2021 Request	FY 2021 Request vs FY 2020 Enacted
	(dollars in thousands)			
Advanced Technology R&D				
Research				
HEP General Accelerator R&D	48,447	43,454	45,606	+2,152
Detector R&D	23,694	20,937	19,450	-1,487
Total, Research	72,141	64,391	65,056	+665
Facility Operations and Experimental Support	27,625	39,232	37,200	-2,032
Projects	10,000	—	—	—
SBIR/STTR	3,740	3,783	3,846	+63
Total, Advanced Technology R&D	**113,506**	**107,406**	**106,102**	**-1,304**
Accelerator Stewardship				
Research	9,083	10,788	8,510	-2,278
Facility Operations and Experimental Support	6,067	6,067	5,200	-867
SBIR/STTR	574	639	519	-120
Total, Accelerator Stewardship	**15,724**	**17,494**	**14,229**	**-3,265**
Subtotal, High Energy Physics	**800,000**	**814,000**	**697,631**	**-116,369**
Construction				
18-SC-42 Proton Improvement Plan II, FNAL	20,000	60,000	20,000	-40,000
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment, FNAL	130,000	171,000	100,500	-70,500
11-SC-41, Muon to Electron Conversion Experiment, FNAL	30,000	—	—	—
Total, Construction	**180,000**	**231,000**	**120,500**	**-110,500**
Total, High Energy Physics	**980,000**	**1,045,000**	**818,131**	**-226,869**

SBIR/STTR funding:

- FY 2019 Enacted: SBIR $21,124,000 and STTR $2,971,000
- FY 2020 Enacted: SBIR $22,265,000 and STTR $3,131,000
- FY 2021 Request: SBIR $18,763,000 and STTR $2,558,000

High Energy Physics
Explanation of Major Changes

	(dollars in thousands) FY 2021 Request vs FY 2020 Enacted
Energy Frontier Experimental Physics The Request will focus support on LHC data analysis activities that are prioritized through a competitive peer review process and which are based on highest scientific merit and potential impact. Efforts associated with the HL-LHC ATLAS and HL-LHC CMS Detector upgrade activities will continue as researchers prepare for project baselining. The Request will support detector operations activities and associated U.S.-based computing infrastructure and resources needed to process the large volume of data anticipated when the LHC resumes running in Q3 of FY 2021. Support for HL-LHC Accelerator Upgrade and HL-LHC ATLAS and HL-LHC CMS Detector Upgrade Projects decreases and funding will support critical path activities to best maintain synchronization with the international HL-LHC schedule. Support for lower priority research, as determined by the FY 2018 HEPAP portfolio review, will ramp down.	**-48,234**
Intensity Frontier Experimental Physics The Request will focus research support towards NOvA, the SBN program, Mu2e, and LBNF/DUNE. Support for lower priority small- to mid-scale neutrino experiments, as determined by the FY 2018 HEPAP portfolio review, will ramp down. The Request will support the Fermilab Accelerator Complex and the neutrino and muon experiments at 80 percent of optimal operations. Support for GPP funding is reduced as the Kautz Road Sub-Station Radial Feed Electrical Upgrade, and the cleanroom consolidation and construction in Industrial Building 4 in support of cryomodule assembly will be fully funded in FY 2020. The Request includes an increase of R&D for the PIP-II injector prototype, which is offset by the decrease for LBNF/DUNE OPC as the pre-excavation construction work approaches completion and is ramping down.	**-45,699**
Cosmic Frontier Experimental Physics The Request will support increased research on the experiments that have recently started and a new MIE start for CMB-S4, while support for the Dark Energy Survey (DES) and research on lower priority experiments, as determined by the FY 2018 HEPAP portfolio review, will ramp down. The Request supports a ramp up in detector and facility operations and data processing for the suite of next generation dark matter and dark energy experiments, while ramping down operations for lower priority experiments.	**-24,981**
Theoretical, Computational, and Interdisciplinary Physics The Request will increase support for AI/ML to address cross-cutting challenges in AI/ML that will advance the mission of the HEP program. The Request will prioritize theoretical support of the HEP experimental program and the highest-impact theoretical research as determined by competitive peer review. The Request supports transformative computational science, high performance computing, and exploratory research on adapting software workflows and testing hardware to make efficient use of Exascale architecture. The Request will support increases for interdisciplinary HEP-QIS consortia for focused research on foundational HEP-QIS including novel experiments, quantum computing, and quantum research technology and SC QIS Center activity in partnership with other SC programs.	**+7,114**

	(dollars in thousands) **FY 2021 Request vs FY 2020 Enacted**
Advanced Technology R&D The Request will capitalize on the science opportunities at the newly completed FACET-II facility and increase the operational hours to 2,500 (83 percent of optimal), grow the Traineeship Program, begin the Strategic Accelerator Technology Initiative to bolster efforts in superconducting Magnet Development, accelerate ultrafast laser R&D, upgrade superconducting radio frequency (SRF) facilities and expand capabilities, and co-fund a multi-office R&D initiative in superconducting materials. Detector R&D support will be prioritized at universities and national laboratories, which enhance collaborative opportunities in support of new directions in HEP discovery science programs, and strengthen new technology developments and capabilities to align with the FY 2020 Basic Research Needs workshop priorities. The Request will support Microelectronics initiative through collaboration with ASCR, BES, and FES to conduct R&D for detector materials, devices, advances in front-end electronics, integrated sensor/processor architectures, and support multi-disciplinary microelectronics research.	**-1,304**
Accelerator Stewardship The Request will enable the start of the Strategic Accelerator Technology Initiative to advance accelerator technologies that define the U.S. competitive advantage in physical sciences research. The ATF at BNL will operate at 86 percent of optimal. Support for accelerator technologies for industrial, medical and security uses, and advanced laser technology R&D will ramp down.	**-3,265**
Construction The Request will continue support for LBNF/DUNE 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. The Request will also support 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. Also, the Request will support the continuation of construction and fabrication for technical systems including contributions to the DUNE detectors, when design is final and authorized by CD-3. The Request will continue support for PIP-II completion of civil engineering design for the conventional facilities, and technical design and prototyping for the accelerator components.	**-110,500**
Total, High Energy Physics	**-226,869**

Basic and Applied R&D Coordination

Accelerator Stewardship provides the fundamental building blocks of new technological advances in accelerator applications, including advanced proton and ion beams for the treatment of cancer, in coordination with the National Institutes of Health (NIH). HEP developed the Accelerator Stewardship subprogram based on input from accelerator R&D experts drawn from other federal agencies, universities, national laboratories, and the private sector to help identify specific research areas and infrastructure gaps where HEP investments would have sizable impacts beyond the SC research mission. This subprogram is closely coordinated with BES, FES, and Nuclear Physics (NP) programs and partner agencies to ensure federal stakeholders have input in crafting funding opportunity announcements, reviewing applications, and evaluating the efficacy and impact of funded activities. Use-inspired accelerator R&D for medical applications has been closely coordinated with the NIH/National Cancer Institute (NCI); ultrafast laser technology R&D with the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA); and microwave and high power accelerator R&D coordinated with the DOD, the Department of Homeland Security's Domestic Nuclear Detection Office in the Countering Weapons of Mass Destruction Office (DHS/CWMD), the NSF/Chemical, Bioengineering, Environmental and Transport (CBET) Systems Division; and the DOE's Office of Environmental Management (EM). Discussions with the National Nuclear Security Administration (NNSA) on mission needs and R&D coordination in laser technology, radioactive source replacement, and particle detector technologies have led to a Basic Research Needs Workshop on Compact Accelerators for Security and Medicine[a] that was held in May 2019 to establish research priorities for accelerator R&D in this critical area.

Ensuring that the Accelerator Stewardship subprogram's use-inspired basic R&D investments result in high-impact applications requires close coordination with other agencies who will carry on the later-stage development. The implementation strategy is to work with applied R&D agencies to jointly define priority research directions at Basic Research Needs Workshops, and then guide R&D and facility investments through joint participation of applied agencies in merit reviews and in the operations review of the BNL ATF. Where an eventual marketable use is envisioned, R&D collaborations are expected to involve a U.S. company to guide the early-stage R&D.

Specific funded examples include collaborative R&D on proton therapy delivery systems (joint with Varian Medical Systems), advanced proton sources for therapy (joint with ProNova Solutions), advanced detectors for cancer therapy (joint with Best Medical International), advanced microwave source development (joint with Communications Power Industries and General Atomics), and technical design studies for high power accelerators for wastewater treatment (joint with Metropolitan Water Reclamation District of Greater Chicago, the Air Force Research Laboratory, and General Atomics). Funded R&D awards have drawn an average of 20 percent of voluntary cost sharing over the initial years of the subprogram, providing evidence of the potential impact.

The HEP QIS research program has coordinated partnerships with the DOD Office of Basic Research (DOD/OBR) as well as the Air Force's Office of Scientific Research (AFOSR) on synergistic research connecting cosmic black holes with quantum error correction in qubit devices, 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 Center effort is a partnership across the HEP, ASCR, and BES programs and engages industry to inform use-inspired research and connect to applied and development activities. These interdisciplinary QIS efforts are aligned with the National Quantum Initiative and SC QIS priorities.

Program Accomplishments

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

Using data collected during the record-setting operations of the LHC through 2018, scientists from the ATLAS and CMS collaborations continued their studies of Higgs boson interactions and searched for signs of dark matter being created in high energy particle collisions. Using AI/ML techniques to enhance their sensitivity, the CMS collaboration used the Higgs boson as a tool for discovery by searching for evidence of it being produced in association with dark matter particles. This sensitive search is the first to combine five Higgs boson decay channels, including some used in searches for the first time.

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

The ATLAS collaboration applied AI/ML techniques to the search for the Higgs boson decaying to pairs of muons, providing the most sensitive analysis to date. While this challenging decay channel is predicted by the standard model at a low rate, the analysis suggests that observation will be possible in the future era of the HL-LHC. These analyses demonstrate the potential for discovery as the LHC will resume operations in 2021 after a scheduled two-year technical stop for accelerator and detector upgrades.

Precision Reactor Oscillation and Spectrum Experiment (PROSPECT) produces first results in reactor based search for sterile neutrinos (Intensity Frontier Experimental Physics).
One major unresolved question about neutrinos is whether there are additional types beyond the three that are known. The known neutrinos change their type as they travel, a phenomenon known as neutrino oscillation, and is it possible that this process allows neutrinos to change into “sterile” types that do not interact directly with other matter. Nuclear reactors provide an intense source of neutrinos that can be used to search for signs of additional neutrino types through oscillations over a few meters of distance. Using data collected during 33 live-days of reactor operation at the High Flux Isotope Reactor (HFIR), scientists on the PROSPECT experiment produced first results their search for sterile neutrinos. The results significantly constrain the favored region for sterile neutrinos from previous experiments, and will continue to improve as more data is recorded.

Dark Energy Survey completes observations and delivers first combined dark energy constraints from several cosmological probes (Cosmic Frontier Experimental Physics).
The Dark Energy Survey (DES) aims to understand why the universe is accelerating in its expansion. If Einstein’s theory of general relativity is correct, then the dark energy that drives this expansion accounts for nearly 70 percent of the total energy in the universe. However, precise measurements of the history of this expansion may reveal that new dynamic forces are in play. DES successfully completed an extended six years of observations in January 2019, reaching its goal of a deep, uniform survey of a large portion of the southern sky. The rich data have already led to over 200 scientific publications, including detailed cosmology results from the first year of observations. In early 2019, the DES collaboration combined several cosmological probes for the first time in order to constrain the properties of dark energy. These combined constraints are competitive with previous experiments and in early 2020 the release of results from three years of observational data will continue to improve our knowledge.

Dark matter experiment produces world’s most sensitive search for axions (Cosmic Frontier Experimental Physics).
The Axion Dark-Matter eXperiment Generation 2 (ADMX-G2), successfully continued the world’s most sensitive search for a candidate dark matter particle known as the axion. Axions are hypothetical dark matter particles with a very low mass, almost a trillion times lighter than an electron, that would also solve a known issue in the theoretical framework of the standard model of particle physics. The ADMX-G2 experiment sweeps through regions of potential axion mass by tuning a radiofrequency cavity through different frequency bands, and major steps in the scan require swapping the cavity. After producing the world’s most sensitive search for axions in the frequency range of 680 MHz to 800 MHz in 2018, the ADMX collaboration continued their search in frequencies up to 1,020 MHz in 2019. ADMX will continue operations in up to three more configurations to eventually reach 2,000 MHz and span an important region of interest in the search for dark matter axions.

Scrambling of quantum information successfully verified in experiment (Theoretical, Computational, and Interdisciplinary Physics).
Quantum systems provide experimental testbeds for understanding the universe in new ways. In quantum simulations, the correlations and flow of information between quantum bits (qubits) in a laboratory experiment may provide insight into difficult problems in many other areas including black holes. A major challenge is understanding how information from one qubit is dispersed, or “scrambled,” into correlations with entangled qubits over the course of an experiment and distinguishing scrambling from external effects that introduce noise in the quantum information. Using trapped atomic ions as qubits, experimenters successfully measured aspects of quantum information scrambling in an entangled multi-body system and provably distinguished it from external noise. The experimental validation of this process opens new doors for exploring the quantum world and related problems through quantum simulation.

World record magnetic field strength achieved for a superconducting accelerator magnet (Advanced Technology R&D). In high-energy circular colliders, strong magnetic fields are needed to steer particle beams so they can be brought into collision at the interaction points. Future particle colliders will require stronger magnets in order to push the frontiers of discovery science. Stroger magnets reduce the ring size needed for a given particle energy or enable higher energies within the same sized ring. In 2019, scientists at FNAL announced the achievement of the highest magnetic field strength ever recorded for an accelerator magnet. The world record field strength of 14.1 teslas was achieved with the advanced superconducting material niobium-tin at a magnet temperature of 4.5 kelvins (minus 450 degrees Fahrenheit). Efforts are underway to push the performance of the accelerator magnet to even higher fields.

Fermi National Accelerator Laboratory breaks ground on new heart of accelerator complex (Line Item Construction). On March 15, 2019, FNAL held the groundbreaking ceremony for a major new accelerator project, the Proton Improvement Plan II (PIP-II), which will provide a powerful beam for the future experiments served by the Fermilab Accelerator Complex. As an innovative application of cutting-edge superconducting technology, PIP-II has attracted the attention of accelerator experts from around the world and the project will benefit from significant contributions from international partners including France, India, Italy, and the UK. The PIP-II accelerator will play a key role in the future Long Baseline Neutrino Facility hosted by FNAL, enabling it to provide the world's most intense neutrino beam to giant particle detectors in a re-purposed mine a mile beneath the Black Hills of South Dakota. Over a thousand scientists from around the world are collaborating to build the international Deep Underground Neutrino Experiment in order to precisely measure properties of the ghostly neutrino, which may in turn help us understand why the universe today is made of matter instead of antimatter.

High Energy Physics
Energy Frontier Experimental Physics

Description
The Energy Frontier Experimental Physics subprogram's focus is on support for the Large Hadron Collider (LHC). 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 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 will be used to address at least three of the five science drivers:

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

<u>Research</u>
The Energy Frontier Experimental Physics subprogram's Research activity supports groups at U.S. academic and research institutions and physicists from national laboratories. These groups, as part of the ATLAS and CMS collaborations, typically have a broad portfolio of responsibilities and leadership roles in support of R&D, experimental design, fabrication, commissioning, operations, and maintenance, and they perform scientific simulations and physics data analyses. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. In FY 2018, HEPAP evaluated the currently operating portfolio of experiments in the Energy Frontier and assessed the priority of their science output in the context of the science drivers. The findings from this review, in combination with input on strategic directions from regular, open community workshops will inform funding decisions in subsequent years. The activity also supports long-term development to efficiently analyze large datasets anticipated during future LHC operations. The next external peer review of the Energy Frontier laboratory research groups is planned for Q4 of FY 2020.

<u>Facility Operations and Experimental Support</u>
U.S. LHC Detector Operations supports the maintenance of U.S.-supplied detector systems for the ATLAS and CMS detectors at the LHC, and the U.S.-based computer infrastructure used by U.S. physicists to analyze LHC data, including 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.

<u>Projects</u>
During the next decade, CERN will undergo a major upgrade to the LHC machine to further increase the particle collision rate by a factor of three to explore new physics beyond its current reach. Through the HL-LHC Accelerator Upgrade Project, HEP will contribute to this upgrade by constructing and delivering the next-generation of superconducting accelerator components, where U.S. scientists have critical expertise. After the upgrade, the HL-LHC beam will make the conditions in which the ATLAS and CMS detectors must operate very challenging. 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 2020 Enacted		FY 2021 Request	Explanation of Changes FY 2021 Request vs FY 2020 Enacted
Energy Frontier Experimental Physics	**$228,438**	**$180,204**	**-$48,234**
Research	$71,125	$50,050	-$21,075
Funding supports U.S. scientists leading high profile analysis topics using the large datasets collected by the ATLAS and CMS experiments.		The Request will support U.S. leadership roles in all aspects of the ATLAS and CMS experimental programs, including the analysis of the large datasets during the next LHC run, which begins in Q3 of FY 2021.	Funding will support LHC data analysis activities that are prioritized through a competitive peer review process and are based on highest scientific merit and potential impact. Efforts associated with the HL-LHC ATLAS and HL-LHC CMS Detector upgrade activities continue in order to prepare for project baselining.
Facility Operations and Experimental Support	$52,650	$48,480	-$4,170
Funding supports ATLAS and CMS detector maintenance and operations at CERN; the U.S.-based computing infrastructure and resources necessary to store and analyze LHC data; and commissioning activities of U.S.-built detector components.		The Request will support ATLAS and CMS detector maintenance and operations at CERN and the U.S.-based computing infrastructure and resources used by U.S. scientists to store and analyze the large volume of LHC data acquired during the next LHC run starting in Q3 of FY 2021.	Funding will support additional compute nodes and data storage needs that are anticipated as a result of the higher demand placed on the U.S.-based computing infrastructure during the next LHC running period that resumes in Q3 of FY 2021. Support for commissioning activities of the U.S.-built detector components installed in prior years will ramp down.
Projects	$100,000	$78,000	-$22,000
Funding supports baselining the detector upgrades projects, and continues procurement of components for the HL-LHC ATLAS and HL-LHC CMS Detector Upgrades, and production of focusing magnets and radio-frequency cavities for the HL-LHC Accelerator Upgrade Project.		The Request will continue support for the critical path items in the production of quadrupole magnets and crab cavities for the HL-LHC Accelerator Upgrade, and continue critical path items and procurements for the Detector upgrades.	Support will focus on critical path items to best maintain synchronization with the international LHC and HL-LHC schedules.

(dollars in thousands)

FY 2020 Enacted		FY 2021 Request	Explanation of Changes FY 2021 Request vs FY 2020 Enacted
SBIR/STTR	$4,663	$3,674	-$989
In FY 2020, SBIR/STTR funding is at 3.65 percent of non-capital funding.		In FY 2021, SBIR/STTR funding will be at 3.65 percent of non-capital funding.	The SBIR/STTR funding will be consistent with the HEP total budget.

High Energy Physics
Intensity Frontier Experimental Physics

Description

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

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

Research

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

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

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

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

The Research activity also includes efforts to search for rare processes in muons to detect physics beyond the reach of the LHC. A new 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, while the Mu2e experiment will search for extremely rare muon decays that, if detected, will provide clear evidence of new physics. The Intensity Frontier subprogram also supports U.S. physicists to participate in select experiments at other international facilities, including experiments in Japan. In particular, the Tokai-to-Kamioka (T2K) long-baseline neutrino experiment in Japan is complementary to NOvA, and together they will offer the best available information on neutrino oscillations prior to LBNF/DUNE. There is also a significant U.S. contingent searching for new physics using the Belle II experiment at the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan supported by this activity.

Facility Operations and Experimental Support

There are several distinct facility operations and experimental support efforts in the Intensity Frontier Experimental Physics subprogram. The largest is the Fermilab Accelerator Complex User Facility. This activity includes the operations of all accelerators and beamlines at FNAL and the operation of the detectors that use those accelerators, as well as 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, an agency of the State of South Dakota, for the operation of the (SURF. Experiments supported by DOE, NSF, and private entities are conducted there. The Nuclear Physics-supported Majorana Demonstrator is currently operating and the HEP-supported LZ experiment is being installed by the LZ collaboration at SURF. Lawrence Berkeley National Laboratory (LBNL) is the lead lab for the LZ collaboration. SURF will be the home of the DUNE far site detectors being built by the LBNF/DUNE project. All costs associated with LBNF and DUNE at SURF are supported by the project and not the cooperative agreement supporting SURF.

Projects

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

PIP-II will upgrade the FNAL linear accelerator to increase beam power and sustain high reliability of the Fermilab Accelerator Complex, ultimately providing the world's highest proton beam intensity of greater than 1.2 megawatts for LBNF/DUNE. PIP-II achieved CD-1 approval on July 23, 2018, and the project is now completing its preliminary design. Two French institutions with expertise in superconducting radio-frequency (SRF) technology have joined the effort, expanding the list of partners that already includes institutions in India, Italy, and the United Kingdom.

Activities and Explanation of Changes

(dollars in thousands)

FY 2020 Enacted		FY 2021 Request	Explanation of Changes FY 2021 Request vs FY 2020 Enacted
Intensity Frontier Experimental Physics	**$250,234**	**$204,535**	**-$45,699**
Research	$58,871	$35,520	-$23,351
Funding prioritizes support for world-leading research efforts on short- and long-baseline neutrino experiments, muon experiments, and technology studies and science planning for LBNF/DUNE. The SBN program is expected to produce its first physics data. The Muon g-2 experiment will achieve the world's most sensitive measurement of the anomalous magnetic dipole moment of a muon. Updated results from NOvA on the neutrino mass ordering and matter-antimatter asymmetry are expected.		The Request will support world-leading research efforts on short- and long-baseline neutrino experiments, muon experiments, and technology studies and science planning for LBNF/DUNE. The FNAL SBN program will move into full operations with all detectors, and the Muon g-2 experiment completes planned data taking. The MicroBoone collaboration will report on their key analyses of the neutrino spectrum anomalies. First joint analyses combining NOvA and T2K data are planned. The Request also will support completion of final analyses on data taken by the Daya Bay and MINERvA neutrino experiments.	Funding will focus research support towards NOvA, the SBN program, Mu2e, and LBNF/DUNE. Support for research on lower priority small- to mid-scale neutrino experiments, as determined by the FY 2018 HEPAP portfolio review, will ramp down.

(dollars in thousands)

FY 2020 Enacted	FY 2021 Request	Explanation of Changes FY 2021 Request vs FY 2020 Enacted
Facility Operations and Experimental Support $177,122	$157,445	-$19,677
Funding supports the Fermilab Accelerator Complex and the neutrino and muon experiments at 85 percent of optimal operations. The Kautz Road Sub-Station Radial Feed Electrical Upgrade GPP will begin as will the Industrial Building 4 cleanroom consolidation and construction GPP in support of cryomodule fabrication. SURF operations will continue to enable operation of the LZ experiment and Majorana Demonstrator. Funding also supports additional investments to enhance SURF infrastructure for reliable and efficient operation of the facility during the construction of LBNF/DUNE.	The Request will support the Fermilab Accelerator Complex and the neutrino and muon experiments at 80 percent of optimal operations; the modernization, repairs, or addition of redundant equipment to help mitigate the risk of slowing down programs and projects; and SURF operations and investments to enhance SURF infrastructure.	Funding will focus support on delivering particle beams at peak power and providing detector and computing operations for ongoing (e.g., NOvA, Muon g-2) and new experiments (e.g., SBN). Overall operations of the Fermilab Accelerator Complex will decrease from 85 to 80 percent of optimal. Support for SURF infrastructure improvements will continue, but at a slightly lower amount.
Projects $5,494	$4,000	-$1,494
Funding supports OPC for R&D related to the PIP-II Injector Test Facility; a prototype for the front-end injector; for plant support costs at SURF during LBNF/DUNE construction; and an MIE to upgrade the control system of the accelerator system which will allow the Fermilab Accelerator Complex to operate more precisely and efficiently, resulting in better performance and lower operating cost.	The Request will support OPC for developing additional PIP-II project scope necessary for upgrading the existing Booster, Recycler, and Main Injector synchrotrons (downstream from the new linac) to accept the increased beam intensity enabled by the new linac. OPC will continue plant support costs at SURF during LBNF/DUNE construction. Also, the Request will continue OPC for the Fermilab Accelerator Control System MIE.	The funding will decrease for the PIP-II injector prototype and plant support costs at SURF for LBNF/DUNE as the pre-excavation construction work approaches completion and is ramping down.
SBIR/STTR $8,747	$7,570	-$1,177
In FY 2020, SBIR/STTR funding is at 3.65 percent of non-capital funding.	In FY 2021, SBIR/STTR funding will be at 3.65 percent of non-capital funding.	The SBIR/STTR funding will be consistent with the HEP total budget.

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, dark energy, and inflation in the early universe, constraints on neutrinos, and other phenomena. The activities in this subprogram use diverse tools and technologies, from ground-based telescopes and space-based missions, to large detectors deep underground to address four of the five science drivers:

- *Identify the new physics of dark matter*
  Overwhelming evidence through the years, starting with measurements of motions within galaxies first made in the 1930s, show that dark matter accounts for five times as much matter in the universe as ordinary matter. Direct-detection experiments provide the primary method to search for cosmic dark matter particles' rare interactions with ordinary matter, while indirect-detection experiments search for the products of dark matter annihilation. A staged series of direct-detection experiments search for the leading theoretical candidate particles using multiple technologies to cover a wide range in mass with increasing sensitivity. Accelerator-based dark matter searches performed in the Intensity Frontier and the Energy Frontier subprograms are complementary to these experiments.
- *Understand cosmic acceleration: dark energy and inflation*
  The nature of dark energy, which drives the accelerating expansion of the universe, continues as one of the most perplexing questions in science. Together, dark energy and dark matter comprise 95 percent of the matter and energy in the universe, leaving approximately five percent ordinary matter, from which all the stars and galaxies, and we, are made. Steady progress continues in a staged set of dark energy experiments of ever-increasing precision, using complementary wide area sky imaging surveys and deep, precise light-spectrum surveys, to determine the nature of dark energy. Experiments studying the oldest observable light in the universe, the cosmic microwave background (CMB), are increasing their sensitivity to explore directly the era of cosmic inflation, the rapid expansion in the early universe shortly after the Big Bang.
- *Pursue the physics associated with neutrino mass*
  The study of the largest physical structures in the Universe may reveal the properties of particles with the smallest known cross section, the neutrinos. Experiments studying dark energy and the CMB will put constraints on the number of neutrino species and their masses. The properties of neutrinos affected the evolution of matter distribution in the universe, leading to changes in the CMB observables when measured in different directions. These measurements are complementary to, and a powerful cross check of, the ultra-sensitive measurements made in the Intensity Frontier.
- *Explore the unknown: new particles, interactions, and physical principles*
  High-energy cosmic rays and gamma rays probe energy scales well beyond what may be produced with man-made particle accelerators, albeit not in a controlled experimental setting. Searches for new phenomena and indirect signals of dark matter in these surveys may yield surprising discoveries about the fundamental nature of the universe.

Research

The Cosmic Frontier Experimental Physics subprogram's Research activity supports groups at U.S. academic and research institutions and national laboratories who perform experiments using instruments on the surface, deep underground, and in space. These groups, as part of scientific collaborations, typically have a broad portfolio of responsibilities and leadership roles in support of R&D, experimental design, fabrication, commissioning, operations, and maintenance, as well as perform scientific simulations and physics data analyses on the experiments in the subprogram. DOE selects research efforts with the highest scientific merit and potential impact based on a competitive peer-review process. HEP conducted an external peer review of the Cosmic Frontier laboratory research groups in FY 2016; the next review is planned for Q4 of FY 2020. In FY 2018, HEPAP evaluated the currently operating portfolio of experiments in the Cosmic Frontier and assessed the priority of their science output in the context of the science drivers. In early FY 2019, HEP conducted a Basic Research Needs[a]

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

workshop to assess the science landscape and new opportunities for dark matter particle searches and to identify which areas would be suitable for small projects in the HEP program. The findings from these reviews, in combination with input on strategic directions from regular, open community workshops, are informing funding decisions in subsequent years.

The Research activity supports collaborations that enable all phases of experiments, from conceptual design through fabrication and operations, in order to ensure delivery of Cosmic Frontier science. The largest investments support scientific efforts to understand cosmic acceleration, from dark energy and inflation, and to search for dark matter produced in nature. The activity also supports R&D efforts to investigate the motivation and feasibility for possible future projects to enhance dark energy and dark matter studies with projects complementary to the current suite, as well as those using potential new methods or opportunities.

Two complementary next-generation experiments will provide greatly increased precision in measuring the history of the expansion of the universe in order to determine the nature of dark energy. The Vera C. Rubin Observatory (previously called the Large Synoptic Survey Telescope) will carry out a 10-year wide-field, ground-based optical and near-infrared imaging Legacy Survey of Space and Time (LSST), which will be used by the Dark Energy Science Collaboration (DESC). The Dark Energy Spectrographic Instrument (DESI) 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 current generation of complementary dark energy experiments, Dark Energy Survey (DES) and extended Baryon Oscillation Spectroscopic Survey (eBOSS) completed operations in FY 2019 and continue to provide insight into the nature of dark energy as scientists continue to explore the data and develop innovative analysis techniques. The next-generation Cosmic Microwave Background-Stage 4 (CMB-S4) experiment will have unprecedented sensitivity and precision in measurements of the temperature fluctuations of the early universe. It will allow us to peer directly into the inflationary era in the early moments of the universe for the first time, at a time scale unreachable by other types of experiments.

The activity supports a portfolio of experiments to probe the most promising avenues in the search for the particle nature of dark matter. Two next-generation dark matter search experiments will use complementary technologies to search for weakly interacting massive particles (WIMP) over a wide range of masses, with LZ searching for heavier WIMPs and SuperCDMS-SNOLAB sensitive to lighter WIMPs. The Axion Dark-Matter eXperiment Generation 2 (ADMX-G2) searches for another theoretical dark matter candidate, the axion. Recent advancements in particle theory and sensor technology have created new opportunities to search for dark matter in previously unexplored mass ranges using small, targeted experiments.

In addition, recent new theoretical ideas have underscored that both candidates for Dark Matter, weakly interacting massive particles (WIMPs) and axions, are special cases of a broader theoretical framework that have many of the same attractive features and provide strong motivation for research and development support on possible future project(s) in Dark Matter parameter space beyond HEP's current program’s sensitivity.

Facility Operations and Experimental Support
This activity supports the DOE share of expenses necessary for the successful pre-operations planning activities and maintenance, operations, and data collection and processing during the operating phase of Cosmic Frontier experiments. These experiments are typically not sited at national laboratories, but at telescopes and observatories that are ground-based, in space, or deep underground. The activity provides support for the experiments currently operating as well as for planning and pre-operations activities for the next-generation experiments in the design or fabrication phase. HEP continues to carry out a series of planning reviews to ensure readiness as each experiment transitions from project fabrication to the science operations phase.

The DESI instrumentation is mounted and operating on the NSF’s Mayall Telescope at Kitt Peak National Observatory, with operations of the instrumentation and telescope supported by DOE. The Vera C. Rubin Observatory, which includes the DOE-provided camera, is being commissioned in Chile. DOE and NSF are partnering in observatory operations, with planning activities in process. The DESC continues its pre-operations activities to prepare for the initation of the 10-year survey.

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

Projects

The next-generation CMB-S4 experiment is planned as a joint DOE and NSF project and will consist of an array of small and large telescopes working in concert at sites in the South Pole and Chile with 500,000 ultra-sensitive sensors and associated readout system.

Activities and Explanation of Changes

(dollars in thousands)

FY 2020 Enacted		FY 2021 Request	Explanation of Changes FY 2021 Request vs FY 2020 Enacted
Cosmic Frontier Experimental Physics	**$94,901**	**$69,920**	**-$24,981**
Research	$48,072	$29,220	-$18,852
Funding prioritizes support for world-leading research efforts on all phases of dark matter and dark energy experiments, as well as technology studies and planning for a CMB-S4 experiment. The Dark Energy Survey (DES) imaging experiment will release all its data from its 5-year survey.		The Request will support core research efforts in all phases of experiments. The collaborations expect to finish data analyses on ADMX-G2 Run 1D, DES year 3 data, and the full data set for eBOSS. Researchers will participate in data planning, collection, and analysis for LZ, SuperCDMS-SNOLAB, and DESI. Researchers will participate in commissioning of the Vera C. Rubin Observatory and the DESC will continue planning for the subsequent LSST. The Request also includes funding for CMB-S4, Dark Matter and Dark Energy planning as well as technology R&D for the future.	Research support will prioritize efforts for the experiments that have recently started and physics studies for CMB-S4. Research on recently completed and lower priority experiments, as determined by the FY 2018 HEPAP portfolio review, will ramp down.
Facility Operations and Experimental Support	$41,358	$37,400	-$3,958
Funding supports experiments in various phases: DESI and LZ will start and ADMX-G2 will continue full science operations; effort will continue on the Vera C. Rubin Observatory, including its associated Legacy Survey of Space and Time (LSST) camera, to carry out commissioning activities and a ramp up of pre-operations planning; and SuperCDMS-SNOLAB will continue commissioning and pre-operations activities.		The Request will support continued science operations on DESI, LZ, ADMX-G2, and partial science operations on SuperCDMS-SNOLAB. The Vera C. Rubin Observatory will continue commissioning and pre-operations efforts.	Support will prioritize the detector and observatory operations and data processing for the next generation dark matter and dark energy experiments, while ramping down operations for lower priority experiments.

(dollars in thousands)

FY 2020 Enacted	FY 2021 Request	Explanation of Changes FY 2021 Request vs FY 2020 Enacted
Projects $2,000	$1,000	-$1,000
Funding supports OPC for technology R&D and planning for the CMB-S4 project.	The Request will support a new MIE start for CMB-S4 as it completes conceptual design and begins preliminary design activities and starts long lead procurements for sensors and cryostats.	The budget will transition support from OPC to preliminary design activities for CMB-S4.
SBIR/STTR $3,471	$2,300	-$1,171
In FY 2020, SBIR/STTR funding is at 3.65 percent of non-capital funding.	In FY 2021, SBIR/STTR funding will be at 3.65 percent of non-capital funding.	The SBIR/STTR funding will be consistent with the HEP total budget.

High Energy Physics
Theoretical, Computational, and Interdisciplinary Physics

Description

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

Theory

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

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. Computational HEP priorities are to promote computing research for HEP future needs across the program, by exploiting the latest architectures like massively-parallel high performance computing platforms and future exascale computer systems. Computational HEP partners with the Advanced Scientific Computing Research (ASCR) program, including via the Scientific Discovery through Advanced Computing (SciDAC) activity, and with ASCR facilities and projects to optimize the HEP computing ecosystem for the near and long term future.

Quantum Information Science (QIS)

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

Artificial Intelligence and Machine Learning

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

Activities and Explanation of Changes

(dollars in thousands)

FY 2020 Enacted		FY 2021 Request	Explanation of Changes FY 2021 Request vs FY 2020 Enacted
Theoretical, Computational, and Interdisciplinary Physics	**$115,527**	**$122,641**	**+$7,114**
Theory	$48,504	$29,480	-$19,024
Funding supports world-leading research that addresses the neutrino mass, the interpretation of experimental results, the development of new ideas for future projects, and the advancement of the theoretical understanding of nature.		The Request will support 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 the advancement of the theoretical understanding of nature.	Funding will prioritize theoretical support of the HEP experimental program and the highest-impact theoretical research as determined by competitive peer review.
Computational HEP	$9,430	$11,440	+$2,010
Funding supports transformative computational science, high performance computing, and SciDAC 4 activities to provide crosscut computational science tools for HEP science.		The Request will support 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 adapting software workflows and testing hardware to make efficient use of the Exascale architecture.	Funding will support increased focus on high performance computing for particle physics and for computational science driven discovery.
Quantum Information Science	$38,500	$43,809	+$5,309
Funding supports interdisciplinary HEP-QIS consortia and exploratory Pioneering Pilots to strengthen foundational HEP-QIS research, quantum computing and quantum research technology. Funding also supports up to five new QIS Centers in partnership with other SC program offices.		The Request will support interdisciplinary HEP-QIS consortia for focused research on foundational HEP-QIS including novel experiments, quantum computing, and quantum research technology. The Request will also continue support for QIS Centers in partnership with other SC program offices.	Increased funding will support quantum simulation experiments and QIS Centers.

(dollars in thousands)

FY 2020 Enacted		FY 2021 Request	Explanation of Changes FY 2021 Request vs FY 2020 Enacted
Artificial Intelligence and Machine Learning	$15,000	$34,500	+$19,500
Funding supports new and existing AI/ML research to explore how DOE high performance computing resources can scale up the optimization, performance, and validation studies of AI/ML tracking models, use pattern recognition to develop production-quality tracking for online triggering systems for HEP experiments, and use statistics and AI/ML to better analyze simulated data.		The Request will support 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.	Funding will support cross-cutting challenges in AI/ML that will advance the HEP program. Science community input and programmatic priorities will inform key investment strategies. HEP will select research efforts with the highest scientific impact and potential based on a competitive peer-review process.
SBIR/STTR	$4,093	$3,412	-$681
In FY 2020, SBIR/STTR funding is at 3.65 percent of non-capital funding.		In FY 2021, SBIR/STTR funding will be at 3.65 percent of non-capital funding.	The SBIR/STTR funding will be consistent with the HEP total budget.

Advanced Technology R&D

Description

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

<u>HEP General Accelerator R&D</u>

The HEP General Accelerator R&D (GARD) activity supports the science underlying the technologies used in particle accelerators and storage rings, as well as the fundamental physics of charged particle beams. Long-term research goals include developing technologies to enable breakthroughs in particle accelerator size, cost, beam intensity, and control. The GARD activity supports groups at U.S. academic and research institutions and national laboratories performing research activity categorized into five areas: accelerator and beam physics; advanced acceleration concepts; particle sources and targetry; radio-frequency acceleration technology; and superconducting magnet and materials. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. HEP conducted an external peer review of the GARD laboratory research groups in FY 2018; the next review is planned for FY 2022. The findings from this review, in combination with input on strategic directions from regular, open community workshops 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. The SC Strategic Accelerator Technology Initiative 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. HEP, BES, FES, NP, and ASCR will enhance coordination and jointly pursue accelerator R&D topics that will have a strong impact on the scientific capabilities of SC facilities.

In addition to providing support for the highly successful U.S. Particle Accelerator School, the GARD activity 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.

<u>Detector R&D</u>

The Detector R&D activity supports the development of the next generation instrumentation and particle 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 impact and potential based on a competitive peer-review process. HEP conducted an external peer review of the Detector R&D laboratory research groups in FY 2016; the next review is planned for FY 2021. In FY 2020, HEP conducted a Basic Research Needs workshop to assess the science landscape and new opportunities for potentially transformative detector technologies, and to identify which R&D areas would be most suitable for new investments in the HEP program. The findings from this workshop, in combination with input on strategic directions from regular, open community workshops will inform funding decisions in subsequent years.

The Detector R&D activity, as well as the GARD activity, supports the Traineeship Program for Accelerator Science and Technology to revitalize education, training, and innovation in the physics of particle detectors and next generation instrumentation 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 Detector R&D research activities as well as the capabilities and assets of DOE laboratories.

SC is in a unique position to both play a critical role in the advancement of microelectronic technologies over the coming decades, and also to benefit from the resultant capabilities in detection, computing, and communications. Four SC programs – ASCR, BES, FES, and HEP – will work together to advance Microelectronics technologies . While there is a significant emphasis across the Federal government on (QIS, including quantum computing, this initiative is intentionally focused on establishing the foundational knowledge base for future microelectronics and computing technologies 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 LBNL; FACET-II, the beam-driven plasma wakefield acceleration facility at SLAC National Accelerator Laboratory (SLAC); and superconducting radio-frequency accelerator and magnet facilities at FNAL. This activity supports the test beam at FNAL, and detector test and fabrication facilities such as the Microsystems Laboratory at LBNL and the Silicon Detector Facility at FNAL. Accelerator Improvement Projects (AIP) support improvements to GARD facilities.

Projects

The Advanced Technology R&D subprogram supports the development of new tools for particle physics through the development of more advanced accelerators and detectors. Plasma wakefield accelerators may have a transformative impact on the size, capabilities, and cost of future machines. FACET-II will be the world’s premier beam driven plasma wakefield acceleration facility and provide intense ultra-short electron beams for other applications in accelerator and related sciences. The FY 2019 Appropriation provided sufficient funds to complete all remaining deliverables. In FY 2020, the project will be completing its Accelerator Readiness Review and final checks of its electronic control systems in anticipation of receiving final CD-4 approval.

High Energy Physics
Advanced Technology R&D

Activities and Explanation of Changes

(dollars in thousands)

FY 2020 Enacted		FY 2021 Request	Explanation of Changes FY 2021 Request vs FY 2020 Enacted
Advanced Technology R&D	**$107,406**	**$106,102**	**-$1,304**
HEP General Accelerator R&D	$43,454	$45,606	+$2,152
Funding supports world-leading General Accelerator R&D that will enable transformative technologies for the next-generation of accelerators for High Energy Physics. Funding also provides support for the Traineeship Program for Accelerator Science and Technology.		The Request will support 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. The Request will also support the Traineeship Program for Accelerator Science and Technology, and will initiate support for the Strategic Accelerator Technology Initiative.	Funding will support capitalization on the science opportunities at the newly completed FACET-II facility, grow the Traineeship Program, begin the Strategic Accelerator Technology Initiative to bolster efforts in superconducting Magnet Development, accelerate ultrafast laser R&D, upgrade SRF facilities and expand capabilities, and co-fund a multi-program R&D initiative in superconducting materials.
Detector R&D	$20,937	$19,450	-$1,487
Funding supports cutting-edge Detector R&D activities at universities and national laboratories, targeted at the most promising, high-impact directions led by U.S. efforts.		The Request will support 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 study on HEP Detector R&D. HEP will collaborate with ASCR, BES, and FES to advance Microelectronics technologies. The Request will also expand the Traineeship Program to Detector R&D.	Funding will support efforts toward the Microelectronic initiative and the Traineeship program, while ongoing Detector R&D support will be prioritized at universities and national laboratories that enhance collaborative opportunities in support of new directions in HEP discovery science programs and strengthen new technology developments and capabilities that address priorities identified in the FY 2020 Basic Research Needs study.

(dollars in thousands)

FY 2020 Enacted	FY 2021 Request	Explanation of Changes FY 2021 Request vs FY 2020 Enacted
Facility Operations and Experimental Support $39,232	$37,200	-$2,032
Funding supports the operation of accelerator, test beam, and detector facilities at FNAL, LBNL, and SLAC and improvements to superconducting radio-frequency facilities. Funding also supports final commissioning, installation, and 1,500 hours (50 percent of optimal) of initial operations for FACET-II.	The Request will support the operation of accelerator, test beam, and detector facilities at FNAL, LBNL, and SLAC and improvements to superconducting radio-frequency and magnet test facilities. The Request also includes support for 2,700 hours (90 percent of optimal) facility operations for FACET-II.	Funding will support FACET-II for additional beam time for experiments and to improve its capabilities. The increase will be offset by a decrease at the facilities at ANL, FNAL, LBNL, and SLAC, which will be guided by recent comparative reviews of the laboratory programs.
SBIR/STTR $3,783	$3,846	+$63
In FY 2020, SBIR/STTR funding is at 3.65 percent of non-capital funding.	In FY 2021, SBIR/STTR funding will be at 3.65 percent of non-capital funding.	The SBIR/STTR funding will be consistent with the HEP total budget.

High Energy Physics
Accelerator Stewardship

Description

The Accelerator Stewardship subprogram has 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 adapt accelerator technology for medical, industrial, security, and defense applications; and driving a limited number of specific accelerator applications towards practical, testable prototypes in a five to seven year timeframe. HEP manages this subprogram as a coordinated interagency initiative, consulting with other SC programs, principally BES, FES, NP; other DOE program offices, principally EM; and other federal stakeholders[a] of accelerator technology. Ongoing interagency consultation guides research and development (R&D) investments, ensuring agency priorities are addressed, exploiting synergies where possible, and identifying new cross-cutting areas of research.

Research

The Research activity supports both near-term translational R&D and long-term basic accelerator R&D, which is conducted at national laboratories, universities, and in the private sector. The needs for applications have been specifically identified by federal stakeholders and developed further by technical workshops. Near-term R&D funding opportunities are specifically structured to foster strong partnerships with the private sector to improve health outcomes while lowering cost, develop technologies that may destroy pollutants and pathogens, detect contraband and radioactive material, and support new tools of science. Long-term R&D funding is targeted at scientific innovations enabling breakthroughs in particle accelerator size, cost, beam intensity, and control.

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. SC's Strategic Accelerator Technology Initiative 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. HEP, BES, FES, NP, and ASCR will enhance coordination and jointly pursue accelerator R&D topics that will have a strong impact on the scientific capabilities of SC facilities.

Facility Operations and Experimental Support

The Facility Operations and Experimental Support activity supports the BNL ATF, which is an SC User Facility providing a unique combination of high quality electron and infrared laser beams in a well-controlled user-friendly setting. Beam time at the BNL ATF is awarded based on merit-based peer review process. The facility remains at the cutting edge of science and works to increase its cost efficiency through ongoing facility R&D. Accelerator Improvement Projects (AIP) support improvements to Accelerator Stewardship facilities.

[a] Partner agencies for the Accelerator Stewardship subprogram currently are: the National Nuclear Security Administration; National Institutes of Health's National Cancer Institute; the Department of Defense's Office of Naval Research, the Air Force Office of Scientific Research, and the Defense Advanced Research Projects Agency; the NSF's Physics Division; Department of Homeland Security's Countering Weapons of Mass Destruction office.

Activities and Explanation of Changes

(dollars in thousands)

FY 2020 Enacted		FY 2021 Request	Explanation of Changes FY 2021 Request vs FY 2020 Enacted
Accelerator Stewardship	**$17,494**	**$14,229**	**-$3,265**
Research	$10,788	$8,510	-$2,278
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.		The Request will support 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. The Request will initiate funding for the Strategic Accelerator Technology Initiative.	Funding will enable the start of the Strategic Accelerator Technology Initiative to advance accelerator technologies that define the U.S. competitive advantage in physical sciences research. There will be an offsetting decrease in R&D on accelerator technologies for industrial, medical and security uses, and advanced laser technology R&D.
Facility Operations and Experimental Support	$6,067	$5,200	-$867
Funding supports the BNL ATF operations at 100 percent of optimal levels and supports facility refurbishments to provide increased reliability and expanded capability to users.		The Request will support the BNL ATF operations at 86 percent of optimal levels.	Operating hours will be decreased to 86 percent of optimal levels.
SBIR/STTR	$639	$519	-$120
In FY 2020, SBIR/STTR funding is at 3.65 percent of non-capital funding.		In FY 2021, SBIR/STTR funding will be at 3.65 percent of non-capital funding.	The SBIR/STTR funding will be consistent with the HEP total budget.

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 both engineering, design, and construction.

Proton Improvement Plan II (PIP-II)

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 megaelectronvolts (MeV) superconducting radio-frequency (SRF) proton linear accelerator, beam transfer line and infrastructure. PIP-II will modify the existing FNAL Booster, Recycler and Main Injector accelerators to accept the increased beam intensity. Some of the new components and the cryoplant will provide through international, in-kind contributions.

The most recent DOE Order 413.3B approved Critical Decision (CD) is CD-1 (Approve Alternative Selection and Cost Range), approved on July 23, 2018. The TPC cost range is $653,000,000 to $928,000,000. The funding profile supports the currently estimated TPC of $888,000,000. The CD-4 milestone is Q1 FY 2030.

Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE)

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 to a large detector in South Dakota, 800 miles away from FNAL, where they are produced in a high-energy beam. The experiment will analyze the rare, flavor-changing transformations of neutrinos in flight, from one lepton flavor to another, which are expected to help explain the fundamental physics of neutrinos and the puzzling 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. LBNF/DUNE will be the first-ever large-scale, international science facility hosted by the U.S. The LBNF/DUNE project consists of two multinational collaborative efforts. LBNF is responsible for the beamline at FNAL and other experimental and civil infrastructure at FNAL and at the SURF in South Dakota. DUNE is an international scientific collaboration responsible for defining the scientific goals and technical requirements for the beam and detectors, as well as the design, construction and commissioning of the detectors and subsequent research.

DOE's High Energy Physics program manages both activities as a single, line-item construction project—LBNF/DUNE. LBNF, with DOE/FNAL leadership and minority participation by a small number of international partners including CERN, will construct a megawatt-class neutrino source and related facilities at FNAL (the "Near Site"), as well as underground caverns and cryogenic facilities in South Dakota (the "Far Site") needed to house the DUNE detectors. DUNE has international leadership and participation by about 1,160 scientists and engineers from 175 institutions in 32 countries. DOE will fund less than a third of DUNE.

The most recent approved DOE Order 413.3B Critical Decision is CD-3A, approval for Initial Far Site Construction. This approval initiated excavation and construction for the LBNF Far Site conventional facilities in order to mitigate risks and minimize delays for providing a facility ready to accept detectors for installation. The preliminary Total Project Cost (TPC) range is $1,260,000,000 to $1,860,000,000, as approved on September 1, 2016, with a preliminary CD-4 date of Q4 FY 2030. Updated planning and analysis has the TPC point estimate for LBNF/DUNE at $2,600,000,000. The cost estimate increased for two reasons. The first is due to the cost of the excavation. The excavation contractor is now on site and has identified deficiencies in the greater than 100 year old infrastructure that will need to be repaired to support the large volume of rock removal. In addition, the time required to complete the excavation was previously underestimated. An independent cost estimator employed by the project and the design firm verified these new findings. The second reason for the increased cost estimate is that contributions from international partners have been lower than expected. DOE and the laboratory are continuing engagement with potential partners. Scope reductions will be considered to reduce the TPC by the time of baseline.

Activities and Explanation of Changes

(dollars in thousands)

FY 2020 Enacted		FY 2021 Request	Explanation of Changes FY 2021 Request vs FY 2020 Enacted
Construction	**$231,000**	**$120,500**	**-$110,500**
18-SC-42, Proton Improvement Plan II, FNAL	$60,000	$20,000	-$40,000
Funding supports engineering design work for conventional facilities and technical systems, continuation of site-preparation activities and initiation of construction for cryogenic plant support systems, as well as continued procurement of prototype accelerator system components.		The Request will support completion of civil engineering design for the conventional facilities, technical design and prototyping for the accelerator components, and initiation of construction and procurement for technical systems when design is final and construction is authorized by CD-3.	Support will continue completion of the design phase of PIP-II, including the fabrication of prototypes.
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment, FNAL	$171,000	$100,500	-$70,500
Funding supports the continuation of pre-construction activities to support the Far Site cavern excavation; design and procurement activities for Far Site cryogenics systems; and beamline and conventional facilities design and site preparation at the Near Site. Funding also supports the start of construction and fabrication for technical systems where design is final and authorized by CD-3, including U.S. contributions to the DUNE detectors.		The Request will support 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. The Request will also support 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. The Request 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.	Support will continue for the transition of Far Site construction work from preexcavation to excavation and the ramp-up of design effort on the Near Site facilities.

High Energy Physics
Capital Summary

(dollars in thousands)

	Total	Prior Years	FY 2019 Enacted	FY 2020 Enacted	FY 2021 Request	FY 2021 Request vs FY 2020 Enacted
Capital Operating Expenses						
Capital Equipment	N/A	N/A	125,260	105,350	84,700	-20,650
Minor Construction Activities						
General Plant Projects (GPP)	N/A	N/A	8,000	10,900	1,000	-9,900
Accelerator Improvement Projects (AIP)	N/A	N/A	5,600	—	—	—
Total, Capital Operating Expenses	**N/A**	**N/A**	**138,860**	**116,250**	**85,700**	**-30,550**

Capital Equipment

(dollars in thousands)

	Total	Prior Years	FY 2019 Enacted	FY 2020 Enacted	FY 2021 Request	FY 2021 Request vs FY 2020 Enacted
Capital Equipment						
Major Items of Equipment[a]						
Energy Frontier Experimental Physics						
HL-LHC Accelerator Upgrade Project[b]	236,672	21,572	50,000	52,025	43,000	-9,025
HL-LHC ATLAS Detector Upgrade[c]	136,000	—	27,500	24,500	17,500	-7,000
HL-LHC CMS Detector Upgrade[d]	121,800	—	13,750	23,475	17,500	-5,975

[a] Each MIE located at a DOE facility Total Estimated Cost (TEC) > $5M and each MIE not located at a DOE facility TEC > $2M.
[b] Critical Decision CD-2/3b for HL-LHC Accelerator Upgrade project was approved on February 11, 2019. The TPC is $242,720,000.
[c] Critical Decision CD-1 for HL-LHC ATLAS Detector Upgrade Project was approved September 21, 2018. The estimated cost range was $149,000,000 to $181,000,000. Critical Decision CD-3a was approved October 16, 2019.
[d] Critical Decision CD-1 for HL-LHC CMS Detector Upgrade Project was approved December 19, 2019. The estimated cost range was $144,100,000 to $183,000,000.

	(dollars in thousands)					
	Total	Prior Years	FY 2019 Enacted	FY 2020 Enacted	FY 2021 Request	FY 2021 Request vs FY 2020 Enacted
Cosmic Frontier Experimental Physics						
Dark Energy Spectroscopic Instrument[a] (DESI)	45,250	39,800	5,450	—	—	—
LUX-ZEPLIN[b] (LZ)	52,050	37,600	14,450	—	—	—
Super CDMS-SNOLAB[c]	15,725	13,175	2,550	—	—	—
CMB-S4[d]	350,000	—	—	—	1,000	+1,000
Advanced Technology R&D						
FACET II[e]	20,500	10,500	10,000	—	—	—
Total, MIEs	N/A	N/A	123,700	100,000	79,000	-21,000
Total, Non-MIE Capital Equipment	N/A	N/A	1,560	5,350	5,700	+350
Total, Capital Equipment	**N/A**	**N/A**	**125,260**	**105,350**	**84,700**	**-20,650**

Minor Construction Activities

	(dollars in thousands)					
	Total	Prior Years	FY 2019 Enacted	FY 2020 Enacted	FY 2021 Request	FY 2021 Request vs FY 2020 Enacted
General Plant Projects (GPP)						
Greater than or equal to $5M and less than $20M						
Utility Corridor	8,000	—	8,000	—	—	—
Kautz Road Sub-Station	7,500	—	—	7,500	—	-7,500
Total GPPs (greater than or equal to $5M and less than $20M)	N/A	N/A	8,000	7,500	—	-7,500
Total GPPs less than $5M[f]	N/A	N/A	—	3,400	1,000	-2,400
Total, General Plant Projects (GPP)	**N/A**	**N/A**	**8,000**	**10,900**	**1,000**	**-9,900**

[a] Critical Decision CD-3 for DESI project was approved on June 22, 2016. The TPC is $56,328,000.
[b] Critical Decision CD-3 for LZ project was approved February 9, 2017. The TPC is $55,500,000.
[c] Critical Decisions CD-2/3 for SuperCDMS-SNOLAB project were approved May 2, 2018. The TPC is $18,600,000.
[d] Critical Decision CD-0 for CMB-S4 was approved July 25, 2019. The estimated cost range was $320,000,000 to $395,000,000.
[e] Critical Decisions CD-2/3 for FACET-II project were approved June 8, 2018. The TPC is $25,600,000.
[f] GPP activities less than $5M include design and construction for additions and/or improvements to land, buildings, replacements or additions to roads, and general area improvements.

(dollars in thousands)

	Total	Prior Years	FY 2019 Enacted	FY 2020 Enacted	FY 2021 Request	FY 2021 Request vs FY 2020 Enacted
Accelerator Improvement Projects (AIP)						
Greater than or equal to $5M and less than $20M						
NuMI Target Systems	5,600	—	5,600	—	—	—
Total, AIPs (greater than or equal to $5M and less than $20M)	N/A	N/A	5,600	—	—	—
Total, AIPs less than $5M[a]	N/A	N/A	—	—	—	—
Total, Accelerator Improvement Projects (AIP)	**N/A**	**N/A**	**5,600**	**—**	**—**	**—**
Total, Minor Construction Activities	**N/A**	**N/A**	**13,600**	**10,900**	**1,000**	**-9,900**

[a] AIP activities less than $5M include minor construction at an existing accelerator facility.

High Energy Physics
Major Items of Equipment Description(s)

Energy Frontier Experimental Physics MIEs:

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

The High Luminosity Large Hadron Collider Accelerator Upgrade Project (HL-LHC Accelerator Upgrade Project) received CD-2/3b approval on February 11, 2019 with a TPC of $242,720,000. Following the major upgrade, the CERN LHC machine will further increase the particle collision rate by a factor of three 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 RF crab cavities that are capable of generating transverse electric fields. The magnets will be assembled at LBNL, BNL, and FNAL, exploiting special expertise and unique capabilities at each laboratory. The FY 2021 Request of TEC funding of $43,000,000 will focus support on critical path items in the production of quadrupole magnets and crab cavities to best maintain international schedule synchronization.

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

The High Luminosity Large Hadron Collider ATLAS Detector Upgrade Project (HL-LHC ATLAS) received CD-1 approval on September 21, 2018 with an estimated cost range of $149,000,000 to $181,000,000 and received CD-3a approval on October 16, 2019. CD-2 is planned for FY 2021. The ATLAS detector will integrate a factor of ten higher amount of data per run, 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) begins support for a Major Research Equipment and Facility Construction (MREFC) Project in FY 2020 to provide different scope to the HL-LHC ATLAS detector. DOE and NSF are coordinating their contributions to avoid duplication. The FY 2021 Request of TEC funding of $17,500,000 will focus support on critical path items to best maintain international schedule synchronization.

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

The High Luminosity Large Hadron Collider CMS Detector Upgrade Project (HL-LHC CMS) received CD-1 approval on December 19, 2019, with an estimated cost range of $144,100,000 to $183,000,000. The project is planning CD-3a approval of long lead procurements in spring 2020, with CD-2 planned for FY 2021. The CMS detector will integrate a factor of ten higher amount of data per run, 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 begins support for a MREFC Project in FY 2020 to provide different scope to the HL-LHC CMS detector. DOE and NSF are coordinating their contributions to avoid duplication. The FY 2021 Request of TEC funding of $17,500,000 will focus support on critical path items to best maintain international schedule synchronization.

Cosmic Frontier Experimental Physics MIEs:

Dark Energy Spectroscopic Instrument (DESI)

The Dark Energy Spectroscopic Instrument (DESI) project received CD-2 approval on September 17, 2015 with a TPC of $56,328,000. CD-3 was approved on June 22, 2016. DESI fabricated a next-generation, fiber-fed, ten-arm spectrograph for operation on NSF's Mayall 4-meter telescope at Kitt Peak National Observatory in Arizona, with operations of the telescope supported by DOE. DESI will measure the effects of dark energy on the expansion of the universe using dedicated spectroscopic measurements and will provide a strong complement to the imaging Legacy Survey of Space and Time carried out by the Vera C. Rubin Observatory. The FY 2019 Appropriation for DESI provided sufficient funds to complete all remaining project deliverables. In FY 2020, the project completed all deliverables, including the installation and commissioning of all ten spectrographs and associated systems, and starts full science operations. CD-4 approval is expected in FY 2020.

LUX-ZEPLIN (LZ)

The LUX-ZEPLIN (LZ) project received CD-2 approval on August 8, 2016 with a TPC of $55,500,000, and a project completion date in FY 2022. CD-3 was approved on February 9, 2017. LZ is one of two MIEs selected to meet the Dark Matter Second

Generation Mission Need and the concept for the experiment was developed by a merger of the LUX and ZEPLIN collaborations from the U.S. and the U.K. respectively. The project will fabricate a detector using seven tons of liquid xenon inside a time projection chamber to search for xenon nuclei that recoil in response to collisions with an impinging flux of dark matter particles known as Weakly Interacting Massive Particles (WIMPs). The detector will be located 4,850 feet deep in the Sanford Underground Research Facility (SURF) in Lead, South Dakota. The FY 2019 Appropriation for LZ provided sufficient funds to complete all remaining project deliverables. In FY 2020, the project will finish underground installation, functional testing, and filling of the detector's chambers with liquid xenon, liquid scintillator, and water, and will start full science operations. CD-4 approval is expected in FY 2020.

Super Cryogenic Dark Matter Search at Sudbury Neutrino Observatory Laboratory (SuperCDMS-SNOLAB)
The Super Cryogenic Dark Matter Search at Sudbury Neutrino Observatory Laboratory (SuperCDMS-SNOLAB) project received CD-2/3 approval on May 2, 2018 with a TPC of $18,600,000 and a project completion date at the end of FY 2021. SuperCDMS-SNOLAB is one of the two MIEs selected to meet the Dark Matter Second Generation Mission Need. The project will fabricate instrumentation that uses ultra-clean, cryogenically-cooled silicon (Si) and germanium (Ge) detectors to search for Si or Ge nuclei recoiling in response to collisions with WIMPs, and will optimize to detect low mass WIMPs to cover a range of masses complementary to that of LZ's sensitivity. The detector will be located 2 km deep in the SNOLAB facility in Sudbury, Ontario, Canada. The FY 2019 Appropriation for SuperCDMS-SNOLAB provided sufficient funds to complete all remaining project deliverables in FY 2021, including installation of the seismic platform and assembly of the shielding, cryostat, and calibration system.

Cosmic Microwave Background Stage 4 (CMB-S4)
The *Cosmic Microwave Background Stage 4 (CMB-S4) project* received CD-0 approval on July 25, 2019, with an estimated cost range of $320,000,000 to $395,000,000. The project is expected to be carried out as a partnership with NSF, with DOE as the lead agency and a distribution of scope determined by FY 2021. The project consists of fabricating an array of small and large telescopes at two locations: the NSF Amundsen-Scott South Pole Station and the Atacama high desert in Chile. It will include 500,000 ultra-sensitive sensors with associated readout systems. The project is expected to obtain CD-1 approval in mid FY 2021, along with CD-3a approval of long lead procurements at the same time. In FY 2021, plans for the sensors and readout systems as well as the conceptual design will be completed and the preliminary design and pre-production efforts will start. The FY 2021 Request of TEC funding of $1,000,000 will enable long lead procurement for sensor production and testing, as well as associated systems and infrastructure.

<u>Advanced Technology R&D MIE:</u>
Facility for Accelerator and Experimental Tests II (FACET-II)
The Facility for Accelerator and Experimental Tests II (FACET-II) project received CD-2/3 on June 8, 2018 with a TPC of $25,600,000. FACET-II will be the world's premier beam driven plasma wakefield acceleration facility. FACET-II is being designed to deliver beams using only one third of the SLAC linear accelerator. FACET-II installation and commissioning work in the SLAC accelerator housing will be constrained by the installation of the Linac Coherent Light Source II (LCLS-II). The FY 2019 Appropriation provided sufficient funds to complete all remaining deliverables. In FY 2020, the project will be completing its Accelerator Readiness Review and final checks of its electronic control systems and receive final CD-4 approval.

High Energy Physics
Construction Projects Summary

(dollars in thousands)

	Total	Prior Years	FY 2019 Enacted	FY 2020 Enacted	FY 2021 Request	FY 2021 Request vs FY 2020 Enacted
18-SC-42, Proton Improvement Plan II, FNAL						
TEC	801,200	1,000	20,000	60,000	20,000	-40,000
OPC	86,800	57,035	15,000	494	2,000	+1,506
TPC	**888,000**	**58,035**	**35,000**	**60,494**	**22,000**	**-38,494**
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment, FNAL						
TEC	2,476,375	206,781	130,000	171,000	100,500	-70,500
OPC	123,625	86,625	1,000	4,000	1,000	-3,000
TPC	**2,600,000**	**293,406**	**131,000**	**175,000**	**101,500**	**-73,500**
11-SC-41, Muon to Electron Conversion Experiment, FNAL						
TEC	250,000	220,000	30,000	—	—	—
OPC	23,677	23,677	—	—	—	—
TPC	**273,677**	**243,677**	**30,000**	**—**	**—**	**—**
Total, Construction						
TEC	**N/A**	**N/A**	**180,000**	**231,000**	**120,500**	**-110,500**
OPC	**N/A**	**N/A**	**16,000**	**4,494**	**3,000**	**-1,494**
TPC	**N/A**	**N/A**	**196,000**	**235,494**	**123,500**	**-111,994**

High Energy Physics
Funding Summary

(dollars in thousands)

	FY 2019 Enacted	FY 2020 Enacted	FY 2021 Request	FY 2021 Request vs FY 2020 Enacted
Research	380,847	390,077	328,906	-61,171
Facility Operations	260,803	316,429	285,725	-30,704
Projects				
Major Items of Equipment	141,350	103,000	80,000	-23,000
Construction	196,000	235,494	123,500	-111,994
Other Projects	1,000	–	–	–
Total, Projects	338,350	338,494	203,500	-134,994
Total, High Energy Physics	**980,000**	**1,045,000**	**818,131**	**-226,869**

High Energy Physics
Scientific User Facility Operations

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

Definitions for TYPE A facilities:

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

Planned Operating Hours –

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

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

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

- For BY and CY, Planned Operating Hours divided by Optimal Hours expressed as a percentage.
- For PY, Achieved Operating Hours divided by Optimal Hours.

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 2019 Enacted	FY 2019 Current	FY 2020 Enacted	FY 2021 Request	FY 2021 Request vs FY 2020 Enacted
TYPE A FACILITIES					
Fermilab Accelerator Complex	**$132,650**	**$133,585**	**$141,520**	**$126,440**	**-$15,080**
Number of users	2,489	2,610	2,450	2,280	-170
Achieved operating hours	N/A	4,911	N/A	N/A	N/A
Planned operating hours	5,740	5,740	4,900	4,580	-320
Optimal hours	5,740	5,740	5,740	5,740	—
Percent optimal hours	100.0%	85.6%	85.4%	79.8%	-5.6%
Unscheduled downtime hours	N/A	829	N/A	N/A	N/A

(dollars in thousands)

	FY 2019 Enacted	FY 2019 Current	FY 2020 Enacted	FY 2021 Request	FY 2021 Request vs FY 2020 Enacted
Accelerator Test Facility (BNL)	**$6,067**	**$4,812**	**$6,067**	**$5,200**	**-$867**
Number of users	118	127	127	101	-26
Achieved operating hours	N/A	2,274	N/A	N/A	N/A
Planned operating hours	2,500	2,020	2,500	2,150	-350
Optimal hours	2,500	2,500	2,500	2,500	—
Percent optimal hours	100.0%	91.0%	100.0%	86.0%	-14.0%
Unscheduled downtime hours	N/A	388	N/A	N/A	N/A
FACET-II (SLAC)	**$1,000**	**$1,300**	**$6,000**	**$10,000**	**+$4,000**
Number of users	N/A	N/A	200	250	+50
Achieved operating hours	N/A	N/A	N/A	N/A	N/A
Planned operating hours	N/A	N/A	1,500	2,500	+1,000
Optimal hours	N/A	N/A	3,000	3,000	—
Percent optimal hours	N/A	N/A	50.0%	83.3%	+33.3%
Unscheduled downtime hours	N/A	N/A	N/A	N/A	N/A
Total Facilities	**$139,717**	**$139,697**	**$153,587**	**$141,640**	**-$11,947**
Number of users	2,607	2,737	2,777	2,631	-146
Achieved operating hours	N/A	7,185	N/A	N/A	N/A
Planned operating hours	8,240	7,760	8,900	9,230	+330
Optimal hours	8,240	8,240	11,240	11,240	—
Percent optimal hours[a]	100.0%	85.7%	84.6%	80.3%	-4.3%
Unscheduled downtime hours	N/A	N/A	N/A	N/A	N/A

[a] For total facilities only, this is a "funding weighted" calculation FOR ONLY TYPE A facilities: $\frac{\sum_1^n[(\%OH \text{ for facility } n) \times (\text{funding for facility } n \text{ operations})]}{\text{Total funding for all facility operations}}$

High Energy Physics
Scientific Employment

	FY 2019 Enacted	FY 2020 Enacted	FY 2021 Request	FY 2021 Request vs FY 2020 Enacted
Number of permanent Ph.D.'s (FTEs)	830	788	648	-140
Number of postdoctoral associates (FTEs)	340	361	295	-66
Number of graduate students (FTEs)	500	486	390	-96
Other scientific employment (FTEs)[a]	1,745	1,625	1,379	-246

[a] Includes technicians, engineers, computer professionals and other support staff.

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

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

Summary
The FY 2021 Request for the Proton Improvement Project II (PIP-II) is $20,000,000. Initial construction funding was provided in FY 2018 through the Consolidated Appropriations Act. The most recent DOE Order 413.3B approved Critical Decision (CD) is CD-1 (Approve Alternative Selection and Cost Range), approved on July 23, 2018, with a preliminary Total Project Cost (TPC) range of $653,000,000 to $928,000,000. The current point estimate is $888,000,000.

Significant Changes
This Construction Project Data Sheet (CPDS) is an update of the FY 2020 CPDS. This project was initiated with Total Estimated Cost (TEC) funds in FY 2018.

The estimated TPC was increased during design work in FY 2019 as the project plan was revised to incorporate a combination of:

- Upgrades to the Fermi National Accelerator Laboratory (FNAL) Booster, Recycler and Main Injector synchrotrons, downstream from the new linear accelerator (Linac), enabling the accelerator complex to achieve the ultimate beam intensity goal of 1.2 megawatts to be delivered for experimental physics;
- Better cost estimates enabled by more mature designs;
- Improved risk analysis;
- Additional prototyping plans to reduce technical risk; and
- Budgeting for spares.

FY 2021 funds will support completion of civil engineering design for the conventional facilities, technical design and prototyping for the accelerator components, and initiation of construction and procurement for technical systems when design is final, and construction is authorized by CD-3.

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

Critical Milestone History

Fiscal Year	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	D&D Complete	CD-4
FY 2020	11/12/15	7/23/18	7/23/18	3Q FY 2020	4Q FY 2021	4Q FY 2021	TBD	1Q FY 2030
FY 2021	11/12/15	7/23/18	7/23/18	3Q FY 2020	4Q FY 2025	4Q FY 2021	N/A	1Q FY 2030

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

CD-3A – Approve long-lead procurement of niobium for superconducting radiofrequency (SRF) cavities, other long lead components for SRF cryomodules, completion of the remaining site preparation work, and construction of the building that will house the cryogenic plant.

Project Cost History

(dollars in thousands)

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

2. Project Scope and Justification

Scope

Specific scope elements of the PIP-II project include construction of (a) the 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 front-end injector and five types of SRF cryomodules that are CW-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 SSR1 cryomodule. It is being developed to reduce technical risks for the project, with participation and in-kind contributions from the India Department of Atomic Energy (DAE) Labs.

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

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 a future possible extension of the Linac energy to 1.0 GeV.

[a] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 is $653,000,000 to $928,000,000. The TPC point estimate is $888,000,000.

[b] See Section 8.

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

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

Components	Quan-tity	Freq. (MHz)	SRF Cavities	Responsibility for Cavity Fabrication	Responsibility for Module Assembly	Responsibility for RF Amplifiers	Cryogenic Cooling Source
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
SSR1 Cryomodule	2	325	16	U.S. DOE (FNAL), India DAE Labs	U.S. DOE (FNAL)	India DAE Labs	India DAE Labs
SSR2 Cryomodule	7	325	35	France CNRS (IN2P3 Lab)	U.S. DOE (FNAL)	India DAE Labs	India DAE Labs
LB-650 Cryomodule	9	650	36	Italy INFN (LASA)	France CEA (Saclay Lab)	India DAE Labs	India DAE Labs
HB-650 Cryomodule	4	650	24	UK STFC Labs	UK STFC Labs, U.S. DOE (FNAL)	India DAE Labs	India DAE Labs

Justification

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

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

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

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

Key Performance Parameters (KPPs)

The Key Performance Parameters (KPPs) are preliminary and may change as the project continues towards CD-2. At CD-2 approval, the KPPs will be baselined. The Threshold KPPs represent the minimum acceptable performance that the project must achieve. The Objective KPPs represent the desired project performance. Achievement of the Threshold KPPs will be a prerequisite for approval of CD-4, Project Completion.

Performance Measure	Threshold	Objective
SRF Linac and Beam Transfer Line	700 MeV proton beam delivered to the Booster Injection Region	800 MeV proton beam delivered to the Booster Injection Region
Booster, Recycler and Main Injector Synchrotron Modifications	Booster injection region, Recycler and Main Injector RF Upgrades installed. Linac beam injected and circulated in the Booster.	8 GeV proton beam transmitted through Recycler and Main Injector to the Main Injector beam dump.
Cryogenic Infrastructure	Cryogenic plant and distribution lines ready to support pulsed RF operation, and operated to 2°K.	Cryogenic plant and distribution lines ready to support CW RF operation, and operated to 2°K.
Civil Construction	Tunnel enclosures and service buildings ready to support 700 MeV SRF Linac and Beam Transfer Line to the Booster.	Tunnel enclosures ready to support 1 GeV SRF Linac and transfer line to the Booster. Service Buildings ready to support 800 MeV SRF Linac and Beam Transfer Line to the Booster.

3. Financial Schedule

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs[a]
Total Estimated Cost (TEC)			
Design			
FY 2018	1,000	1,000	—
FY 2019	20,000	20,000	17,812[b]
FY 2020	51,000	51,000	51,000
FY 2021	10,000	10,000	10,000
Outyears	102,000	102,000	105,188
Total, Design	184,000	184,000	184,000
Construction			
FY 2020	9,000	9,000	9,000
FY 2021	10,000	10,000	10,000
Outyears	598,200	598,200	598,200
Total, Construction	617,200	617,200	617,200

[a] Costs through FY 2019 reflect actual costs; costs for FY 2020 and the outyears are estimates.

[b] Includes initiation of civil engineering design and site preparation for the cryoplant housing.

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs[a]
Total Estimated Cost (TEC)			
FY 2018	1,000	1,000	—
FY 2019	20,000	20,000	17,812
FY 2020	60,000	60,000	60,000[a]
FY 2021	20,000	20,000	20,000
Outyears	700,200	700,200	703,388
Total, TEC	**801,200**	**801,200**	**801,200**
Other Project Cost (OPC)			
FY 2016	18,715	18,715	12,724
FY 2017	15,220	14,155	17,494
FY 2018	23,100	24,165[b]	22,214
FY 2019	15,000	15,000	15,000
FY 2020	494	494	494
FY 2021	2,000	2,000	6,603
Outyears	12,271	12,271	12,271
Total, OPC	**86,800**	**86,800**	**86,800**
Total Project Cost (TPC)			
FY 2016	18,715	18,715	12,724
FY 2017	15,220	14,155	17,494
FY 2018	24,100	25,165	22,214
FY 2019	35,000	35,000	32,812
FY 2020	60,494	60,494	60,494
FY 2021	22,000	22,000	26,603
Outyears	712,471	712,471	715,659
Total, TPC	**888,000**	**888,000**	**888,000**

[a] Planned TEC activities are completion of site preparation and initiation of procurement for the cryoplant housing and the cryomodules.
[b] $1,065,000 of FY 2017 funding was attributed towards the Other Project Costs activities in FY 2018.

4. Details of Project Cost Estimate

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design			
Design	170,000	76,000	—
Contingency	14,000	15,000	—
Total, Design	184,000	91,000	—
Construction			
Site Work	18,000	20,000	—
Civil Construction	145,000	81,000	—
Technical Equipment	245,000	246,965	—
Contingency	209,200	200,000	—
Total, Construction	617,200	547,965	—
Total, TEC	**801,200**	**638,965**	**—**
Contingency, TEC	223,200	215,000	—
Other Project Cost (OPC)			
OPC except D&D			
R&D	67,700	50,935	—
Conceptual Planning	9,000	15,000	—
Conceptual Design	4,000	4,000	—
Contingency	6,100	12,100	—
Total, OPC	**86,800**	**82,035**	**—**
Contingency, OPC	*6,100*	*12,100*	—
Total Project Cost	**888,000**	**721,000**	**—**
Total, Contingency (TEC+OPC)	**229,300**	**227,100**	**—**

5. Schedule of Appropriations Requests

(dollars in thousands)

Request Year	Type	Prior Years	FY 2019	FY 2020	FY 2021	Outyears[a]	Total
FY 2020	TEC	1,000	20,000	20,000	—	597,965	638,965
	OPC	57,035	15,000	5,000	—	5,000	82,035
	TPC	58,035	35,000	25,000	—	602,965	721,000

[a] Outyear requests are grouped as the project is pre-CD-2 and has not been baselined. All estimates are preliminary. For the first column of Request Year, the outyears represent the time period beyond that specific requested Budget Year.

(dollars in thousands)

Request Year	Type	Prior Years	FY 2019	FY 2020	FY 2021	Outyears[a]	Total
FY 2021[a]	TEC	1,000	20,000	60,000	20,000	700,200	801,200
	OPC	57,035	15,000	494	2,000	12,271	86,800
	TPC	58,035	35,000	60,494	22,000	712,471	888,000

6. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy	FY 2030
Expected Useful Life	20 years
Expected Future Start of D&D of this capital asset	FY 2050

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	127,540
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"	127,540
Total area eliminated	—

[a] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 is $653,000,000 to $928,000,000. The TPC point estimate is $888,000,000.

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, 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 (DOE)	Fermi National Accelerator Laboratory (FNAL); Lawrence Berkeley National Laboratory (LBNL); Argonne National Laboratory (ANL)
India	Department of Atomic Energy (DAE)	Bhabha Atomic Research Centre (BARC), Mumbai; Inter University Accelerator Centre (IUAC), New Delhi; Raja Ramanna Centre for Advanced Technology (RRCAT), Indore; Variable Energy Cyclotron Centre (VECC), Kolkata
Italy	National Institute for Nuclear Physics (INFN)	Laboratory for Accelerators and Applied Superconductivity (LASA), Milan
France	Atomic Energy Commission (CEA) National Center for Scientific Research (CNRS)	Saclay Nuclear Research Center; National Institute of Nuclear & Particle Physics (IN2P3), Paris
UK	Science & Technology Facilities Council (STFC)	Daresbury Laboratory

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 (LBNF/DUNE)
Fermi National Accelerator Laboratory
Project is for Design and Construction

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

Summary

The FY 2021 Request for Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE) is $100,500,000. The most recent approved DOE Order 413.3B critical decision is CD-3A, approval for Initial Far Site Construction: initiating excavation and construction for the LBNF Far Site conventional facilities in order to mitigate risks and minimize delays for providing a facility ready to accept detectors for installation. The preliminary Total Project Cost (TPC) has been revised to $2,600,000,000 which exceeds by 40 percent the top of the cost range of $1,260,000,000 to $1,860,000,000 that was approved for CD-1(R) on November 5, 2015. (If the top end of the original approved CD-1 cost range grows by more than 50 percent as the project proceeds toward CD-2 then the Program, in coordination with the Project Management Executive, must reassess the alternative selection process.[a]) The TPC range includes the full cost of the DOE contribution to the LBNF host facility and the DUNE experimental apparatus excluding foreign contributions. The preliminary CD-4 date is 4Q FY 2033.

Significant Changes

This Construction Project Data Sheet (CPDS) is an update of the FY 2020 CPDS. This project was initiated with TEC funds in FY 2012.

Updated planning and analysis in FY 2019 have increased the TPC point estimate for the LBNF/DUNE project to $2,600,000,000 which exceeds by 40 percent[b] the upper end of the Cost Range of $1,260,000,000 to $1,860,000,000 that was approved for CD-1(R) on November 5, 2015. The cost estimate increased for two reasons. The first is due to the cost of the excavation. The excavation contractor is now on site and has identified deficiencies in the greater than 100 year old infrastructure that will need to be repaired to support the large volume of rock removal. In addition, the time required to complete the excavation was underestimated. The independent cost estimator employed by the project and the design firm verified these findings. The second reason for the increased cost is that contributions from international partners have been lower than expected. DOE and the laboratory are continuing engagement with potential partners. Scope reductions will be considered to reduce the TPC by the time of baseline. The increased estimates will be reviewed by Independent Cost Review (ICR) and Independent Project Review (IPR) in FY 2020.

A Baseline Change Proposal (BCP) has been submitted to DOE for approval. It seeks approval to reduce the approved scope and authorized expenditures related to work previously approved by CD-3A. The BCP was triggered by higher cost estimates for the scope approved by CD-3A. The baseline change transfers some of the scope that had been advanced by CD-3A back to CD-3B, where it will be executed in regular order following CD-2 in FY 2021.

The FY 2021 Request will support 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. The Request will also support 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. The Request 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

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

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

[b] If the top end of the original approved CD-1 cost range grows by more than 50% as the project proceeds toward CD-2, the Program, in coordination with the AE, must reassess the alternative selection process. (From DOE Order 413.3B, Appendix A-6, 11/29/2010.)

Critical Milestone History

Fiscal Year	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	D&D Complete	CD-4
FY 2011	1/08/10		1Q FY 2011	TBD	4Q FY 2013	TBD	TBD	TBD
FY 2012	1/08/10		2Q FY 2012	TBD	2Q FY 2015	TBD	TBD	TBD
FY 2016[a]	1/08/10	12/10/12	12/10/12	4Q FY 2017	4Q FY 2019	4Q FY 2019	N/A	4Q FY 2027
FY 2017	1/08/10	11/05/15[b]	11/05/15[b]	4Q FY 2017	4Q FY 2019	4Q FY 2019	N/A	4Q FY 2030
FY 2018	1/08/10	11/05/15[b]	11/05/15[b]	1Q FY 2021	1Q FY 2022	1Q FY 2022	N/A	4Q FY 2030
FY 2019	1/08/10	11/05/15[b]	11/05/15[b]	1Q FY 2021	1Q FY 2022	1Q FY 2022	N/A	4Q FY 2030
FY 2020	1/08/10	11/05/15[b]	11/05/15[b]	1Q FY 2021	1Q FY 2022	1Q FY 2022	N/A	4Q FY 2030
FY 2021	1/08/10	11/05/15[b]	11/05/15[b]	1Q FY 2021	4Q FY 2023	4Q FY 2023	N/A	4Q 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-1R	CD-3A	CD-3B	CD-3(C)
FY 2017	1Q FY 2020	11/05/15	2Q FY 2016	3Q FY 2018	1Q FY 2020
FY 2018	1Q FY 2021	11/05/15	9/01/16	1Q FY 2021	1Q FY 2022
FY 2019	1Q FY 2021	11/05/15	9/01/16	1Q FY 2021	1Q FY 2022
FY 2020	1Q FY 2021	11/05/15	9/01/16	1Q FY 2021	1Q FY 2022
FY 2021	1Q FY 2021	11/05/15	9/01/16	1Q FY 2021	4Q FY 2023

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, cryogenic systems and detectors.
CD-3C – Approve Start of Near Site Construction: procurement of Near Site scope and any remaining LBNF/DUNE scope. (Same as CD-3.)

[a] No CPDS was submitted for FY 2013, FY 2014 or FY 2015 because no TEC funds were requested; however, design funds were provided in each year's appropriation.
[b] Critical Decision CD-1 was approved for the new conceptual design (CD-1R) on November 5, 2015.

Project Cost History

(dollars in thousands)

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

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

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

Justification

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

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[a] No CPDS was submitted for FY 2013, FY 2014 or FY 2015 because no TEC funds were requested; however, design funds were provided in each year's appropriation.

[b] 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 estimate has increased to $2,600,000,000 and will be reviewed by Independent Cost Review (ICR) and Independent Project Review (IPR) in FY 2020.

[c] No construction, other than site preparation, approved civil construction or long-lead procurement will be performed prior to validation of the Performance Baseline and approval of CD-3.

[d] 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.

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

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

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

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

DOE's High Energy Physics program manages both activities as a single, line-item construction project—LBNF/DUNE. LBNF, with DOE/FNAL leadership and minority participation by a small number of international partners including CERN, will construct a megawatt-class neutrino source and related facilities at FNAL (the "Near Site"), as well as underground caverns and cryogenic facilities in South Dakota (the "Far Site") needed to house the DUNE detectors. DUNE has international leadership and participation of over 1,000 scientists and engineers from over 170 institutions in over 30 countries. DOE will fund less than a third of DUNE. DOE continues to refine the development of the design and cost estimates as the U.S. DOE contributions to the multinational effort are now better understood. FNAL continues to identify and incorporate additional design activities and prototypes into the project design.

FNAL and DOE have confirmed contributions documented in international agreements from CERN and the UK to LBNF. Discussions are ongoing with several other countries for additional contributions. For the DUNE detectors, the collaboration put in place a process to complete a technical design of the detectors and divide the work of building the detectors between the collaborating institutions. The review of the detector design with a complete set of funding responsibilities by the Long Baseline Neutrino Committee began in 2019, and development of the set of funding responsibilities continues progress. 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 Key Performance Parameters (KPPs) are preliminary and may change as the project continues towards CD-2. At CD-2 approval, the KPPs will be baselined. The Threshold KPPs represent the minimum acceptable performance that the project must achieve. The Objective KPPs represent the desired project performance. Achievement of the Threshold KPPs will be a prerequisite for approval of CD-4, Project Completion.

The preliminary Key Performance Parameters (KPPs) for project completion that were approved by CD-1 in FY 2015 include the primary beam and neutrino beam production systems as well as underground caverns excavated for four separate, 10 kiloton detectors (of liquid-argon, time-projection detectors) at the SURF site, 1000-1500 kilometers (km) from the neutrino source. The DOE contribution for DUNE will include technical components for two of the four detectors, which will be installed and tested with cosmic rays, and components of the cryogenic systems for the detectors, which will be installed and pressure tested.

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

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

3. Financial Schedule[a]

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs[b]
Total Estimated Cost (TEC)			
Design[c]			
FY 2012	4,000	4,000	—[d]
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[e]
FY 2017	48,585	48,585	36,924
FY 2018	25,000	25,000	44,749[f]
FY 2019	70,000	70,000	53,841
FY 2020	20,000	20,000	20,000
FY 2021	10,000	10,000	10,000
Outyears	64,634	64,634	84,349
Total, Design	300,000	300,000	300,000
Construction			
FY 2017	1,415	1,415	333
FY 2018	70,000	70,000	1,427[g]
FY 2019	60,000	60,000	25,865
FY 2020	151,000	151,000	151,000[h]
FY 2021	90,500	90,500	90,500
Outyears	1,803,460	1,803,460	1,907,250
Total, Construction	2,176,375	2,176,375	2,176,375

[a] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 is $1,260,000,000 to $1,860,000,000. Design and international collaboration plans are currently being developed; outyears are preliminary. An Independent Project Review was held January 8-10, 2019.
[b] Costs through FY 2019 reflect actual costs; costs for FY 2019 and the outyears are estimates.
[c] Design Only CPDS was prepared in FY 2012; no CPDS was prepared FY 2013-2015. Funding amounts shown for traceability. FY 2016 and onward CPDS prepared as Design and Construction.
[d] $1,078,000 was erroneously costed to this project in FY 2012, the accounting records were adjusted in early FY 2013.
[e] Costs were for starting Far Site preparation including safety and reliability refurbishment of the underground infrastructure, which was needed prior to initiating excavation of the equipment caverns.
[f] Costs were for continuing project engineering design in preparation for CD-2.
[g] Costs were for initiating excavation of the equipment caverns at the Far Site as approved by CD-3A.
[h] Estimated costs are for the Far Site civil construction excavation activities as well as design and procurement for Far Site cryogenics systems. Also will support beamline and conventional facilities design and a site-preparation construction subcontract at the Near Site (FNAL).

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs[b]
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	171,000
FY 2021	100,500	100,500	100,500
Outyears	1,868,094	1,868,094	1,991,599
Total, TEC	**2,476,375**	**2,476,375**	**2,476,375**
Other Project Cost (OPC)			
FY 2009[a]	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[b]	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	4,000
FY 2021	1,000	1,000	1,000
Outyears	31,000	31,000	32,889
Total, OPC	**123,625**	**123,625**	**123,625**
Total Project Cost (TPC)			
FY 2009	12,486	12,486	—
FY 2010	14,178	14,178	11,032

[a] $13,000,000 of 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.

[b] $18,000 of FY 2011 funding was attributed towards the Other Project Costs activities in FY 2012.

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs[b]
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	175,000
FY 2021	101,500	101,500	101,500
Outyears	1,899,094	1,899,094	2,024,488
Total, TPC	**2,600,000**	**2,600,000**	**2,600,000**

4. Details of Project Cost Estimate

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design			
Design	270,000	234,000	N/A
Contingency	30,000	25,000	N/A
Total, Design	300,000	259,000	N/A
Construction			
Construction[a]	1,146,000	891,000	N/A
Equipment[b]	381,000	308,000	N/A
Contingency	649,375	297,000	N/A
Total, Construction	2,176,375	1,496,000	N/A
Total, TEC	**2,476,375**	**1,755,000**	**N/A**
Contingency, TEC	*679,375*	*322,000*	*N/A*

[a] 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.
[b] 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.

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Other Project Cost (OPC)			
OPC except D&D			
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	38,000	9,375	N/A
Contingency	—	—	N/A
Total, OPC	**123,625**	**95,000**	**N/A**
Contingency, OPC	—	—	*N/A*
Total Project Cost	**2,600,000**	**1,850,000**	**N/A**
Total, Contingency (TEC+OPC)	***679,375***	***322,000***	***N/A***

5. Schedule of Appropriations Requests

(dollars in thousands)

Request Year	Type	Prior Years	FY 2019	FY 2020	FY 2021	Outyears[a]	Total
FY 2011	TEC	102,000	—	—	—	—	102,000
	OPC	22,180	—	—	—	—	22,180
	TPC	124,180	—	—	—	—	124,180
FY 2012	TEC	133,000	—	—	—	—	133,000
	OPC	42,621	—	—	—	—	42,621
	TPC	175,621	—	—	—	—	175,621
FY 2016	TEC	51,781	—	—	—	731,612	783,393
	OPC	89,539	—	—	—	—	89,539
	TPC	141,320	—	—	—	731,612	872,932
FY 2017	TEC	106,802	—	—	—	1,307,659	1,414,461
	OPC	85,539	—	—	—	—	85,539
	TPC	192,341	—	—	—	1,307,659	1,500,000
FY 2018	TEC	166,681	—	—	—	1,266,694	1,433,375
	OPC	85,725	—	—	—	16,900	102,625
	TPC	252,406	—	—	—	1,283,594	1,536,000
FY 2019	TEC	166,681	113,000	—	—	1,185,319	1,465,000
	OPC	85,725	1,000	—	—	8,275	95,000
	TPC	252,406	114,000	—	—	1,193,594	1,560,000

[a] Outyear requests are grouped as the project is pre-CD-2 and has not been baselined. All estimates are preliminary. For the first column of Request Year, the outyears represent the time period beyond that specific requested Budget Year.

(dollars in thousands)

Request Year	Type	Prior Years	FY 2019	FY 2020	FY 2021	Outyears[a]	Total
FY 2020[a]	TEC	206,781	130,000	100,000	—	1,318,219	1,755,000
	OPC	86,625	1,000	4,000	—	3,375	95,000
	TPC	293,406	131,000	104,000	—	1,321,594	1,850,000
FY 2021	TEC	206,781	130,000	171,000	100,500	1,868,094	2,476,375
	OPC	86,625	1,000	4,000	1,000	31,000	123,625
	TPC	293,406	131,000	175,000	101,500	1,899,094	2,600,000

6. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy	FY 2030
Expected Useful Life	20 years
Expected Future Start of D&D of this capital asset	FY 2050

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

Related Funding Requirements
(dollars in thousands)

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

7. D&D Information

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

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

[a] 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. An Independent Project Review was held January 8-10, 2019.

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

8. Acquisition Approach

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

- FNAL is the site of the only existing neutrino beam facility in the U.S. and, in addition to these facilities, provides a source of existing staff and expertise to be utilized for beamline and detector construction.
- FNAL can best ensure that the design, construction, and installation of key LBNF and DUNE components are coordinated effectively and efficiently with other research activities at FNAL.
- FNAL has a DOE-approved procurement system with established processes and acquisition expertise needed to obtain the necessary components and services to build the scientific hardware, equipment and conventional facilities for the accelerator beamline, and detectors for LBNF and DUNE.
- FNAL has extensive experience in managing complex construction, fabrication, and installation projects involving multiple national laboratories, universities, and other partner institutions, building facilities both on-site and at remote off-site locations.
- FNAL, through the LBNF Project, has established a close working relationship with SURF and the South Dakota Science and Technology Authority (SDSTA), organizations that manage and operate the remote site for the far detector in Lead, SD;
- FNAL has extensive experience with management and participation in international projects and international collaborations, including most recently the LHC and CMS projects at CERN, as well as in the increasingly international neutrino experiments and program.

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

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

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

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

FNAL has chosen the Construction Manager/General Contractor (CM/GC) model to execute the delivery of LBNF conventional facilities at the SURF Far Site. The Laboratory is contracting with an architect/engineer (A/E) firm for design of LBNF Far Site conventional facilities at SURF and with a CM/GC subcontractor to manage the construction of LBNF Far Site facilities. FNAL selected this strategy to reduce risk, enhance quality and safety performance, provide a more collaborative approach to construction, and offer the opportunity for reduced cost and shortened construction schedules, via options for the CM/GC to self-perform or competitively bid subcontract award packages.

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

For the LBNF Far Site conventional facilities at SURF, DOE entered into a land lease with SDSTA on May 20, 2016 covering the area on which the DOE-funded facilities housing and supporting the LBNF and DUNE detector will be built. The lease and related realty actions provides the framework for DOE and FNAL to construct federally-funded buildings and facilities on non-federal land, and to establish a long-term (multi-decade) arrangement for DOE and FNAL to use SDSTA space to host the DUNE experiment. Modifications, repairs, and improvements to the SDSTA infrastructure to support the LBNF/DUNE project are costed to the project. Repairs and improvements for the overall facility are costed to the cooperative agreement that HEP has with 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.