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% of the universe, the remainder being 70% dark energy and 25% 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.

A world-wide program of particle physics research is underway to discover what lies beyond the Standard Model. Five intertwined science drivers of particle physics provide compelling lines of inquiry that show 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
- Explore the unknown: new particles, interactions, and physical principles

The HEP program enables scientific discovery through three experimental frontiers of particle physics research and aligned with three HEP subprograms:

- Energy Frontier, 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, 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, where researchers use a combination of intense particle beams and highly sensitive detectors to make extremely precise measurements of particle properties, study some of the rarest particle interactions predicted by the Standard Model of particle physics, and 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, 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 the distribution of dark matter to be mapped and perhaps the nature of dark energy and inflation to be unraveled. Ultra-sensitive detectors deep underground may glimpse the dark matter passing through Earth. Observations of the cosmic frontier may reveal a universe far stranger than ever thought possible.

This program of scientific discovery is formulated and enabled through the support of the Theoretical and Computational Physics and the Advanced Technology Research and Development (R&D) subprograms. Theoretical and Computational Physics 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 that are necessary for designing, operating, and interpreting experiments while performing the computational science and simulations on extremely large data sets that enable discovery research in the three frontiers. Advanced Technology R&D 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 the DOE's strategic goals for science.

The Accelerator Stewardship subprogram supports R&D efforts that are synergistic with the HEP mission but also impact activities outside the traditional HEP boundaries. The activities of the Stewardship subprogram include: improving access to Office of Science (SC) accelerator R&D infrastructure for industrial 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. 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 industry, medicine, and national security.

Highlights of the FY 2018 Budget Request

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 Contexta. The P5 report 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. Guided by the vision of the P5 report, the FY 2018 Budget Request focuses support on the highest priority elements of the P5 strategy. The P5 report identified the High-Luminosity Large Hadron Collider (HL-LHC) accelerator and A Toroidal LHC Apparatus (ATLAS) and Compact Muon Solenoid (CMS) detector upgrade projects as the highest priority in the near-term and the Long Baseline Neutrino Facility and Deep Underground Neutrino Experiment (LBNF/DUNE) as the highest-priority large project in its timeframe. The Request supports these high-priority projects with the least adjustment possible to their planned scope and schedule. Other efforts across Research, Facility Operations, and Projects will have their scope reduced or schedules delayed, based on factors including the P5 report strategy and project maturity. The FY 2018 Request supports the Large Synoptic Survey Telescope camera (LSSTcam), Muon to Electron Conversion Experiment (Mu2e), and the Large Underground Xenon (LUX)-ZonEd Proportional scintillation in LIquid Nobles gases (ZEPLIN) experiment (LZ) projects consistent with the planned fabrication funding profiles. The Dark Energy Spectroscopic Instrument (DESI) project, which received CD-3 approval for start of fabrication, will be rebaselined in coordination with DOE's partnering agency, NSF, so that it can be completed on a delayed timescale. The Request provides funding for a new Major Item of Equipment (MIE), the Facility for Advanced Accelerator Experimental Tests II (FACET-II), for the design and fabrication of the Super Cryogenic Dark Matter Search at Sudbury Neutrino Observatory Laboratory (SuperCDMS-SNOLAB) project, and for research and conceptual design of the Proton Improvement Plan II (PIP-II) construction project. Most research activities will be reduced; higher priority will be given to support the laboratory research programs that are critical to executing the P5 recommendations, and for R&D that requires long-term investments including Accelerator Stewardship, Detector R&D, and Quantum Information Science (QIS). The Request provides reduced funding for the Fermi National Accelerator Laboratory (Fermilab) Accelerator Complex to operate and support the neutrino and muon experiments.

Energy Frontier Experimental Physics

The LHC has exceeded its goals as it operates at collision energies of 13 teraelectronvolt (TeV), setting new performance records and delivering at an unprecedented pace the number of particle collisions, or luminosity, to the ATLAS and CMS experiments. Physics results from this higher-energy and higher-luminosity data will continue through FY 2018, critically

[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.energy.gov/~/media/hep/hepap/pdf/May-2014/FINAL_P5_Report_053014.pdf

informing future HEP research directions and opportunities. HEP will continue investment in the LHC by contributing to the U.S. share of the HL-LHC accelerator and detector upgrades.

Intensity Frontier Experimental Physics
The FY 2018 Request supports activities necessary to establish a U.S.-hosted, world-leading neutrino physics program, consisting of LBNF/DUNE, the related Short-Baseline Neutrino (SBN) program at Fermilab, and R&D efforts surrounding the prototypes for DUNE (protoDUNE) at CERN. This includes continued funding for the PIP-II project that will upgrade the Fermilab linear accelerator to increase beam power and sustain high reliability of the Fermilab Accelerator Complex. These upgrades are necessary to provide proton beam intensity of greater than one megawatt for LBNF/DUNE, as recommended in the P5 report. Fermilab will plan for an extended shutdown of the accelerator complex in FY 2018.

Cosmic Frontier Experimental Physics
Two complementary next-generation experiments will advance our understanding of dark energy. The LSSTcam will scan half of the sky repeatedly with optical imaging sensors, building up a “cosmic cinematography” of the changing universe, while DESI will study 30 million galaxies and quasars by creating three-dimensional maps of the distribution of matter over two-thirds of the age of the universe. The LSSTcam and DESI projects will be in their fabrication phases in FY 2018. Two second-generation direct-detection dark matter experiments, LZ and SuperCDMS-SNOLAB, will carry out complementary searches for dark matter candidates over a broad range of masses. LZ will use a liquid xenon detector located at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, and will continue its fabrication phase in FY 2018. SuperCDMS-SNOLAB will use cryogenic semi-conductor detectors located at SNOLAB in Sudbury, Canada and will move into final design and then start the fabrication phase in FY 2018.

Theoretical and Computational Physics
The FY 2018 Request will support major theoretical research thrusts that focus on the P5 science drivers, intertwining the physics of the Higgs boson, neutrino masses, the dark universe, and exploring the unknown. Computational physics efforts focus on emerging computational science techniques that advance the HEP mission and new computing models and technology that will address projected needs in data management and computing resources across the program. The FY 2018 Request includes new funding for QIS research in which HEP has an important role in the national program.

Advanced Technology R&D
The LHC Accelerator Research Program (LARP) ramps down as development and prototyping efforts for powerful new focusing magnets for the LHC transition into production efforts as part of the HL-LHC Accelerator Upgrade Project (HL-LHC AUP). The FACET-II project will continue design and development for the positron beam system. The Detector R&D subprogram develops cutting-edge instrumentation to enable experimental research at the forefront of the field while training the next generation of detector experts. The FY 2018 Request supports R&D to inform the planning and selection of next-generation HEP experiments.

Accelerator Stewardship
The Accelerator Stewardship subprogram supports R&D where advances potentially impact both physical science research and other applications of benefit to the general public, and where there is no private sector R&D activity. The FY 2018 Request reduces support for the Brookhaven National Laboratory’s (BNL) Accelerator Test Facility (ATF).

Construction
The FY 2018 Request will increase support for LBNF/DUNE, the highest-priority large project in its timeframe in the P5 report. The requested investment will support the Critical Decision (CD)-3A approved scope of early far-site construction, including site preparation and cavern excavation. The Muon to Electron Conversion Experiment (Mu2e) continues with construction in FY 2018 according to its approved baseline funding profile.

High Energy Physics
Funding ($K)

	FY 2016 Enacted[a b]	FY 2017 Annualized CR[c]	FY 2018 Request	FY 2018 vs FY 2016
Energy Frontier Experimental Physics				
Research	73,505	—	56,290	-17,215
Facility Operations and Experimental Support	54,779	—	44,290	-10,489
Projects	21,085	—	39,000	+17,915
SBIR/STTR	4,659	—	4,265	-394
Total, Energy Frontier Experimental Physics	**154,028**	**—**	**143,845**	**-10,183**
Intensity Frontier Experimental Physics				
Research	54,683	—	42,220	-12,463
Facility Operations and Experimental Support	148,863	—	129,304	-19,559
Projects	36,036	—	14,100	-21,936
SBIR/STTR	7,235	—	6,944	-291
Total, Intensity Frontier Experimental Physics	**246,817**	**—**	**192,568**	**-54,249**
Cosmic Frontier Experimental Physics				
Research	47,326	—	35,530	-11,796
Facility Operations and Experimental Support	13,777	—	8,199	-5,578
Projects	67,780	—	31,600	-36,180
SBIR/STTR	2,337	—	1,800	-537
Total, Cosmic Frontier Experimental Physics	**131,220**	**—**	**77,129**	**-54,091**
Theoretical and Computational Physics				
Research				
Theory	48,615	—	33,850	-14,765
Computational HEP	8,829	—	23,213	+14,384
Total, Research	57,444	—	57,063	-381
Projects	2,000	—	0	-2,000
SBIR/STTR	2,092	—	2,162	+70
Total, Theoretical and Computational Physics	**61,536**	**—**	**59,225**	**-2,311**

[a] The FY 2016 Enacted level includes SBIR and STTR and reflects updates through the end of the fiscal year.
[b] SBIR/STTR is requested in FY 2018 within the various subprograms instead of a consolidated requested as an independent subprogram, as it has been in previous years. The FY 2016 column has been adjusted for comparison purposes.
[c] FY 2017 Annualized CR amounts reflect the P.L. 114-254 continuing resolution level annualized to a full year. These amounts are shown only at the congressional control level and above; below that level, a dash (-) is shown.

	FY 2016 Enacted[a b]	FY 2017 Annualized CR[c]	FY 2018 Request	FY 2018 vs FY 2016
Advanced Technology R&D				
Research				
HEP General Accelerator R&D	44,608	—	32,701	-11,907
HEP Directed Accelerator R&D	21,020	—	5,000	-16,020
Detector R&D	16,587	—	16,450	-137
Total, Research	82,215	—	54,151	-28,064
Facility Operations and Experimental Support	36,300	—	28,670	-7,630
Projects	2,100	—	2,000	-100
SBIR/STTR	4,210	—	3,043	-1,167
Total, Advanced Technology R&D	**124,825**	**—**	**87,864**	**-36,961**
Accelerator Stewardship				
Research	5,643	—	8,953	+3,310
Facility Operations and Experimental Support	4,517	—	3,350	-1,167
SBIR/STTR	314	—	466	+152
Total, Accelerator Stewardship	**10,474**	**—**	**12,769**	**+2,295**
Subtotal, High Energy Physics	**728,900**	**727,514**	**573,400**	**-155,500**
Construction				
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment	26,000	25,951	54,900	+28,900
11-SC-41, Muon to Electron Conversion Experiment	40,100	40,024	44,400	+4,300
Total, Construction	**66,100**	**65,975**	**99,300**	**+33,200**
Total, High Energy Physics	**795,000**	**793,489**	**672,700**	**-122,300**

SBIR/STTR Funding:

- FY 2016 Enacted: SBIR: $18,128,000; STTR: $2,719,000
- FY 2018 Requested: SBIR: $16,377,000; STTR: $2,303,000

High Energy Physics
Explanation of Major Changes ($K)

	FY 2018 vs FY 2016
Energy Frontier Experimental Physics: The Request prioritizes support for National Laboratory research programs critical to executing the P5 recommendations. Increased project funding supports the HL-LHC AUP MIE (new start), as well as conceptual design activities for the HL-LHC ATLAS and HL-LHC CMS Detector Upgrade projects. FY 2017 is the final year of funding planned for LHC ATLAS and LHC CMS Detector Upgrade projects. The Request reduces funding for research activities at universities. Decreases in operations funding will require a reduction of support to detector maintenance and data management and a delay to planned procurement of compute nodes and data storage.	-10,183
Intensity Frontier Experimental Physics: The Request includes project funding reductions due to the scheduled completion of Muon g-2 project funding in FY 2017 and reductions in pre-conceptual R&D for PIP-II and early investments in the Fermilab SBN program. Operations reductions are driven by the extended shutdown of the Fermilab accelerator complex. The Request supports higher priority laboratory research programs critical to executing the P5 recommendations and reduces funding for research activities at universities.	-54,249
Cosmic Frontier Experimental Physics: The Request includes reductions driven by the planned conclusion of the LSSTcam project. LZ will continue planned fabrication, DESI will be rebaselined, and SuperCDMS-SNOLAB will transition from design to fabrication. The Request supports higher priority laboratory research programs critical to executing the P5 recommendations and reduces funding for research activities at universities. Decreases in funding for currently operating experiments will partially be offset by an increase for early operations of the LSSTcam.	-54,091
Theoretical and Computational Physics: The Request supports higher priority laboratory research programs critical to executing the P5 recommendations and reduces funding for research activities at universities. The Lattice Quantum Chromodynamics (LQCD) project receives final funding in FY 2017. Increased funding will support QIS efforts in quantum computing and quantum sensor development.	-2,311
Advanced Technology R&D: The Request supports reduced funding for research activities at universities and national laboratories. Higher priority will be given to support laboratory research programs critical to executing the P5 recommendations and for R&D that requires long-term investments, including Detector R&D. Funding will decrease as LARP development and prototyping efforts for the LHC focusing magnets transition into production efforts as part of the HL-LHC AUP. The Muon Accelerator Program (MAP) receives final funding in FY 2017. The FACET facility has completed its run and operations funding for it will be minimal until the completion of FACET-II.	-36,961
Accelerator Stewardship: Funding for research will increase to support targeted R&D efforts to develop new uses of accelerator technology with broad applicability, offset by a decrease to support for BNL ATF operations.	+2,295
Construction: The funding request supports the planned profile for construction of Mu2e. The increase to LBNF/DUNE Construction funding will support cavern excavation for LBNF/DUNE as approved at approved CD-3A, and will establish the facility and enable the scheduled delivery of contributions from international partners.	+33,200
Total, High Energy Physics	**-122,300**

Basic and Applied R&D Coordination
Accelerator Stewardship enables development of real-world 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 universities, national laboratories, and industry to help identify specific research areas and infrastructure gaps where HEP investments would have sizable impacts beyond the SC research mission. This program is closely coordinated with the SC's Basic Energy Sciences (BES) and Nuclear Physics (NP) programs and partner agencies[a] 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 (DHS/DNDO), the NSF/ Chemical, Bioengineering, Environmental and Transport (CBET) Systems Division, and the DOE's Office of Environmental Management (EM).

The Accelerator Stewardship conducts use-inspired basic R&D at stages Technology Readiness Levels (TRL)-1 through TRL-4; ensuring the investments will eventually result in high-impact applications requires close coordination with other agencies who will carry on the development. The implementation strategy is to work with applied R&D agencies to define priority research directions at Basic Research Needs Workshops, and through direct participation of applied agency program managers in merit reviews. 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 gantries (joint with Varian Medical Systems), advanced proton sources for therapy (joint with ProNova Solutions), advanced detectors for therapy (joint with Best Medical International) advanced microwave source development (joint with Communications Power Industries), and technical design studies for high power accelerators for environmental cleanup, wastewater treatment (joint with Metropolitan Water Reclamation District of Greater Chicago, General Atomics, Advanced Energy Systems, and Euclid Techlabs). Funded R&D awards have drawn an average of 20% of voluntary cost sharing over the first two years of the program, providing evidence of the potential impact.

Program Accomplishments
Record-breaking LHC performance leads to data accumulation 60% beyond goal for 2016 (Energy Frontier). The LHC is the highest energy particle collider in the world and has nearly doubled its particle collision energy since it was used to discover the Higgs boson particle in 2012. The LHC far exceeded its goal for producing particle collisions in 2016 while continually breaking performance records. While it will take time for the ATLAS and CMS experiment collaborations to analyze the data, early results are already probing the Higgs boson for any sign of new physics. In August 2016, the ATLAS collaboration used data from the highest energy LHC collisions to confirm that Higgs boson's rate of production at 13 TeV collision energy agrees with the predictions of the Standard Model of particle physics. The LHC aims to continue running at its record pace for the next two years and more than double the delivered particle collisions to the experiments, which will enable more detailed measurements of the Higgs boson and more sensitive searches for new physics.

Combined analysis from MINOS and Daya Bay experiments constrain possible sterile neutrino properties (Intensity Frontier). The discovery of neutrino oscillations, which garnered the 2015 Nobel Prize in Physics, proves not only that neutrinos have mass but that the Standard Model of particle physics is incomplete. While three types of neutrinos have been discovered so far, results from some previous experiments are consistent with a theoretical fourth type of neutrino. This additional "sterile" neutrino would not interact with other matter and would only be accessible by studying neutrino oscillations. If a sterile neutrino were discovered, it would be the first discovery of an unexpected fundamental particle since the Standard Model was established. A combined result from the MINOS experiment at Fermilab and the Daya Bay Reactor Neutrino experiment in China released in 2016 yielded the world's most stringent constraints on the properties of a sterile neutrino

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[a]Partner agencies for the Accelerator Stewardship program currently are: the National Institutes of Health's National Cancer Institute; the Department of Defense's Office of Naval Research and Air Force Office of Scientific Research; the NSF's Physics Division and Chemical, Bioengineering, Environmental and Transport Systems Division; Department of Homeland Security's Domestic Nuclear Detection Office, and NASA's Remote Sensing Branch.

and narrows the region where scientists must hunt. The remaining allowed region will be searched by the SBN program at Fermilab and other experiments to obtain a definite answer to the question of whether light sterile neutrinos exist.

U.S. Belle II project recognized with DOE Project Management Achievement Award (Intensity Frontier). The U.S. Belle II project, at the Pacific Northwest National Laboratory, successfully developed, assembled, and delivered advance detector systems to the Japanese High Energy Accelerator Research Organization (KEK) laboratory in Tsukuba, Japan, that are essential for efficiently collecting high-precision data on positron-electron collisions within the SuperKEKB accelerator. The $14.8 million project will be part of one of the premier experiments exploring "new physics" beyond the Standard Model through high-precision measurements over the coming decade. The project met Belle II's very tight schedule for integration and completed successfully in July 2016, two months ahead of schedule and under budget while meeting or exceeding the objective Key Performance Parameters.

Fermilab achieves milestone beam power for neutrino experiments (Intensity Frontier). On January 24, 2017, Fermilab's flagship particle accelerator delivered a sustained 700-kilowatt proton beam over one hour at an energy of 120 billion electronvolts (GeV). Achieving this record-setting performance required scientists and engineers to apply their expertise to the technical and physics challenges of high-intensity particle beams. With more beam power, Fermilab can provide more neutrinos in a given amount of time and advance the scientific reach of the neutrino experiments served by the Neutrinos at the Main Injector (NuMI) beam, including the NuMI Off-axis electron Neutrino Appearance (NOvA) Experiment and the Main Injector Experiment for ν-A (MINERvA).

World's most sensitive search performed for direct evidence of dark matter (Cosmic Frontier). The Large Underground Xenon (LUX) experiment completed the world's most sensitive search for direct evidence of dark matter in 2016, improving upon its own previous world's best search by a factor of four and narrowing the hiding space for an important class of theoretical dark matter particles. Located a mile beneath the Black Hills of South Dakota, the LUX experiment directly searched for the dark matter particles that may be continually passing through Earth. These results set the stage for a suite of complementary next-generation experiments, LZ and SuperCDMS-SNOLAB, that the U.S. community is already beginning to build, which aim to improve the detection sensitivity by an order of magnitude to reveal the nature of dark matter.

First demonstration of laser-plasma accelerator staging at the Berkeley Lab Laser Accelerator (BELLA) at Lawrence Berkeley National Laboratory (LBNL) (Advanced Technology R&D). An experiment at BELLA successfully accelerated an electron beam through two back-to-back laser-plasma accelerator modules in 2016. Plasma wakefield particle acceleration is an advanced technology that may boost the energy and shrink the size of future linear particle accelerators and have broad impact within the SC. Single-stage laser plasma wakefield acceleration has been previously demonstrated at BELLA using a drive pulse of a high-power laser that generates a plasma wake and a trailing electron pulse that is accelerated by "surfing" on the plasma wake. The staging of multiple acceleration modules is needed to implement this technology in a future Energy Frontier collider.

High Energy Physics
Energy Frontier Experimental Physics

Description

The Energy Frontier will focus on the Large Hadron Collider (LHC). Data collected will be used to address at least three of the five science drivers identified by the P5 report:

- *Use the Higgs boson as a new tool for discovery*
- In the Standard Model of particle physics, the Higgs boson is responsible for generating the mass for all fundamental particles. Since the 2012 Nobel-winning discovery, experiments at the LHC continue to actively measure the Higgs's properties to establish its exact character and 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 LHC detectors will be increasingly more sensitive to potential deviations from the Standard Model that may be exposed by the high collision energy of at least 13 TeV.
- *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 measured by inference, since they interact only weakly with normal matter. This "indirect" detection of dark matter is complementary to, and a powerful cross-check on, the ultra-sensitive "direct" detection experiments on the Cosmic Frontier.

The LHC hosts two large multi-purpose particle detectors, CMS and ATLAS, which are partially supported by DOE and the NSF and used by large international collaborations of scientists. U.S. researchers make up approximately 20% of the ATLAS collaboration and approximately 30% of the CMS collaboration, and play critical leadership roles in all aspects of each experiment.

<u>Research</u>

The Energy Frontier experimental research subprogram consists of groups at U.S. academic and research institutions and physicists from national laboratories. These groups, as part of the CMS and ATLAS 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. The subprogram selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. HEP conducted an external peer review of laboratory research groups in this activity in 2015, and findings from this review are being used to inform the funding decisions in subsequent years. HEP plans to review this activity again in 2019 and evaluate progress.

<u>Facility Operations and Experimental Support</u>

U.S. LHC Detector Operations funding supports the maintenance of U.S.-supplied detector systems for the CMS and ATLAS detectors at the LHC and for the U.S.-based computer infrastructure used by U.S. physicists to analyze LHC data, including Tier 1 computing centers at Fermilab and BNL. The Tier 1 centers provide round-the-clock support for the LHC Computing Grid and are responsible for storing a portion of raw and processed data, as well as performing large-scale data reprocessing and storing the corresponding output. This program also supports transatlantic networking capabilities that enable U.S. scientists to analyze the large amount of data produced at the LHC.

<u>Projects</u>

The ongoing LHC ATLAS and LHC CMS Detector Upgrade MIE projects receive final funding in FY 2017.

During the next decade, CERN plans a major upgrade to the LHC machine to further increase the instantaneous luminosity by a factor of three times its design value to explore new physics beyond the reach of the current LHC program. The new MIE for the High-Luminosity LHC Accelerator Upgrade Project (HL-LHC AUP) will deliver LHC components for which U.S. scientists have the critical expertise. After the upgrade, the HL-LHC beam will make the conditions in which the ATLAS and CMS detectors must operate challenging. Conceptual design continues in FY 2018 for the HL-LHC ATLAS and HL-LHC CMS Detector Upgrades that will enable them to operate for an additional decade and collect a factor of ten more data.

Energy Frontier Experimental Physics

Activities and Explanation of Changes

FY 2016	FY 2018 Request	Explanation of Changes FY 2018 vs FY 2016
Energy Frontier Experimental Physics $154,028,000	**$143,845,000**	**-$10,183,000**
Research $73,505,000	**$56,290,000**	**-$17,215,000**
U.S. university and laboratory scientists started analyzing the newly acquired data from LHC's 13 TeV run. Research activities focused on addressing key areas within the science drivers outlined in the P5 report, which include using the Higgs boson as a new tool for discovery, searching for dark matter, and exploring new particles and their interactions.	Funding for the Energy Frontier research will continue to support U.S. scientists leading high-profile analysis topics using the data collected by the ATLAS and CMS experiments at the LHC.	Decrease will require reduced research activities at universities and national laboratories. Higher priority will be given to support laboratory research programs critical to executing the P5 recommendations.
Facility Operations and Experimental Support $54,779,000	**$44,290,000**	**-$10,489,000**
Funding supported the operation of the LHC ATLAS and CMS detectors during LHC's 13 TeV run. Major activities included continuing the routine maintenance and calibration of the detectors as well as the processing of newly acquired data. Initial investments supported critical R&D activities for longer-term operations of the LHC detectors at higher luminosities.	Funding will support critical ATLAS and CMS detector maintenance and operations during LHC's 13 TeV run as well as the U.S.-based computing infrastructure and resources used by U.S. scientists to analyze LHC data.	Decreases in operations funding will require a reduction of support to detector maintenance and data management and a delay to planned procurement of compute nodes and data storage.
Projects $21,085,000	**$39,000,000**	**+$17,915,000**
The LHC ATLAS and CMS Detector Upgrade projects were baselined in FY 2015 and fabrication activities continued. Conceptual design activities commenced for HL-LHC AUP and HL-LHC ATLAS and HL-LHC CMS detectors.	Funding will be provided for a new HL-LHC AUP MIE (new start) to advance that concept and design. Funding will also be provided to continue conceptual design activities for HL-LHC ATLAS and HL-LHC CMS Detector Upgrade projects.	Increased funding supports the HL-LHC AUP MIE (new start), as well as conceptual design activities for the HL-LHC ATLAS and HL-LHC CMS Detector Upgrade projects. FY 2017 is the final year of funding planned for LHC ATLAS and LHC CMS Detector Upgrade projects.
SBIR/STTR $4,659,000	**$4,265,000**	**-$394,000**
In FY 2016, SBIR/STTR funding was set at 3.45% of non-capital funding.	In FY 2018, SBIR/STTR funding will be assumed to be 3.65% of non-capital funding.	Decreased funding represents mandated percentages for non-capital funding.

High Energy Physics
Intensity Frontier Experimental Physics

Description
The Intensity Frontier investigates some of the rarest processes in nature including unusual interactions of fundamental particles or subtle effects requiring large data sets to observe and measure. Generally, 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 cannot be directly observed at the Energy Frontier, either because they occur at much higher energies and their effects can only be seen indirectly, or because they are due to interactions that are too weak to be detected in high-background conditions at the LHC. Data collected from Intensity Frontier experiments during this period will be used to address at least three of the five key science drivers identified by the P5 report:

- *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.
- *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 "dark" particles and forces which have ultra-weak couplings to normal matter. These particles and forces are effectively invisible to conventional experiments, but may be connected to the cosmic dark matter. Using intense accelerator beams at national laboratories outfitted with highly efficient high-rate detectors allows for probes of these models via subtle quantum mechanical mixing effects.
- *Explore the unknown, new particles, interactions, and physical principles*
  Prominent in this category are experiments addressing the poorly understood large scale absence of antimatter in the universe and the puzzling three generation family structure of the fundamental constituents of matter.

<u>Research</u>
The Intensity Frontier experimental research subprogram consists of groups at U.S. academic and research institutions and national laboratories that perform experiments. 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. The subprogram selects research efforts with the highest scientific merit and potential impact based on a competitive peer-review process. HEP is conducting an external peer review of all laboratory research groups in this subprogram in 2017, and the recommendations will be used to inform funding decisions in subsequent years.

The largest component of the Intensity Frontier subprogram supports research in accelerator-based neutrino physics centered at Fermilab with multiple experiments running concurrently in two separate neutrino beams with different beam energies. The flagship NOvA experiment uses the Neutrinos at the Main Injector (NuMI) beam, and the Booster Neutrino Beam (BNB) will be used to study different aspects of neutrino physics. The other major component to the Intensity Frontier is the muon program at Fermilab where rare processes in muons are studied to detect physics beyond the reach of the LHC. The Muon g-2 experiment is being commissioned and a full physics run will follow in FY 2018. The Intensity Frontier subprogram also supports U.S. physicists to participate in select experiments at foreign facilities, including neutrino experiments in China and Japan. There is also a U.S. contingent working on the Belle II experiment at KEK in Japan.

<u>Facility Operations and Experimental Support</u>
There are several distinct facility operations and experimental support efforts in the Intensity Frontier subprogram. The largest is the Fermilab Accelerator Complex User Facility. This activity includes computing and the operation of the accelerator and detectors. General Plant Project (GPP) and Accelerator Improvement Project (AIP) funding supports improvements to facilities. The FY 2018 Request includes funding to continue refurbishment of the oldest parts of the complex, including the linear particle acceleration (linac) and the Booster in order to maintain the reliability and efficiency

of the complex. Fermilab manages a contract with the South Dakota Science and Technology Authority for the operation of Sanford Underground Research Facility (SURF) where the Nuclear Physics-supported Majorana Demonstrator is operated and the LZ experiment will be installed. SURF will also be the home of the DUNE far detectors built by the LBNF/DUNE project.

Projects

The P5 report recommended an increase in power for the Fermilab accelerator complex so that PIP-II will provide a 1.2 megawatt beam to LBNF/DUNE, which is higher than the 0.7 megawatt beam used by NOvA. The FY 2018 Request includes Other Project Cost (OPC) funding for conceptual design of the PIP-II upgrade to the front-end of the Fermilab Accelerator complex. The front-end is the oldest part of the complex and needs to be replaced to improve reliability and to produce higher intensity muon and neutrino beams. Fermilab is developing a conceptual design and establishing partnerships with institutions in India and Italy to contribute to the project.

Intensity Frontier Experimental Physics

Activities and Explanation of Changes

FY 2016	FY 2018 Request	Explanation of Changes FY 2018 vs FY 2016
Intensity Frontier Experimental Physics $246,817,000	**$192,568,000**	**-$54,249,000**
Research $54,683,000	**$42,220,000**	**-$12,463,000**
The first physics analyses from the NOvA experiment were published and new results presented at conferences. LBNF/DUNE physics studies and detector optimization advanced under the umbrella of a new, fully internationalized program. R&D in support of the Fermilab SBN program increased. Physics studies to optimize the operation of the under construction Mu2e experiment continued. Muon g-2 physics commissioning efforts ramped up in preparation for first data in FY 2017. Physics commissioning of the Belle II detector at KEK began.	The NOvA experiment, currently the world's longest-baseline neutrino experiment using the world's most powerful neutrino beam at Fermilab, will be in its fourth year of data taking as the collaboration seeks to resolve the neutrino mass hierarchy. The Fermilab SBN program will continue to advance as MicroBooNE produces new physics results, Imaging Cosmic And Rare Underground Signals (ICARUS) begins physics data taking, and Short Baseline Near Detector (SBND) starts physics commissioning. ProtoDUNE will take data in the CERN beam in FY 2018. The Fermilab Muon g-2 experiment will present first physics data at conferences. R&D, physics studies, and detector simulations will continue for Mu2e and LBNF/DUNE. The Belle II experiment will take first data at the SuperKEKB accelerator in Japan to search for new physics through precision measurements of composite particles made of bottom quarks.	Decrease will require reduced research activities at universities and national laboratories. Higher priority will be given to support laboratory research programs critical to executing the P5 recommendations.

FY 2016	FY 2018 Request	Explanation of Changes FY 2018 vs FY 2016
Facility Operations and Experimental Support $148,863,000	**$129,304,000**	**-$19,559,000**
The Fermilab Accelerator complex continued to operate to support neutrino physics. The operations of the Main Injector Neutrino Oscillation Search (MINOS+) experiment concluded in June 2016. FY 2016 was an important funding year for two AIPs that provided enhancements for the future operations program: the delivery ring AIP, which modified the antiproton accumulator to store protons for the muon program, and the Recycler RF AIP, which upgraded the RF power in the recycler to handle high intensity proton beams for both the muon program and the short baseline neutrino program at Fermilab. Funding for the SBN Far Hall GPP was completed. SURF operations continued as LUX completed its data-taking and the Majorana demonstrator continued.	The Fermilab Accelerator Complex will operate to support the neutrino and muon experiments. Construction of the Industrial Central Building addition GPP project will finish in FY 2018. SURF operations will support the ongoing Majorana demonstrator activities and preparations for the LZ experiment and LBNF/DUNE construction.	Decreases will result from an extended shutdown of the Fermilab accelerator complex with commensurate reductions in operations support for detectors and computing. The decrease will also delay completion of the first phase of the Proton Improvement Plan, and no new AIPs or GPPs will be started.
Projects $36,036,000	**$14,100,000**	**-$21,936,000**
Funding for the Muon g-2 MIE project continued accelerator modifications and fabrication of the beamline and detectors. A combination of OPC funding and preconceptual R&D funding supported the development of PIP-II, a new superconducting proton linac to replace the more than 40-year-old existing front-end linac at Fermilab. Funding for the SBN program supported subsystems integration and infrastructure needed for the program.	Funding will support the OPC for plant support costs at SURF during LBNF/DUNE construction. In addition OPC is provided to continue the conceptual design for the PIP-II project.	The Request includes no funding for the Muon g-2 project, or for future project R&D.
SBIR/STTR $7,235,000	**$6,944,000**	**-$291,000**
In FY 2016, SBIR/STTR funding was set at 3.45% of non-capital funding.	In FY 2018, SBIR/STTR funding will be assumed to be 3.65% of non-capital funding.	Decreased funding represents mandated percentages for non-capital funding.

Description

The Cosmic Frontier supports the study of high energy physics through measurements of naturally occurring cosmic particles and observations of the universe. The activities in this subprogram use diverse tools and technologies, from ground-based telescopes and space-based experiments to large detectors deep underground, to probe fundamental physics questions and offer new insight about the nature of dark matter, dark energy, inflation in the early universe and other phenomena. Data collected from Cosmic Frontier experiments during this period will be used to address at least three of the five key science drivers identified in the P5 report:

Understand cosmic acceleration: dark energy and inflation

Steady progress continues in studying the nature of dark energy since the Nobel Prize in Physics in 2011 awarded for the
discovery of the acceleration of the expansion of the universe. The Baryon Oscillation Spectroscopic Survey (BOSS) measured galactic distances to a precision of 1% and growth rates through galaxy clustering. Cosmology results from the Dark Energy Survey (DES) includes precision results from Weak lensing cosmic shear, galaxy-galaxy lensing, galaxy clustering, and cross-correlations with cosmic microwave background (CMB) data from the third-generation South Pole Telescope (SPT-3G) experiment, which began operations in February 2017. Inflation, a period of rapid expansion in the universe at extremely high energy shortly after the Big Bang, is the target of the increasing sensitivity of operating and planned CMB experiments seeking direct detection of its quantum fluctuations in space-time. The LSSTcam and DESI projects are in their fabrication phase and will enable complementary, next-generation "Stage-IV" imaging and spectroscopic surveys respectively that will provide over a factor of ten better precision in comparison to current experiments.

Identify the new physics of dark matter

Measurements of motions within galaxies, weighing the universe as a whole, and the primordial abundance of elements all show that dark matter, which is not explained by the Standard Model, accounts for five times as much of the universe as ordinary matter. Direct-detection experiments in the laboratory provide the primary method to search for cosmic dark matter particles' rare interactions with atomic nuclei, while indirect-detection observatories measuring high energy gamma rays search for the products of dark matter annihilation in the core of galaxies. The first generation of direct-detection experiments have completed operations and have significantly tightened the limits on dark matter properties, including world-leading results by the Large Underground Xenon (LUX) experiment. The second generation of experiments, which are currently in various phases of design and fabrication, will achieve an order of magnitude or more improvement in sensitivity to detect direct dark matter. These experiments complemented those searching for dark matter performed in the Intensity Frontier subprogram using accelerator-based experiments and in the Energy Frontier subprogram using LHC data.

Explore the unknown: new particles, interactions, and physical principles

High-energy cosmic and gamma rays probe energy scales well beyond what can be produced with man-made particle accelerators, albeit not in a controlled experimental setting. Searches for new phenomena and for indirect signals of dark matter in high-energy cosmic surveys may yield surprising discoveries about the fundamental nature of the universe.

Research

The Cosmic Frontier experimental research subprogram consists of 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. The subprogram 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 all laboratory research groups in this subprogram in 2016 and the next review will be in 2020. The findings from these reviews will inform the funding decisions in subsequent years.

Facility Operations and Experimental Support

This activity will support the DOE share of personnel, data processing, and other expenses necessary for the successful pre-operations planning activities and maintenance, operations, and data production during the operating phase of Cosmic Frontier experiments. These experiments are typically not sited at national laboratories. They are located at telescopes, in space, or underground. The subprogram provides support for the experiments currently operating as well as for planning for the next generation experiments in the design or fabrication phase. HEP conducted a scientific peer review of Cosmic Frontier operations in early FY 2015 and has held subsequent status reviews or operations planning reviews. HEP uses the findings from the reviews to monitor the experiments and inform decisions concerning the level of operations support needed in subsequent years.

Projects

The visible matter in the universe accounts for only 5% of the mass and energy of the universe; therefore, P5 recommended robust programs to search for dark matter particles and study the nature of dark energy and the inflationary epoch on the early universe. Two experiments will use different technologies to measure the effect of dark energy on the expansion of the universe, which allows differentiation between models of dark energy. The LSSTcam will scan half of the sky repeatedly with optical imaging sensors, building up a “cosmic cinematography” of the changing universe, while DESI will study 30 million galaxies and quasars with spectroscopy over two-thirds of the age of the universe. Two experiments will use different technologies to search for dark matter: LZ will use a liquid xenon detector and SuperCDMS-SNOLAB will use cryogenic semiconductor detectors. LZ is better at detecting heavier dark matter particles while SuperCDMS-SNOLAB will be sensitive to lighter dark mass particles, so the two combine to provide the largest search currently feasible.

Cosmic Frontier Experimental Physics

Activities and Explanation of Changes

FY 2016	FY 2018 Request	Explanation of Changes FY 2018 vs FY 2016
Cosmic Frontier Experimental Physics $131,220,000	**$77,129,000**	**-$54,091,000**
Research $47,326,000	**$35,530,000**	**-$11,796,000**
Research activities focused on addressing key areas within the science drivers outlined in the P5 report. The LUX direct-detection dark matter experiment completed its planned data-taking run and produced the world's best search results for Weakly Interacting Massive Particles (WIMPs). BOSS published the most precise measurements yet of the effects of dark energy in the expansion of the universe by collecting data from 1.2 million galaxies. The SPT-3G experiment achieved first light in its four year survey of CMB polarization data to study cosmic inflation.	Funding will continue to support scientific efforts to analyze current dark matter and cosmic acceleration experiments and for the design and physics optimization for next-generation projects in those areas.	Decrease will require reduced research activities at universities and national laboratories. Higher priority will be given to support laboratory research programs critical to executing the P5 recommendations.
Facility Operations and Experimental Support $13,777,000	**$8,199,000**	**-$5,578,000**
Funding supported underground, surface-based, and space-based experiments in the data-taking phase, including direct-detection dark matter experiments, cosmic acceleration experiments, and cosmic-ray and gamma-ray experiments.	Funding will support early operations activities necessary for projects near completion, such as LSSTcam, and reduced operations of on-going experiments in the physics data-taking phase.	Decreases in operations funding for currently operating experiments will be partially offset by an increase for early operations of LSSTcam.
Projects $67,780,000	**$31,600,000**	**-$36,180,000**
Funding was provided for LSSTcam according to its approved baseline funding profile. DESI and LZ were baselined. SuperCDMS-SNOLAB funding supported design work towards project baseline.	Funding for the LSSTcam project will complete in FY 2018. Funding will support fabrication of the LZ direct-detection dark matter experiment as a priority. DESI fabrication will continue with reduced support. SuperCDMS-SNOLAB will transition from design to fabrication.	The LSSTcam and the LZ projects are funded according to their planned profiles, with a decrease for the LSSTcam and an increase for LZ in FY 2018. Additional decreases result from rebaselining DESI to be consistent with reduced allocation, and reducing SuperCDMS-SNOLAB funding that slows the project.
SBIR/STTR $2,337,000	**$1,800,000**	**-$537,000**
In FY 2016, SBIR/STTR funding was set at 3.45% of non-capital funding.	In FY 2018, SBIR/STTR funding will be assumed to be 3.65% of non-capital funding.	Decreased funding represents mandated percentages for non-capital funding.

Description

The Theoretical and Computational Physics subprogram provides the mathematical, phenomenological, and computational 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. Major theoretical research thrusts focus on the P5 science drivers, intertwining the physics of the Higgs boson, neutrino masses, and the dark universe along with exploring the unknown. Theory and computation cut across all the five science drivers and the Energy, Intensity, and Cosmic Frontier Experimental Physics subprograms.

<u>Theory</u>

The HEP theory subprogram supports 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, with laboratory groups typically more focused on data-driven theoretical investigations and precise calculations of experimental observables and university groups focused on building models of physics beyond the Standard Model and studying their phenomenology as well as on formal and mathematical theory. The subprogram selects research efforts with the highest scientific impact and potential based on a competitive peer-review process with. HEP conducted an external peer review of all laboratory research groups in Theory in 2014 and the next review will be in 2018. Findings are used to inform the funding decisions in intervening years.

<u>Computational HEP</u>

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. Computational HEP priorities are to advance computing research for HEP future needs across the program, including exploiting latest architectures. HEP partners with the Advanced Scientific Computing Research (ASCR), including via the Scientific Discovery through Advanced Computing (SciDAC) program, to optimize the HEP computing ecosystem for the near and long term future.

In addition, to supporting the science and technology thrusts, Computational HEP fosters advanced simulations and computational science that extends the boundaries of scientific discovery to regions not directly accessible by experiments, observations, or traditional theory. One focus area in FY 2018 is to use Quantum Information Science (QIS) and advanced computing for discovery along the P5 science drivers. Precision measurements using quantum sensors may yield information on fundamental Beyond the Standard Model physics and the dark sector. Technologies being developed for quantum computing are also candidates for sophisticated sensors for particle physics experiments.

<u>Projects</u>

The Projects activity currently funds acquisition of dedicated hardware for the Lattice Quantum Chromodynamics (LQCD) computing effort. This activity receives final funding in FY 2017.

Theoretical and Computational Physics

Activities and Explanation of Changes

FY 2016	FY 2018 Request	Explanation of Changes FY 2018 vs FY 2016
Theoretical and Computational Physics $61,536,000	**$59,225,000**	**-$2,311,000**
Theory $48,615,000	**$33,850,000**	**-$14,765,000**
Funding continued to support a balanced theoretical research program at universities and national laboratories for the interpretation of experimental results, the development of new ideas for future projects, and the advancement of our theoretical understanding of nature.	Funding will be focused on providing theoretical research support along P5 science drivers.	Decrease will require reduced research activities at universities and national laboratories. Higher priority will be given to support laboratory research programs critical to executing the P5 recommendations.
Computational HEP $8,829,000	**$23,213,000**	**+$14,384,000**
Funding continued to support R&D for computational tools that enable scientific advances in the HEP program. SciDAC 3 projects selected in FY 2015 continued in FY 2016.	Funding will be focused on QIS and advanced computing initiatives. Funding will be provided for SciDAC 4 projects that were competed in FY 2017.	Increased funding will support new QIS and advanced computing initiatives.
Projects $2,000,000	**$0**	**-$2,000,000**
Funding provided for the acquisition of new LQCD hardware.	No funding will be requested for this activity.	LQCD receives final funding in FY 2017.
SBIR/STTR $2,092,000	**$2,162,000**	**+$70,000**
In FY 2016, SBIR/STTR funding was set at 3.45% of non-capital funding.	In FY 2018, SBIR/STTR funding will be assumed to be 3.65% of non-capital funding.	Increased funding represents mandated percentages for non-capital funding.

High Energy Physics
Advanced Technology R&D

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

HEP General Accelerator R&D
HEP General Accelerator R&D (GARD) focuses on understanding 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 program consists of groups at U.S. academic and research institutions and national laboratories performing research activity categorized into five thrust areas: accelerator and beam physics; advanced acceleration concepts; particle sources and targetry; radio-frequency acceleration technology; and superconducting magnet and materials. GARD prioritizes research topics based on input from the April 2015 HEPAP Accelerator R&D subpanel report. The subprogram selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. HEP conducted an external peer review of all GARD laboratory research groups in 2013 and the next review will be in 2018. The findings of these reviews inform the funding decisions in intervening years.

HEP Directed Accelerator R&D
HEP Directed Accelerator R&D supports strategic investments in innovative technologies for possible future HEP accelerator projects, with proof-of-principle demonstrations, prototype component development, and advancing technical readiness. The LHC Accelerator Research Program (LARP) is carrying out R&D needed to produce prototypes for U.S. deliverables to the HL-LHC accelerator upgrade that CERN is planning to begin building late in this decade.

Detector R&D
Detector R&D addresses the need for continuing development of the next generation instrumentation and particle detectors at the Energy, Intensity, and Cosmic Frontiers in order to keep scientific leadership in a worldwide experimental program that is broadening into new research areas. In order to meet this challenge, HEP aims to foster a program appropriately balanced 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 subprogram 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 as well as the development of technologies that turn these insights into working detectors. The subprogram 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 2016 and the next review will be in 2020. The findings of these reviews inform the funding decisions in intervening years.

Facility Operations and Experimental Support
This activity provides funding for GARD laboratory experimental and test facilities, including BELLA at LBNL and superconducting radio-frequency (SRF) and magnet facilities at Fermilab. This activity also funds detector test beams at SLAC National Accelerator Laboratory (SLAC) and detector test and fabrication facilities like the Microsystem System Laboratory at LBNL and the Silicon Detector Facility at Fermilab.

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 provide compact or more energetic particle beams for the same lower costs as current ones. FACET-II will support the continuation of the plasma wakefield research started at FACET which was displaced by the construction of Linac Coherent Light Source II (LCLS-II).

Advanced Technology R&D

Activities and Explanation of Changes

FY 2016	FY 2018 Request	Explanation of Changes FY 2018 vs FY 2016
Advanced Technology R&D $124,825,000	**$87,864,000**	**-$36,961,000**
HEP General Accelerator R&D $44,608,000	**$32,701,000**	**-$11,907,000**
Funding supported the topics that were emphasized in the April 2015 HEPAP Accelerator R&D Subpanel report[a].	The program will execute the research roadmaps developed with the community, and research support will focus in the areas of advanced accelerator concepts and superconducting magnets.	Decrease will require reduced research activities at universities and national laboratories. Higher priority will be given to support laboratory research programs critical to executing the P5 recommendations and for R&D that requires long-term investments, including Detector R&D.
HEP Directed Accelerator R&D $21,020,000	**$5,000,000**	**-$16,020,000**
LARP increased effort to develop a prototype superconducting quadrupole magnets with the large apertures needed to increase luminosity at the LHC. MAP effort ramped down as recommended by P5.	LARP will complete the R&D needed to produce prototypes for U.S. deliverables to the HL-LHC accelerator upgrade at CERN.	Funding will decrease as LARP development and prototyping efforts for the LHC focusing magnets transition into production efforts as part of the HL-LHC AUP. MAP receives final funding in FY 2017.
Detector R&D $16,587,000	**$16,450,000**	**-$137,000**
Research activities continued at universities and national laboratories, with resources shifted towards near-term requirements of the high-priority efforts and towards strengthening the university activities, as recommended in the P5 report.	Research activities will continue at universities and national laboratories, with increased emphasis on long-term, high-risk, high potential impact R&D efforts and strengthening of the university efforts.	Funding will decrease due to reduced support for the Large Area Picosecond Photo-Detector effort, partially offset by increased support for advanced sensor development.
Facility Operations and Experimental Support $36,300,000	**$28,670,000**	**-$7,630,000**
Funding supported the continued operation of BELLA, superconducting magnet fabrication, and fabrication of test-beam facilities. FACET was supported at a reduced level due to a shorter run dictated by a shutdown for LCLS-II construction.	Operations of the BELLA facility and the SRF infrastructure at Fermilab will continue. AIP project, Sector 10 Injector Infrastructure continues which started in FY 2017.	Funding of FACET operations will decrease because the FACET facility cannot run due to LCLS-II construction. Technical support, materials and supplies, and access to SRF, detector fabrication and test-beam facilities will be reduced. This is partially offset by the increase for the Sector 10 Injector Infrastructure AIP project.

[a] http://science.energy.gov/~/media/hep/hepap/pdf/Reports/Accelerator_RD_Subpanel_Report.pdf

FY 2016	FY 2018 Request	Explanation of Changes FY 2018 vs FY 2016
Projects $2,100,000	**$2,000,000**	**-$100,000**
Approve Mission Need (CD-0) for the FACET-II MIE project was approved in September 2015, and the project began receiving funding for OPC in FY 2016.	During the LCLS-II shutdown, work on FACET-II will concentrate on what is needed to prepare for installation.	The program will reduce project funding for FACET-II as support is provided to higher priority projects in FY 2018.
SBIR/STTR $4,210,000	**$3,043,000**	**-$1,167,000**
In FY 2016, SBIR/STTR funding was set at 3.45% of non-capital funding.	In FY 2018, SBIR/STTR funding will be assumed to be 3.65% of non-capital funding.	Decreased funding represents mandated percentages for non-capital funding.

Description

The Accelerator Stewardship subprogram has three principal activities: improving access to SC accelerator R&D infrastructure for industrial and other users; near-term translational R&D to adapt accelerator technology for medical, industrial, security, and defense applications; and long-term R&D for the science and technology needed to build future generations of accelerators. HEP manages this program in close consultation with other SC programs, including NP and BES, and in consultation with other federal stakeholders of accelerator technology, most notably NSF, the DOD, NIH, and NASA.

Accelerator Stewardship pursues targeted R&D to develop new uses of accelerator technology with broad applicability. Initial workshops and a request for information identified target application areas with broad impact in accelerator technologies for ion beam therapy of cancer and laser technologies for accelerators. As the program evolves, it will identify new cross-cutting areas of research based on input from the federal stakeholders, R&D performers, and U.S. industry.

<u>Research</u>

Accelerator Stewardship research is conducted at national laboratories, universities, and in industry. The stewardship program supports both near-term translational R&D and long-term basic accelerator R&D. Near-term R&D funding is structured to produce practical prototypes of new applications in five to seven years. The needs for applications chosen for this category have been specifically identified by federal stakeholders and developed further by workshops. Near-term R&D funding opportunities are specifically structured to strengthen academic-industrial collaboration. Long-term R&D funding is targeted at scientific innovations enabling breakthroughs in particle accelerator size, cost, beam intensity, and control.

<u>Facility Operations and Experimental Support</u>

The Accelerator Stewardship subprogram supports the BNL's 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 a merit-based peer review process.

Accelerator Stewardship

Activities and Explanation of Changes

FY 2016	FY 2018 Request	Explanation of Changes FY 2018 vs FY 2016
Accelerator Stewardship $10,474,000	**$12,769,000**	**+$2,295,000**
Research $5,643,000	**$8,953,000**	**+$3,310,000**
Research continued at laboratories, universities, and in industry. New research support was initiated for selected technology areas identified by SC workshops such as technologies for particle beam therapy and ultrafast laser technology R&D.	The Request will support research activities at laboratories, universities, and in industry for technology R&D areas such as laser, ion-beam therapy, and accelerator technology.	R&D on high power electron beam technologies for science and other applications will ramp up.
Facility Operations and Experimental Support $4,517,000	**$3,350,000**	**-$1,167,000**
Support continued for BNL ATF operations and the relocation of the ATF to a larger building.	The Request will support the BNL ATF operations.	The ATF relocation completes in FY 2017. Funding will support reduced ATF operating hours.
SBIR/STTR $314,000	**$466,000**	**+$152,000**
In FY 2016, SBIR/STTR funding was set at 3.45% of non-capital funding.	In FY 2018, SBIR/STTR funding will be assumed to be 3.65% of non-capital funding.	Increased funding represents mandated percentages for non-capital funding.

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.

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

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 Fermilab 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 matter-antimatter asymmetry of the universe.

Fermilab is leading the construction of the LBNF project and is responsible for design, construction, and operation of the LBNF beamline; design, construction, and operation of the conventional facilities and experiment infrastructure on the Fermilab site required for the near detector; and design, construction, and operation of the conventional facilities and experiment infrastructure at SURF, including the cryostats and cryogenics systems, required for the far detector. DUNE is an international collaboration that has formed to carry out the neutrino experiment enabled by the LBNF facility. The DUNE collaboration will be responsible for: the definition of the scientific goals; the design, construction, commissioning, and operation of the near detector at Fermilab and the far detectors at the Sanford Underground Research Facility (SURF); and the scientific research program conducted with the DUNE detectors. The DUNE collaboration currently consists of about 1,000 physicists from nearly 160 institutes from 30 countries. Each of the collaborating institutions is responsible for delivering in-kind detector components that they have proven to have the expertise to build and install. Presently, the DOE contribution to the detectors will be a minority portion of the scope. Fermilab, as host, will oversee all LBNF/DUNE construction. Fermilab's oversight of the neutrino detectors includes technical coordination to ensure the various pieces will fit and operate together and arrive on time. The technical coordination group will document all work scope assignments, uphold a schedule, and provide design, production readiness, and operational readiness reviews in cooperation with the collaboration.

The construction of a particle beam at Fermilab and the infrastructure for DUNE detectors at SURF are being managed as a single project called LBNF/DUNE. The critical path item for LBNF/DUNE is excavation of the equipment caverns. Installation of the cryogenic systems and detectors cannot start until the caverns are ready. Critical site preparations such as safety and reliability refurbishments for the underground infrastructure as well as a waste-rock handling system must be completed before excavation can begin. The preparation work was started with funding received in FY 2016. CD-3A approval for initiating excavation of the equipment caverns at SURF was approved September 1, 2016. The FY 2017 construction funds are being used to complete the final design of the underground detector caverns, continue site preparation, develop detector prototypes for testing at CERN, and initiate a contract with a construction manager/general contractor who will oversee the civil construction. The FY 2018 Request is $54,900,000 and will support completion of the site preparation and detector prototypes, continue the detector and beam line designs needed for CD-2, and begin excavation of the underground detector caverns.

Muon to Electron Conversion Experiment (Mu2e)

Mu2e, under construction at Fermilab, will utilize a proton beam to produce muons and determine whether those muons, on rare occasions, can transform into electrons in apparent violation of lepton flavor symmetry. Evidence of muon-to-electron flavor change would further probe physics beyond the Standard Model at very high energy scales. The project received approval for its performance baseline (CD-2) and for civil construction and long-lead procurement of the most challenging superconducting solenoid magnets (CD-3B) on March 4, 2015. The Mu2e Project completed its technical design phase (CD-3) on July 14, 2016 and moved into full construction at that time. FY 2017 construction funds are being used to modify the Fermilab accelerator complex to deliver muons to Mu2e, to fabricate the two remaining superconducting solenoid magnets, and to fabricate the particle detection systems for Mu2e. The FY 2018 Request is $44,400,000 and will support continued procurement and fabrication work.

Construction

Activities and Explanation of Changes

FY 2016	FY 2018 Request	Explanation of Changes FY 2018 vs FY 2016
Construction $66,100,000	**$99,300,000**	**+$33,200,000**
11-SC-40, Long Baseline Neutrino Facility/ Deep Underground Neutrino Experiment $26,000,000	**$54,900,000**	**+$28,900,000**
Total Estimated Cost (TEC) funding supported the following: civil and geotechnical engineering design of the detector cavern in South Dakota; technical design of the neutrino-production beam line and related facilities at Fermilab; site preparation; and modifications to the technical design of the experimental facility, infrastructure, and detectors in light of the new international participation.	The Request will support the completion of site preparation activities, and will initiate the procurement of civil construction for excavation of the underground equipment caverns. Funding will also support design activities for the cryogenics system, detectors, and neutrino beam.	The increase is a result of the major transition from design and site preparation to the initiation of underground construction. Funding will also support design activities for the cryogenics system, detectors, and neutrino beam.
11-SC-41, Muon to Electron Conversion Experiment $40,100,000	**$44,400,000**	**+$4,300,000**
Funding continued for the civil construction and to initiate accelerator modifications and fabrication of technical components (solenoid magnets and particle detectors).	The Request will support continued accelerator modifications and fabrication of technical components.	The increase will be consistent with the baseline plan for continuation of fabrication of the accelerator modifications, magnets, and particle detectors.

High Energy Physics
Performance Measures

In accordance with the GPRA Modernization Act of 2010, the Department sets targets for, and tracks progress toward, achieving performance goals for each program.

	FY 2016	FY 2017	FY 2018
Performance Goal (Measure)	**HEP Construction/MIE Cost & Schedule - Cost-weighted mean percentage variance from established cost and schedule baselines for major construction, upgrade, or equipment procurement projects**		
Target	< 10 %	< 10 %	< 10 %
Result	Met	TBD	TBD
Endpoint Target	Adhering to the cost and schedule baselines for a complex, large scale, science project is critical to meeting the scientific requirements for the project and for being good stewards of the taxpayers' investment in the project.		
Performance Goal (Measure)	**HEP Facility Operations - Average achieved operation time of HEP user facilities as a percentage of total scheduled annual operation time**		
Target	≥ 80 %	≥ 80 %	≥ 80 %
Result	Met	TBD	TBD
Endpoint Target	Many of the research projects that are undertaken at the Office of Science's scientific user facilities take a great deal of time, money, and effort to prepare and regularly have a very short window of opportunity to run. If the facility is not operating as expected the experiment could be ruined or critically setback. In addition, taxpayers have invested millions or even hundreds of millions of dollars in these facilities. The greater the period of reliable operations, the greater the return on the taxpayers' investment.		
Performance Goal (Measure)	**HEP Neutrino Model - Carry out series of experiments to test the standard 3-neutrino model of mixing**		
Target	Physics analyses results from data taking will be presented by the NOvA and MicroBooNE experimental collaborations at the FY 2016 summer conferences.	Fermilab switches operations mode over from neutrino beam to antineutrino beam delivery to the NOvA experiment. NOvA accumulates physics data in antineutrino mode.	MicroBooNE data taking will complete final year of phase-1. NOvA will publish the first muon and electron anti-neutrino oscillation results. ICARUS data taking will begin. SBND physics commissioning will continue.
Result	Met	TBD	TBD
Endpoint Target	Similar to quarks, the mixing between neutrinos is postulated to be described by a unitary matrix. Measuring the independent parameters of this matrix in different ways and with adequate precision will demonstrate whether this model of neutrinos is correct. Such a model is needed to correctly extract evidence for CP violation in the neutrino sector.		

High Energy Physics
Capital Summary ($K)

	Total	Prior Years	FY 2016 Enacted	FY 2017 Annualized CR[a]	FY 2018 Request	FY 2018 vs FY 2016
Capital Operating Expenses Summary						
Capital equipment	n/a	n/a	105,205	—	57,800	-47,405
General plant projects (GPP)	n/a	n/a	9,160	—	2,310	-6,850
Accelerator improvement projects (AIP) (<$5M)	n/a	n/a	8,280	—	1,500	-6,780
Total, Capital Operating Expenses	**n/a**	**n/a**	**122,645**	**—**	**61,610**	**-61,035**
Capital Equipment						
Major items of equipment[b]						
Energy Frontier Experimental Physics						
LHC ATLAS Detector Upgrades[c]	20,821	2,821	9,500	—	0	-9,500
LHC CMS Detector Upgrades[d]	22,629	5,162	9,500	—	0	-9,500
HL-LHC AUP[e]	206,380	0	0	—	27,000	+27,000
Intensity Frontier Experimental Physics						
Muon g-2 Experiment[f]	27,549	11,000	10,200	—	0	-10,200
Cosmic Frontier Experimental Physics						
Large Synoptic Survey Telescope Camera (LSSTcam)[g]	150,300	54,700	40,800	—	9,800	-31,000
Dark Energy Spectroscopic Instrument[h] (DESI)	40,122	500	9,800	—	1,900	-7,900
LUX-ZEPLIN[i] (LZ)	52,050	500	10,500	—	14,100	+3,600
SuperCDMS-SNOLAB[j]	16,725	0	2,375	—	2,000	-375

[a] FY 2017 Annualized CR amounts reflect the P.L. 114-254 continuing resolution level annualized to a full year. These amounts are shown only at the congressional control level and above; below that level, a dash (-) is shown.
[b] Each MIE located at a DOE facility Total Estimated Cost (TEC) > $5M and each MIE not located at a DOE facility TEC > $2M.
[c] Critical Decisions CD-2 and 3 for the LHC ATLAS Detector Upgrade Project were approved on November 12, 2014. The TPC is $33,250,000.
[d] Critical Decisions CD-2 and 3 for the LHC CMS Detector Upgrade Project were approved on November 12, 2014. The TPC is $33,217,000.
[e] Critical Decision CD-0 for HL-LHC AUP was approved April 13, 2016. The estimated cost range was $180,000,000 to $250,000,000.
[f] Critical Decision CD-2 and 3 for Muon g-2 Experiment were approved August 20, 2015. The TPC is $46,400,000.
[g] Critical Decision CD-3 for the LSSTcam project was approved on August 27, 2015. The TPC is $168,000,000.
[h] Critical Decision CD-3 for DESI project was approved on June 22, 2016, with a TPC of $56,328,000, project will be rebaselined.
[i] Critical Decisions CD-2 and 3B for LZ were approved August 9, 2016. The TPC is $55,500,000.
[j] The estimated cost range for SuperCDMS-SNOLAB at Critical Decision CD-1 approved December 21, 2015 was $16,000,000–$21,500,000.

	Total	Prior Years	FY 2016 Enacted	FY 2017 Annualized CR[a]	FY 2018 Request	FY 2018 vs FY 2016
Advanced Technology R&D						
FACET II[a]	53,000	0	0	—	2,000	+2,000
Total MIEs	n/a	n/a	92,675	—	56,800	-35,875
Total Non-MIE Capital Equipment	n/a	n/a	12,530	—	1,000	-11,530
Total, Capital equipment	**n/a**	**n/a**	**105,205**	**—**	**57,800**	**-47,405**
General Plant Projects (GPP)						
Short-Baseline Neutrino Far Hall	8,700	6,298	2,402	—	0	0
Short-Baseline Neutrino Near Hall	5,250	2,050	3,200	—	0	0
Industrial Center Building addition	9,760	0	1,760	—	1,500	-260
Other projects under $5 million TEC	n/a	n/a	1,798	—	810	-988
Total, Plant Project (GPP)	**n/a**	**n/a**	**9,160**	**—**	**2,310**	**-6,850**
Accelerator Improvement Projects (AIP)						
Muon Campus Cryogenics	9,600	7,500	700	—	0	-700
Recycler RF Upgrades	7,450	5,200	2,250	—	0	-2,250
Beam Transport	6,500	6,400	100	—	0	-100
Delivery Ring	9,600	5,200	4,400	—	0	-4,400
ATF-II Upgrade	5,000	2,500	830	—	0	-830
Sector 10 Injector Infrastructure	5,000	0	0	—	1,500	+1,500
Total, Accelerator Improvement Projects	**n/a**	**n/a**	**8,280**	**—**	**1,500**	**-6,780**

[a] The estimated cost range for FACET II at CD-1 approved on December 21, 2015 was $46,000,000–$60,000,000.

Major Items of Equipment Descriptions

Energy Frontier Experimental Physics MIEs:

The *LHC ATLAS Detector Upgrade Project* started as a new MIE in FY 2015 and the subsequent ramp-up of fabrication activities for U.S. built detectors continues through FY 2017. The U.S. scope includes upgrades to the muon subsystem, the liquid argon calorimeter detector, and the trigger and data acquisition system to take advantage of the increased LHC luminosity. The LHC ATLAS Detector Upgrade Project was baselined (CD-2) and approved for a fabrication start (CD-3) on November 12, 2014, with a total project cost of $33,250,000 and project completion date (CD-4) in FY 2019. The project is currently producing subsystem components and will begin to install them in FY 2018. The FY 2018 Request does not include funding for this project. It has sufficient funds to complete all remaining deliverables.

The *LHC CMS Detector Upgrade Project* started as a new MIE in FY 2015 and will complete the bulk of its deliverables in FY 2017. The planned U.S. scope includes upgrades to the pixelated inner tracking detector, the hadron calorimeter detector, and trigger system to take advantage of the increased LHC luminosity. The LHC CMS Detector Upgrade Project was baselined (CD-2) and approved for a fabrication start (CD-3) on November 12, 2014, with a total project cost of $33,217,000 and project completion date in FY 2020. The project has successfully installed the pixelated inner tracking detector and portions of the trigger and hadron calorimeter. The remaining components are being produced now and will be installed in FY 2018. The FY 2018 Request does not include funding for this project. It has sufficient funds to complete all remaining deliverables.

The *High Luminosity Large Hadron Collider Accelerator Upgrade Project (HL-LHC AUP)* starts as a new MIE in FY 2018 with initial TEC funding. Following the major upgrade, the CERN LHC machine will further increase the instantaneous luminosity by a factor of three times its design value to explore new physics beyond the reach of the current LHC program. The project will deliver components for which the U.S. scientists have critical expertise: interaction region focusing quadrupole magnets and special superconducting RF crab cavities, capable of generating transverse electric fields that rotate each bunch longitudinally such that they collide effectively head on, overlapping perfectly at the collision points. The HL-LHC AUP received CD-0 on April 13, 2016 with an estimated cost range of $180,000,000 to $250,000,000. The FY 2018 Request includes TEC funding of $27,000,000 for HL-LHC AUP.

Intensity Frontier Experimental Physics MIE:

The *Muon g-2* project received CD-2 and CD-3 approval on August 20, 2015, with a TPC of $46,400,000 and project completion date in FY 2019. The FY 2018 Request does not include funding for this project. It has sufficient funds to complete all remaining deliverables.

Cosmic Frontier Experimental Physics MIEs:

The *Large Synoptic Survey Telescope Camera (LSSTcam*) project fabricates a state-of-the-art three billion pixel digital camera for a next-generation, wide-field, ground-based optical and near-infrared LSST observatory, located in Chile, and is designed to provide deep images of half the sky every few nights. The project is carried out in collaboration with NSF, which leads the project, along with private and foreign contributions. DOE will provide the camera for the facility. CD-2 for the LSSTcam project was approved on January 7, 2015, with a DOE TPC of $168,000,000 and a project completion date in FY 2022. CD-3 was approved on August 27, 2015. The project is currently producing many of the camera components, which are being tested and integrated before shipment to Chile in 2020. The FY 2018 Request of TEC funding for the LSSTcam is $9,800,000, which is $31,000,000 lower than the FY 2016 Enacted level of $40,800,000 and consistent with the approved baseline funding profile.

The *Dark Energy Spectroscopic Instrument (DESI)* project started fabrication in FY 2015. The project is fabricating an instrument that will measure the effect of dark energy on the expansion of the universe using spectroscopic measurements. The DESI survey will provide different, complementary measurements to those of the LSST survey. The instrument will be mounted on NSF's Mayall 4-meter telescope at Kitt Peak National Observatory in Arizona, with operations of the telescope supported by DOE. DESI remains unique in its use of dedicated spectroscopic measurements to measure dark energy at its planned precision. It provides a strong complement to the LSST being built by NSF and DOE. CD-2 was approved on September 17, 2015 with a TPC of $56,328,000, and a project completion date of FY 2021. CD-3 was approved on June 22, 2016. The project is currently producing many of the camera components, which are being tested and integrated. The FY

2018 Request of TEC funding is $1,900,000, which is $7,900,000 below the FY 2016 Enacted level of $9,800,000. HEP plans to rebaseline the project when the FY 2017 appropriations are finalized.

The LUX-ZEPLIN (LZ) project started MIE fabrication in FY 2015. This MIE is one of two 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 (TPC) 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. CD-2 and CD-3b were approved on August 8, 2016 with a project completion data in FY 2022. CD-3 was approved in February 2017, and the project is producing components and testing them before integration in 2019. The FY 2018 Request of TEC funding for LZ is $14,100,000, which is $3,600,000 above the FY 2016 Enacted level of $10,500,000 and consistent with the approved baseline funding profile.

The *Super Cryogenic Dark Matter Search at Sudbury Neutrino Observatory Laboratory (SuperCDMS-SNOLAB)* is one of the two MIEs selected to meet the Dark Matter Second Generation Mission Need. The project will fabricate an instrument 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. The detector will be located 2 km deep in the SNOLAB facility in Sudbury, Ontario, Canada. SuperCDMS will be optimized to detect low mass WIMPs and will cover a range of WIMP mass complementary to that of LZ's sensitivity. CD-1 was approved on December, 21, 2015. The project will be completing its preliminary design and preparing of CD-2. The FY 2018 Request of TEC funding for SuperCDMS-SNOLAB is $2,000,000, which is $375,000 below the FY 2016 Enacted level of $2,375,000. The project has not yet been baselined so the project does not have an official CD-4 date, but the project will be slowed compared to the estimated schedule at CD-1.

Advanced Technology R&D MIE:

The *Facility for Accelerator and Experimental Tests II (FACET-II)* is a new MIE fabrication start in FY 2018. It will succeed FACET as the world's premier beam driven plasma wakefield facility and provide intense ultra-short electron beams for other applications in accelerator and related sciences. The successful FACET program ended due to the construction of the Linac Coherent Light Source II (LCLS-II) in a portion of the SLAC tunnel used by FACET. FACET-II will be designed to deliver beams using only one third of the SLAC linac. CD-0 was approved September 18, 2015. CD-1 was approved December 21, 2015. The FY 2018 Request of TEC funding for FACET-II is $2,000,000. At this funding level, work will continue on the critical infrastructure that needs to be installed during the shutdown of the linac for the LCLS-II installation.

High Energy Physics Construction Project Summary ($K)

	Total	Prior Years	FY 2016 Enacted	FY 2017 Enacted	FY 2018 Request	FY 2018 vs FY 2016
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment						
TEC	1,433,375	35,781	26,000	50,000	54,900	+28,900
OPC	102,625	85,539	86	—	100	+14
TPC	1,536,000	121,320	26,086	50,000	55,000	+28,914
11-SC-41, Muon to Electron Conversion Experiment						
TEC	250,000	92,000	40,100	43,500	44,400	+4,300
OPC	23,677	23,677	0	—	0	0
TPC	273,677	115,677	40,100	43,500	44,400	+4,300
Total, Construction						
TEC	n/a	n/a	66,100	93,500	99,300	+33,200
OPC	n/a	n/a	86	—	100	+14
TPC	n/a	n/a	66,186	93,500	99,400	+33,214

Funding Summary ($K)

	FY 2016 Enacted	FY 2017 Annualized CR[a]	FY 2018 Request	FY 2018 vs FY 2016
Research	341,663	—	272,887	-68,776
Facilities Operations				
Scientific User Facilities Operations	135,848	—	112,439	-23,409
Other Facilities	122,388	—	101,374	-21,014
Total, Facilities Operations	**258,236**	**—**	**213,813**	**-44,423**

[a] FY 2017 Annualized CR amounts reflect the P.L. 114-254 continuing resolution level annualized to a full year. These amounts are shown only at the congressional control level and above; below that level, a dash (-) is shown.

	FY 2016 Enacted	FY 2017 Annualized CR[a]	FY 2018 Request	FY 2018 vs FY 2016
Projects				
Major Items of Equipment[b]	95,900	—	72,600	-23,300
Other Projects	14,300	—	0	-14,300
Construction[b]	84,901	—	113,400	+28,499
Total, Projects	**195,101**	**—**	**186,000**	**-9,101**
Total, High Energy Physics	**795,000**	**793,489**	**672,700**	**-122,300**

[b] Includes Other Project Costs.

Scientific User Facility Operations ($K)

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:

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.

	FY 2016 Enacted	FY 2017 Annualized CR[a]	FY 2018 Request	FY 2018 vs FY 2016
TYPE A FACILITIES				
Fermilab Accelerator Complex	**$125,481**	**—**	**$109,089**	**-$16,392**
Number of Users	2,246	—	1,945	-301
Achieved operating hours	5,983	—	N/A	N/A
Planned operating hours	4,800	—	1,800	-3,000
Optimal hours	4,800	—	4,800	0
Percent optimal hours	124.6%	—	37.5%	-87.1%
Unscheduled downtime hours	590	—	N/A	N/A

[a] FY 2017 Annualized CR amounts reflect the P.L. 114-254 continuing resolution level annualized to a full year. These amounts are shown only at the congressional control level and above; below that level, a dash (-) is shown.

	FY 2016 Enacted	FY 2017 Annualized CR[a]	FY 2018 Request	FY 2018 vs FY 2016
FACET (SLAC)	**$5,850**	**—**	**$0**	**-$5,850**
Number of Users	96	—	0	-96
Achieved operating hours	2,146	—	N/A	N/A
Planned operating hours	3,096	—	0	-3,096
Optimal hours	4,448	—	0	-4,448
Percent optimal hours	48.2%	—	N/A	N/A
Unscheduled downtime hours	485	—	N/A	N/A
Accelerator Test Facility (BNL)	**$4,517**	**—**	**$3,350**	**-$1,167**
Number of Users	50	—	52	+2
Achieved operating hours	2,113	—	N/A	N/A
Planned operating hours	2,189	—	1,681	-508
Optimal hours	2,500	—	2,050	-450
Percent optimal hours	84.5%	—	82.0%	-2.5%
Unscheduled downtime hours	0	—	N/A	N/A
Total Facilities	**$135,848**	**—**	**$112,439**	**-$23,409**
Number of Users	2,392	—	1,997	-395
Achieved operating hours	10,242	—	N/A	N/A
Planned operating hours	10,085	—	3,481	-6,604
Optimal hours	11,748	—	6,850	-4,898
Percent of optimal hours[a]	120.0%	—	38.8%	-81.2%
Unscheduled downtime hours	1,075	—	N/A	N/A

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

Scientific Employment

	FY 2016 Enacted	FY 2017 Annualized CR[a]	FY 2018 Estimate	FY 2018 vs FY 2016
Number of permanent Ph.D.'s (FTEs)	940	—	720	-220
Number of postdoctoral associates (FTEs)	300	—	240	-60
Number of graduate students (FTEs)	460	—	345	-115
Other[b]	1,875	—	1,810	-65

[a] FY 2017 Annualized CR amounts reflect the P.L. 114-254 continuing resolution level annualized to a full year. These amounts are shown only at the congressional control level and above; below that level, a dash (-) is shown.

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

11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE),
Fermi National Accelerator Laboratory, Batavia, Illinois
Project is for Design and Construction

1. Significant Changes and Summary

Significant Changes

This Construction Project Data Sheet (CPDS) is an update of the FY 2017 CPDS and does not include a new start for FY 2018.

Development of the design and cost estimates have been refined and the U.S. DOE contributions to the multinational effort are now better understood. Additional design activities and prototypes have been identified by the project team.

Summary

The FY 2018 Request for LBNF/DUNE is $54,900,000. The most recent DOE Order 413.3B approved 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. CD-3A was approved September 1, 2016 with a preliminary total project cost (TPC) range of $1,260,000,000 to $1,860,000,000 and CD-4 date of 4Q FY 2030. The range includes the full cost of the LBNF host facility excluding foreign contributions, as well as the full cost of the DOE contribution to the DUNE experimental apparatus.

DOE entered into a land lease with the South Dakota Science and Technology Authority (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 provides the framework for DOE and Fermilab to construct federally funded buildings and facilities on non-federal land, and to establish a long-term (multi-decade) arrangement for DOE and Fermilab to use SDSTA space to host the neutrino detector. Other Project Costs (OPC) funding has been identified in years FY 2018-FY 2026 for plant support costs provided by SDSTA...

The Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE) comprise 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 HEPAP-Particle Physics Project Prioritization Panel (P5) recommendations, the LBNF/DUNE Project consists of two multinational collaborative efforts:

- LBNF (the facility) is responsible for the beamline at Fermilab and other experimental and civil infrastructure at Fermilab and at the Sanford Underground Research Facility (SURF) in South Dakota.
- DUNE (the experiment) is an international scientific collaboration responsible for defining the scientific goals & technical requirements for the beam and detectors, as well as the design, construction & commissioning of the detectors and subsequent research program.

DUNE will analyze transformations of muon neutrinos in a beam from Fermilab to a large detector in South Dakota, 800 miles away. The experiment will analyze the rare, flavor-changing transformations of neutrinos in flight, from one lepton flavor to another, that are expected to help elucidate the fundamental physics of neutrinos and may explain the puzzling matter-antimatter asymmetry that enables our existence in a matter-dominated universe.

DOE HEP manages both activities as a single, line-item construction project—LBNF/DUNE. LBNF, with DOE/Fermilab leadership and minority participation by a small number of international partners including CERN, will construct a MW-class neutrino source and related facilities at Fermilab (the “near site”), as well as underground cavern(s) and cryogenic facilities in South Dakota (the “far site) needed to house the DUNE detector(s). DUNE has international leadership and participation by about 1000 scientists and engineers from more than 160 institutions in 30 countries. The detector mass totaling 40 kilotons will be distributed in four cryostats housed in large caverns at SURF. An additional cavern at SURF will accommodate the cryogenic and other utility systems. DOE will fund less than a third of DUNE. Development of the design and cost estimates have been refined and the U.S. DOE contributions to the multinational effort are now better understood. Additional design activities and prototypes have been identified.

Contributions from the international partners to LBNF/DUNE are currently being negotiated by Fermilab and DOE. For the DUNE detector, the process is being driven from the principal investigator level up to the funding agencies as was done for U.S. contributions to the Large Hadron Collider (LHC) accelerator and detectors. Proposals are under review by the other funding agencies. CERN put funding into its medium-term budget plan for one detector cryostat worth $90 million in U.S. accounting. All DOE contributions to the facility and the detectors will be managed according to DOE Order 413.3B, and Fermilab will provide unified project management reporting.

Fermilab has initiated site preparation at SURF with maintenance and refurbishment activities to the mine shaft, hoists, ventilation systems, and general support infrastructure to allow for safe and reliable access prior to initiating excavation and underground construction.

The FY 2018 Request will support initiating the excavation of the underground equipment caverns.

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

2. Critical Milestone History

(fiscal quarter or date)

	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	D&D Complete	CD-4
FY 2011	1/8/2010		1Q FY 2011	TBD	4Q FY 2013	TBD	TBD	TBD
FY 2012	1/8/2010		2Q FY 2012	TBD	2Q FY 2015	TBD	TBD	TBD
FY 2016[a]	1/8/2010	12/10/2012	12/10/2012	4Q FY 2017	4Q FY 2019	4Q FY 2019	N/A	4Q FY 2027
FY 2017	1/8/2010	11/5/2015[b]	11/5/2015[b]	1Q FY 2020	1Q FY 2020	1Q FY 2020	N/A	4Q FY 2030
FY 2018	1/8/2010	11/5/2015[b]	11/5/2015[b]	1Q FY 2021	1Q FY 2022	1Q FY 2022	N/A	4Q FY 2030

CD-0 – Approve Mission Need
Conceptual Design Complete – Actual date the conceptual design was completed
CD-1 – Approve Design Scope and Project Cost and Schedule Ranges
CD-2 – Approve Project Performance Baseline
Final Design Complete – Estimated date the project design will complete
CD-3 – Approve Start of Construction
D&D Complete – Completion of D&D work (see section 9)
CD-4 – Approve Start of Operations or Project Closeout

(fiscal quarter or date)

	CD-1R	CD-3A	CD-3B	CD-3(C)	Performance Baseline Validation
FY 2017	11/5/2015	2Q FY 2016	3Q FY 2018	1Q FY 2020	1Q FY 2020
FY 2018	11/5/2015	9/1/2016	1Q FY 2021	1Q FY 2022	1Q FY 2021

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.

[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 by an ESAAB approval (CD-1R) on November 5, 2015.

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

3. Project Cost History

(dollars in thousands)

	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	85,539	N/A	85,539	1,500,000
FY 2018[bc]	234,375	1,199,000	1,433,375	102,625	N/A	102,625	1,536,000

4. 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 Fermilab 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 Fermilab 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.

For the LBNF/DUNE project, Fermilab 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 Fermilab site required for the near detector; and the conventional facilities and experiment infrastructure at SURF for the large detector 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 is $1,260,000,000 to $1,860,000,000. The TPC point estimate is $1,536,000,000.
[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.

Among the technical issues addressed in the alternatives analysis were the preferred detector technology and the neutrino beamline design. After a thorough study, both technologies were found to be capable of meeting the performance requirements if located underground, only liquid argon could work on the surface, and is less expensive. A low energy neutrino beam to SURF and the current NuMI beam were compared. The new LBNF beam with its lower energy and longer distance to the detector was shown to be superior.

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

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 kton detector modules (of liquid-argon, time-projection detectors) at the SURF site, 1000-1500 km from the neutrino source. The DOE contribution for DUNE will include technical components for two of the four detector modules, 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. The KPPs will be finalized at CD-2.

Preliminary Key Performance Parameters

Scope	Threshold KPP	Objective KPP
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 kilometers	
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

5. Financial Schedule[b]

[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.

[b] 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. The TPC point estimate is $1,536,000,000. Design and international collaboration plans are currently being developed; outyears are preliminary.

	(dollars in thousands)			
	Appropriations	Obligations	Recovery Act Costs	Costs[a]
Total Estimated Cost (TEC)				
Design Only[b]				
FY 2012	4,000	4,000	0	0[c]
FY 2013	3,781	3,781	0	801
FY 2014	16,000	16,000	0	7,109
FY 2015	12,000	12,000	0	15,791
FY 2016	0	0	0	12,080
Subtotal, Design Only	35,781	35,781	0	35,781
Design (Design and Construction)				
FY 2016	N/A	N/A	0	26,436[d]
FY 2017	N/A	N/A	0	45,021
FY 2018	N/A	N/A	0	11,000[e]
Outyears	N/A	N/A	0	116,137
Subtotal, Design (Design and Construction)	N/A	N/A	0	198,594
Total, Design	N/A	N/A	0	234,375
Construction				
FY 2017	N/A	N/A	0	0
FY 2018	N/A	N/A	0	43,900[f]
Outyears	N/A	N/A	0	1,155,100
Total, Construction	N/A	N/A	0	1,199,000
TEC				
FY 2012	4,000	4,000	0	0
FY 2013	3,781	3,781	0	801
FY 2014	16,000	16,000	0	7,109
FY 2015	12,000	12,000	0	15,791
FY 2016	26,000	26,000	0	38,516
FY 2017	50,000	50,000	0	50,000
FY 2018	54,900	54,900	0	54,900
Outyears	1,266,694	1,266,694	0	1,266,258
Total, TEC	1,433,375	1,433,375	0	1,433,375

[a] Costs through FY 2016 reflect actual costs; costs for FY 2017 and the outyears are estimates.
[b] 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.
[c] $1,078,000 was erroneously costed to this project in FY 2012, the accounting records were adjusted in early FY 2013.
[d] Costs were for Far Site preparation including safety and reliability refurbishment of the underground infrastructure, which is needed prior to initiating excavation of the equipment caverns.
[e] Estimated costs are for continuing project engineering design in preparation for CD-2.
[f] Estimated costs are for initiating excavation of the equipment caverns at the Far Site as approved by CD-3A.

	(dollars in thousands)			
	Appropriations	Obligations	Recovery Act Costs	Costs[a]
Other Project Cost (OPC)				
OPC except D&D				
FY 2009 Recovery Act	12,486[a]	12,486	0	0
FY 2010	14,178	14,178	4,696	6,336
FY 2011	7,768	7,750	7,233	11,321
FY 2012	17,000	17,018[b]	557[c]	17,940
FY 2013	14,107	14,107	0	13,232
FY 2014	10,000	10,000	0	11,505
FY 2015	10,000	10,000	0	10,079
FY 2016	86	86	0	2,284
FY 2017	0	0	0	442
FY 2018	100	100	0	100
Outyears	16,900	16,900	0	16,900
Total, OPC	102,625	102,625	12,486	90,139
Total Project Cost (TPC)				
FY 2009 Recovery Act	12,486	12,486	0	0
FY 2010	14,178	14,178	4,696	6,336
FY 2011	7,768	7,750	7,233	11,321
FY 2012	21,000	21,018	557	17,940
FY 2013	17,888	17,888	0	14,033
FY 2014	26,000	26,000	0	18,614
FY 2015	22,000	22,000	0	25,870
FY 2016	26,086	26,086	0	40,800
FY 2017	50,000	50,000	0	50,442
FY 2018	55,000	55,000	0	55,000
Outyears	1,283,594	1,283,594	0	1,283,158
Total, TPC	1,536,000	1,536,000	12,486	1,523,514

[a] $13,000,000 of Recovery Act funding was originally planned for the conceptual design; the difference of $512,000 relates to pre-conceptual design activities needed prior to approval of mission need (CD-0).
[b] $18,000 of FY 2011 funding was attributed towards the Other Project Costs activities in FY 2012.
[c] During FY 2012, $1,000 of Recovery Act funding was recategorized from pre-conceptual design and so became part of the OPC. $3,000 was deobligated and expired because Recovery Act funds are no longer available for obligation.

6. Details of Project Cost Estimate[a]

	(dollars in thousands)		
	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design			
Design	201,375	100,000	N/A
Contingency	33,000	23,781	N/A
Total, Design	234,375	123,781	N/A
Construction			
Site Preparation[b]	0	20,000	N/A
Far Site Civil Construction[c]	300,000	300,000	N/A
Fermilab Site Civil Construction[d]	281,000	270,000	N/A
Far Site Technical Infrastructure[e]	98,000	110,000	N/A
Fermilab Site Beamline[e]	110,000	130,000	N/A
DUNE Detectors	75,000	120,000	N/A
Contingency	335,000	340,680	N/A
Total, Construction	1,199,000	1,290,680	N/A
Total, TEC	1,433,375	1,414,461	N/A
Contingency, TEC	368,000	364,461	N/A
Other Project Cost (OPC)			
OPC except D&D			
R&D	20,625	18,000	N/A
Conceptual Planning	30,000	30,000	N/A
Conceptual Design	35,000	36,689	N/A
Plant Support Costs	17,000	0	N/A
Contingency	0	850	N/A
Total, OPC	102,625	85,539	N/A
Contingency, OPC	0	850	N/A
Total, TPC	1,536,000	1,500,000	N/A
Total, Contingency	368,000	365,311	N/A

[a] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The TPC point estimate is $1,536,000,000. The preliminary TPC range at CD-1 was $1,260,000,000 to $1,860,000,000.
[b] Construction work now approved under CD-3A is included in the next row.
[c] Far Site civil construction involves excavation of caverns at SURF, 4850 ft below the surface, for technical equipment including particle detectors and cryogenic systems.
[d] Fermilab Site civil construction involves construction of the housing for the neutrino-production beam line and the near detector.
[e] 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.

7. Schedule of Appropriation Requests[a]

Request Year		Prior Years	FY 2015	FY 2016	FY 2017	FY 2018	Outyears	Total
		(dollars in thousands)						
FY 2011	TEC	102,000	0	0	0	0	0	102,000
	OPC	22,180	0	0	0	0	0	22,180
	TPC	124,180	0	0	0	0	0	124,180
FY 2012	TEC	91,000	42,000	0	0	0	0	133,000
	OPC	42,621	0	0	0	0	0	42,621
	TPC	133,621	42,000	0	0	0	0	175,621
FY 2016	TEC	23,781	12,000	16,000	TBD	TBD	TBD	783,393
	OPC	75,539	10,000	4,000	TBD	TBD	TBD	89,539
	TPC	99,320	22,000	20,000	TBD	TBD	TBD	872,932
FY 2017	TEC	23,781	12,000	26,000	45,021	TBD	1,307,659	1,414,461
	OPC	75,539	10,000	0	0	0	0	85,539
	TPC	99,320	22,000	26,000	45,021	TBD	1,307,659	1,500,000
FY 2018[b]	TEC	23,781	12,000	26,000	50,000	54,900	1,266,694	1,433,375
	OPC	75,539	10,000	86	0	100	16,900	102,625
	TPC	99,320	22,000	26,086	50,000	55,000	1,283,594	1,536,000

8. 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 facility. 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	
	Current Total Estimate	Previous Total Estimate	Current Total Estimate	Previous Total Estimate
Operations	9,000	9,000	180,000	180,000
Utilities	8,000	8,000	160,000	160,000
Maintenance & Repair	1,000	1,000	20,000	20,000
Total	18,000	18,000	360,000	360,000

[a] Design and international collaboration plans are currently being developed; outyears are preliminary.

[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 point estimate is $1,536,000,000.

9. Required D&D Information

	Square Feet
Area of new construction	142,000 SF
Area of existing facility being replaced and D&D'd by this project	0
Area of other D&D outside the project	0
Area of any additional D&D space to meet the "one-for-one" requirement taken from the banked area.	142,000 SF

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

10. Acquisition Approach

The LBNF and the DUNE detector apparatus comprise a unique, geographically distributed, complex system of scientific equipment consisting of a beam source at Fermilab and particle detectors both nearby at Fermilab and at a remote site 800 miles away in Lead, South Dakota. The overall DOE Project defined for delivery of LBNF and DUNE is referred to as LBNF/DUNE. The acquisition approach is documented in the Acquisition Strategy approved as part of CD-1. DOE is acquiring design, construction, fabrication, and operation of LBNF through the M&O contractor responsible for Fermilab, Fermi Research Alliance (FRA). FRA and Fermilab, through the LBNF Project based at Fermilab, is responsible to DOE to manage and complete construction of LBNF at both the near and remote site locations. FRA and Fermilab 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:

- Fermilab 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.
- Fermilab 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 Fermilab.
- Fermilab 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.
- Fermilab 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.
- Fermilab, 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;
- Fermilab 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.

In leading the LBNF/DUNE Project, Fermilab will collaborate and work with many institutions, including several DOE national laboratories (BNL, LBNL and LANL), dozens of universities, foreign research institutions, SURF, and the SDSTA. Fermilab will be responsible for overall project management, near site conventional facilities, and the beamline. Fermilab will work with SDSTA and SURF to complete the conventional facilities construction at the remote site needed to house and outfit the DUNE far detector. With the DUNE collaboration, Fermilab 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. For the DUNE detector, the process of developing in-kind contributions is being driven by the principal investigators and being reviewed by their funding agencies.

DOE funding for the LBNF/DUNE Project will be provided directly to Fermilab and collaborating DOE national laboratories via approved financial plans, and under management control of the LBNF Project Office. The LBNF Project Office will also manage and control DOE funding to the other LBNF/DUNE institutions contributing to detector design and construction. In addition to the work performed by DOE national laboratories, a combination of university subcontracts and direct fixed-price purchases with vendors is anticipated to design, fabricate, and install the LBNF and DUNE technical components. The DUNE-U.S. Project Office at Fermilab will manage and control DOE funding to the other U.S. institutions contributing to DUNE detector design and construction. All actions will be in accordance with the DOE approved procurement policies and procedures.

Much of the neutrino beamline component design, fabrication, assembly, and installation will be done by Fermilab staff or by subcontract temporary staff working directly with Fermilab personnel. The acquisition approach includes both new procurements based on existing designs, and re-purposed equipment from the Fermilab accelerator complex. Some highly specialized components will be designed and fabricated by or in consultation with long-standing Fermilab collaborators having proven experience with such components.

Delivery of LBNF conventional facilities at the Fermilab near site and SURF far site will be via the Construction Manager/General Contractor (CM/GC) model. This strategy was chosen 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.

For the LBNF near site conventional facilities at Fermilab, procurement is through existing Fermilab master subcontracts with national architect/engineering companies for design services and contracts will be incrementally phase-funded since they will span multiple years.

For the LBNF far site conventional facilities at SURF, Fermilab will work with SDSTA, the owner of the site and land, which has been donated to SDSTA by the Homestake Mining Company for the sole purpose of facilitating scientific and technological research and development. Fermilab will contract directly with SDSTA to provide pre-construction services and with an A&E firm for design of LBNF far site conventional facilities at SURF. Fermilab will solicit bids for CM/GC services to manage the construction of LBNF far site facilities. The CM/GC subcontractor will furnish all labor, equipment and materials for far site conventional facilities construction management. Work includes pre-construction construction management services and an option for executing the construction and management of the construction. The CM/GC subcontractor staff will have proven experience in the area of construction management and construction of industrial and heavy construction projects. The CM/GC firm will provide support services to the LBNF and A/E teams, including input regarding the selection of materials, building systems and equipment, construction feasibility, value engineering, and factors related to construction, plus cost estimates and schedules, including estimates of alternative designs or materials. The CM/GC will also provide recommendations of actions designed to minimize adverse effects of labor or material shortages, time requirements for procurement and installation and construction completion.

The overall approach to both near and far site enables Fermilab to gain construction management expertise early in the design phase to produce well-integrated designs and well understood constructability, with potential cost and management efficiencies and reduced construction risk as a result.

DOE has 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 provides the framework for DOE and Fermilab to construct federally funded buildings and facilities on non-federal land, and to establish a long-term (multi-decade) arrangement for DOE and Fermilab to use SDSTA space to host the DUNE experiment. Modifications, repairs, replacements, and improvements to SDSTA infrastructure will be funded by the project to ensure safe and reliable operations of the systems required to carry out the DOE mission. 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 Fermilab to have responsibility for managing and operating the LBNF and DUNE far detector and facilities for a useful lifetime of 20 year duration, 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. An appropriate decommissioning plan will be developed prior to lease signing.

11-SC-41, Muon to Electron Conversion Experiment (Mu2e), Fermi National Accelerator Laboratory, Batavia, Illinois
Project is for Design and Construction

1. Significant Changes and Summary

Significant Changes
This Construction Project Data Sheet (CPDS) is an update of the FY 2017 CPDS and does not include a new start for FY 2018.

Summary
The FY 2018 Request for the Muon to Electron Conversion Experiment (Mu2e) is $44,400,000, consistent with the approved baseline funding profile. The most recent DOE Order 413.3B approved Critical Decision (CD) is CD-3 (Approve Start of Construction) concurrent with completion of the final design, approved on July 14, 2016. In FY 2015, CD-2 established the scope, cost, and schedule baseline and CD-3B initiated civil construction and long-lead procurement of the Transport Solenoid modules. Total Project Cost was approved at $273,677,000. The funding profile supports this TPC. The CD-4 milestone is 1Q FY 2023.

A Federal Project Director with Certification Level 2 has been assigned to this project and has approved this CPDS. The FPD will complete the Level-3 Certification requirements in FY 2017.

The Mu2e project provides the accelerator beam and experimental apparatus to unambiguously identify neutrinoless muon-to-electron conversion events. The conversion of a muon to an electron in the field of a nucleus would probe new physics for discovery at mass scales far beyond the reach of any existing or proposed experiment. Civil construction was completed in FY 2017. Throughout FY 2017 and FY 2018, procurement and fabrication activities for the accelerator, beamline, superconducting magnets and particle detector technical systems will continue.

2. Critical Milestone History

(fiscal quarter or date)

	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	D&D Complete	CD-4
FY 2011	11/24/2009		4Q FY 2010	TBD	4Q FY 2012	TBD	TBD	TBD
FY 2012	11/24/2009		4Q FY 2011	TBD	4Q FY 2013	TBD	TBD	TBD
FY 2013	11/24/2009		4Q FY 2012	4Q FY 2013	4Q FY 2014	4Q FY 2014	N/A	4Q FY 2018
FY 2014	11/24/2009		7/11/2012	2Q FY 2014	2Q FY 2015	4Q FY 2015	N/A	2Q FY 2021
FY 2013 Repro-gramming	11/24/2009		7/11/2012	2Q FY 2014	2Q FY 2015	4Q FY 2015	N/A	2Q FY 2021
FY 2015	11/24/2009		7/11/2012	4Q FY 2014	2Q FY 2015	4Q FY 2014	N/A	2Q FY 2021
FY 2016	11/24/2009	7/11/2012	7/11/2012	2Q FY 2015	3Q FY 2016	3Q FY 2016	N/A	1Q FY 2023
FY 2017 PB	11/24/2009	7/11/2012	7/11/2012	3/4/2015	3Q FY 2016	3Q FY 2016	N/A	1Q FY 2023
FY 2018	11/24/2009	7/11/2012	7/11/2012	3/4/2015	7/14/2016	7/14/2016	N/A	1Q FY 2023

CD-0 – Approve Mission Need
Conceptual Design Complete – Actual date the conceptual design was completed
CD-1 – Approve Design Scope and Project Cost and Schedule Ranges
CD-2 – Approve Project Performance Baseline
Final Design Complete – Estimated/Actual date the project design will be/was completed
CD-3 – Approve Start of Construction
D&D Complete – Completion of D&D work (see section 9)
CD-4 – Approve Start of Operations or Project Closeout
PB – Indicates the Performance Baseline

	Performance Baseline Validation	CD-3A	CD-3B	CD-3(C)
FY 2014		3Q FY 2013		
FY 2013 Reprogramming		3Q FY 2013		
FY 2015		3Q FY 2014		
FY 2016	2Q FY 2015	7/10/2014	2Q FY 2015	3Q FY 2016
FY 2017 PB	3/4/2015	7/10/2014	3/4/2015	3Q FY 2016
FY 2018	3/4/2015	7/10/2014	3/4/2015	7/14/2016

CD-3A – Approve Long-Lead Procurement of superconducting wire for the magnet systems.
CD-3B – Approve Long-Lead Procurement for superconducting solenoid magnet modules and for construction of the detector hall.
CD-3(C) – Approve All Construction and Fabrication (same as CD-3)

3. Project Cost History

(dollars in thousands)

	TEC, Design	TEC, Construction	TEC, Total	OPC Except D&D	OPC, D&D	OPC, Total	TPC
FY 2011	35,000	TBD	TBD	10,000	TBD	TBD	TBD
FY 2012	36,500	TBD	TBD	18,777	TBD	TBD	TBD
FY 2013	44,000	N/A	N/A	24,177	0	24,177	68,177
FY 2014	61,000	162,000	223,000	26,177	0	26,177	249,177
FY 2013 Reprogram-ming	49,000	162,000	211,000	23,677	0	23,677	234,677
FY 2015	47,000	162,900	209,900	23,677	0	23,677	233,577
FY 2016	57,000	193,000	250,000	23,677	N/A	23,677	273,677
FY 2017 PB	57,000	193,000	250,000	23,677	N/A	23,677	273,677[a]
FY 2018	60,598[b]	189,402	250,000	23,677	N/A	23,677	273,677

4. Project Scope and Justification

Scope

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

[a] No construction, other than approved long-lead procurement and detector hall civil construction, was performed prior CD-3 approval.
[b] Increased final design development work in FY 2016 reduced the estimated construction cost with modest delay of final design completion and Critical Decision CD-3.

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

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

Justification

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

Key Performance Parameters

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

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

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

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

5. Financial Schedule

	(dollars in thousands)		
	Appropriations	Obligations	Costs[a]
Total Estimated Cost (TEC)			
Design			
FY 2013	N/A	N/A	14,653
FY 2014	N/A	N/A	15,404
FY 2015	N/A	N/A	16,892
FY 2016	N/A	N/A	13,649
Total, Design	N/A	N/A	60,598
Construction			
FY 2014	N/A	N/A	0
FY 2015	N/A	N/A	9,907
FY 2016	N/A	N/A	24,300
FY 2017	N/A	N/A	40,000
FY 2018	N/A	N/A	40,000
FY 2019	N/A	N/A	40,000
FY 2020	N/A	N/A	24,000
FY 2021	N/A	N/A	10,000
FY 2022	N/A	N/A	1,195
Total, Construction	N/A	N/A	189,402
TEC			
FY 2012	24,000	24,000	0
FY 2013	8,000[b]	8,000	14,653
FY 2014	35,000[c]	35,000	15,404
FY 2015	25,000[d]	25,000	26,799
FY 2016	40,100	40,100	37,949
FY 2017	43,500	43,500	40,000
FY 2018	44,400	44,400	40,000
FY 2019	30,000	30,000	40,000
FY 2020	0	0	24,000
FY 2021	0	0	10,000
FY 2022	0	0	1,195
Total, TEC	250,000	250,000	250,000
Other Project Costs (OPC)			
OPC except D&D			
FY 2010	4,777	4,777	3,769
FY 2011	8,400	8,400	8,940

[a] Costs through FY 2016 reflect actual costs; costs for FY 2017 and the outyears are estimates.
[b] Congress approved a reprogramming that reduced the FY 2013 funding to $8,000,000 from the $22,685,000 that was originally appropriated.
[c] $5,162,907 was for long-lead procurements of superconducting wire for the magnet systems.
[d] $25,000,000 was for long-lead procurements for the superconducting solenoid magnet modules and for civil construction of the detector hall.

	(dollars in thousands)		
	Appropriations	Obligations	Costs[a]
FY 2012	8,000	8,000	6,740
FY 2013	2,500	2,500	1,020
FY 2014	0	0	2,136
FY 2015	0	0	159
FY 2016	0	0	252
FY 2017	0	0	661
Total, OPC	23,677	23,677	23,677
Total Project Cost (TPC)			
FY 2010	4,777	4,777	3,769
FY 2011	8,400	8,400	8,940
FY 2012	32,000	32,000	6,740
FY 2013	10,500	10,500	15,673
FY 2014	35,000	35,000	17,540
FY 2015	25,000	25,000	26,958
FY 2016	40,100	40,100	38,201
FY 2017	43,500	43,500	40,661
FY 2018	44,400	44,400	40,000
FY 2019	30,000	30,000	40,000
FY 2020	0	0	24,000
FY 2021	0	0	10,000
FY 2022	0	0	1,195
Total, TPC	273,677	273,677	273,677

6. Details of Project Cost Estimate

	(dollars in thousands)		
	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design			
Design	60,598	52,000	49,000
Contingency	0	5,000	8,000
Total, Design	60,598	57,000	57,000
Construction			
Site Work	2,000	2,000	2,000
Construction	13,000	13,000	13,000
Equipment	129,400	133,000	133,000
Contingency	45,002	45,000	45,000
Total, Construction	189,402	193,000	193,000
Total, TEC	250,000	250,000	250,000
Contingency, TEC	45,002	50,000	53,000
Other Project Cost (OPC)			
OPC except D&D			
R&D	8,200	8,200	8,200
Conceptual Planning	2,300	2,300	2,300
Conceptual Design	13,177	13,177	13,177
Total, OPC	23,677	23,677	23,677

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total, TPC	273,677	273,677	273,677
Total, Contingency	45,002	50,000	53,000

7. Schedule of Appropriation Requests

(dollars in thousands)

Request Year		Prior Years	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	Total
FY 2011	TEC	5,000	30,000	0	0	0	0	0	0	0	35,000
	OPC	10,000	0	0	0	0	0	0	0	0	10,000
	TPC	15,000	30,000	0	0	0	0	0	0	0	45,000
FY 2012	TEC	0	24,000	12,500	0	0	0	0	0	0	36,500
	OPC	12,777	6,000	0	0	0	0	0	0	0	18,777
	TPC	12,777	30,000	12,500	0	0	0	0	0	0	55,277
FY 2013	TEC	0	24,000	20,000	0	0	0	0	0	0	44,000
	OPC	13,177	6,000	5,000	0	0	0	0	0	0	24,177
	TPC	13,177	30,000	25,000	0	0	0	0	0	0	68,177
FY 2014	TEC	0	24,000	24,147	35,000	32,000	44,000	45,000	23,000	0	223,000
	OPC	13,177	8,000	8,049	0	0	0	0	0	0	26,177
	TPC	13,177	32,000	32,196[a]	35,000	32,000	44,000	45,000	23,000	0	249,177
FY 2013 Repro-gram-ming	TEC	0	24,000	8,000[b]	35,000	32,000	44,000	45,000	23,000	0	211,000
	OPC	13,177	8,000	2,500	0	0	0	0	0	0	23,677
	TPC	13,177	32,000	10,500	35,000	32,000	44,000	45,000	23,000	0	234,677
FY 2015	TEC	0	24,000	8,000	35,000	25,000	42,000	43,000	32,900	0	209,900
	OPC	13,177	8,000	2,500	0	0	0	0	0	0	23,677
	TPC	13,177	32,000	10,500	35,000	25,000	42,000	43,000	32,900	0	233,577
FY 2016	TEC	0	24,000	8,000	35,000	25,000	40,100	43,500	44,400	30,000	250,000
	OPC	13,177	8,000	2,500	0	0	0	0	0	0	23,677
	TPC	13,177	32,000	10,500	35,000	25,000	40,100	43,500	44,400	30,000	273,677
FY 2017 PB	TEC	0	24,000	8,000	35,000	25,000	40,100	43,500	44,400	30,000	250,000
	OPC	13,177	8,000	2,500	0	0	0	0	0	0	23,677
	TPC	13,177	32,000	10,500	35,000	25,000	40,100	43,500	44,400	30,000	273,677
FY 2018	TEC	0	24,000	8,000	35,000	25,000	40,100	43,500	44,400	30,000	250,000
	OPC	13,177	8,000	2,500	0	0	0	0	0	0	23,677
	TPC	13,177	32,000	10,500	35,000	25,000	40,100	43,500	44,400	30,000	273,677

8. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy	FY 2023
Expected Useful Life	10 years

[a] The FY 2013 amount shown reflected the P.L. 112-175 continuing resolution level annualized to a full year. The TEC, OPC, and TPC total and outyear appropriation assumptions were not adjusted to reflect the final FY 2013 level; the FY 2013 Request level of $25,000,000 ($20,000,000 TEC and $5,000,000 OPC) were assumed instead.

[b] Congress approved a reprogramming that reduced the FY 2013 funding to $8,000,000 from the $22,685,000 that was originally appropriated.

Expected Future Start of D&D of this capital asset	FY 2033

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

(Related Funding Requirements)

(dollars in thousands)

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

9. Required D&D Information

	Square Feet
Area of new construction	~25,000
Area of existing facility being replaced and D&D'd by this project	0
Area of other D&D outside the project	0
Area of any additional D&D space to meet the "one-for-one" requirement taken from the banked area.	~25,000

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

10. Acquisition Approach

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

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

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

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

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