Mission Need Statement
for

HL-LHC Accelerator Upgrade

Non-Major Acquisition Project

Office of High Energy Physics
Office of Science
U.S. Department of Energy

Date Approved:
March 2016

Mission Need Statement
HL-LHC Accelerator Upgrade

Submitted by:

Bruce P. Strauss, Program Manager
Office of High Energy Physics, Office of Science, DOE

Date: 12-17-15

Michael Procario, Director of Facilities Operation
Office of High Energy Physics, Office of Science, DOE

Date: 12-18-15

James Siegrist, Associate Director
Office of High Energy Physics
Office of Science, DOE

Date: 12/21/15

Concurrence:

Stephen W. Meador, Director
Office of Project Assessment, Office of Science, DOE

Date: 12/22/15

Patricia Dehmer, Deputy Director for Science Programs
Office of Science, DOE

Date: 3/7/2016

Approval:

Cherry Murray, Director
Office of Science

Date: 3/7/2016

1. STATEMENT OF MISSION NEED

The mission of the Department of Energy (DOE) is to advance the energy, environmental, and nuclear security of the United States; promote scientific and technological innovation in support of that mission; and ensure the environmental cleanup of the national nuclear weapons complex. The DOE Strategic Plan 2014-2018 includes the following goals and objectives that are relevant to this mission:

Goal 1: **Science and Energy**	*Strategic Objective 3 – Deliver the scientific discoveries and major scientific tools that transform our understanding of nature and strengthen the connection between advances in fundamental science and technology innovation*

The mission of the Office of Science (SC) is to deliver the scientific discoveries and major scientific tools that transform our understanding of nature and advance the energy, economic, and national security of the United States. SC accomplishes this mission through direct support of research, construction, and operation of national scientific user facilities, and the stewardship of ten world-class national laboratories. The SC national laboratories collectively comprise a preeminent federal research system that develops unique, often multidisciplinary, scientific capabilities beyond the scope of academic and industrial institutions, to benefit the nation's researchers and national strategic priorities.

The mission of the High Energy Physics (HEP) program is to understand how the universe works at its most fundamental level by discovering the elementary constituents of matter and energy, probing the interactions between them, and exploring the basic nature of space and time. 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.

The experimental HEP program is focused on three frontiers of scientific discovery: the Energy, Intensity, and Cosmic Frontiers. At the Energy Frontier, powerful accelerators are used to create new particles, reveal their interactions, and investigate fundamental forces. The only Energy Frontier facility presently operating is the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN). Located near Geneva, on the border of Switzerland and France, CERN is the largest particle physics laboratory in the world and has twenty-one Member States . In May 2015, CERN and the U.S. signed a scientific and technical cooperation agreement that renewed the framework for continued U.S. involvement in the LHC program.

The DOE HEP program provided major material support to the original construction of the LHC ring by constructing the superconducting magnet systems for the final focusing of the proton beams at the CMS and ATLAS detectors. The DOE-delivered systems consisted of half of the quadrupole magnet cold masses, cryostats for all of the superconducting quadrupole cold masses, beam separation dipoles known as D1s, cryogenic feed boxes, and collimators. The LHC successfully completed its initial three year run in 2012 at center-of-mass energies of 7–8 TeV, reaching a peak luminosity of 7.7×10^{33} $cm^{-2}s^{-1}$ and resumed operations in 2015 at energies of 13–14 TeV with planned increases to luminosities of $2–3 \times 10^{34}$ $cm^{-2}s^{-1}$ through 2023.

CERN's long term plan for the LHC facility is to implement a High Luminosity upgrade of the LHC (HL-LHC) to begin operations in the middle of the next decade with levelled luminosities reaching 5–7.5 x 10^{34} $cm^{-2}s^{-1}$, delivered luminosity of 3000-4000 fb^{-1} (around 10 times the planned delivered luminosity up to 2023). In order to achieve this major luminosity upgrade, changes will be need to the focusing systems of the accelerator as well as increases in the number of protons stored in the machine.

In May 2014, the U.S. HEP program completed its long-term strategic plan through the Particle Physics Project Prioritization Panel (P5), a subpanel of the High Energy Physics Advisory Panel (HEPAP). The P5 plan for Energy Frontier recommended that U.S. actively continue its participation in the LHC program at CERN, and specifically, in the planned HL-LHC upgrades for accelerator and detectors, designating it as the "highest-priority near-term large project". The recommendation is motivated by the fact that the HL-LHC will offer unique physics opportunities that address key science drivers identified by P5 for particle physics. This Mission Need Statement motivates the need for the U.S. to continue to be a leader and major contributor to the LHC facility and the HL-LHC, which will boost the luminosity and extend the discovery reach for new physics for the next two decades.

2. CAPABILITY GAP/MISSION NEED

Capability Gap

The primary motivation of the LHC research program is to study very high energy collisions in order to probe fundamental particles and their interactions at extreme conditions such as those present during the early stages of the universe. Two methods can increase the rate of the collisions of interest. The first is to increase the energy of the accelerating beams, which increases the maximum energy collision that can be generated. Another method is to increase the beam brightness, which requires the use of very high intensity beams. Intensity can be increased by either increasing the number of particles being accelerated or concentrating theminto a smaller point. A familiar analogy using light would be to increase the brightness of the lamp or to use a magnifying glass to focus the light. Increasing the brightness of the beams increases the particle collision rate for all energies such that they can be selected for further study.

In order to achieve the goals of the LHC research program, it will be necessary to increase both the energy of the accelerator and the brightness of the colliding beams. The LHC is now operating at a center of mass collision energy of 13 TeV and it is expected that in the near future (Run 2 & Run 3, by 2019) the energy can be increased to the design energy of 14 TeV. Increasing the beam brightness is more challenging. Over a period of two and a half years in 2024 to 2026, an upgrade to the LHC will be installed (HL-LHC). After this work, the beam brightness will be approximately three times higher than is currently possible. The expected instantaneous luminosity, which is the technical term for beam brightness, is expected to have an ultimate value of 7.5 x 10^{34} $cm^{-2}s^{-1}$.

The increase from 2–3 x 10^{34} $cm^{-2}s^{-1}$ through 2023 to an ultimate value of 7.5 x 10^{34} $cm^{-2}s^{-1}$ in 2026 is the capability gap described in this Mission Need.

The priority of fulfilling the mission need relative to other programs

In 2014, the HEPAP/P5 strategic plan identified continued U.S. participation in the LHC physics program as central to the U.S. particle physics research enterprise and specifically recommended support for the HL-LHC upgrades both in the accelerator and detectors arena as the highest priority large-category project for the U.S. HEP program in the near-term.

Benefits from Closing the Gap

The high energy and luminosity available at the LHC offers singular opportunities for exploration of new physics beyond the Standard Model and for making precision measurements of properties of known phenomena. There is no other comparable facility in the world; participation in the LHC is the only pathway for U.S. scientists to be at the forefront of Energy Frontier experimental research.

Experiments at the LHC completed their first successful run in 2012 that highlighted the discovery of the long-sought Higgs boson particle. The experiments continue to collect data and are therefore poised to extend the discovery potential that will change our fundamental understanding of nature. As identified by the 2014 P5 plan, continuing strong U.S. participation in the full exploitation of the LHC is an integral part of the U.S. HEP program. Currently, approximately 1,200 physicists from U.S. institutions conduct research as collaborators on ATLAS and CMS, and an additional 400–500 technical staff and engineers lead operations for the experiments as well as design and build critical components for the detectors. In addition, approximately 100 physicists and engineers are contributing to the development of accelerator elements. Given the broad experience gained during both the original construction project and the ongoing LHC runs as well as R&D conducted by the U.S. LHC Accelerator Research program (LARP), U.S. physicists, technicians and engineers are in a unique position to contribute to the future LHC program in the best possible way while maintaining the leadership role the U.S. has had over the past two decades.

DOE support of the HL-LHC upgrade with emphasis on the final focus magnet system would enable the U.S. scientific community to remain at the forefront of accelerator science and technology and enable U.S. scientists' continued pursuit of the prime mission of the HEP program.

Other Potential Capabilities

There are no other facilities in the world capable of addressing the fundamental physics research questions described above. The LHC is a machine of singular capabilities that has no current peer.

Impact if Gap is Not Resolved

The DOE's High Energy Physics program has invested in the construction and operations of the LHC and is a major participant and contributor in the physics research that the ATLAS and CMS detectors enable. If the U.S. fails to contribute to the HL-LHC High Luminosity upgrade, the ability of U.S. scientists to participate in future Energy Frontier physics would be severely impaired.

Internal/External Drivers

As described above, the HEPAP P5 report is a major driver to close the capability gap because it signifies the U.S. particle physics community's consensus opinion that continuing research at the Energy Frontier has the potential for extremely high impact on the course of the science.

3. POTENTIAL APPROACH

Because of the uniqueness of the LHC capabilities (described above) and CERN's existing plan to undertake an upgrade, the potential approaches described here focus on potential U.S. participation in that project.

The upgrade schedule defined by CERN for the HL-LHC and subsequent operation during the HL-LHC period severely constrains the schedule for the U.S. contribution to the HL-LHC. A subsequent 30-month long shutdown is planned to begin in 2024, which will result in the LHC delivering much higher luminosities of 5–7.5 x 10^{34} $cm^{-2}s^{-1}$ during the HL-LHC period from 2026–2035. Such operating conditions are enabled by the upgrade of critical machine elements described in the following and for which the U.S. scientist have critical expertise:

Interaction Region Focusing Magnets: A classical route for a luminosity upgrade is to reduce β^*, a quantity related to the transverse size of the beam at the interaction point. Values of β^* of 5-15 cm can be envisaged in the HL-LHC, down from the present nominal value of 55 cm. However a reduction in β^* values implies larger beam sizes, and therefore larger bore of 150 mm, in the final focusing magnets and because these are quadrupoles a concurrent increase in their peak field of 50% above the magnets presently employed at the LHC. This criterion implies the use of new superconducting technology for the construction of larger bore quadrupoles in the HL-LHC.

Crab Cavities: The drawback of very small β^* is that it also requires a larger crossing angle. This causes a reduction of the geometrical luminosity. The most efficient and elegant solution for compensating the geometric reduction factor is the use of 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. Crab cavities allow access to the full performance reach of the small β^* values offered by the larger quadrupole magnets.

Hollow-electron lens: At high beam intensities, such as those planned for the HL-LHC, beam halo must be kept under strict control to avoid unwanted beam losses and subsequent unwanted magnet quenches. The hollow-electron lens consists of a hollow electron beam, running parallel to the proton or ion beam that is on the axis of a cylindrical layer of electron. This hollow beam produces an electromagnetic field affecting only halo particles above a given transverse amplitude and can change their transverse speed, removing them from the beam in a controlled fashion.

The planned shutdown during 2024–2026, specifically aimed at the establishment of the HL-LHC era, is the time at which the above-mentioned U.S. contributions will maximize the exploitation of the physics opportunities afforded by the machine upgrades.

There are few options available for DOE to participate in the HL-LHC upgrade. DOE could participate through:

Option 1 Develop a suite of in-kind contributions that utilize the expertise of the U.S. accelerator community including the national laboratories. These contributions should be in a form that utilizes U.S. expertise that CERN does not already have. This option best addresses the goals and priorities for HEP at the Energy Frontier outlined by the 2014 P5 strategic plan including the international partnership of the U.S. on the LHC program at CERN.

Option 2 Provide CERN with cash payments for contributions to the upgrade or pay annual operating costs to CERN during the operation of the HL-LHC. Currently, the U.S. does not have a comparable user facility in particle physics to host European researchers, so the historical reciprocal relationship whereby facilities in different global regions hosted foreign users without charging user fees or operating costs no longer exists. This cash payment option does nothing to advance the skills of the U.S. accelerator building community and may slow the upgrade of the HL-LHC since the U.S. is currently ahead of CERN in high field superconducting magnet technology.

Option 3 Do nothing. This option would severely impact the international partnership of the U.S. on the LHC program at CERN and would result in HEP being unable to maintain a meaningful Energy Frontier research program, which P5 affirms is necessary for mission success. This approach could also impede the U.S.-hosted Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment, which depends on contributions of cryogenic infrastructure from CERN. It is also possible that this approach could damage the U.S.'s standing in the international scientific community.

Based on this analysis it is the preliminary judgment that Option 1 would provide the highest benefit to the DOE and to U.S. scientists.

Environmental, Safety and Health

All work at DOE sites will be conducted under DOE-approved Integrated Safety Management System (ISMS). All facilities will comply with the requirements of the National Environmental Policy Act (NEPA). Based on the nature of the projects, and their planned locations at an existing laboratory, impacts to the environment are anticipated to be minimal. For locations in foreign countries, the ES&H policies of the host country will be observed.

Cost Risks

The cost risks are well known because the HL-LHC project is likely to embrace upgrades to existing technology previously developed through HEP-funded activities. In early 2000, HEP recognized that an increase in luminosity for the LHC was necessary to cope with future demands from the experimental programs. DOE initiated a long-term R&D program, the

Conductor Development Program (CDP), to increase the performance of niobium-tin (Nb_3Sn), a superconductor capable of exceeding the limits of the presently employed niobium-titanium (NbTi). In addition DOE initiated the LHC Accelerator Research Program (LARP) with the main goal of developing the next generation of focusing magnets. Both programs proved extremely successful and have positioned the U.S. to lead the field of high-field magnets for accelerators and enable the HL-LHC project. HEP believes that the CDP and LARP programs have already successfully mitigated many of the cost risks associated with a potential U.S. hardware contribution to the HL-LHC through a thorough technology evaluation program that has been going on for several years and has included building a series of larger and more refined prototypes.

Schedule Risks

CERN Council has approved the HL-LHC, and CERN has established a schedule for HL-LHC project with installation of components planned to start in FY 2024, so now is the appropriate time to begin our planning for a contribution. The HL-LHC project will be closely coordinated with CERN's operations schedule of the LHC. As part of regular HEP oversight of the Energy Frontier program and the ATLAS and CMS Operations and Upgrade programs, HEP is in regular communication with CERN management and is well informed of CERN plans for operations and upgrades. Superconducting cable for magnet fabrication requires long-lead times, at least 12 months, for procurement. The DOE national laboratories had experience with these types of procurements from the U.S. LHC Accelerator Project and LARP.

Safeguards and Security

DOE contributions to experiments would be managed by DOE national laboratories with existent safeguards and security policies and procedures.

There may be International Traffic in Arms Regulations (ITAR) controlled parts of the scientific instrumentation. DOE national laboratories have extensive experience in dealing with the ITAR regulations and no issues are foreseen. A majority of the scientific and technical work is expected to fall under the fundamental research exemption of ITAR.

4. RESOURCE AND SCHEDULE FORECAST

4.1 Cost Forecast

Under Options 1 and 2 the DOE contribution to the HL-LHC project would be funded as a Major Item of Equipment (MIE). The cost forecast provided here is given for Option 1 in which DOE contributes in-kind hardware to the HL-LHC Upgrade. The preliminary DOE Total Project Cost (TPC) range is $180–250 million in then-year dollars.

HEP's experience with the original LHC project, the existing LHC facilities, and successful execution of the initial U.S. Contribution to the LHC provides the basis for estimating a U.S. contribution to HL-LHC Upgrade.

4.2 Schedule Forecast

The current estimated dates for major milestones are:

Critical Decisions (CD)	*Fiscal Year*
CD-0, Approve Mission Need	*FY 2016*
CD-1, Approve Alternative Selection and Cost Range	*FY 2017*
CD-3a, Approve Purchase of Long-Lead Items	*FY 2017*
CD-2, Approve Performance Baseline	*FY 2018*
CD-3, Approve Start of Construction	*FY 2018*
CD-4, Approve Project Completion	*FY 2026*

4.3 Funding Forecast

The funding profile shown below supports the TPC of the project cost estimate.

DOE Funding Plan: HL-LHC Upgrade Project (AY$ Millions)									
Fiscal Year	*FY 2017*	*FY 2018*	*FY 2019*	*FY 2020*	*FY 2021*	*FY 2022*	*FY 2023*	*FY 2024*	*Total ($M)*
Total Project Cost (TPC)	*0.5*	*15.0*	*31.0*	*46.5*	*39.0*	*25.0*	*25.0*	*18.0*	*$200.0*

Critical Decision 0, Approve of Mission Need
High Luminosity LHC (HL-LHC) Accelerator Upgrade Project

Recommendations:

The undersigned "Do Recommend" (Yes) or "Do Not Recommend" (No) approval of CD-0, for the HL-LHC Accelerator Upgrade Project.

4/13/16 Yes ✓ No____
ESAAB Secretariat, Office of Project Assessment — Date

4/13/16 Yes ✓ No____
Representative, Office of Budget — Date

Yes____ No____
Representative, Safety and Security Policy (ES&H) — Date

4/5/2016 Yes ✓ No____
Representative, Safety and Security Policy (Security) — Date

4/13/16 Yes ✓ No____
Representative, Operations Program Management (Facilities and Infrastructure) — Date

4/13/16 Yes ✓ No____
Representative, Non-Proponent SC Program Office — Date

4/13/16 Yes ✓ No____
Representative, Non-Proponent Federal Project Director — Date

Concurrence:

4/13/2016
Patricia M. Dehmer — Date
Deputy Director for Science Programs
Office of Science

Critical Decision 0, Approve of Mission Need
High Luminosity LHC (HL-LHC) Accelerator Upgrade Project

Approval:

Based on the information presented in this approval document and at ESAAB Equivalent Review, CD-0, Approve Mission Need, for the HL-LHC Accelerator Upgrade project is approved.

C. A. Murray, Project Management Executive
Director
Office of Science

4/13/2016
Date