Mission Need Statement
for

Proton Improvement Plan-II (PIP-II)
Fermilab

Non-major acquisition project

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

Date Approved:

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Mission Need Statement
Proton Improvement Plan-II (PIP-II)

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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. 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.

In September 2013, the DOE and the National Science Foundation (NSF) charged the High Energy Physics Advisory Panel (HEPAP) to convene a Particle Physics Project Prioritization Panel (P5) in order to develop a ten-year strategic plan for U.S. high energy physics in the context of a 20-year global vision. In May 2014, HEPAP unanimously approved the P5 report and its recommendations. The report provides a practical, long-term strategy that enables discovery and maintains the U.S. position as a global leader in particle physics. The DOE accepted the recommendations in the P5 report and is committed to implementing a successful program based on this new vision. Consistent with the P5 report, a centerpiece of the HEP program strategy is exploration of neutrino physics.

Fermi National Accelerator Laboratory (Fermilab) is the Department's single-purpose particle physics and accelerator laboratory. Fermilab's vision is to lead the world in neutrino science with particle accelerators, lead the nation in the development of particle colliders and their use for scientific discovery, and advance particle physics through measurements of the cosmos. The Fermilab Accelerator Complex currently hosts two neutrino beams, including the world's most intense neutrino beam, called Neutrinos at the Main Injector (NuMI). Fermilab's three core capabilities—particle physics, accelerator science and large scale user facilities/advanced instrumentation/computing—uniquely combine to support the DOE Office of Science's mission to foster, formulate and support forefront basic research programs that advance the fundamental understanding of matter and energy.

The U.S. currently occupies a leading position in the exploration of neutrino properties based on the research program at Fermilab, including the MINOS long baseline experiment and the state-of-the-art experiment, NOvA, now in operation. MINOS and NOvA use neutrino beams generated from a target that is driven by proton beam with a power that reaches up to 700 kW.

2. CAPABILITY GAP/MISSION NEED

The current neutrino beam production capabilities at Fermilab are insufficient for the further study of neutrino physics called for by the HEP Strategic plan developed by the HEPAP subpanel, the Particle Physics Project Prioritization Panel (P5). Three critical parameters remain to be determined in order to form a complete understanding of neutrino physics: a remaining mixing strength (parameterized as "θ_{13}"); the mass ordering of the three types of neutrino; and the search for matter-antimatter asymmetry (parameterized as "CP violating phase δ").

Since the acceptance of the P5 report by DOE HEP, the world high energy physics community has come together to form the Deep Underground Neutrino Experiment (DUNE), an experimental research collaboration that plans to build and operate a detector deep underground at the Sanford Underground Research Facility (SURF), in South Dakota. The *European Strategy for Particle Physics Update 2013*[1] recommended that European physicists collaborate with either the U.S. or Japan rather than build a neutrino experiment in Europe. This recommendation and the subsequent P5 recommendation to increase the power of the LBNF neutrino beam encouraged a strong European involvement in DUNE. The DUNE collaboration currently includes 144 institutions in 26 countries.

The Long Baseline Neutrino Facility (LBNF) will support DUNE in both Illinois and South Dakota. Fermilab, as host laboratory, will produce the neutrinos and house the neutrino detector for DUNE, along with a small number of international partners that includes CERN. In all, DOE will provide the majority contribution to LBNF and a minority contribution to DUNE. Together, the DOE contributions to LBNF and DUNE

[1] https://council.web.cern.ch/council/en/EuropeanStrategy/esc-e-106.pdf

comprise a single project in terms of DOE Order 413.3B, called "LBNF/DUNE." LBNF/DUNE has been granted CD-1 for a configuration that includes a liquid argon detector with an initial mass of 10 kton, growing eventually to 40 kton.

The performance of LBNF/DUNE is determined by four factors: the proton beam power delivered to the neutrino production target; the neutrino spectrum; the mass and technology deployed in the detector; and the distance from Fermilab to SURF. With the neutrino spectrum generated by a target driven by beam from the Fermilab Main Injector, P5 established an intermediate term goal of 120 MW-kton-years in a liquid argon detector, delivered by 2035. A fully definitive exploration of CP violation in the neutrino sector is expected to require 500 MW-kton-years.

The current beam power of 700 kW is insufficient to meet the P5 goal of delivering 120 MW-kton-years by 2035. Increasing the beam power to 1.2 MW would roughly double the DUNE data-taking rate, significantly increasing the competitive edge of the experiment by halving the time it would take to achieve significant scientific results. This in turn raises the probability that the U.S. neutrino physics program will continue to outperform the Japanese program – the closest competitor – in the 2020s.

This need for higher proton beam power comes at a time when many components of the existing Fermilab accelerator complex that delivers beam to the Main Injector – especially the linear accelerator (linac) and the Booster – are approaching 50 years old. Thus, a proton beam power upgrade is proposed to meet two main capability gap and mission need goals:

1. To reduce the time for LBNF/DUNE to achieve world-first results
2. To sustain high reliability operation of the Fermilab accelerator complex.

3. POTENTIAL APPROACH

Fermilab proposes to enhance its accelerator complex to deliver higher-power proton beams to the neutrino-generating target that serves the LBNF/DUNE program, enabling a capability of 1.2 MW on target at 120 GeV, a significant increase beyond the current capability of 700 kW beam power on target at 120 GeV. This will be accomplished by replacing the current 400 MeV linac with an entirely new 800 MeV linac. A beam power capability of 1.2 MW (at 120 GeV) is not possible without the new linac.

Fermilab has named its proposal the Proton Improvement Plan II (PIP-II), a name that may be somewhat confusing. The original Proton Improvement Plan – a series of equipment refurbishments to improve the reliability of the Fermilab accelerator complex – fell below the thresholds for DOE Order 413.3b. The new proposal, PIP-II, would be a line item construction project. We continue to use the name PIP-II for this proposed effort due to its widespread use in the community, and its use in P5 recommendations and comments.

PIP-II will enable Fermilab to better meet Strategic Objective 3 from the DOE Strategic Plan 2014-2018, which is to:

> "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."

PIP-II directly employs one of the three strategies called out to meet that objective:

> "Provide the nation's researchers with world-class scientific user facilities that enable mission-focused research and advance scientific discovery."

Furthermore, it indirectly employs a second strategy by supporting the LBNF/DUNE program:

> "Conduct discovery-focused research to increase our understanding of matter, materials and their properties through partnerships with universities, national laboratories, and industry."

PIP-II thereby addresses two of the missions of the High Energy Physics (HEP) program:

> "to illuminate and answer questions about the unification of the forces of nature, the nature and origin of dark energy and dark matter, and the origins of the universe,"

and

> "to deliver scientific breakthroughs and extend our knowledge of the natural world by capitalizing on the capabilities available at the national laboratories, and through partnerships with universities and industry."

The centerpiece of the PIP-II proposal is the design and construction of a new 800 MeV superconducting proton linac that would replace the current 400 MeV normal-conducting linac. Doubling the energy of the beam that is injected from the linac into the Booster significantly ameliorates the space-charge effects that limit the maximum bunch charge that can be transferred. The higher-energy linac would enable the on-target delivery of more than 1 MW of beam power from the Main Injector over an energy range from 60 GeV to 120 GeV.

The PIP-II proposal also includes upgrades further down the injection chain, including:

1. A new Booster injection area.
2. Increasing the repetition rate of the Booster from 15 Hz to 20 Hz.
3. Enhanced (or new) transition-crossing systems in the Booster and Main Injector.
4. New or upgraded RF systems in the Booster, Recycler and Main Injector.

PIP-II capabilities conform with a potential future Booster replacement that could deliver 2.4 MW at 120 GeV to the LBNF/DUNE target, as also recommended by P5. The evaluation of the implications of such a Booster replacement would be considered as part of the CD-1 approval process.

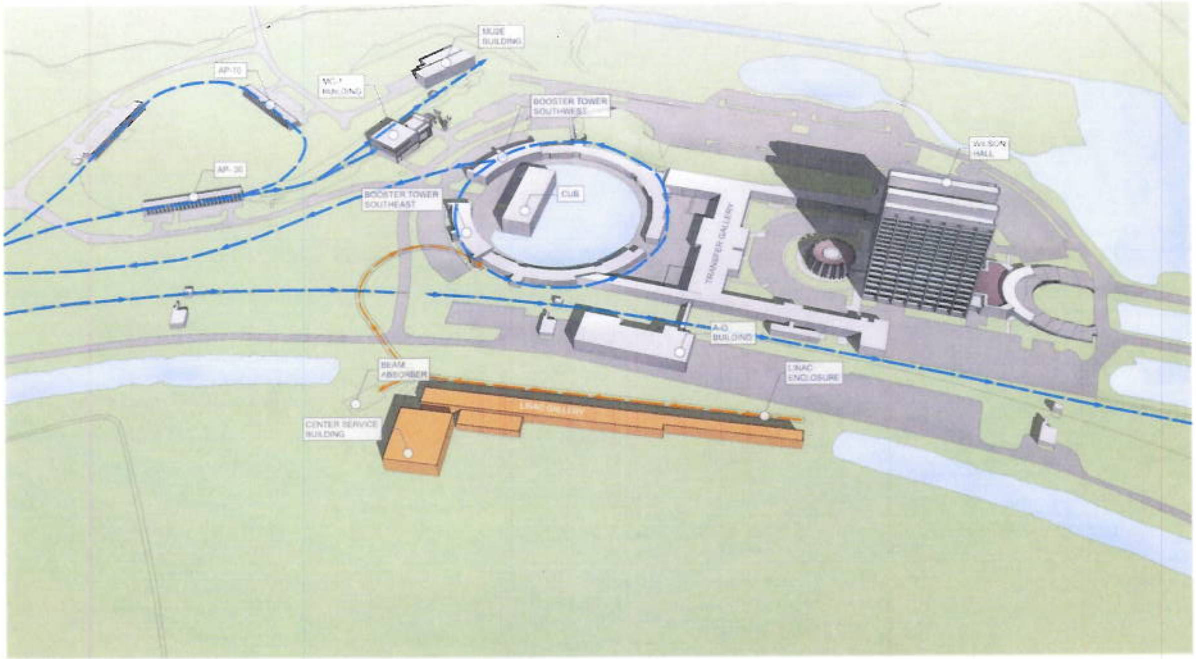
The reference design for the PIP-II linac is compatible with future operation in a continuous- waveform (CW) mode, providing the potential for a broader spectrum of upgrade possibilities after PIP-II and a possible Booster replacement. Nonetheless, a potential alternative that could be considered as part of the CD-1 approval process is a purely pulsed linac design that is incapable of CW operation. Similar high-performance superconducting linacs have been built and are in operation (for example at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory), or are being built (for example at the European Spallation Source (ESS) in Sweden). The SNS and the ESS provide a proven technology basis, making PIP-II a state-of-the-art project with moderate technical risk. Nonetheless, there remains a need for R&D leading to the technical fabrication of PIP-II custom prototypes and to the verification of required component performance.

Physicists in India have been interested in developing high power proton linacs, and Fermilab has been discussing this topic with several Indian national laboratories. The U.S. DOE and the Indian Department of Atomic Energy (DAE) signed an Implementing Agreement in July 2011, "for Cooperation in the Area of Accelerator and Detector Research & Development for Discovery Science". Annex I to the Implementing Agreement, signed in January 2015, enables a significant Indian contribution to an accelerator upgrade at Fermilab to increase proton beam power.

Financial and other interfaces with all the international partners could present cost and schedule advantages, or conversely, constraints. A detailed cost and benefit analysis will be performed as part of the analysis of alternatives in the CD-1 approval process.

PIP-II has the potential to support all experiments using beams at Fermilab due to its role as the front-end of the accelerator complex, but the highest priority use will be for LBNF/DUNE. LBNF/DUNE can use the currently configured complex, but its performance will be enhanced by the higher power provided by PIP-II, and so it is desirable to complete PIP-II as closely as possible to the completion of LBNF/DUNE.

There are no nuclear safety, nor safeguards and security issues, nor design process constraints associated with the execution of this mission need.



Location of the proposed PIP-II linac, adjacent to the Booster and the Wilson Hall high-rise.

4. RESOURCE AND SCHEDULE FORECAST

4.1 Cost Forecast

HEP requested the Office of Project Assessment to conduct a review of PIP-II cost-range estimates. The PIP-II proponents developed a cost range using both a bottom-up analysis and also a benchmark comparison to the cost to build the linac for the SNS.

The proponents stated at the DOE review (June 2015) that the project cost range is $465 million to $695 million. This range was based on a bottom-up cost estimate that was expanded based on the maturity of the design. It was then adjusted by assuming that India would contribute at least $100 million of scope. The benchmark comparison with the SNS linac was also adjusted by removing unrelated technical scope and by applying appropriate escalation for the proposed PIP-II start date. After taking credit for $100 million of in-kind scope contribution by India, the upper end of the cost range was adjusted to $600 million.

The bottom-up estimate started by reviewing and updating the estimate originally developed for P5 in 2013. Since then Fermilab has refined the set of activities and improvements – including those in downstream accelerators – that are necessary to more fully exploit PIP-II capabilities. Items added to the PIP-II scope include: Superconducting RF R&D; Low Level RF; RF interlocks; warm magnets; Recycler, Booster and Main Injector upgrades.

The benchmark cost estimate was based on the available 2003 costing data for the 1.0 GeV

SNS linac, scaling down to the 0.8 GeV energy of the PIP-II linac, with appropriate escalation. This procedure errs on the high cost side, since differences in accelerator efficiency and overall beam power levels – 1 MW at 1 GeV in the SNS, compared with 1.2 MW at 120 GeV with PIP-II – tends to make SNS more expensive than PIP-II. Similarly, accelerator technology has become more cost-effective since 2003, for example with solid-state amplifiers replacing klystrons in some applications.

In 2007 Fermilab and four Indian institutions (the Inter-University Accelerator Centre [IUAC] in Delhi, the Raja Rammana Centre for Advanced Technology [RRCAT] in Indore, the Bhabha Atomic Research Centre [BARC] in Mumbai, and the Variable Energy Cyclotron Centre [VECC] in Kolkata) established an R&D collaboration for the purpose of jointly developing technologies for high power proton accelerators. In 2011 an Implementing Agreement "for Cooperation in the Area of Accelerator and Detector Research & Development for Discovery Science" was established between the U.S. DOE and the Indian DAE. In January 2015 Annex I to the Implementing Agreement was co-signed, aiming at the co-development of a superconducting CW proton linac with an energy of approximately 1 GeV.

All Indian development activities undertaken within this R&D collaboration during the 12th Indian five-year plan are directly aligned with the planned evolution of Indian in-kind contributions from R&D to the construction of PIP-II during the 13th five-year plan.

A number of PIP-II prototype components have recently been delivered to Fermilab from the four Indian laboratories in the collaboration. They include: two single-spoke resonator accelerating cavities for use in the prototype SSRl cryomodule; two prototype magnets for the medium energy beam transport line within the PIP-II front-end development; a 325 MHz, 3 kW, solid-state radio frequency source to be used to energize the PIP-II SSRl and SSR2 cavities; and a complete set of drawings for the 650 MHz, beta=0.92, cavities that will be used in the final PIP-II acceleration stage. This provides clear evidence of Indian interest to participate in PIP-II. The Indian institutions continue to work on other agreed-upon deliverables.

A joint DAE-DOE review will take place in 2018, to provide the go-ahead to initiate in-kind construction deliverables. Up to $200 million (direct) funding has been authorized in the 12th and 13th five-year plans, with a maximum $60 million / $140 million split during the R&D and construction phases, respectively.

Discussions are ongoing with international partners from three other nations who have expressed interest in the PIP-II project, although no commitments have been made to date.

Project cost estimates were vetted by a "Cost and Schedule" committee of experts at the DOE review of the cost range. They commented that:

> "The PIP-II definition and data was found to be well beyond the CD-0 stage and well on its way to a CD-1 definition. The project utilized data from the Spallation

Neutron Source (SNS) project for benchmarking purposes. With this benchmark, SNS actual cost was $777 million. In order to do a proper comparison, the PIP project removed costs for unlike scope. This brought the actual costs for SNS down to $701 million, which compared to PIP-II estimated cost of $568 million (including contribution from India) this makes for a very good benchmark."

Using an average of the two estimates of the upper end of the cost range, we arrived at a cost range of $465 million to $650 million.

4.2 Schedule Forecast

The project nominally runs from FY15 until FY25, with commissioning beginning at the low energy end of the linac in FY23, concluding with 1.2 MW power capability at 120 GeV in FY25. The following schedule of Critical Decisions is consistent with the requirements of LBNF/DUNE.

Critical Decisions (CD)	Year
CD-0, Approve Mission Need	FY15
CD-1, Approve Alternative Selection and Cost	FY17
CD-2/3a, Approve Performance Baseline	FY18
CD-3, Approve Start of Construction	FY20
CD-4, Approve Project Completion	FY26

4.3 Funding Forecast

The funding profile shown below supports the high end of the stated cost range.

$M	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	Total
OPC	19.5	19.5	25	-	-	-	-	-	-	-	64
TEC	-	-	-	40	60	100	100	100	100	86	586
TPC	**19.5**	**19.5**	**25**	**40**	**60**	**100**	**100**	**100**	**100**	**86**	**650**