PIP-II Global Requirements Document

ED0001222

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Revision	Date	Section No.	Revision Description
	9/2/10	All	Draft version 4.5 posted to Project X DOCDB
	9/23/10	All	Draft version 4.6 posted to Project X DOCDB
	11/10/10	All	Draft version 4.8 posted to Project X DOCDB, PX retreat conclusions included
	1/5/11	4	Draft version 4.9 change FE to 162.5 MHz, 5 mA, 10 % DF upgrade
	10/5/11	4.11	Draft version 4.11 change first CM to 162.5 MHz
	10/14/11	4.12	Update for high intensity workshop
	11/8/12	All	Update to reflect staging, including joint 1/3 GeV operations at 1/3 MW
	7/29/14	All	Updated to reflect migration to Teamcenter.
	3/17/17	All	Updated to reflect PIP-II project scope; version approved by Director's Office (CRO and CAO).
A	1/4/18	5.1	Section 5.1 added to incorporate definition of CW-compatible
B	3/28/18	5	Modified CW-compatible discussion following P2MAC Meeting
	11/27/18	All	Renamed to GRD, clarified CW-compatibility, added 1 GeV upgradability
C	1/27/20	3	Updated Design Criteria section to state that >1 MW of proton beam power from the Main Injector over an energy
	1/27/20	U4	Removed "SRF linac, cryogenic system, Booster, and conventional facilities" and replaced with "Linac Tunel."
	5/3/22	5.1	The CW-compatible requirement for the front end changed from CW-beam compatible to CW-RF and pulsed beam
	5/3/22	5.2	Section 5.2 added to incorporate background and justification of keeping the Linac cold during maintenance & repair.
	5/3/22	L3	Beam Pulse Length changed from 0.54 to 0.55 msec
	5/3/22	I7	Added new Integration functional requirement supporting the scope of Section 5.2.
	5/9/22	3	G-2 experiment removed from supported programs list in second bullet

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1. Introduction

Proton Improvement Plan-II (PIP-II) encompasses a set of upgrades and improvements to the Fermilab accelerator complex aimed at supporting a broad physics research program over the next several decades, and enables the world's most powerful high-energy neutrino beam for the international Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE). PIP-II is an integral part of the strategic plan for U.S. High Energy Physics as described in the Particle Physics Project Prioritization Panel (P5) report of May 2014 [1], and formally established via the Mission Need Statement (MNS) and CD-0 in November 2015 [2]. As an immediate goal PIP-II is focused on upgrades to the Fermilab accelerator complex capable of providing proton beam power in excess of 1 MW on target at the initiation of the LBNF/DUNE program. PIP-II is a part of a longer-term vision of establishing a high-intensity proton facility that is unique within the world, ultimately leading to multi-MW proton beam capabilities at Fermilab.

The P5 report contains two recommendations specifically aimed at meeting these goals:

> <u>Recommendation 13</u>: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.
>
> <u>Recommendation14</u>: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP- II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

The P5 report quantifies the requirements associated with these recommendations: "..we set as a goal a mean sensitivity to CP violation of better than 3σ…over 75% of the range of possible values of the unknown CP-violating phase δ_{CP}. Using a wideband neutrino beam produced by a proton beam…requires…600 kT*MW*yr of exposure assuming systematic uncertainties of 1% and 5% for the signal and background respectively. The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power." Additionally, the P5 report addresses the requirements for muon-based physics: "Looking farther into the future, progress in precision physics and rare processes will be shaped partly by what particle physicists learn in the coming decade. Upgrades to the accelerator complex at Fermilab (PIP-II and additional improvements) will offer opportunities to further this program. For example, combined with modest upgrades to Mu2e, improvements in the Fermilab accelerator complex potentially could provide increased sensitivity (by a factor of ten) to muon-to-electron conversion and allow one to search for this very rare process in different nuclei. This will provide crucial clues on the nature of the new physics revealed in the event of an observation in the next-generation experiments."

These requirements set the goals for an upgrade to the Fermilab accelerator complex to support long-term research in neutrinos and muons, both in terms of initial capabilities and future upgradability.

Following acceptance of the P5 report by the Department of Energy/Office of High Energy Physics, an international collaboration was formed to mount the Deep Underground Neutrino Experiment (DUNE) based on the LBNF at Fermilab. Shortly thereafter the Office of Science approved a Mission Need Statement for PIP-II followed by Critical Decision-0 (CD-0).

The PIP-II Project will incorporate significant in-kind contributions from international partners. International partner countries/agencies participating in the PIP-II Project include: India/DAE, Italy/INFN, UK/UKRI, France/CEA, France/IN2P3, and Poland/WUST.

2. Mission Need

The Mission Need Statement (MNS) for PIP-II represents the implementation of the P5 plan by the Department of Energy. The MNS identifies two primary goals:

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

The MNS establishes 1.2 MW as the goal for beam power delivered from the Main Injector following implementation of PIP-II. The MNS also describes the need to implement PIP-II in a manner that will allow a subsequent doubling of power delivered from the Main Injector based on future upgrades, and the desirability of maintaining compatibility with a subsequent upgrade to continuous wave (CW) beam operations in support of a broader spectrum of particle physics research opportunities, including muons.

3. Design Criteria

Design criteria for PIP-II are established on the basis of the P5 report and the approved MNS as follows:

- Deliver > 1 MW of proton beam power from the Main Injector over the energy range 60 – 120 GeV and 1.2 MW at 120 GeV;
- Support the current 8-GeV program at Fermilab including the Mu2e and short-baseline neutrinos experiments;
- Provide a platform for extension of beam power to LBNF to >2 MW;
- Provide a path to increase the beam power to the Mu2e experiment to ~100 kW at 800 MeV, with a duty factor of up to 100%;
- Provide a platform for extension of capability to flexible bunch pattern, high duty factor/higher beam power operations to multiple experiments simultaneously.

The above capabilities should be provided in a cost-effective manner.

4. Key Assumptions, Interfaces and Constraints

Assumptions related to the development of PIP-II are contained in the Assumptions Document prepared in advance of CD-1 [3].

5. Facility Scope

The PIP-II concept is based on an 800-MeV superconducting linac (SRF Linac), injecting into the existing 8-GeV Booster via a newly constructed injection area, augmented by upgrades to the Main Injector and Recycler ring to allow them to accommodate the high Booster intensities enabled by the SRF Linac. This concept was identified by DOE/OHEP as the preferred option following review of the Analysis of Alternatives report prepared after CD-0 [4].

Specific scope elements of the PIP-II project include:

- An 800-MeV superconducting H^- linac, constructed of CW-compatible components as defined in section 5.1, and operating initially in pulsed beam mode. Note: Full CW RF operational capability is expected to be available for the duration of the project.
- Beam transport of 800-MeV H^- from the SRF Linac to the Booster, including accommodation of a beam dump capable of accommodating full intensity at low (~1%) duty factor and future delivery of beam to the Muon Campus.
- A new injection area in the Booster to accommodate 800-MeV injection and any modifications required to support increased beam intensity.
- Modifications to the Main Injector and Recycler Ring to support acceleration and extraction of high intensity/high power proton beams over the range 60-120 GeV.
- Associated conventional facilities including enclosures, equipment galleries, and utilities. The linac enclosure will be constructed with a length to accommodate at least two High Beta 650 MHz (HB650) cryomodules beyond the nominal compliment required for 800 MeV.

5.1 Definition of CW-compatible

The PIP-II superconducting linac is expected to operate initially in pulsed-beam mode, in support of the LBNF/DUNE program. However, the linac is specified to be “CW-compatible” in order to support longer-term research goals at Fermilab and to provide the option for mitigation of Lorentz Force Detuning (LFD) impacts on performance. From a general perspective, the term “CW-compatible” refers to CW operations at the average current referred to in requirement L6 below, and means that all systems and components will be constructed and installed with a capability to support CW-RF and pulsed-beam operations at the project completion. Construction and installation of systems and components that will be capable of CW-beam operations will be judged on a case-by-case basis, taking into account the costs to accommodate CW operations at a later time. Development of pulsed-RF capability is motivated by two factors: a) the interest to support the DAE partners’ plans to construct a pulsed-RF superconducting linac (ISNS), and b) the desire to operate PIP-II in a cost-efficient operating mode. Therefore, while pulsed-RF capability is <u>not</u> a global PIP-II requirement, it will be carefully assessed for each system and be incorporated in its design wherever possible.

At the systems level the following are identified as being required to support CW-compatible operations as installed by the PIP-II Project:

- Warm front end as installed in the PIP-II linac enclosure will be capable of CW-RF and pulsed-beam operation.

- Superconducting cavities and cryomodules: All cavities and cryomodules, including RF couplers, will be constructed with a capability for CW-beam operations. In particular, the specification for cavity Q_0 will be established on the basis of CW operations.
- RF Sources: All RF sources and RF distribution infrastructure will be constructed with a capability for CW-beam operations.
- Linac warm magnets: All warm focusing and correction magnets will be capable of CW-beam operations.
- Cryogenic plant and cryo distribution systems: The cryogenic plant capacity and the cryogenic distribution system will be capable of supporting CW-beam operations.
- Low level RF (LLRF): The LLRF system will be capable of supporting CW-RF within the superconducting cavities, during pulsed-beam operations.
- Instrumentation, Controls/Timing, and Machine Protection systems: These systems will be implemented in a manner that minimizes the resources required to convert to CW-beam operations at a later time.
- Magnet power supplies: Power supplies will be implemented in a manner that minimizes the resources required to convert to CW-beam operations at a later time.
- Electrical and Water Infrastructure: All conduits and piping will be sized to support CW-beam operations.
- Conventional facilities: Adequate space will be provided to implement HVAC systems capable of supporting CW-beam operations at a later time.

Note: A beam absorber capable of accommodating full current CW beam operations will not be incorporated into the PIP-II Project

5.2 Maintainability and fault tolerance of the PIP-II cryo-system

Following best practices adopted at other large-scale SRF linac facilities, the PIP-II cryogenic and its supporting auxiliary systems will be designed and constructed in a manner that allows their operation and maintenance without warming up the SRF linac. The cryogenic auxiliary systems include instrument air, cooling water, insulating vacuum systems, electrical power, controls, networking, etc. Warm-up and cool-down cycles of the PIP-II Linac can negatively affect performance of SRF cavities and the entire accelerator. Also, thermal cycling can cause vacuum leaks requiring lengthy and costly repairs. To minimize negative impact on the PIP-II accelerator performance,

- The PIP-II cryogenic and auxiliary systems will be designed and constructed to avoid warming up the SRF linac (cavities, solenoids, and cryomodule beam line vacuum components) above 6K through the lifetime of the project.
- The design of the PIP-II cryogenic and auxiliary systems will be fault-tolerant to prevent the SRF linac from warming up above 6K in case of a component failure or short service outage (as compared to the time required for the SRF linac to warm above 6K).
- The design of the SRF linac will allow warming up and cooling down individual cryomodules for maintenance and repair while keeping the rest of the cryomodules at cryogenic temperatures.

6. Functional Requirements

The following function requirements meet the design criteria listed above in a cost-effective manner, while providing flexibility for future development of the Fermilab accelerator complex.

Superconducting Linac

Requirement	Description	Value
L1	Delivered Beam Energy (kinetic)	800 MeV
L2	Beam Particles	H^-
L3	Beam Pulse Length	0.55 msec
L4	Particles per Pulse	6.7×10^{12}
L5	Pulse repetition Rate	20 Hz
L6	Average Beam Current during Pulse	2 mA
L7	Maximum Bunch Intensity	1.9×10^{8}
L8	Max Bunch Repetition Rate	162.5 MHz
L9	Bunch Pattern	Programmable and arbitrary
L10	RF Frequency	162.5 MHz and harmonics thereof
L11	Bunch Length (rms)	<4 psec
L12	Transverse Emittance (rms, normalized)	≤0.3 mm-mrad
L13	Longitudinal Emittance (rms)	≤0.35 mm-mrad (1.1 keV-nsec)

8-GeV Booster

Requirement	Description	Value
B1	Injection Energy (kinetic)	800 MeV
B2	Extraction Energy (kinetic)	8 GeV
B3	Beam Particles	Protons
B4	Particles per Pulse (extracted)	6.5×10^{12}
B5	Beam Pulse Repetition Rate	20 Hz
B6	Capture/Acceleration Efficiency	97%
B7	Maximum Bunch Intensity	8.1×10^{10}
B8	RF Frequency (injection – extraction)	44.7-52.8 MHz

Requirement	Description	Value
B9	Bunch Length (97% full length)	8.2 nsec
B10	Transverse Emittance (rms, normalized)	2.7 mm-mrad
B11	Longitudinal Emittance (97%)	0.08 eV-sec

Recycler Ring/Main Injector

Requirement	Description	Value
M1	Injection Energy (kinetic)	8 GeV
M2	Extracted Beam Energy	60-120 GeV
M3	Beam Power (60-120 GeV)	1.0-1.2 MW
M4	Beam Particles	Protons
M5	Protons per Pulse (extracted)	7.5×10^{13}
M6	Cycle Time (60-120 GeV)	0.7-1.2 sec
M7	Slip-stacking/Acceleration Efficiency	97%
M8	Extracted Beam Pulse Length	~10 μsec
M9	Bunches per Pulse	~500
M10	Bunch Spacing	18.8 nsec (1/53.1 MHz)
M11	Transverse Emittance (rms, normalized)	3.3 mm-mrad

Integration

Requirement	Description	Value
I1	The 800 MeV SRF Linac will be constructed in a manner that allows installation and commissioning with minimum interruption to ongoing accelerator operations.	
I2	Residual Activation from Uncontrolled Beam Loss in areas requiring hands-on maintenance.	<20 mrem/hour (average) <100 mrem/hour (peak) @ 1 ft
I3	Scheduled Maintenance Weeks/Year	8
I4	SRF Linac Operational Reliability	90%

Requirement	Description	Value
I5	60-120 GeV Operational Reliability	85%
I6	Facility Lifetime	≥40 years
I7	The PIP-II SRF Linac's supporting infrastructure shall provide capability to maintain cryomodule accelerator components to less than 6K during maintenance, repair, or service interruptions.	

Upgradability

Requirement	Description	Value
U1	The siting of the PIP-II facility will be consistent with future replacement of the existing 8-GeV Booster with either an 8 GeV Rapid Cycling Synchrotron or superconducting pulsed linac.	
U2	The siting of the PIP-II facility will be consistent with future upgrades to provide 100 kW beams to the Mu2e hall on the Muon Campus.	
U3	The SRF Linac will be constructed of components capable of operating in two additional modes: a) CW-beam and b) pulsed-RF, following modest upgrades.	
U4	The Linac Tunnel will be consistent with a future upgrade of the linac energy to 1 GeV.	

7. Safety Requirements

The Project will be built to applicable DOE and FNAL engineering, safety, and radiation standards as outlined in the Fermilab Engineering Manual [5] and Fermilab ES&H Manual [6].

8. References

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

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[2] PIP-II Mission Need Statement

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[3] PIP-II Project Assumptions Document, PIP-II Document #144

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[4] Analysis of Alternatives: Proton Improvement Plan-II, PIP-II Document #107
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[5] Fermilab Engineering Manual
http://www.fnal.gov/directorate/documents/FNAL_Engineering_Manual_REVISED_070810.pdf

[6] Fermilab ES&H Manual
http://esh.fnal.gov/xms/ESHQ-Manuals/FESHM