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Proton Improvement Plan-II

December 2013

This document presents a plan for improvements to the Fermilab accelerator complex aimed at providing a beam power capability of at least 1 MW on target at the initiation of LBNE operations. This plan is embedded within a longer-term concept for a sustained campaign of upgrades and improvements to achieve multi-MW, continuous wave capabilities.

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1 Introduction and Summary

This document describes a conceptual plan for upgrading the Fermilab proton accelerator complex to a beam power capability of at least 1 MW delivered to the neutrino production target at the initiation of LBNE (Long Baseline Neutrino Experiment) operations. This plan is responsive to the vision articulated in the Snowmass report [1] which highlights the opportunity for the U.S. to host a world-leading long baseline neutrino research program that would anchor a broader program of intensity frontier research. The plan is structured to deliver, in a cost effective manner, more than 1 MW of beam power to LBNE while creating a flexible platform for longer-term development of the Fermilab complex to multi-MW capabilities in support of a broader research program, as future resources become available.

The starting points of this plan are the recently completed upgrades to the Recycler and Main Injector for the NOvA experiment, the Proton Improvement Plan [2] currently underway, and the Project X Reference Design Report [3].The Proton Improvement Plan (PIP) consolidates a set of improvements to the existing Linac, Booster, and Main Injector aimed at supporting 15 Hz beam operations. In combination, the NOvA upgrades and the PIP create a capability of delivering 700 kW from the Main Injector at 120 GeV. The Project X Reference Design Report (RDR) goes well beyond this in describing a complete concept for a multi-MW proton facility that could support a broad particle physics program based on neutrino, kaon, muon, and nucleon probes [4]. The present document describes an initial step that is focused on the long baseline neutrino mission, while preserving straightforward upgrade paths to the opportunities identified in the Snowmass process.

1.1 Design Criteria and Considerations

A number of approaches can be taken to achieving in excess of 1 MW on the LBNE target. The challenge is to identify a solution(s) that provides an appropriate balance between minimization of near-term costs and flexibility to support longer-term research opportunities. In order to limit consideration to a modest number of options the following criteria are applied to possible solutions:

- The plan should support the delivery of 1.2 MW of proton beam power from the Main Injector to the LBNE target at 120 GeV, with power approaching 1 MW at energies down to 60 GeV;
- The plan should provide support to the currently envisioned 8 GeV program, including Mu2e, g-2, and the suite of short-baseline neutrino experiments;
- The plan should provide a platform for eventual extension of beam power to LBNE to >2 MW;
- The plan should provide a platform for eventual extension of capability to support high duty factor/high power beams.

The primary bottleneck limiting beam power to the LBNE target is the 40-year-old Linac/Booster complex. Performance is limited to about 4.3×10^{12} protons per Booster pulse by beam loss – primarily driven by space-charge forces at the 400 MeV injection energy. The secondary potential bottleneck is slip-stacking of twelve Booster pulses at high intensity in the Recycler. This capability is currently being commissioned for the NOvA experiment, with performance determined jointly by characteristics of the Recycler itself and of beam delivered from the Booster.

The ideal facility meeting the above criteria would be a modern 8 GeV superconducting linac for injection either into the Main Injector or Recycler as described in the RDR, or the pairing of a ~3 GeV linac with a modern Rapid Cycling Synchrotron (RCS). These options provide performance that would significantly exceed the first design criterion, and would meet all subsequent criteria; however they would also significantly exceed the likely available near-term funding.

1.2 Options Considered

Two options are considered that could meet the first three design criteria listed above. These options assume completion of the Proton Improvement Plan, enabling 15 Hz beam operations of the Booster at 4.3×10^{12} protons per pulse. They are based on raising the injection energy of the Booster to 800 MeV, enabling a 50% increase in delivered protons per pulse while reducing space-charge forces by about 30%. Paired with a modest decrease of the Main Injector cycle time (from 1.333 to 1.2 seconds) this provides 1.2 MW beam power at 120 GeV.

1. 800 MeV superconducting pulsed linac

This option is a partial implementation of Stage 1 of the Project X Reference Design, focused on increasing the Main Injector beam power to support the LBNE research program. It consists of an 800 MeV superconducting linac, injecting into the existing Booster. Compared to the Project X Reference Design significant cost savings are achieved with a low duty factor configuration and siting in close proximity to existing electrical, water, and cryogenic infrastructure. Constructing the linac with continuous wave (CW) capable cavities and cryomodules offers a straightforward future upgrade path with minimal additional up-front costs. This approach maintains the full breadth of opportunities described in the RDR while meeting all the design criteria listed above. Moreover, this approach is expected to be attractive to potential international partners.

2. 400 MeV “afterburner” to the existing 400 MeV linac

It is possible to contemplate construction of a new 400 MeV pulsed linac at the end of the existing 400 MeV linac. Superconducting and room temperature implementations are both possible, at comparable costs, with superconducting preferred because of superior upgradability.

This implementation would require physical relocation of the existing linac, upstream by about 50 m, to accommodate the extension. The motivation for this approach would be to achieve lower costs than option 1. The disadvantages are: 1) upgrade paths to CW operations are problematic because of the extended room temperature section; 2)the frequency (805 MHz), while the same as the SNS linac frequency, is not consistent with the significant R&D investment made to date at 650 MHz and would preclude subsequent capitalization on the investment to be made in supplying 1.3 GHz cryomodules to LCLS-II; 3)a significant contribution from our Indian collaborators would probably not be possible due to 1) and 2); 4)significant vulnerabilities would remain in the existing linac; in particular the drift tube linac portion is the oldest accelerator within the Fermilab complex and is currently reliant on rf sources for which there is a single vendor supplying a minimal market; and 5)this approach would require a significant interruption to the operating program (~1 year) for relocation and installation.

Option 1 is preferred, and will be described in this report, because it provides the most robust accelerator complex in support of the neutrino programs, and because it offers straightforward and cost-effective extensions to the multi-MW, high duty factor, capabilities required to support a world-leading research program based on intense beams in the longer term. This approach also minimizes disruption to the ongoing operating program, removes inherent reliability risks in linac operations, and directly capitalizes on a large amount of conceptual and technological development undertaken as part of the Project X, ILC, and LCLS-II programs. Because this option represents a natural continuation of the performance improvements being implemented within the PIP, it has been assigned the designation Proton Improvement Plan-II (PIP-II).

1.3 Overview of Proton Improvement Plan-II

High-level goals, and supporting beam performance parameters, for PIP-II are given in Table 1-1. The central element of PIP-II is a new 800 MeV superconducting linac, situated in close proximity to the existing Booster as shown in Figure 1-1. This site offers several advantages in terms of minimizing cost while retaining options for future development; in particular the site affords direct access to significant electrical, water, and cryogenic infrastructure.

Performance Parameter	Requirement	
Linac Beam Energy	800	MeV
Linac Beam Current	2	mA
Linac Beam Pulse Length	0.6	msec
Linac Pulse Repetition Rate	15	Hz
Linac Upgrade Potential	CW	
Booster Protons per Pulse	6.4×10^{12}	
Booster Pulse Repetition Rate	15	Hz
Booster Beam Power @ 8 GeV	120	kW
8 GeV Beam Power to LBNE	80-120*	kW
Beam Power to 8 GeV Program	40-0*	kW
Main Injector Protons per Pulse	7.5×10^{13}	
Main Injector Cycle Time @ 120 GeV	1.2	sec
Main Injector Cycle Time @ 60 GeV	0.8	sec
LBNE Beam Power @ 60 GeV	0.9	MW
LBNE Beam Power @ 120 GeV	1.2	MW
LBNE Upgrade Potential @ 60-120 GeV	>2	MW

*First number refers to Main Injector operations at 120 GeV; second number to 60 GeV. The PIP-II configuration is capable of maintaining 1.2 MW down to 80 GeV.

Table 1-1: PIP-II high level performance goals

The linac energy is selected to support a 50% increase in Booster beam intensity, accompanied by a space-charge tune shift that is reduced by 30% as compared to current operations. The linac is constructed nearly entirely of components that are capable of operating in CW mode – the primary exception being the cryogenics system, which is aligned with the low duty factor requirements. The incremental cost in constructing the linac from CW compatible components is minimal.

Upgrades to a number of systems in the Booster, Recycler, and Main Injector will be required to support the higher Booster injection energy and higher beam intensities. These include upgrades to the Booster injection system, the rf systems in all rings, and various feedback systems. The upgrade to the Booster injection system is the most significant of these.

PIP-II provides a variety of straightforward and cost effective upgrade paths. Delivery of >2 MW to the LBNE target will require replacement of the existing Booster. The most effective strategy would be to extend the 0.8 GeV linac to 6-8 GeV and inject directly into the Main Injector at the MI-10 straight section. This linac would be based on the superconducting technologies developed for PIP-II, and would have significant technological overlap with the 1.3 GHz cryomodules Fermilab will be supplying to the LCLS-II Project at SLAC over the next five years. Alternatively, the linac could be extended to 2-3 GeV, followed by a RCS. Upgrade of the linac to CW operations is achievable by upgrading performance of the PIP-II cryogenic and rf systems. CW operations of the linac could support MW-class beam delivery to a variety of rare processes experiments, including Mu2e.

The estimated cost of PIP-II is $540 M in 2020 dollars, including direct and indirect costs, and 40% contingency. Potential offsets to this number in the form of possible international in-kind contributions are valued at $150-200M.

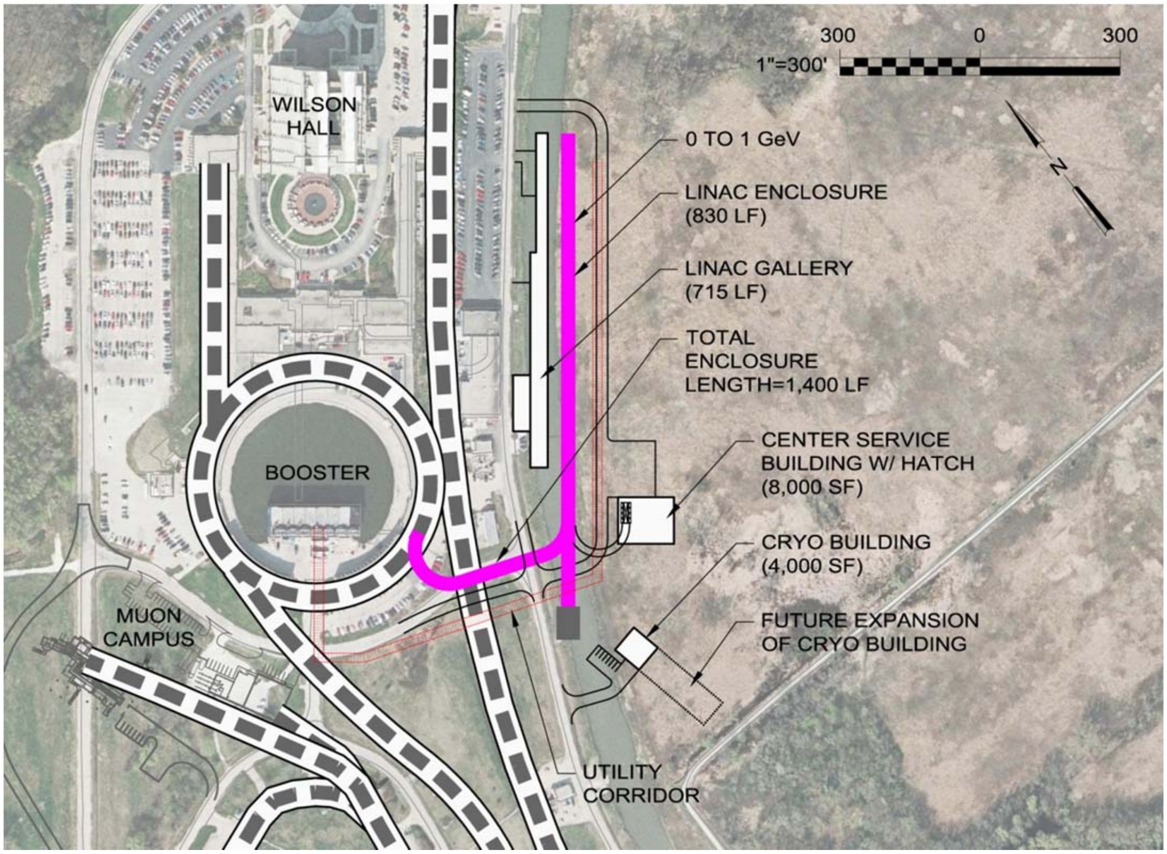

Figure 1-1: Site layout of PIP- II. New construction includes the linac enclosure, transfer line enclosure, linac gallery, center service building, utility corridor, and cryo building. Dashed areas represent existing or planned underground enclosures.

2 Design Concept and Performance Goals

The goal of Proton Improvement Plan-II is to increase the capabilities of the existing accelerator complex at Fermilab to support delivery of 1.2 MW of beam power to the LBNE production target, while simultaneously providing a platform for subsequent upgrades of the complex to multi-MW capability. The primary bottleneck to providing increased beam power at Fermilab is the Fermilab Booster, driven by space-charge forces at injection. In the intermediate term the most cost effective approach to removing this bottleneck is to increase the injection energy into the Booster.

The PIP-II meets this goal via an 800 MeV superconducting linac, operated at low duty factor, but constructed of accelerating modules that are capable of CW operations if provided with sufficient cryogenic cooling and appropriate rf power. The goal is to increase the beam intensity delivered from the Booster by 50% relative to current operations. The choice of 800 MeV is conservative – for nominal operating parameters the space-charge tune shift is 30% lower than current experience while the beam intensity is 50% higher. This choice will assure lower fractional beam loss, which will be required at the higher operating intensities.

The scope encompassed by the PIP-II and described in this document includes:

- An 800 MeV superconducting (SC) linac, constructed of CW-capable accelerating structures and cryomodules, operating with a peak current of 2 mA and a beam duty factor of 1%
- Beam transport from the end of the SC linac to the new Booster injection point, and to a new 800 MeV dump
- Upgrades to the Booster to accommodate 800 MeV injection, and acceleration of 6.4×10^{12} protons per pulse
- Upgrades to the Recycler to accommodate slip-stacking of 7.7×10^{13} protons delivered over twelve Booster batches
- Upgrades to the Main Injector to accommodate acceleration of 7.5×10^{13} protons per pulse to 120 GeV with a 1.2 second cycle time, and to 60 GeV with a 0.8 second cycle time

Modifications to the LBNE target facility to accept 1.2 MW protons are assumed to be undertaken by the LBNE project. However, requirements are described in this document.

The basic accelerator requirements are shown in Table 1-1; more detailed sets are described in subsequent sections of this document. Note that the concept presented here is capable of delivering 1.2 MW of beam power to LBNE at all energies between 80-120 GeV. For 120 GeV operations significant beam power is also available to support an 8 GeV program in parallel with LBNE. However, for LBNE operations at 80 GeV or below any beam power delivered to an 8 GeV program would come at the expense of beam power to LBNE. This situation could be ameliorated by upgrading the Booster to 20 Hz operations, and while this possibility is currently under investigation it remains outside the purview of this report.

It is also worth noting that while the configuration described here is cost effective, no system-wide (Linac, Booster, Recycler, Main Injector) optimization has been completed at this time. It is anticipated that such an optimization will occur as planning becomes further advanced.

3 800 MeV Linac

The PIP-II 800 MeV linac is a derivative of the Project X Stage 1 design as described in the RDR. Detailed technical requirements and specifications, and the status of development programs, are described in that document and will not be repeated here. This document presents a description of the new concept with an emphasis on requirements that are modified as a result of the lower energy and lower duty factor of PIP-II.

3.1 Technical Requirements/Scope

Figure 3-1 shows the configuration of the 800 MeV linac. A room temperature (RT) section accelerates H^- ions to 2.1 MeV and creates the desired bunch structure for injection into the superconducting (SC) linac. Five cavity types operating at three different frequencies are required for acceleration to 800 MeV. While the linac operates at low duty factor as part of the PIP-II program, all accelerating structures are CW compatible, meaning they can be operated in CW mode if supplied with sufficient cryogenic cooling and rf power.

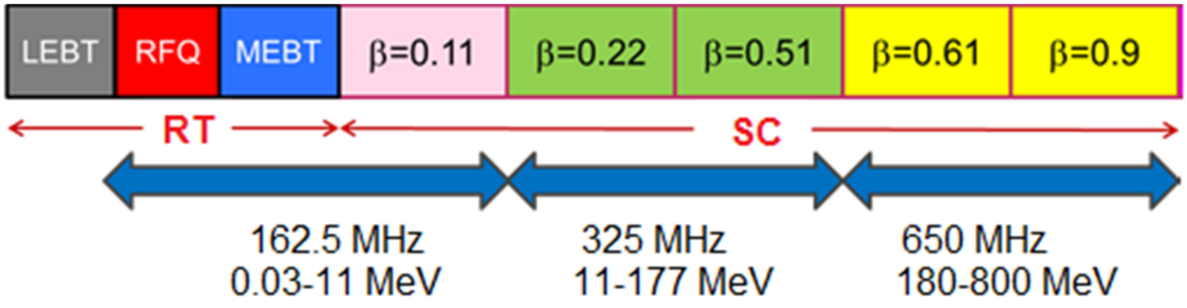

Figure 3-1: **The PIP-II linac technology map**

The room temperature front end is composed of an ion source, low energy beam transport line (LEBT), radio frequency quadrupole (RFQ), and medium energy beam transport line (MEBT). The RFQ delivers a peak current of up to 10 mA, with a 162.5 MHz time structure, to the MEBT where a bunch-by-bunch chopper removes undesired bunches to create a beam current of 2 mA (averaged over a few μs period) for further acceleration. Although the MEBT chopper requirements are relaxed as compared to those described in the RDR, the chopper described in that report will meet the needs of PIP-II. The MEBT chopper is augmented by a “slow” chopper in the LEBT with a rise and fall time of about 100 ns. This chopper allows forming of a macro-structure in the beam timing required for machine commissioning and to avoid unnecessary beam loading in normal operations. Together the LEBT and MEBT choppers form the desired bunch structure for injection into the Booster.

The SC linac is required to accelerate an average beam current of 2 mA to 800 MeV, with peak currents up to 10 mA for periods of less than a few μs. This is possible because the energy stored in the superconducting cavities is quite large, allowing one to keep accelerating voltage fluctuations due to beam loading below 10^{-3} if the bunch structure is repetitive with period below about 3 μs (one-and-a-half times the circumference of the Booster).

To support beam injection into the Booster the linac operates at 15 Hz with a beam pulse duration of 0.56 ms, resulting in a 0.84% beam duty factor. Cavity filling with rf requires a significantly longer time. The effective duty factor for high power rf is about 10%, while the effective duty factor associated with cryogenic load is about 5%. The reduced cryogenic load is achieved by shifting the phase of the rf amplifiers by 180^{o} to accelerate the voltage decay in the cavities following the beam pulse.

The linac is followed by beam delivery to the Booster injection point through a beam transport line incorporating a $210\text{-}225^{o}$ arc. The bending radius of the arc is maintained above 23 m to prevent stripping of the H^- beam prior to Booster injection. The geometry of the linac/beamline is compatible with the installation of an rf separator and septum required to support a subsequent upgrade to provide beams to multiple experiments including Mu2e.

The superconducting linac operational parameters are summarized in Table 3-1.

Performance Parameter	**Requirement**	
Particle species	H^-	
Input beam energy (Kinetic)	2.1	MeV
Output beam energy (Kinetic)	0.8	GeV
Average beam current	2	mA
Bunch repetition rate	162.5	MHz
Beam pulse length	0.6	msec
Pulse repetition rate	15	Hz
RF pulse length	7	msec
Delivered transverse emittance (rms, norm; $\varepsilon_x = \varepsilon_y$)	<0.3	mm-mrad
Delivered longitudinal emittance (rms, norm)	<1.1	keV-nsec
Delivered bunch length (rms)	4	psec

Table 3-1: Superconducting linac parameters

3.2 Accelerator Physics Design

The PIP-II linac includes the following major elements:

1. The warm front-end
2. One superconducting accelerating section based on 162.5 MHz Half-Wave Resonators (HWR, 1 cryomodule)
3. Two superconducting accelerating sections based on 325 MHz Single-Spoke Resonators (SSR1 & SSR2, 9 cryomodules total);
4. Two superconducting accelerating sections based on 650 MHz elliptical cavities (LB650 & HB650, 9 cryomodules total)

3.2.1 Front End

A complete front-end concept, supported by simulations and significant hardware development, is described in the RDR. PIP-II adopts the same front end operating in a pulsed beam mode. The front end consists of an ion source, LEBT, RFQ, and MEBT. This configuration is currently being assembled at Fermilab to support a complete systems test as part of the PXIE [5] development program. The nominal beam current from the ion source through the RFQ is 5 mA, with a maximum of 10 mA. The ion source produces H^- beam at 30 keV. The LEBT transports this beam to the RFQ. The LEBT length is about 2 m. The main requirements on the LEBT are 1) good differential pumping between the ion source and RFQ, 2) beam envelope match to the RFQ, and 3) beam chopping required for commissioning of the RFQ and downstream accelerators. The 162.5 MHz RFQ accepts and accelerates this beam to 2.1 MeV. A wideband chopper situated within the MEBT removes ~50-80% of bunches emanating from the RFQ in order to form appropriate bunch patterns for acceleration in the SC linac.

The RFQ energy of 2.1 MeV is chosen because it is below the neutron production threshold for most materials. At the same time this energy is sufficiently high to mitigate the space-charge effects in the MEBT at currents as high as 10 mA. The choice of a comparatively low energy for the LEBT (30 keV) allows reducing the length of RFQ adiabatic buncher section and, consequently, achieving sufficiently small longitudinal emittance so that at the exit of the RFQ the beam phase space will be close to emittance equipartitioning. To mitigate space-charge effects in the LEBT, compensation of beam space charge by residual gas ions can be applied either for the full or partial LEBT length.

3.2.2 Accelerating Structures

The SC linac starts immediately downstream of the MEBT, accelerating the H^- beam from 2.1 to 800 MeV. Five types of superconducting cavities are used to cover the entire velocity range required for beam acceleration. The cavity frequencies and cell configurations are chosen to maximize acceleration efficiency for each accelerating structure, minimize the cost of the accelerator and its operation, and to address other factors helping to minimize beam loss.

Development of 1.3 GHz superconducting cavity technology for the ILC, and its adoption by the European XFEL, have established this technology as the preferred choice for the acceleration of ultra-relativistic beams. This development has been supported by a very significant investment in 1.3 GHz infrastructure at Fermilab and concurrent development of expertise with this technology. These factors motivated the recent adoption of 1.3 GHz technologies for the LCLS-II project at SLAC, with Fermilab committed to the development and production of a significant number of 1.3 GHz cryomodules over the next five years. The capabilities and infrastructure developed through these investments make 1.3 GHz the preferred choice for long-term upgrades of the Fermilab accelerator complex, and in order to maintain compatibility with this frequency it is highly desirable to select technologies for PIP-II that are harmonically related. This has yielded 162.5, 325 and 650 MHz as the choice of frequencies for the PIP-II linac. This choice results in a comparatively smooth frequency increase during beam acceleration, accommodating bunch shortening due to adiabatic damping.

Table 3-2 and Figure 3-2 present the cavity types utilized through the PIP-II SC linac. Acceleration starts with the half-wave resonators operating at 162.5 MHz. It is followed by two types of single spoke resonators (SSR1 and SSR2) operating at 325 MHz, and finally by two types of elliptical 5-cell cavities, low beta (LB650) and high beta (HB650), at 650 MHz. Figure 3-3 displays the transit time factors for the cavities utilized in the linac. The voltage gain in each cavity type is significantly larger than its immediate predecessor. This leads to transitions between cavity types at lower energies than one would infer from equal transit time factors.

Name	**β_G**	**β_{opt} †**	**Freq (MHz)**	**Type of cavity**	**B_{peak} (mT)**	**E_{peak} (MV/m)**	**E_{acc} (MV/m)**	**ΔE (MeV)**
HWR	0.094	0.112	162.5	Half wave resonator	41	38	8.2	1.7
SSR1	0.186	0.222	325	Single-spoke resonator	58	38	10	2.05
SSR2	0.431	0.515	325	Single-spoke resonator	70	40	11.2	5.32
LB650	0.61*	0.647	650	Elliptic 5-cell	70	37.5	16.5	11.6
HB650	0.9*	0.95	650	Elliptic 5-cell	64	35.2	17.5	17.7

* To be consistent with previously written documents β_G for the elliptic cavities is defined as the ratio of regular cell length to half-wavelength.

† β_{opt} corresponds to the particle velocity at which the maximum acceleration is achieved.

Table 3-2: Accelerating cavity types and characteristics for the SC linac.

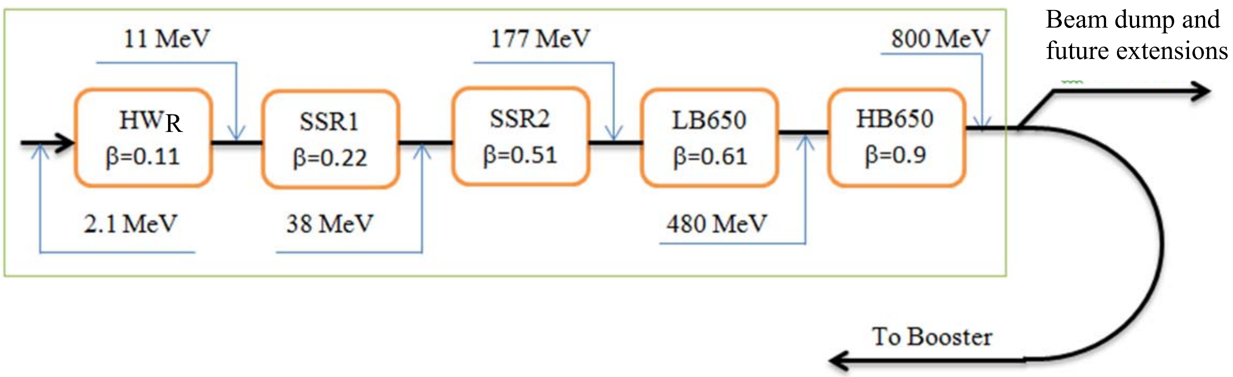

Figure 3-2: Configuration of the PIP-II superconducting linac.

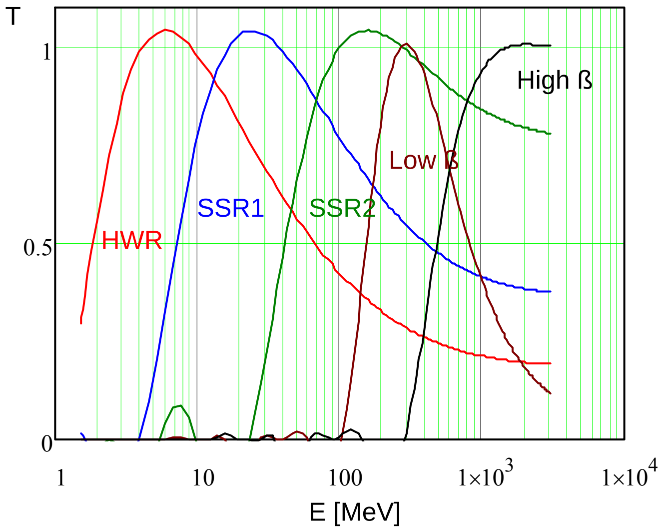

Figure 3-3: Transit time factors for PIP-II superconducting cavities.

Table 3-3 presents the structure and number of superconducting cavities and cryomodules deployed in the linac. The first three types use superconducting solenoids, located inside the cryomodules, for focusing. The LB650 cryomodule has one quadrupole doublet located inside the cryomodule and one outside, and the HB650 does not have any focusing elements inside cryomodule – all focusing is external.

Section	Energy (MeV)	R/Q (Ω)	Cav/mag/CM	CM Config.	CM length (m)
HWR	2.1-11	272	8 /8/1	8 x (sc)	5.8
SSR1	11-38	242	16 /8/ 2	4 x (csc)	5.2
SSR2	38-177	275	35 /21/ 7	sccsccsc	6.5
LB650	177-480	378	30 /20*/ 5	ccc-fd-ccc	7.1
HB650	480-800	638	24/ 10†/ 4	cccccc	9.5

*5 superconducting and 5 warm (external to the cryomodule) doublets
†All doublets are warm, i.e. external to the cryomodule

Table 3-3: Accelerating cryomodule requirements for the PIP-II linac. Within the CM configuration column "c" refers to an individual accelerating cavity, "s" refers to a solenoid magnet, and "fd" refers to a quadrupole doublet.

3.2.3 RF Requirements

The rf system is required to support 2 mA beam delivered in a 0.6 msec pulse at 15 Hz. The system is based on a single rf source driving each rf cavity, for a total of 114 rf sources. It is anticipated that the amplifiers in the 162.5 and 350 MHz sections will be solid state, while those in the 650 MHz sections will be either inductive output tubes (IOTs) or solid state.

The average rf power delivered to the cavities consists of two contributions: 1)the energy transferred to the beam; and 2)the energy required to fill and discharge the accelerating cavities. The second contribution is about ten times larger than the first and in general the average power associated with this contribution does not depend on the peak rf power. For a fixed average power the rf cost increases with peak power and therefore the rf cost minimum is achieved with rf power equal to that required to accelerate the beam. Adopting this strategy yields a duty factor for the rf power amplifiers of about 12%. One consequence of this strategy is that the cost savings associated with the pulsed power amplifiers in going from CW to low duty factor is modest (~10%) and therefore CW capable rf amplifiers are planned. The rf requirements are summarized in Table 3-4.

Section	Q_0@2K (10^{10})	Microphonics ampl. (Hz)	Optimum loaded Q	Peak RF power per cavity* (kW)
HWR	0.5	20	3.3×10^6	4.9
SSR1	0.5	20	5.8×10^6	5.5
SSR2	1.2	20	7.2×10^6	17
LB 650	1.5	20	1.4×10^7	34
HB 650	2.0	20	1.4×10^7	50

* Power is computed for 2 mA. Allowances for transmission loss and microphonics suppression are included.

Table 3-4: RF power requirements in the superconducting pulsed linac.

3.2.4 Cryogenic Requirements

The 800 MeV linac will be run in pulsed mode, with the capability to be upgraded to CW operations at a later time. To minimize the cost a system sized to the needs of PIP-II will be assembled utilizing considerable existing Tevatron cryogenic infrastructure, including the Central Helium Liquefier (CHL), transfer line, and compressors. A future upgrade to CW operation would require a new 2K cryogenic plant.

It is estimated that the pulsed operation described here will result in 5% of the nominal cryogenic CW dynamic load. The estimated cryogenic heat load is displayed in Table 3-5, based on the cavity and cryomodule requirements described in sections 3.2.2 and 3.3.3. The total cryogenic heat load at 2K is dominated by the static load, and is about 14% of the CW load.

		Static Load per CM [W]			Dynamic Load per CM [W]	
Type	**# of CM**	**70 K**	**5 K**	**2 K**	**2 K CW**	**2 K Pulsed***
HWR	1	250	60	14	10	0.5
SSR1	2	195	70	16	11	0.6
SSR2	7	145	50	8.8	43	2.2
LB 650	5	145	45	8.1	145	7.3
HB 650	4	120	30	6.2	147	7.4
Total		**2860**	**895**	**173**	**1646**	**83**

Total CM Heat Loads [W]			
	70 K	**5 K**	**2 K**
Pulsed	**2,860**	**895**	**256**
CW	2,860	895	1819

* Nominally 5% of CW dynamic load

Table 3-5: Cryogenic heat loads for the pulsed superconducting linac, with comparisons to CW operations.

3.2.4.1 Assumptions and Constraints

The cryogenic system design is developed based on a number of assumptions:

- CHL must be upgraded to allow for safe unattended operation. This is a much more cost effective approach than utilizing 24/7 staff as was done during Tevatron operations; and in any event staffing is a problematic option due to retirements and reassignments.
- It is assumed that the SC linac cryomodules will not have cool-down constraints. If they do, this will complicate the 19 bayonet cans to allow flow mixing to achieve desired temperatures for each circuit.
- Two compressors at A0 can be used to support the two satellite refrigerators required for PIP-II. The two compressors are currently assigned to the experimental program at the Muon Campus. It is assumed that these compressors will become available at the time of PIP-II operations. As an alternative, headers could be run to the B0 compressor building or compressors could be moved to a new refrigerator building. The latter solution would require additional power and cooling water capability in the vicinity of A0.

- A cryogenic transfer line capable of supporting CW operations will be installed in the linac tunnel to support initial pulsed operations.

3.2.4.2 Cryogenic System Configuration

The configuration of the PIP-II cryogenic system is given in Figure 3-4. CHL and warm vacuum pumps will be used to satisfy the 2 K requirements. Supercritical helium at about 5K will be distributed directly to the JT heat exchanger in each cryomodule. The heat exchanger will reduce the temperature to 2K prior to throttling down to 31 mbar. This heat exchanger helps maximize the useful liquid percentage at the outlet of the JT valve. The 31 mbar operating pressure is achieved using room temperature vacuum pumping. To achieve the required flow rate, two of the large Kinney vacuum skids used at NML would be required. They would be housed in a separate room of the new refrigerator building along with a small purifier compressor and a purifier.

CHL will need to be upgraded to allow unattended operation as well as addressing deferred maintenance issues. LHe and LN_2 will be fed into the Tevatron transfer line near A3 and transported as far as A1. LHe and LN_2 u-tubes at A2 and A3 will be modified to eliminate the local refrigerator feeds. The LN_2 subcoolers at A1, A2 and A3 will need to be operating and vented outside. The u-tubes at A1 will be replaced with existing L-tubes. From an ODH perspective, it would be advisable to remove the A1, A2 and A3 valve boxes and seal the tunnel penetrations. Two of the valve boxes will be modified for use in a new refrigerator building.

A new transfer line will run from the A1 refrigerator to the new refrigerator building. This will be a two circuit transfer line and will reuse the Tevatron transfer line and expansion can.

A new multi-circuit transfer line will run from the new refrigerator building, into the tunnel and along the length of the SC linac. The design of this transfer line will be consistent with CW operation since it would be impractical to replace it during a CW upgrade. The transfer line requires 19 in-line bayonet cans, one for each cryomodule, and a turnaround box at the end. In parallel, there will be a warm nitrogen vent header (not used in the CW upgrade) and a helium relief header.

Two satellite refrigerators will be used to satisfy the 5 K requirements at 4.5 K. They will receive LHe and LN_2 from CHL to allow them to operate in a more reliable satellite mode. Since LN_2 will be supplied from CHL through the transfer line, no new LN_2 storage will be required for the initial pulsed mode.

Two compressors at the Tevatron A0 building will be used by the two satellite refrigerators. Helium inventory management will be added to the new refrigerator building. Two new headers will be run to the existing Tevatron tank farm for warm gas storage as well as warm gas return to the CHL. A new suction and discharge headers will need to be run between the new refrigerator building and the A0 compressor building.

Liquid nitrogen will be used to satisfy 40 K to 80 K requirements at 77 K.

3.2.4.3 Risks

The operating margin inherent in this system is very large – in excess of 100%. However certain risks remain that will be addressed during the detailed design phase:

- Reliability: reciprocating expanders and warm vacuum pumps
- Tevatron transfer line stability: due to low flow and single ended operation
- Compressor availability: new compressors will be required, with supporting infrastructure if two compressors are not available from the Muon Campus experimental program

3.2.4.4 Infrastructure/Utilities Requirements

The two satellite refrigerators and associated vacuum pumps require the following infrastructure/utilities support:

- Building floor space: 13'h x 30'w x 50'l. The existing A0 high-bay area is being evaluated for this space. If not suitable, it will require a new building.
- Electrical Power: 650 kW, distribution panels, 480V/3ph
- Cooling water: 600 gpm
- Ventilation: 4 x 4,500 CFM fans, outside air intake louvers, space heaters
- General lighting

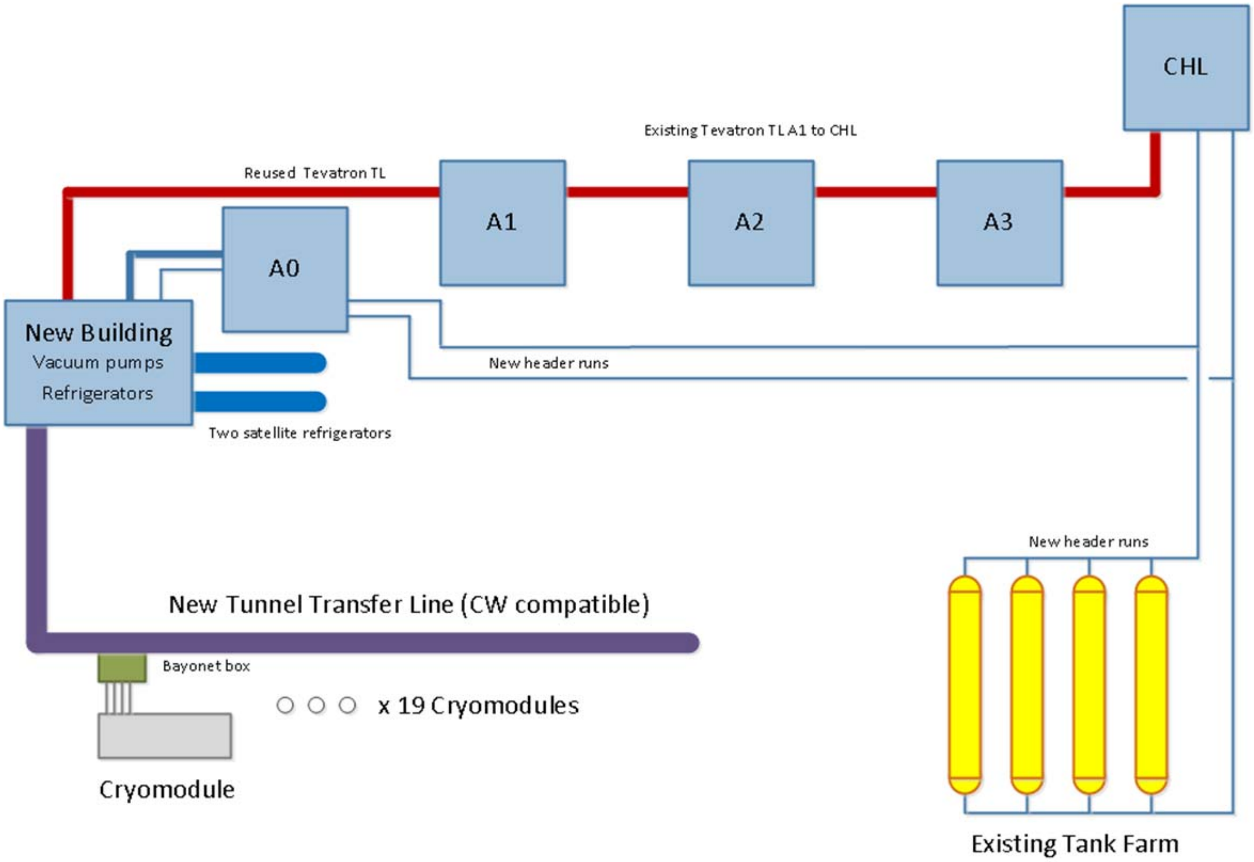

Figure 3-4: Cryogenic system layout supporting the superconducting linac

3.2.5 Booster Injection

Following acceleration in the SC linac the beam is delivered to the Booster for injection and subsequent acceleration to 8 GeV. There are two possible scenarios for rf capture during injection into the Booster. The first is similar to that presently used, based on multi-turn injection with the rf turned off, followed by capture/bunching with the rf adiabatically turned on. The second utilizes injection into existing rf buckets (i.e. rf voltage is non-zero at injection). In the latter scenario the bunch-by-bunch chopper in the MEBT is required to remove bunches coming at the boundaries between Booster rf buckets. The second scenario is slightly preferred due to its ability to form a desired longitudinal distribution with help of the MEBT chopper. Note that for both scenarios the relative change of main dipoles bending field during injection does not exceed 0.1% and can be easily compensated either by ramping the horizontal Booster correctors or by ramping the accelerating cavities at the end of the linac, or perhaps ignored.

3.3 R&D Required

The following major R&D activities should be completed in advance of SC linac construction.

- Construction and operations of PXIE with beam through the HWR cryomodule (11 MeV). The front end represents the primary technical risk with PIP-II, and so this step will validate the concept and demonstrate that the hardware can meet the specified requirements. PXIE will also provide the Fermilab accelerator staff with their first experience in accelerating protons utilizing superconducting rf. The demonstration of the wideband chopper may or may not be required for neutrino operations, depending on the method adopted to fill the Booster. However it would be required to support enhanced Mu2e operations.
- Single spoke resonator cavities are a novel technology that have not been deployed in accelerators constructed to date. A complete SSR1 (β=0.22) cryomodule will be constructed and tested as part of the PXIE program. The accelerating cavities required for this cryomodule have been received and have surpassed the specified gradient and Q_0 in vertical tests. A set of SSR2 (β=0.51) cavities will be procured and tested, but it is not required to assemble a complete cryomodule as part of the R&D program.
- The major project cost is associated with the 650 MHz elliptical cavities and cryomodules (LB650 and HB650). Improving the accuracy of the cost estimate requires the delivery (from industrial vendors and potential international partners) and successful testing of cavities of both type, and completion of cryomodule designs. A complete cryomodule is not required as Fermilab will gain relevant experience in the assembly of cryomodules based on elliptical cavities via LCLS-II construction.
- Cost effective solid state rf power amplifiers are generally available at 325 MHz, and are under active development in India at both 325 and 650 MHz. Magnetron-based rf power amplifiers also represent significant potential cost savings for rf power at 650 MHz and therefore corresponding R&D is highly desirable.

The beam transport from the linac to Booster is relatively straightforward and does not require R&D. Beam dynamics in the linac have been carefully studied for the Project X Reference Design and do not require significant additional effort before the start of construction.

4 Booster

4.1 Technical Requirements /Scope

The performance requirements of the Booster are summarized in Table 4-1. The 800 MeV injection energy is selected to provide an increase in beam intensity of about 50% beyond current operations, accompanied by a 30% decrease in the space-charge (Laslett) tune shift at injection. This choice is made to provide more efficient beam capture and acceleration, in order to minimize losses at the higher beam intensity required in PIP-II. The requirements on longitudinal beam emittance are set by slip-stacking in the Recycler.

Performance Parameter	**Requirement**	
Particle Species	Protons	
Input (H^-) Beam Energy (Kinetic)	800	MeV
Output Beam Energy (Kinetic)	8.0	GeV
Protons per Pulse (injected)	7.0×10^{12}	
Protons per Pulse (extracted)	6.4×10^{12}	
Beam Pulse Repetition Rate	15	Hz
RF Frequency (injection)	44.7	MHz
RF Frequency (extraction)	52.8	MHz
Injection Time	0.6	msec
Injection Turns	315	
Beam Emittance (6σ, normalized; $\varepsilon_x = \varepsilon_y$)	15	π mm-mrad
Laslett Tune Shift at Injection (Gaussian)	-0.34	
Delivered Longitudinal Emittance (97%)	0.08	eV-sec
Delivered Momentum Spread (97% full height)	12.2	MeV
Delivered Bunch Length (97% full length)	8.2	nsec

Table 4-1: Performance requirements for the Booster

The primary areas that need to be addressed in order to reach the performance goals listed above are given in Table 4-2. Among these injection and beam quality are expected to present the primary challenges.

Topic	Associated Items
Injection	Injection girder and loss control
Capture	RF capture, timing and emittance control
Acceleration and Transition	Loss control, RF requirements and transition control
Extraction	Loss control, timing and beam manipulations
Beam Quality	MI/Recycler requirements
Operations	Shielding, Booster Hardware

Table 4-2: Booster areas requiring consideration as part of PIP-II.

This section will describe concepts and approaches in the areas listed above. These descriptions assume successful completion of the PIP tasks currently underway. However, the discussion is preliminary and may change after more extensive investigations are completed. It is required that Booster beam losses be maintained at less-than-or-equal-to present levels. The current operating limit is 525 watts ring-wide, augmented by independently set beam loss monitor (BLM) trip points in each long and short straight section.

4.1.1 Injection

Upgrading Booster injection will be the major effort within PIP-II, with improvements required to accommodate increases in both the injection energy and beam intensity. Injection will be via H^- stripping through a carbon foil, as done currently, but with many more turns (315 vs. 15). The options being developed for the new injection system are based on consideration of the following:

1. The new injection line can enter the Booster either horizontally or vertically.
2. Beam painting at injection will be desirable to mitigate space-charge effects.
3. The injection foil must have a sufficient lifetime under the injection conditions.
4. A new injection girder must be developed to accept the higher energy beam. This may require increasing the length of the injection straight section.
5. Beam loss control at injection will likely require a beam absorber.

Possible approaches to injection are described below.

4.1.2 Capture

There are two possible methods for capturing beam in the Booster, the present method of adiabatic capture and bucket-to-bucket transfer. Both capture methods are fairly well understood and would work. Both have positive and negative aspects but neither presents a significant technical concern. A choice will be made on the basis of optimized performance/cost.

4.1.3 Acceleration and Transition

A review of acceleration related issues associated with the higher beam intensity does not present any significant challenges. However, there is concern over the ability to deliver the required longitudinal emittance and to maintain losses at levels similar to current performance. The Booster crosses transition at about 5.5 GeV, typically an area of concern for both loses and emittance dilution. There are several proposed solutions and studies. An evaluation of RF constraints, and ways in which longitudinal motion and growth could be reduced are described below.

4.1.4 Extraction

A review of the present extraction systems does not show any limitation to the goals and is a low concern.

4.1.5 Beam Quality

The Booster rf systems currently have the capability of accelerating a per pulse beam intensity approaching that required for PIP-II. However, the acceleration efficiency is unacceptably low and slip-stacking in the Recycler places constraints that will require improvements in the longitudinal emittance delivered from the Booster. The beam quality required appears feasible but will require improvements several fronts. In addition to the already mentioned transition crossing, work on beam dampers, phase locking, and bunch rotation will be needed.

4.1.6 Operational Reliability

There are no operational concern beyond the anticipated duration of operations and losses. Once an implementation timeline is better defined, a risk assessment of various systems will need to be done.

4.2 Accelerator Physics Design

4.2.1 Injection

The Booster injection girder will require a major reconfiguration as part of PIP-II. In particular design development will be required on the following components:

- Chicane Dipoles: A new 3-bump system capable of accommodating the (~50%) higher momentum of the injected beam will have to be designed and implemented.
- Stripping foil: Injection of higher beam intensity, over a much larger number of turns, creates challenges relating to foil heating and beam loss control. However, the longer injection time associated with the lower beam current and low injected beam emittance provide opportunities for phase space painting, allowing reduction of distribution tails, reduction of space charge effects, and, consequently, resulting in smaller beam loss.
- Painting: The transverse painting system will utilize either direct control of the chicane dipoles or dedicated low field painting magnets. Painting could be done in either plane, but consideration of the lattice functions in the Booster indicates that vertical painting may be the better choice. Figure 4-1shows recent simulations of painting for 1 GeV injection.
- Beam Absorber and Girder Integration: The present Booster has no beam loss absorber at injection – there is a concern that a 50% increase in beam intensity, accompanied by the high energy, will require incorporation of such a device into the redesigned injection area. Two options under consideration are: 1)the placement of absorptive material inside a gradient magnet; or 2) the rebuilding of some number of gradient magnets to make space for the absorber. At this time, the preferred solution is to rebuild the injection straight with shorter (higher strength) gradient magnets which adds flexibility to the design of the injection girder.

The beam absorber and girder integration are expected to present the primary challenges in development of the new injection system.

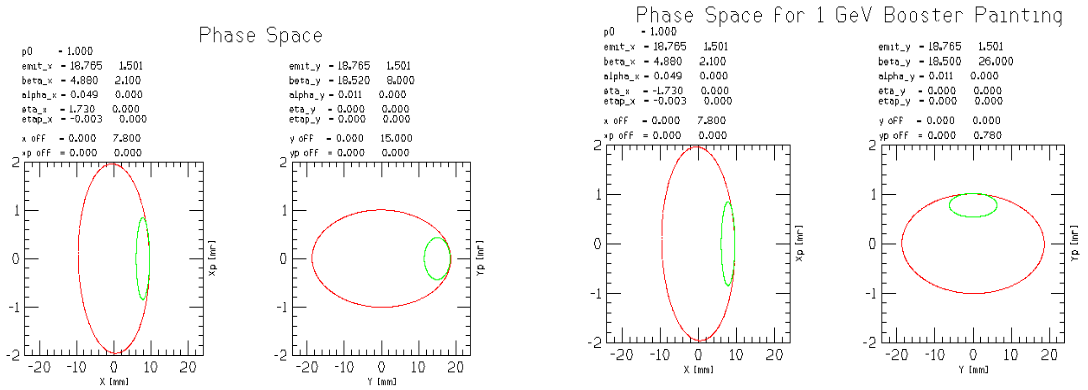

Figure 4-1: Simulations of two injection painting schemes: H and V position offsets (left) and H position/V angle offset (right). The green contours represent incoming beam from the linac; red contours represents the beam phase space after painting.

4.2.2 Capture

4.2.2.1 Bucket-to-bucket injection from the Linac to the Booster at 800 MeV

Bucket-to-bucket beam injection from the SC linac into the Booster will require a chopper to clear the beam in unwanted linac buckets because the rf frequencies of the linac and Booster are not integer multiples. More specifically, the linac bunch frequency is 162.5 MHz, while for 800 MeV injection the Booster RF frequency is 44.7 MHz – a ratio of 3.6. Figure 4-2 shows the longitudinal phase space in the Booster for injection of beam without chopping in the linac. The result is significant un-captured beam outside the rf bucket, which is unacceptable from the perspective of loss limitations during acceleration.

When chopping is applied, bunches that fall within a certain phase relative to the center of the Booster bucket can be selected. This selection is made in the linac MEBT, at low energy. Two examples are shown in Figure 4-3 corresponding to a phase width (at 44.7 MHz) of 180° and 120°. As seen from the figure 180° (50%) beam chopping provides efficient injection.

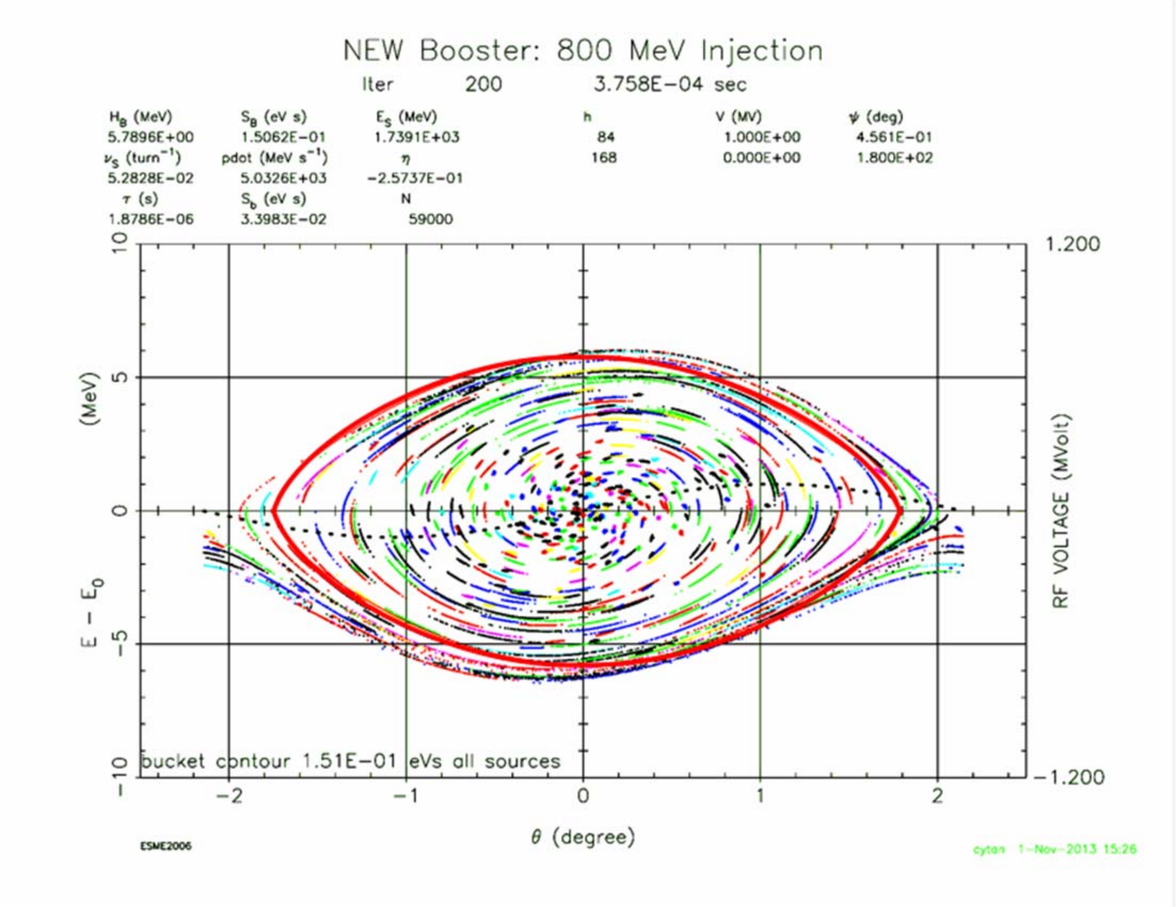

Figure 4-2: Longitudinal phase space for bucket-to-bucket transfer into the Booster in the absence of linac chopping. The solid red line indicates the rf bucket boundary.

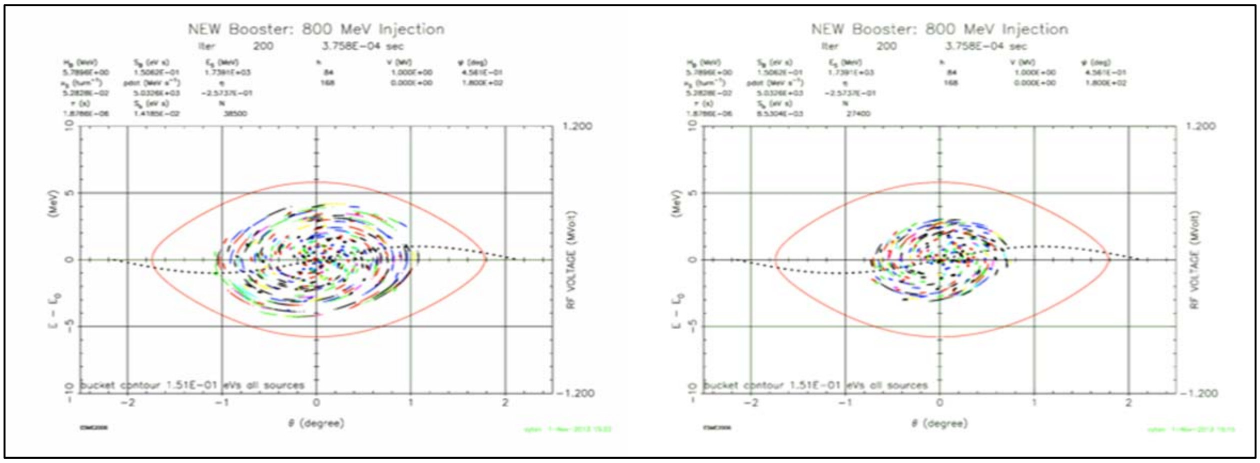

Figure 4-3: When chopping is applied to the injected beam, bunches can be selected to fill 180 deg (left) or 120 deg (right) of the Booster bucket. This is the distribution after 200 turns in the Booster.

4.2.2.2 Adiabatic capture of the beam in Booster at 800 MeV

Adiabatic capture of the beam is another injection option. In this case the beam is allowed to debunch in the Booster before the Booster rf is adiabatically ramped up to 1 MV over 0.4 ms to capture the beam. Figure 4-4 shows the result of beam captured via this method based on 7×10^{12} injected protons with and energy spread of ±300 keV. In this simulation, 100% of the injected beam is captured. The exact longitudinal distribution of the beam depends strongly on how the rf is ramped.

Simulations with the addition of 2nd harmonic cavities for capture at injection have also been done. Due to the limited space in Booster with 22 first harmonic cavities installed, at best only two 2nd harmonic cavities can be added. This means that the maximum combined 2nd harmonic voltage is about ~120 kV. Unlike injection at 400 MeV, it is found that this arrangement does not improve beam capture. Furthermore, space-charge forces are greatly reduced through flattening of the longitudinal beam distribution via injection painting, leading to the conclusion that 2nd harmonic cavities are likely unnecessary.

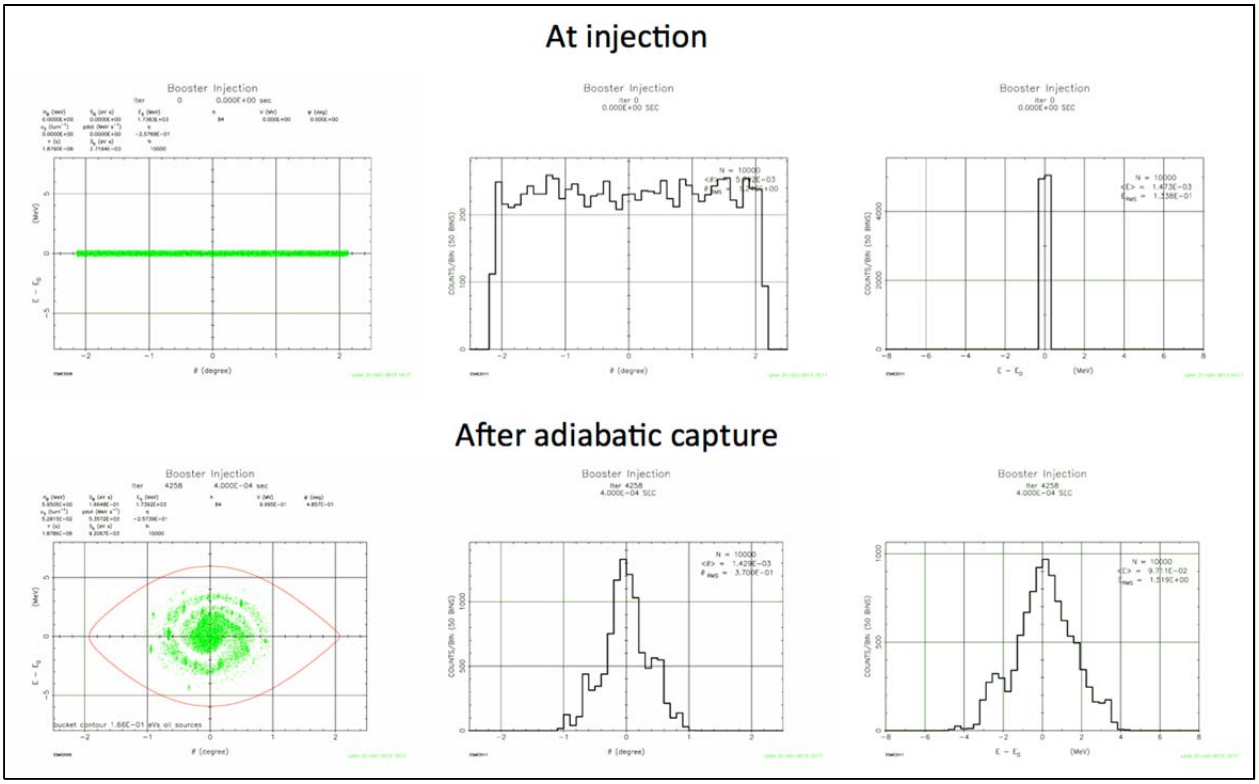

Figure 4-4: Simulation of adiabatic capture at 800 MeV in the Booster after 0.4 ms.

4.2.3 Acceleration and Transition

The Booster is expected to deliver 4.3×10^{12} protons per pulse at 15 Hz after the completion of the PIP effort. The 50% batch intensity increase for PIP-II will require about 25% more rf voltage than the PIP. This implies a total of 22-23 rf stations (3-4 more than present). The additional rf is helpful for efficient acceleration, but is a necessity for transition.

Constraints on the longitudinal phase space imposed by Recycler will require the upgraded Booster rf systems to provide improved transition crossing relative to current operations. The ability to effectively utilize either rf voltage bumps or quadrupole damping at transition requires rf voltage 20-25% beyond the nominal operating voltage. The present system (with 19 stations) provides some quadrupole damping, but does not allow rf voltage jumps. Simulations indicate that beam loss and bunch oscillations produced at transition could be greatly reduced with the more aggressive damping schemes. Figure 4-5 shows how one might apply an rf voltage bump to suppress quadrupole oscillations after transition. Another option that could be considered is to re-implement a γ_t jump.

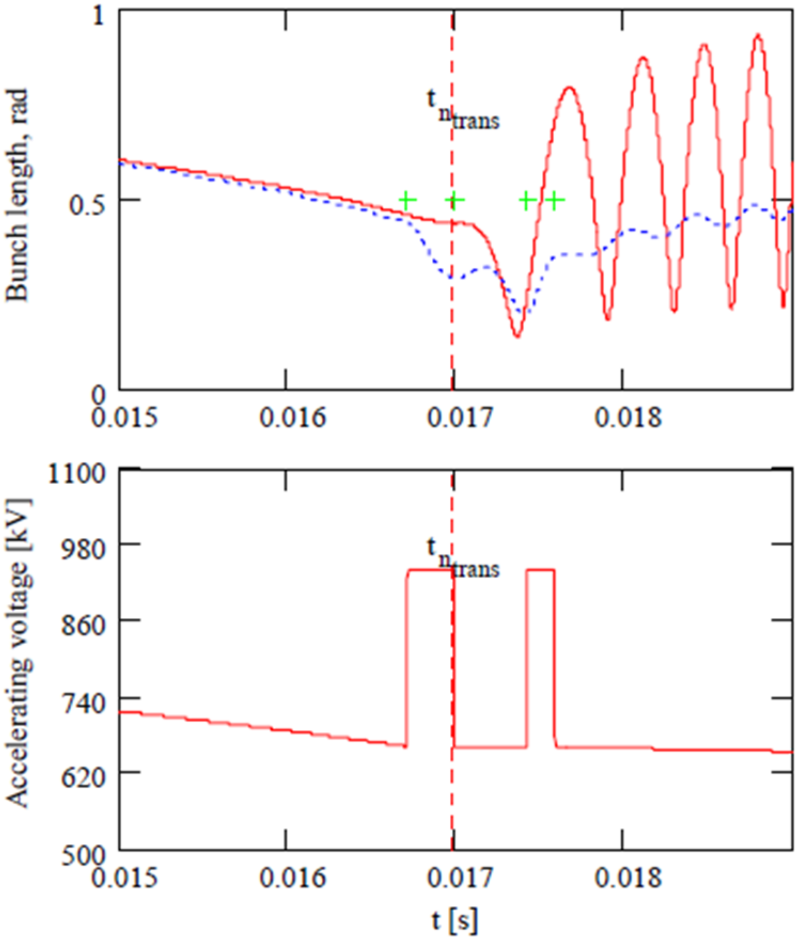

Figure 4-5: Voltage jumps to control quadrupole oscillations at transition. The upper figure shows quadrupole (bunch length) oscillations following transition without (red) and with (blue) the rf voltage jumps shown in the lower figure.

4.2.4 Beam Quality/Operations

The Booster is required not only to delivery 6.4×10^{12} protons per pulse at 15 Hz, but also to meet the beam requirements set by slip stacking in the Recycler. The most challenging aspect will be delivery of beam with less than 6 MeV (half-width) momentum spread. The longitudinal characteristics of the Booster beam are largely determined by capture, transition crossing, and coupled bunch instabilities above transition. The capture process outlined in sections 4.2.1 and 4.2.2 does significantly better than required, leaving transition crossing and post-transition instabilities as the primary concerns. This will require implementation of transition crossing measures as outlined above and possibly improvements to the Booster longitudinal damper system.

The Recycler transverse emittance constraints are less stringent, but loss limits in the Booster will likely require work on alignment, collimation, transverse dampers and extraction systems.

4.3 R&D Required

The R&D program for the Booster will be aimed at better understanding of beam dynamics issues associated with injection, transition, and acceleration. This work will be used to guide machine studies and hardware development.

4.3.1 Injection and Capture

It is expected that capture studies will include analysis of the current foil – stripping processes and orbit control. The simulation of various schemes for capturing the low current Linac beam will be done.

It is expected that the most intensive job will be the design and testing of the injection girder and beam loss absorber design. This will impact the Booster optics and is likely to require a considerable simulation and design effort.

4.3.2 Acceleration and Transition

The work for PIP will help in the understanding of the requirements for the high power upgrade but additional research into transition crossing will be needed. The damping schemes mentioned above will require further evaluation. The likely need for additional rf voltage will require understanding and development of the most cost effective manner to provide additional rf voltage.

5 Main Injector/Recycler

5.1 Technical Requirements/Scope

The performance requirements of the Main Injector/Recycler complex are summarized in Table 5-1. The Recycler has recently been reconfigured as a proton accumulation ring in support of the NOvA experiment. For PIP-II an increase in beam intensity of 50% over current operations is required accompanied by a modest (10%) decrease in the Main Injector cycle time to 120 GeV. The primary requirement on the Recycler is to slip-stack twelve Booster batches and to deliver this accumulated beam to the Main Injector in a single turn. In order to maintain losses at current levels the efficiency of this operation has to be at least 97%.

Performance Parameter	Requirement	
Particle Species	Protons	
Injection Beam Energy (kinetic)	8.0	GeV
Extracted Beam Energy (kinetic)	60-120	GeV
Protons per Pulse (injected)	7.7×10^{13}	
Protons per Pulse (extracted)	7.5×10^{13}	
Slip-stacking Efficiency	97	%
Controlled 8 GeV losses to Abort	0.8	%
Controlled 8 GeV losses to Collimators	1.7	%
Uncontrolled 8 GeV losses	0.5	%
Transition Losses	0.2	%
Cycle Time	0.8-1.2	sec
Beam Power	0.9-1.2	MW
Beam Emittance (6σ, normalized)	20	π mm-mrad
Bunching Factor	0.5	
Laslett Tune Shift (Injection)	-0.06	

Table 5-1 : Main Injector/Recycler requirements for 0.9-1.2 MW operations at 60-120 GeV. The Main Injector is capable of maintaining beam power of 1.2 MW for energies as low as 80 GeV.

5.2 Accelerator Physics Design

The Main Injector/Recycler complex operates in the same manner for PIP-II as for NOvA, but with 50% higher beam intensity delivered from the Booster. The primary issues that need to be considered in planning for increased intensity are slip-stacking in the Recycler and acceleration in the Main Injector. Secondary issues are Main Injector transition crossing, electron-cloud, and beam loss control/mitigation.

5.2.1 Recycler Slip Stacking

The Recycler will slip stack twelve Booster batches containing 6.4×10^{12} protons each. The longitudinal separation required between incoming and previously captured batches is determined by stored beam slippage of one Booster circumference every 1/15th of a second. This corresponds to an energy difference of 24 MeV, or 1260 Hz at the rf frequency of 53 MHz. The figure of merit in slip stacking is the parameter alpha that relates the frequency separation in synchrotron frequency units to the energy separation in bucket height units:

$$\alpha \equiv \frac{\Delta f}{f_s} = 2\frac{\Delta E}{H_B}$$

For α=2, the hypothetically independent buckets overlap 50% in energy, and the single particle motion is chaotic everywhere within the overlap region. The case α=4 gives tangent boundaries for the hypothetical buckets and in the case of α=8 there is space for a complete empty bucket between the upper and lower hypothetical buckets. In practice a value of α greater than 5 is adequate for a highly efficient process. A plot of α as a function of the rf voltage for 1260 Hz separation is shown in Figure 5-1. From that figure we can see that an rf voltage of 80 kV meets the PIP-II requirements.

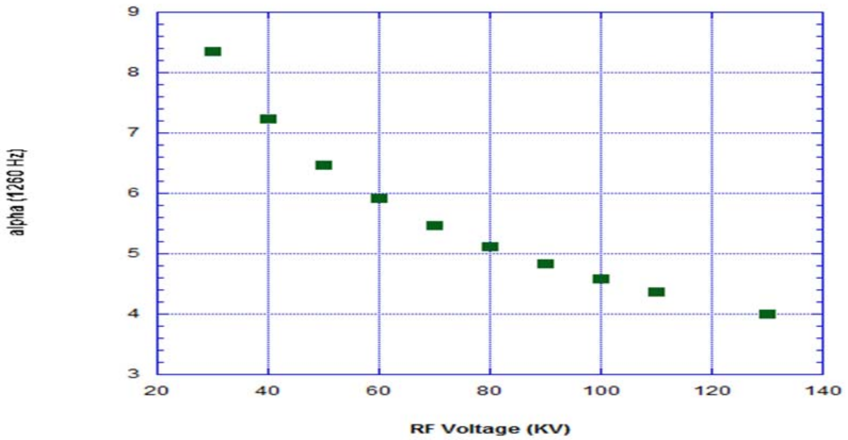

Figure 5-1: α vs. RF voltage for 1260 Hz separation in the Recycler.

With the Recycler rf voltage fixed, the longitudinal beam phase space required for delivery from the Booster are determined by the largest beam contour within an 80 kV bucket that provides 100% capture during the slip stacking process. Figure 5-2 displays beam particles characterized by their position on an initial matching beam contour – only those particle that are captured within the slip stacking process are displayed. The largest beam contour without particle loss corresponds to an emittance of 0.08 eV-sec (±4.1 nsec, ±6.1 MeV). The requirement of 97% efficiency then corresponds to requiring 97% of particles delivered from the Booster to lie within this matched contour.

The slip stacking system in the Recycler is now under commissioning in support of the NOvA program. This will provide valuable operational experience well in advance of the initiation of operations to LBNE at PIP-II beam intensity.

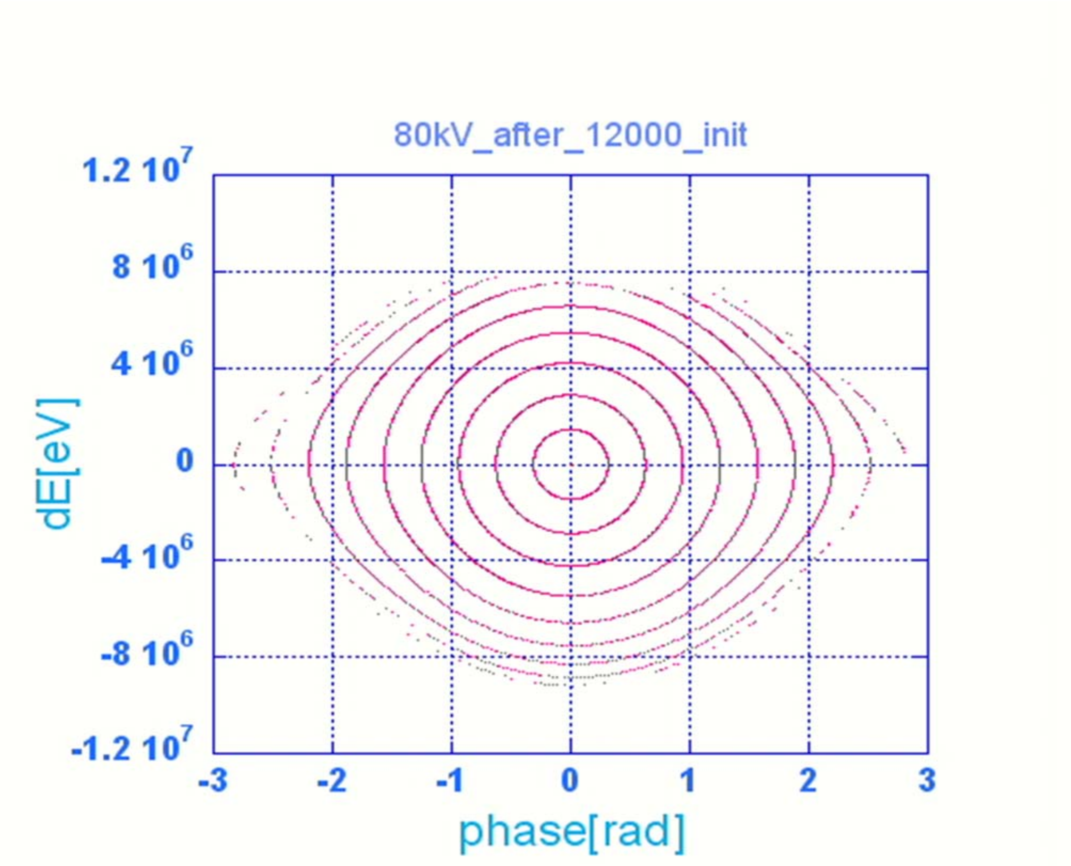

Figure 5-2: Particles on initial matching contours in an 80 KV bucket after 120 msec of slip stacking with 1200 Hz separation. Only particles captured are displayed.

5.2.2 Main Injector RF

The Main Injector rf systems are required to support the acceleration of 7.5×10^{13} protons to 120 GeV at a 1.2 second cycle time. Table 5-2 displays these rf system requirements in comparison to current capabilities. As is evident from the table the present system has sufficient voltage to support acceleration at the required rate; however it does not provide sufficient power to accelerate the required beam intensity at the required rate.

Performance Parameter	Present Capability	PIP-II Requirement	
Beam Intensity	6.2×10^{13}	7.5×10^{13}	
Harmonic Number	588	588	
Number of Filled Buckets	504	504	
RF Frequency Range	52.811-53.104	52.811-53.104	MHz
Acceleration Rate	240	240	GeV/s
Main Injector Ramp Rate:	1.2 s	1.2 s	
Accelerating Cavities	20	20	
Maximum Accelerating Voltage	235	235	kV/cavity
Total Available Accelerating Voltage	4.7	4.7	MV
Total Required Accelerating Voltage ($V\sin\phi_s$)	2.7	2.7	MV
Total Required Cavity Power	204	240	kVA/cavity
Robinson Stability Factor	4	4	

Table 5-2: Present and required MI RF capabilities

In order to provide the rf power required to accelerate 7.5×10^{13} protons three options could be considered:

1. Operate the current rf cavities with two power tubes instead of one in a push-pull configuration. This will require doubling of the number of modulators and solid state drivers.
2. Use a new more powerful power tube, such as the EIMAC 4CW250,000B. This will require a new mounting configuration (to accommodate the much longer tube), new modulators, and upgraded power amplifier cooling.
3. Replace the entire rf system with a new one (new cavities and PAs). The advantage of this solution is that it can accelerate enough intensity to reach 2.3 MW.

Options 1 and 2 will be considered for PIP-II as they are substantially less expensive than Option 3.

5.2.3 Transition Crossing/Electron Cloud/Loss Control

A design of a first order γ_t jump system for the Main Injector was completed as part of the Project X Reference Design. This system is required for 2.3 MW operations – further simulations are needed to verify if it is required for 1.2 MW operation.

Recent electron cloud measurements in Main Injector indicate that beam scrubbing is quite effective in reducing the SEY of the beam pipe so no problems are anticipated at PIP-II intensities.

Realistic space charge simulations for the Main Injector and Recycler are under development and benchmarking. These will provide guidance on understanding and mitigating emittance growth and beam loss at low energy.

5.3 R&D Required

In addition to the efforts listed above it will be required to develop a new slip-stacking cavity system in the Recycler if it is desired to support Main Injector at the higher repetition rates corresponding to energies below 120 GeV. This is due to limited cooling available within the existing cavities.

6 LBNE Neutrino Beam

6.1 Technical Requirements/Scope

The parameters of the proton beam that will be delivered by the Main Injector to the LBNE target are given in Table 5-1. The increase in proton per pulse intensity, from 4.9×10^{13} within the current LBNE baseline to 7.5×10^{13}, and the concomitant increase in thermal pulsing requires changes in the design of the primary proton beam window, target, both horns, decay pipe windows, and hadron monitor relative to the current design for 700 kW operation. These changes, while challenging, are understood and will be supported by R&D and/or prototyping for each device, which will be undertaken in support of the LBNE project. Additionally, incremental enhancements are required for the target shield pile cooling, water systems, remote handling, and shielding on top of the target hall. This section focuses solely on items that need to be changed for 1.2 MW operation – many other systems are left unchanged.

6.2 Accelerator Physics Design

The LBNE beamline has been designed for initial 700 kW operations and to be upgradeable to 2.3 MW [6]. Beamline elements which cannot be practically changed later, e.g. the hadron absorber and shielding for the target chase and the decay pipe, are designed to a 2.3 MW requirement. Elements which can be upgraded later, e.g. the target and horns, are designed for the lower initial beam power, which PIP-II will increase to 1.2 MW. The design difference between 700 kW and 1.2 MW can be substantial, particularly for items that adopted established NuMI designs, which originally were meant for 400 kW operation.

The neutrino beam elements whose current (700 kW) design must be reconsidered for higher beam power are listed in Table 6-1. The current design for 700 kW is briefly described, and potential design changes to accommodate the higher 1.2 MW beam power are listed. For the target and horns, several options are listed; the choice of which one(s) to use will be the subject of design studies and R&D that will be performed in the context of the LBNE project.

6.3 R&D Required

Medium-term R&D can be applied to reduce the uncertainty in how aggressive the new designs need to be and to develop solutions where we do not yet have a demonstrated solution. In particular:

- Cooling calculations of the primary beam window can decide whether an actively cooled design is required and establish requirements for that system.
- A conceptual design of a 1.2 MW target must be demonstrated through simulation and engineering analysis. Eventual prototyping will also be required. Demonstrating the performance of beryllium in targets would go a long way toward producing a concept.

- New horn cooling and/or construction technologies must be developed to deal with the higher beam power. These technologies must be eventually validated in full-scale horn prototypes.
- Some new technology needs to be developed for the hadron monitor to measure beam in the intense environment while surviving long-term. This technology will need to be tested in beam and/or radiation.

Element	**700 kW Design**	**Potential 1.2 MW Design**
Primary Beam Window	Passively cooled beryllium	Possibly active cooled beryllium
Target	Segmented graphite, water cooled.	- Increased target fin width and beam diameter - Encapsulated, prestressed graphite target segments - gas cooling - beryllium target
Horns	NuMI horns: aluminum conductor, water spray cooling	- reduced current pulse length - improved water spray cooling - two-phase cooling - beryllium alloy inner conductor - increased neck diameter
Decay pipe upstream window		
Air-filled (ref. design)	No window	No window
He-filled (alt. design)	Aluminum disk with beryllium center section, air cooled	To be studied
Hadron Monitor	Parallel-plate, low-pressure argon ionization chambers	To be studied
Remote Handling	Six short-term storage cells in target hall	Additional short-term storage required
Target chase cooling	Air-cooled; provision for water cooling	Possibly add water cooling system
Target chase shielding	Steel and concrete	Additional 25 cm of concrete on roof

Table 6-1: Neutrino beam elements whose design must be reconsidered for 1.2 MW operation.

7 Site Layout

7.1 Considerations

The Linac site is in close proximity to the Booster, in the Tevatron infield (see Figure 1-1). This location affords direct access to existing electrical, water, and cryogenic infrastructure. Surface construction includes buildings, road and parking relocation, and additional roadways and access from the Fermilab Central Campus. Underground construction includes the linac enclosure, the transfer line enclosure, and a beam dump.

The linac enclosure is sited at the same elevation as the Booster. Adequate shielding is provided over the enclosure to keep radiation levels in all areas below the level for continuous occupancy. Booster injection occurs in the Long 10 or Long 11 straight section. Using these straight sections displaces minimal tunnel equipment and also reduces the interference with electrical utilities. The transfer line does cross through the existing Tevatron tunnel. As the 120 GeV Switchyard program is assumed to continue, it must be integrated with continued operation of that program.

The linac gallery is of similar length as the underground linac enclosure, housing the utilities and support equipment to operate the RF power systems, magnets, vacuum, and controls. It is located between the linac enclosure and the Tevatron tunnel.

While the working cryogenics arrangement does not necessarily require new building space, a possible siting has been identified at the downstream end of the linac, somewhat further into the Tevatron infield.

Construction of the underground enclosures as well as the surface buildings is similar to proven construction methods previously executed at Fermilab. Construction of all below-grade enclosures consists of conventional open-cut type construction techniques. The architectural style of the new buildings reflects, and is harmonious with, the existing buildings. Currently, the layout has been chosen for the accelerator requirements. Future layouts will consider existing topography, sustainability, watersheds, vegetation, natural habitat, and wetlands. All the aspects will be thoroughly addressed in the Environmental Assessment for this project.

7.2 Technical Requirements/Scope

The configuration and siting selected for the SC linac and supporting buildings and transfer lines is displayed in Figure 7-2. Also shown in the figure is a concept for subsequent development of the accelerator complex, beyond the scope of PIP-II, through the addition of 1-3 GeV and 3-8 GeV linacs (cyan and green lines).

The linac enclosure is sized to accommodate the length of a 1 GeV linac (~250 m, 830 ft), to provide adequate space and penetrations for utilities (power, water, cryogens) and cabling, to allow for installation and maintenance, and to include access points for moving equipment in and out of the enclosure. The linac gallery is slightly shorter than the enclosure (~220 m, 715 ft).

The linac beam elevation is chosen to match the Booster elevation. A concept cross section of the enclosure can be seen in Figure 7-1. It is surrounded by 7.5 m (24.5 ft) of passive earth shielding to allow unlimited occupancy of the linac gallery and surrounding areas [3].

The transfer line brings the beam from end of the linac to the Booster. The enclosure has a similar cross section to the existing Tevatron tunnel and is ~175 m (570 ft) in length. The arc radius of the transfer line enclosure is 23 m (75 ft) to minimize magnetic stripping for the 800 MeV H^- beam. Although a detailed optical design has not been done the requirements are well understood. In particular, the line Twiss parameters must be matched to those required for Booster injection in order to optimize the beam painting scheme. The total bend in the line is approximately 225° (210°) for injection at the Long 10 (11) straight section. The linac dump handles the full beam power (13 kW) of the linac.

The current concept for the cryogenics configuration utilizes space in the A0 high-bay building to host the required compressors and refrigerators. If for some reason (extended operations of Muon Campus operations) this is not achievable a new cryogenics building will be constructed.

An estimate of site power requirements for the linacs and beam transfer lines is given in Table 7-1.

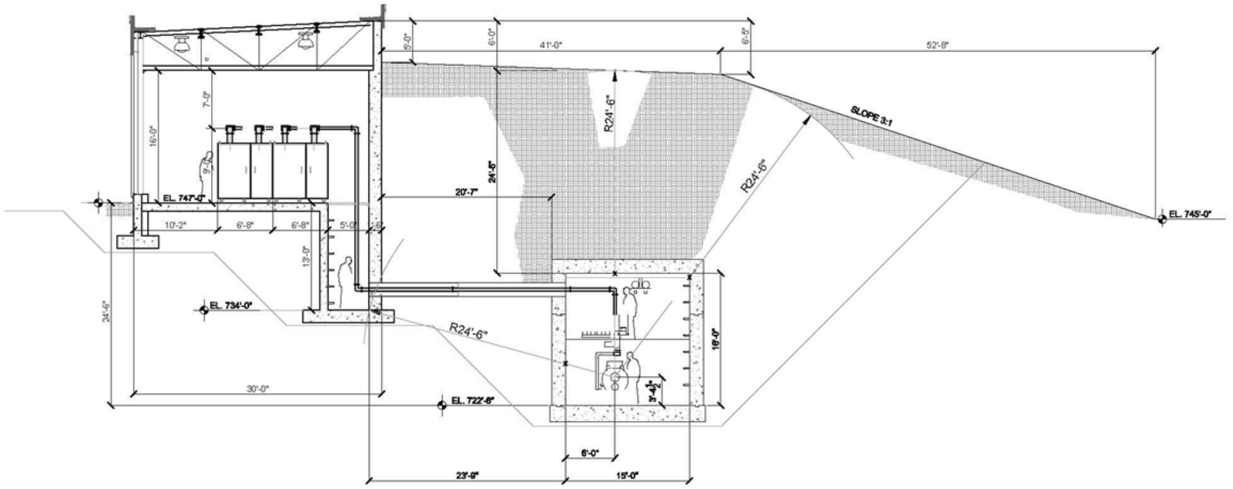

Figure 7-1: A concept cross section of the linac gallery and tunnel.

System	Wall-Plug Power (MW)
Pulsed Linac RF	1.5
Cryogenic Systems	0.6
Low Conductivity Water	0.2
Industrial Chilled Water	0.1
HVAC	0.4
Conventional Systems	0.5
Total	3.3

Table 7-1: Site power estimates.

7.3 Other Options

Several other options have been or are still under consideration. The existing Linac gallery could be extended to the north, preserving the injection area into the Booster and reducing new gallery and underground construction. This option does not lend itself as well to future upgrade plans as it presents difficulties in siting 3 GeV and 8 GeV linacs.

A folded linac, where the fold is in the vertical direction, would allow for a shorter linac enclosure and gallery. It would be natural to fold at a transition in the cryomodule type (e.g., 177 MeV after the SSR2), although the optics to preserve transverse and longitudinal emittance through such a dogleg have not been worked out.

While the working cryogenics arrangement does not require new building space, a possible siting has been done. The cryogenics building is sited at the downstream end of the linac, somewhat further into the Tevatron infield (see Figure 7-2). It is sized at 4000 sqft to contain the pump, compressor, and refrigeration equipment needed for pulsed operation of the 800 MeV linac, but is expandable to accommodate future upgrades for CW operation and additional higher energy linac sections.

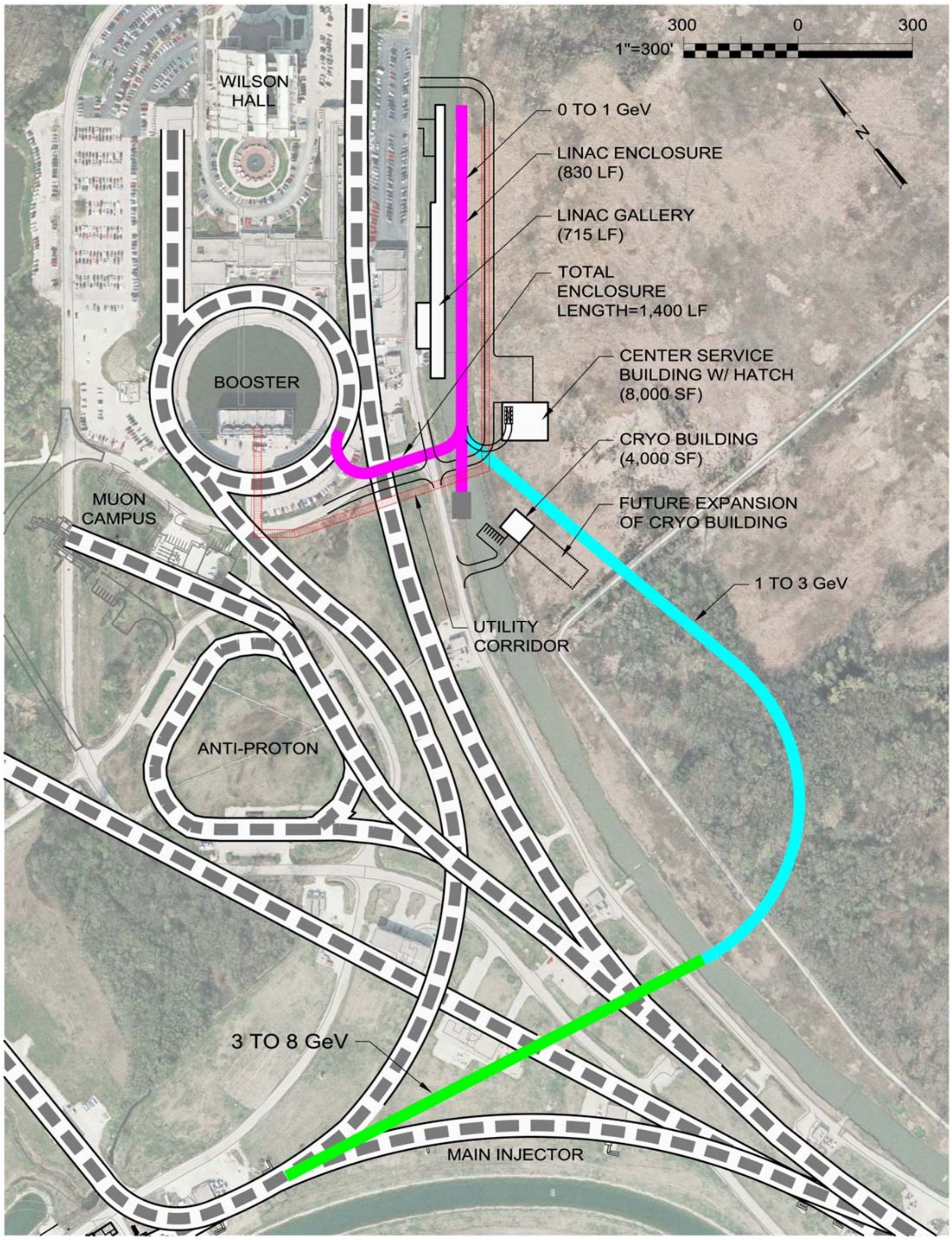

Figure 7-2: Site layout of the SC Linac, including siting of future possible upgrades. Magenta is the 800 MeV linac enclosure and transfer line, cyan is a 1-3 GeV CW linac and transfer line, and green is a 3-8 GeV pulsed linac. The dashed areas are existing (or planned) tunnel enclosures.

8 Cost Estimate

The scope encompassed by the PIP-II cost estimate includes the SC linac from ion source through 800 MeV, the beam transport line required to deliver beam to the Booster injection point, and the associated R&D program. It is assumed that modifications to the Booster, Recycler, and Main Injector will be managed by the corresponding operating Departments in the Fermilab Accelerator Division and funded as Accelerator Improvement Projects (AIPs), and that the LBNE target facility will be managed and funded through the LBNE project.

The estimate has been developed based on prior work done in estimating the cost of the Project X Reference Design. The primary modifications to the Reference Design/Stage 1 that are reflected in the PIP-II estimate include:

- Lowering the linac energy from 1 GeV to 800 MeV
- Lowering the cryogenic duty factor from 100% to 5%
- Lowering the rf duty factor from 100% to 10%
- Reutilizing R&D components in the PIP-II linac front-end
- Siting the linac in close proximity to the Booster

These factors account for nearly the entire cost reductions inherent in the PIP-II estimate.

8.1 Assumptions and Methodology

The cost estimate is assembled in the following manner:

- Estimates are made for all major subsystems at the component level
- Estimates are entered in FY2013 dollars for Materials & Services and in person-years for effort
- Effort is translated into FY2013 dollars utilizing Fermilab standard labor rates
- Project overheads are applied
- An across-the-board 40% contingency is applied
- The resulting estimate is escalated to FY2020 dollars utilizing DOE escalation rates

This procedure results in an estimate that has the characteristics of a DOE Total Project Cost (TPC). An estimated value of potential international contributions is developed separately, and is discussed in Section 8.5.

There are several inherent assumptions included in this approach. It is assumed that: 1)all work associated with the PIP has been successfully completed; 2)PIP-II is completed over seven years, starting with CD0 in FY2015; and 3)large-project overhead rates will be established at levels lower than current Fermilab rates.

8.2 Cost Summary

The Total Project Cost for PIP-II is estimated at $542M. A breakdown by major components is displayed in Table 8-1 and Figure 8-1. As can be seen accelerating cavities/cryomodules and civil construction represent the primary cost drivers, accounting for ~50% of the total estimated cost. It is worth noting that the incremental cost of the superconducting linac at 800 MeV is roughly $0.2M/MeV in the TPC metric. The BOE (basis of estimate) column is described in section 8.3.

PIP-II Major Cost Component	Estimate ($M)	BOE
R&D	$26.6	Mixed
Project Management	$26.1	LE
Accelerating Cavities and Cryomodules	$70.5	CD
RF Sources	$29.4	VQ
Cryogenic Systems	$13.7	CD
Civil Construction	$65.6	PE
Instrumentation	$11.7	ECS
Controls	$13.0	ECS
Mechanical Systems	$2.5	CD
Electrical Systems	$1.9	CD
Beam Transport	$4.8	ECS
Sub-total (direct, FY2013 dollars)	$265.8	
Indirect Costs	$61.9	
Contingency (40%)	$131.1	
Escalation (18%)	$82.9	
TOTAL PROJECT COST (FY2020 Dollars)	**$541.7**	

Table 8-1: Major cost elements for PIP-II and the corresponding basis of estimate (BOE)

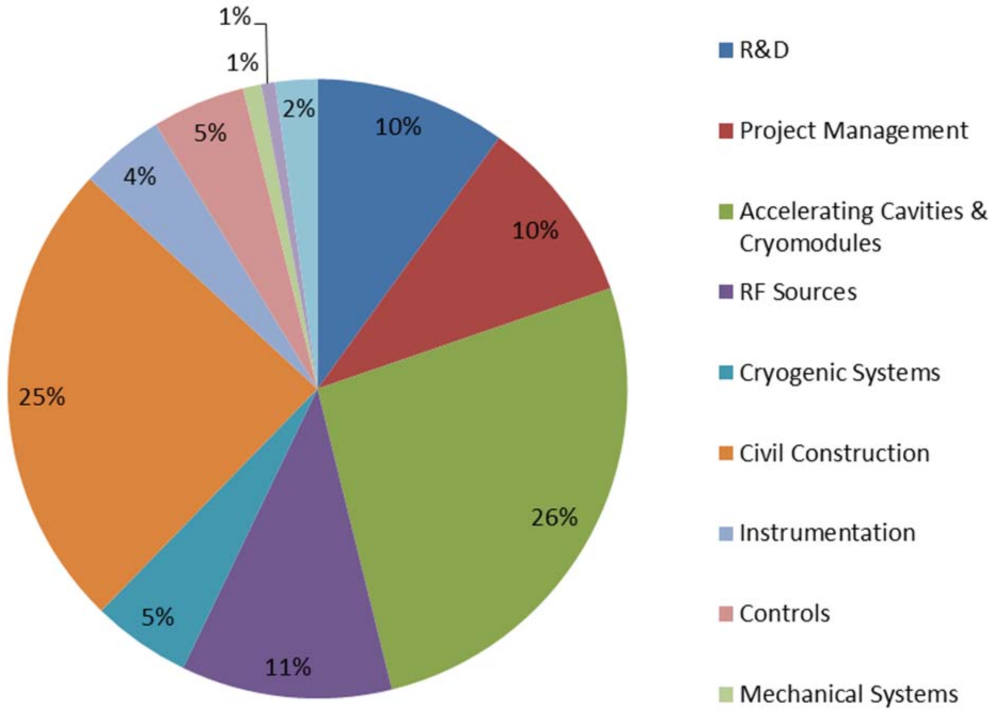

Figure 8-1: Breakdown of PIP-II by major cost components

8.3 Basis of Estimate

The estimate presented is relatively well developed for a pre-conceptual design. The basis of estimate for the various components and systems can be characterized as:

<u>Level of Effort (LE)</u>

Activities characterized by a number of people working for a certain period of time. An example is Project Management.

<u>Complete Conceptual Design (CD)</u>

Estimates based on analysis of complete concepts of individual components, often associated with R&D prototyping of identical or similar items. Examples are the superconducting accelerating modules.

<u>Vendor Informational Quotes (VQ)</u>

Information quotes from vendors and/or catalog prices on stock items. Examples include rf sources and distribution systems.

Informed Estimates based on Comparable Systems (ECS)

Extrapolation from similar systems constructed in the past. Examples include instrumentation and controls systems.

Parametric Estimates (PE)

Estimates based on industry standards and parameterized in terms of basic characteristics such as volumes, lengths, or areas. An example is civil construction.

A broad characterization of the basis of estimate for the major systems making up PIP-II has been given in Table 8-1.

8.4 Benchmark Comparisons

The cost estimate prepared for the Project X Reference Design, which forms the basis for much of the PIP-II estimate, is based on the pre-conceptual design described in the RDR. Because of the early nature of the design activities this estimate is assigned a 40% across-the-board contingency. The resulting estimate is compared to the actual costs accrued during the construction of the Spallation Neutron Source (SNS) facility at Oak Ridge. The SNS is selected for comparison because it is the closest comparable facility to Project X/PIP-II.

Specifically, a comparison is made between the construction cost of the 1 GeV/1 MW SNS linac and the 1 GeV/1 MW Project X/Stage 1 linac. This comparison provides a more useful benchmark than comparison to PIP-II because of the significant difference in beam power between PIP-II and SNS. To provide an apples-to-apples comparison the following construction activities/components are included in the comparison:

- Project Management
- Linac Technical Components
- Cryogenic Systems
- Civil Construction

The comparison is done in FY2013 dollars, which requires escalation of SNS costs from 2003 to 2013 (about 40%). This comparison is given in Table 8-2. As can be seen the estimated cost of the Project X/Stage 1 linac is about 8% lower than SNS. While both linacs deliver 1 MW at 1 GeV, there are differences in implementation that will affect costs: 1)the SNS linac operates at lower gradient, thereby increasing its length; 2)the SNS operates at higher peak current, thereby increasing the cost of rf sources; and 3)the SNS operates at lower duty factor, thereby decreasing the cost of the cryogenic system. A more systematic study of these effects at the major component level indicates that the costs of these systems in terms of their fundamental underlying parameters are quite comparable.

Major Cost Component	SNS Linac ($M, 2003)	SNS Linac ($M, 2013)	PX/Stage1 ($M, 2013)
Project Management	30.5	42.3	64.0
Linac Components	347.0	486.5	352.9
Cryogenic Systems	26.7	37.4	92.7
Civil Construction	107.2	150.2	148.5
TOTAL	511.4	716.4	658.2

Table 8-2: Comparison of as-built costs for the SNS linac to the comparable scope within Stage 1 of Project X.

8.5 Potential International Contributions

The SC linac is expected to be attractive to international partners with an interest in the physics research program enabled by PIP-II and/or in acquiring capabilities in the underlying technologies. The most advanced discussion on potential contributions is with India, although discussions have recently engaged other European and Asian institutions. All of these discussions are in terms of in-kind contributions rather than direct funding. It is impossible to identify specifically what contributions could/will materialize at this time, but we can identify the areas of opportunity.

Fermilab and four Indian Laboratories (BARC/Mumbai, IUAC/New Delhi, RRCAT/Indore, and VECC/Kolkata) established the Indian Institutions and Fermilab Collaboration (IIFC) in February, 2009. The initial framework covered joint development of superconducting radiofrequency technologies with applications to high intensity proton accelerators. The collaboration has since expanded into other relevant technologies including rf sources, cryogenic systems, instrumentation, and controls. Discussions of potential in-kind contributions to a MW-class superconducting linac at Fermilab have proceeded under the auspices of the “Implementing Agreement between the Department of Energy of the United States of America and the Department of Atomic Energy of the Republic of India for Cooperation in the Area of Accelerator and Particle Detector Research and Development of Discovery Science”, signed July 19, 2011. This discussion is currently being reoriented to correspond to the SC linac within PIP-II. A significant in-kind contribution is under discussion.

More general discussions have occurred with potential European and Asian collaborators outside of India. While these discussions have not progressed to the same degree as those with India, significant opportunities exist.

Systems and components identified as candidates for international in-kind contribution include:

- SSR1 and SSR2 cavities and cryomodules

- LB650 and HB650 cavities and cryomodules
- 325 MHz rf sources
- 650 MHz rf sources
- Corrector magnets
- Beam transport magnets
- Magnet power supplies
- Beam position monitors

Any in-kind contributions will be valued in terms of the offset to DOE costs, i.e. they are to be valued according to how much they would cost the U.S. within the TPC metric. In assigning this valuation, 20% of the in-kind value will be retained within the contingency pool for PIP-II. Following this approach the potential value of international in-kind contributions to PIP-II could lie within the range $150-200M. A more specific value will be developed as part of the PIP-II planning process following a prospective CD-0.

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