Analysis of Alternatives: Proton Improvement Plan-II

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This document presents an analysis of alternative implementations of Proton Improvement Plan-II (PIP-II), as required by DOE O413.3b for consideration in advance of CD-1.

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Introduction

This document describes and analyzes potential alternative implementations of Proton Improvement Plan-II (PIP-II). The analysis of alternative means of achieving established goals is mandated by DOE O 413.3b as a requirement for CD-1. It is expected that this analysis will lead to the selection of a specific alternative that will provide the basis of the Conceptual Design Report developed in support of CD-1. The relevant language in the order includes: "The recommended alternative should provide the essential functions and capabilities at an optimum life-cycle cost, consistent with required cost, scope, schedule, performance, and risk considerations. It should be reflected in the site's long-range planning documents as well."

We interpret "essential functions and capabilities" as referring to the performance requirements included in the approved PIP-II Mission Needs Statement, released in November 2015 concurrent with the issuance of CD-0 for the PIP-II Project. These capabilities are derived from, and described in somewhat more detail in, the May 2014 report of the Particle Physics Project Prioritization Panel (P5)[1]. These documents call for a performance upgrade of the Fermilab accelerator complex to support a world-leading neutrino program, while maintaining high reliability operations through the rejuvenation of aging systems within this complex and providing a platform for future enhancements. Based on these performance requirements pre-conceptual development for PIP-II has proceeded on the basis of the following design criteria:

- Deliver 1.2 MW of proton beam power from the Fermilab Main Injector, over the energy range 60 – 120 GeV, at the start of operations of the Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE) program;
- Sustain high reliability operations of the Fermilab accelerator complex through the initial phase of LBNF/DUNE operations;
- Support the currently operating and envisioned 8-GeV program at Fermilab including the Mu2e, g-2, and the suite of short-baseline neutrino experiments;
- Provide a platform for eventual extension of beam power to LBNF/DUNE to >2 MW;
- Provide a flexible platform for long-range development of the Fermilab complex; in particular provide an upgrade path for a factor of ~10 increase in beam power to the Mu2e experiment, and for extension of accelerator capabilities to include flexible high-bandwidth pulse formatting/high beam power operations.

A specific concept, designated the PIP-II Reference Design, has been developed to satisfy these criteria and is described in a Reference Design Report[2].

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

[2] The PIP-II Reference Design Report, V. Lebedev editor, June 2015
http://pip2-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=1&filename=PIP-II_RDR_v0.0.pdf&version=1

The Department of Energy/Office of High Energy Physics (OHEP), in discussions with PIP-II Integrated Project Team (IPT), has developed a three-step process for completion of the PIP-II analysis of alternatives:

1) Preparation of an Analysis of Alternatives (AoA) Report by the PIP-II team, based upon alternatives and evaluation criteria provided by the OHEP;
2) A review of the AoA Report by an independent committee convened by the OHEP, culminating in a final AoA report that provides well-documented and accurate evaluation of alternatives;
3) Transmission of the final AoA report to the Office of Science for selection of the preferred alternative.

This document represents step 1) in this process. It should be noted that no recommendation is made in either step 1) or 2). OHEP has provided four alternatives for analysis based on ten evaluation criteria. Descriptions of the four alternatives and their associated performance characteristics are given in the second section of this document, the cost estimates, including annual operating costs, are described in the third section, and evaluations of each alternative relative to each evaluation criteria are contained in the fourth section. The report concludes with a Summary table displaying the high-level evaluations contained in this report. In general this report finds that all alternatives can meet the near-term needs of the neutrino program as identified within the Mission Need Statement, while the Reference Design (Alternative 1) provides significant long term opportunities for development into a world-leading high intensity hadron facility. Furthermore, Alternative 1 is found to be realizable at a cost comparable to the other alternatives under the assumption that in-kind contributions from international partners are forthcoming as currently envisioned.

It is noted that the “no-action” alternative is not considered in this process as it does not meet the requirements contained in the Mission Need Statement for PIP-II.

Description of Alternatives

Four alternative implementations of PIP-II are described. The first listed has been developed in significant conceptual detail over the last three years and corresponds to the configuration described in the PIP-II Reference Design Report. The additional three alternatives are identified for analysis as representative of approaches that could be taken to achieve the first of the design criteria listed above while addressing some common concerns that have been raised by review committees concerning the Reference Design. There has been no extensive attempt to optimize these three alternatives, however we would claim that an optimization would not change the evaluations presented in the last section of this report in a significant way. Our expectation is that if one of Alternatives 2-4 were selected as the preferred alternative a more complete cost/technical optimization would be completed in preparation of the Conceptual Design Report required at CD-1.

The most fundamental choice to be made in selecting an alternative is the underlying acceleration technology, with the primary discriminator being the utilization of superconducting (SC) or normal-conducting (NC) radiofrequency acceleration. SC technologies are compatible with continuous wave (CW) operations while NC technologies are not. In general, operation in CW mode is not required to support neutrino production. The most obvious optimization within a specific alternative is the beam current and this is the fundamental parameter that has been varied within this report to illuminate the choices inherent among the alternatives. In brief the four alternatives are:

- **Alternative 1 (800-MeV SC Linac, CW-compatible; Reference Design)**: 800-MeV superconducting linac, constructed of CW-capable components, operated initially in pulsed mode at an average beam current (during the pulse) of 2 mA, located on the Tevatron infield, accompanied by necessary modifications to the existing Booster/Recycler/Main Injector accelerators.
- **Alternative 2 (800-MeV SC Linac, pulsed, higher current)**: 800-MeV superconducting Linac, optimized for low-duty factor pulsed operations, at an average beam current of 5 mA, located on the Tevatron infield, accompanied by necessary modifications to the existing Booster/Recycler/Main Injector accelerators.
- **Alternative 3 (Hybrid; Relocated 400-MeV NC Linac, add 400-MeV SC Linac)**: 800-MeV linac constructed by adding a 400-MeV superconducting linac, optimized for low-duty factor pulsed operations, at an average beam current of 20 mA, to the existing but relocated 400-MeV Linac, accompanied by necessary modifications to the existing Booster/Recycler/Main Injector accelerators.
- **Alternative 4: (Relocated 400-MeV NC Linac, add 400-MeV NC Linac)**: 800-MeV linac constructed by adding a 400-MeV normal-conducting linac, optimized for low-

duty factor pulsed operations, at an average beam current of 20 mA, to the existing but relocated 400-MeV Linac, accompanied by necessary modifications to the existing Booster/Recycler/Main Injector accelerators.

The balance of this section describes in further detail these four alternatives, their performance characteristics, and their integration into the existing Fermilab accelerator complex. For each alternative we provide:

- Technical description, including configuration and schematic layout, and performance characteristics
- Description of the associated conventional construction
- Potential schedule for construction, including interruption to operations

These descriptions form the basis of the cost estimates and comparison to evaluation criteria contained in the third and fourth sections.

Approach

To the extent possible we utilize common performance objectives and common configurations except in those cases in which the objectives vary in direct relationship to the underlying technologies. This approach is taken to minimize artificial distinctions between the alternatives and to simplify the cost comparisons. Specific examples include:

- All four alternatives are based on a linac operating at 800 MeV.
- The combined choice of beam current × pulse length is maintained over all four alternatives. However, current and pulse length are not individually maintained because of variations in the essential capabilities of CW versus pulsed and SC versus NC linacs. Choices made in this report are representative of the differing requirements among the configurations – further optimization can be expected as the design of the selected alternative matures.
- All alternatives use a common configuration of the front end: an ion source followed by a Low Energy Beam Transport line, a room temperature 2.1-MeV RFQ, and a long (~10 m) Medium Energy Beam Transport line. This configuration is chosen to allow similar beam chopping within the front end for all configurations, as is required by the Booster injection scheme.
- Alternatives 1 and 2 are both constructed of CW-capable SC cavities and cryomodules. This choice is made because there is no significant cost penalty for doing so in Alternative 2.
- The 201 MHz triodes currently utilized in the existing drift-tube linac represent a long-identified vulnerability – a single vendor exists and Fermilab is one of only two customers. In order to mitigate the associated risk Alternatives 3 and 4 utilize new

klystrons as the RF power source in the 201 MHz section. It is assumed that these klystrons are provided via the ongoing Proton Improvement Plan (PIP) and hence are not costed against PIP-II.

- The linac operates at 20 Hz in all alternatives. This provides for comparable performance in support of both the long-baseline neutrino program over the range 60-120 GeV and the ongoing 8-GeV program, including the short-baseline neutrino program.
- All alternatives are situated in newly constructed tunnel enclosures and associated equipment galleries on the Tevatron infield. This location, which is used in the Reference Design, provides the most straightforward path to an eventual capability of >2 MW to LBNF. Utilization of the existing (Linac and Booster) enclosures for the PIP-II linac and an eventual new RCS is precluded by inadequate shielding for anticipated intensities, with no practical options for increasing this shielding. Further details are provided in the description of Alternative 3 conventional construction. The proposed location is shown in Figure 1.
- In all alternatives the linac enclosure is constructed with sufficient free space at the downstream end to allow eventual upgrading of the linac to 1 GeV; the transfer line to Booster is configured to allow for eventual direct connection from the linac to the Muon Campus;
- The configuration and performance parameters of the existing Booster, Main Injector, and Recycler Ring are the same in all four alternatives with the single exception of the number of injected turns into the Booster (a reflection of the varying beam currents). The primary modifications required in the existing rings are:
    - Implementation of a new Booster injection area capable of accepting beam at 800 MeV;
    - Upgrade of the Booster to 20 Hz operations;
    - Modifications to the Booster transition crossing scheme to improve longitudinal emittance preservation;
    - Upgrades to Booster damper and collimation systems;
    - A new RF system in the Recycler to accommodate enhanced slip-stacking requirements;
    - A power upgrade to the Main Injector RF system to support higher beam intensity;
    - Introduction of a gamma-t jump system in the Main Injector to mitigate beam loss and/or emittance dilution.
- The construction cost estimates include the new linac plus required modifications to the existing Booster/Recycler/Main Injector accelerator complex. All alternatives utilize a common estimate for the existing accelerators, and common estimates for shared portions of the Reference Design (for example Project Management).

Alternatives 3 and 4 utilize a common estimate for the relocation of the existing 400-MeV NC linac.

- The cost estimate methodology for international in-kind contributions follows the approach of the LBNF/DUNE project. The assumption is that international partners will successfully deliver all identified in-kind contributions.
- Life-cycle costs are presented as the initial construction cost and the required annual operations funding support. A 30 year operational lifetime can be assumed for translation into a life-cycle cost.

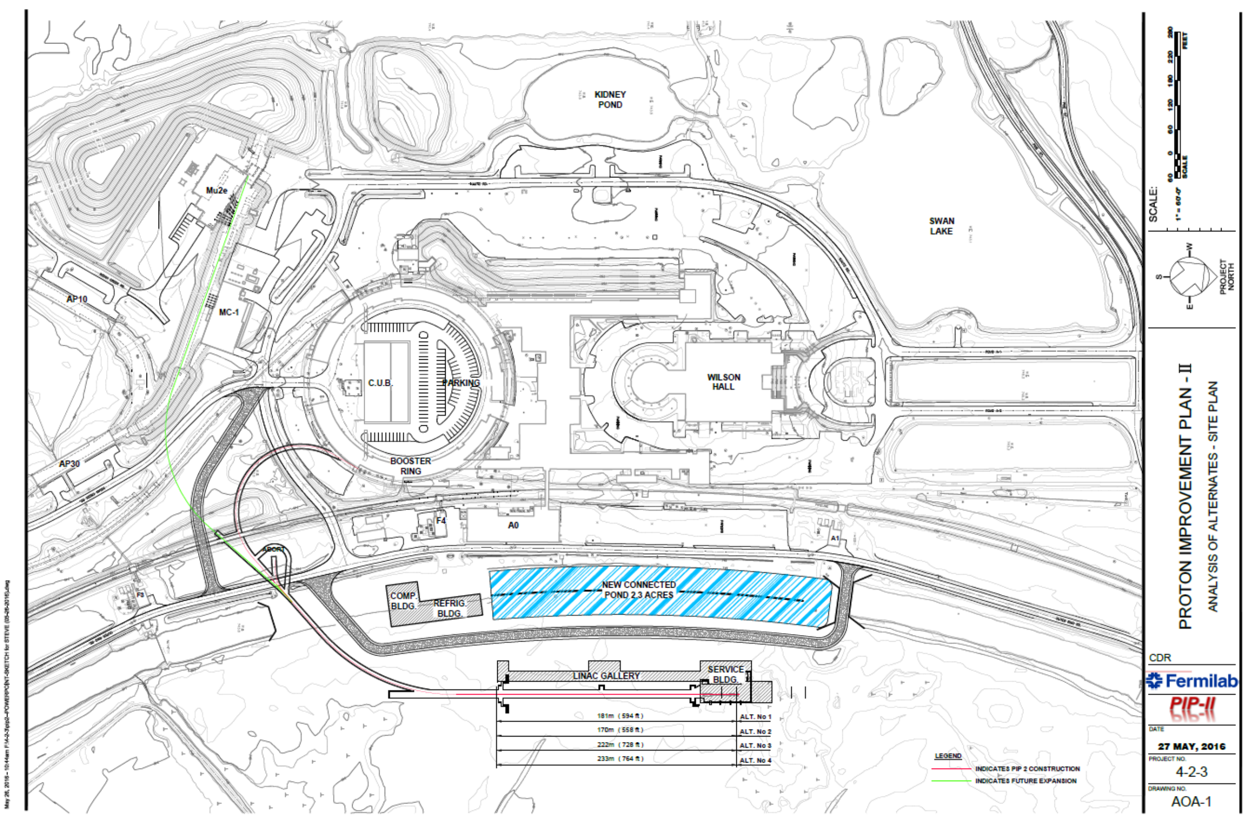

Figure 1: Site layout of Alternatives 1 - 4. For all alternatives the downstream beamline enclosure location remains fixed – the upstream (service building) location is adjusted to provide the appropriate length. Lengths refer to the linac length – and additional ~80 m of enclosure is provided to allow future extension of the linac to 1000 MeV. The compressor and refrigerator buildings do not exist in Alternative 4.

In addition certain assumptions are made in completing the analysis:

- The PIP-II Project will span the period 2016-2025, with construction taking place over 2020-2025, independent of the alternative chosen. This assumption does not distort the configuration of any alternative while simplifying the comparison. It is also consistent with the Mission Need Statement.
- The PIP-II Injector Test (PIP2IT) facility is reutilized to the extent possible in all alternatives. In Alternatives 1 and 2 the complete facility (Ion Source, LEBT, RFQ, MEBT, HWR, SSR1) is physically moved to form the PIP-II front end. In Alternatives 3 and 4 the LEBT and MEBT are physically moved, and augmented by the existing IS, a new 201 MHz RFQ, and a new drift tube linac tank ("tank-one") to form the PIP-II front end.
- The operating costs presented are associated specifically with the linac only. This is because operating costs associated with the existing accelerators (Booster, Main Injector, Recycler) are independent of the alternative chosen, and should be very close to current operating costs. A total of 5600 hours of operations annually is assumed in all alternatives (40 weeks × 140 hours/week).
- Accelerator operations in the Main Injector will be shut down for integration of LBNF into the accelerator complex – this interruption is currently scheduled over the period December 1, 2022 – November 1, 2024 (23 months). It is anticipated that there will be opportunities during this period for beam operations to the 8-GeV short baseline neutrino (SBN) program.
- The Indian DAE laboratories are developing CW, solid state RF amplifiers (SSRA) prototype units at both 325 and 650 MHz for utilization in PIP-II and in Indian domestic accelerators. These units range from 7 kW to 70 kW. Based on the scale and the enhanced cost of SSRAs relative to klystrons at high power we assume that any RF amplifiers with requirements above 100 kW (peak power) would be klystrons (or IOTs), not SSRAs.
- Construction costs presented are costs to DOE, i.e. netted against anticipated international in-kind contributions. Such contributions are valued at the incremental cost that would be borne by the DOE in their absence.
- A model of Indian in-kind contributions has been developed for Alternative 1. It is assumed that the same contributions would apply in Alternative 2 with the exception of 650 MHz RF power sources which have a peak power beyond the 100 kW limit given above. It is further assumed that international in-kind contributions would not be forthcoming in Alternative 3 and 4 due to misalignment with the technology interests of India and other potential international partners. Further details may be found in the International Contributions section.
- Substantial investments have been made by both the U.S. DOE and the India DAE in the R&D program associated with the Reference Design. In all alternatives it is assumed that the half-wave Resonator (HWR) and single-spoke resonator (SSR1)

cryomodules currently under construction are completed and tested, and that all commitments to India are completed within the R&D phase. In Alternatives 3 and 4 this leads to substantial R&D investments not directly related to construction of the facility.

Summary Parameter Table

Based on the above considerations we summarize in Table 1 the performance characteristics of the four alternatives described in this document. Details are contained in the following sections.

Table 1: Performance Parameters for the four alternatives.

Alternatives	1	2	3	4	
Linac					
Beam Energy (kinetic)	800	800	800	800	MeV
Beam Current (peak)	4	10	40	40	mA
Beam Current (chopped)	2	5	20	20	mA
Beam Pulse Length	0.54	0.215	0.054	0.054	msec
RF Pulse Length	6.0	2.4	0.35	0.10	msec
Pulse Repetition Rate	20	20	20	20	Hz
Beam Power to Booster	17	17	17	17	kW
Beam Transverse Emittance (rms, normalized)	0.3	0.3	2	2	mm-mr
Beam Longitudinal Emittance (rms)	1.1E-06	1.2E-06	6.30E-05	6.30E-05	eV-s
Number of Superconducting Cavities	116	110	32	NA	
Installed RF Peak Power (total)	4.0	7.7	102.0	148.1	MW
Cavity Bandwidth	60	110	507	NA	Hz
Operational RF Duty Factor	12.00	4.70	0.71	0.14	%
Beam Duty Factor	1.07	0.43	0.11	0.11	%
Heat Load @ 2K	276	260	164	NA	W
Wall-plug Power (@operational duty factor)	3.3	3.1	3.6	3.8	MW
Length of Linac	181	170	222	233	m
Booster					
Beam Energy (Kinetic)	8.0	8.0	8.0	8.0	GeV
Injected Protons per Pulse	6.7E+12	6.7E+12	6.7E+12	6.7E+12	
Acceleration Efficiency	97	97	97	97	%
Extracted Protons per Pulse	6.5E+12	6.5E+12	6.5E+12	6.5E+12	
Injection Turns	296	118	30	30	
Pulse Repetition Rate	20	20	20	20	Hz
Beam Transverse Emittance (rms, normalized)	2.7	2.7	2.7	2.7	mm-mr
Beam Longitudinal Emittance (97%)	0.08	0.08	0.08	0.08	eV-sec
Beam Power (Total)	166	166	166	166	kW
Beam Power to MI/RR/120 GeV	83	83	83	83	kW
Beam Power to 8 GeV Program/120 GeV	83	83	83	83	kW
Beam Power to MI/RR/ 60 GeV	142	142	142	142	kW
Beam Power to 8 GeV Program/60 GeV	24	24	24	24	kW
Recycler/Main Injector					
Slip-stacked Pulses	12	12	12	12	
Slip-stacking Efficiency	97	97	97	97	%
Maximum Beam Energy	120	120	120	120	GeV
Protons per Pulse	7.53E+13	7.53E+13	7.53E+13	7.53E+13	
Cycle Time @ 120 GeV	1.2	1.2	1.2	1.2	sec
Beam Power @ 120 GeV	1.2	1.2	1.2	1.2	MW
Cycle Time @ 60 GeV	0.7	0.7	0.7	0.7	sec
Beam Power @ 60 GeV	1.0	1.0	1.0	1.0	MW

Alternative 1: 800-MeV SC Linac, CW-compatible; Reference Design

The initial concept of the PIP-II linac, designated the Reference Design, is described in detail in the 2015 Reference Design Report. The Reference Design is an H^- superconducting linear accelerator with beam energy of 800 MeV. The machine is capable of high duty factor (CW compatible) operations, however is expected initially to be operated in pulsed mode with a peak beam current of 4 mA and an average beam current (during the pulse) of 2 mA. The beam and RF duty factors are 1.1% and 12% respectively. The location of the PIP-II linac is situated on the Tevatron infield, in a new enclosure. Furthermore, its location is strategically situated to provide the ability to upgrade the linac to a higher beam power and/or to add a new rapid cycling synchrotron to replace the Booster, as will be determined by future needs.

Technical description and performance characteristics

The main linac parameters are based on the requirements for being capable of injecting beam into Booster at 6.7×10^{12} protons per pulse, a factor of about 1.5 higher than the present operational intensity. The maximum repetition rate is 20 Hz, which enables additional beam power for the 8 GeV experimental program. The configuration and performance characteristics of the Alternative 1 linac are described in Table 2.

The SC Linac, is derived from the 1.3 GHz superconducting technology developed over the last several decades at multiple laboratories, including Fermilab. PIP-II utilizes three different accelerating frequencies, which are subharmonics of 1.3 GHz. The overall architecture of Alternative 1 is shown schematically in Figure 2 – note that this figure is not to scale.

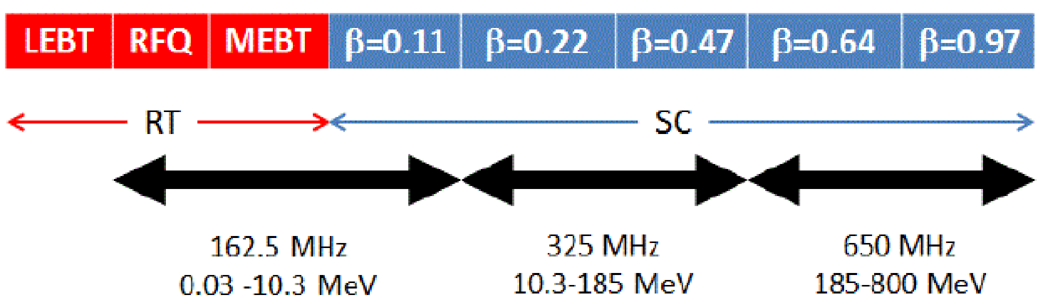

Figure 2: Functional configuration of the Alternative 1 linac (not to scale).

Table 2: Linac configuration and performance parameters for Alternative 1.

	Front End	SC Linac					
Kinetic Energy (out)	2.1	800					MeV
H- Beam Current (peak)	4	4					mA
Chopping Fraction	0.5	0.5					
H- Beam Current (averaged over pulse)	2	2					mA
Beam Pulse Length	540	540					μsec
Total Particles	6.7E+12	6.7E+12					
Pulse Repetition Rate	20	20					Hz
Beam Duty Factor	100	1.1					%
RF Duty Factor	100	12					%
Cavity β_g		0.09	0.19	0.40	0.61	0.92	
RF frequency	162.5	162.5	325	325	650	650	MHz
Cells/accelerating gaps/cavity	-	2	2	2	5	5	
Cavity effective length	-	0.20	0.20	0.42	0.75	1.12	m
Cavity gradient	-	9.7	10.0	11.4	15.9	17.8	MV/m
Cavities/cryomodule	-	8	8	5	3	6	
Number of cryomodules	-	1	2	7	11	4	
Accelerating cryomodule length	-	6.0	5.2	6.5	4.3	9.6	m
Inter-module spacing	-	0.3	0.5	0.5	1.0	0.8	m
Focusing elements (Quad. (NC) / Sol. (SC))	18	8	8	21	22	8	
Total length		6	10.4	45.5	47.3	38.2	m
Beam power	-	17.9					kW
Beam transverse emittance (rms, normalized)	-	0.3					mm-mr
Beam longitudinal emittance (rms)	-	1.1E-06					eV-s
Installed RF peak power (total)		4.0					MW
Cavity bandwidth	-	60					Hz
Heat load (@ 2K)	-	276					W
Linac wall-plug power (@operational duty factor)		3.3					MW
Length of linac	17.2	164					m

The low-energy front-end uses normal-conducting accelerating structures up to an energy of 2.1 MeV and creates the desired bunch structure for further acceleration. Five different types of SC accelerating structures boost the beam energy up to 800 MeV: one section of 162.5 MHz Half-Wave Resonators (HWR) up to 10.3 MeV; two sections of 325 MHz Single-Spoke Resonators (SSR) up to 185 MeV and two sections of 650 MHz elliptical cavities to the final energy. The RFQ, bunching cavities and the first SC accelerating section (HWR) operate at frequency of 162.5 MHz and in CW mode. To reduce the required cryogenic power the other accelerating structures operate in pulsed mode. Under this mode of operation Lorentz force detuning (LFD) is an important aspect of cavity resonance control. A conservative approach to LFD compensation is to have single radio frequency (RF) power sources to feed individual cavities for the regulation of the accelerating field. Full technical description and performance characteristics are found in the 2015 Reference Design Report.

Description of the associated conventional construction

The siting of Alternative 1 is shown in Figure 1. The total enclosure length of Alternative 1 is 181 m to accommodate the full 800-MeV linac.

The primary conventional construction requirements for Alternative 1 include:

- Extension of existing utilities, such as domestic water service, industrial cooling water, natural gas, chilled water, electrical power, to the PIP-II site; wetland mitigation, roadwork and parking areas;
- Construction of an ~260 m below grade linac enclosure of 15’ × 15’ cross section that accommodates the 800-MeV linac, the interface to the beam transfer line, and appropriate room for eventual extension of the linac to 1000 MeV;
- Construction of a new associated above grade Linac Support Building with loading dock and related services to support installation and services of beamline components;
- Construction of a refrigerator and compressor building to house the required cryoplant;
- Modernization of the A-0 cooling pond to provide cooling for Low Conductivity Water process load heat exchangers.

The beam transfer line enclosure from the linac to Booster is common to all alternatives, as is the reconfiguration of the Booster injection point.

Potential schedule for construction, including interruption to operations

Construction and assembly of components is planned over the period of 2020-2025. The construction of the linac enclosure plus the required service buildings and galleries can take place coincident with ongoing accelerator operations, with the exception of the final connection into the Booster. The strategy will be to install and commission as much of the linac and its support systems as possible prior to the initiation of the shutdown anticipated for the LBNF connection to the Main Injector, currently scheduled over December 1, 2022 – November 1, 2024. How much work can be completed in advance of this shutdown will depend upon when the shutdown actually starts. The long duration of the LBNF shutdown will provide nearly two years for completion of any remaining linac installation, for the civil construction to tie the transfer line into the Booster, and for component installation required for the new Booster injection system. Booster commissioning can start at any point following completion of this work. It is envisioned that substantial time will remain during which the Booster can be commissioned and operated to support the 8-GeV SBN program prior to completion of the LBNF shutdown.

Alternative 2: 800-MeV SC Linac, Pulsed, Higher Current

Alternative 2 is largely based on the Reference Design. It consists of an 800 MeV H- pulsed superconducting linac operating with a peak beam current of 10 mA and an average current of 5 mA. The increased beam current relative to Alternative 1 provides operational advantages in ameliorating cavity resonance control effects and reducing the number of injected turns into the Booster. The location of this machine is also envisioned as situated in the Tevatron infield in the same location established for the Reference Design.

The beam transfer line between the linac and the Booster, and modifications to the existing Booster, Recycler, and Main Injector are identical to those described in the Reference Design (Alternative 1).

<u>Technical description and performance characteristics</u>

Alternative 2 is an 800-MeV superconducting linac with a 20 Hz repetition rate and 215 μsec pulse length. To obtain the same beam power as Alternative 1 (17 kW), the average beam current is 5 mA. The configuration and performance characteristics of the Alternative 2 linac are described in Table 3.

As explained above, in order to facilitate the comparison among the alternatives, top-level parameters including output energy, beam power, pulse repetition rate and the location of the machine, are constrained. By allowing a single mode of operation a plausible tradeoff would be to reduce the length of the beam pulse and increase the beam current accordingly to maintain the same beam power delivery. The advantage of such tradeoff is primarily linked to mitigating the challenges in controlling cavity detuning from microphonics and Lorentz force detuning inherent in Alternative 1. The secondary advantage is that the increased beam current reduces the time over which the beam traverses the stripping foil during the multi-turn injection into the Booster. This reduction is expected to increase the foil lifetime. Therefore, a factor of 2.5 higher beam current is adopted in Alternative 2. The beam and RF duty factors are 0.43% and 4.8% respectively.

The increase in beam current will require an increase of the peak power from the RF sources. Through the 325 MHz sections (up to 185 MeV) the power sources will remain as solid-state amplifiers as in the Reference Design, with the appropriate adjustment on the peak power to compensate for the higher beam current. We assume the 325 MHz sources will be contributed by India as in Alternative 1.

The cost drivers of the PIP-II linac are the cryomodules and RF systems. There are a combination of parameters that can be adjusted in order to reduce the number of cryomodule and

RF system needs. However, working within the boundaries and constraints stated above, the increase of the accelerating gradient by allowing a higher peak surface field in the superconducting cavities was the selected approach to be taken into consideration in the Alternative 2.

The current design of the elliptical cavities has an upper limit on the peak surface electric field of 40 MV/m, in order to avoid the risk of strong field emission. Furthermore, the operational gradient is chosen to remain below the high-field Q-slope. The accelerating gradient in the LB (HB) 650MHz section of the Reference Design linac meeting these criteria is 15.9 (17.8) MV/m. Because of the low duty factor we can tolerate a reduction in Q_0 accompanied by an increase in gradient – we have chosen to increase the LB (HB) gradients to 17.5 (20.0). This allows us to remove one high beta cryomodule from the linac and still maintain the desired output energy of 800 MeV. With the higher accelerating gradient, in addition to the higher current described above, an increase in RF power will be required for the remaining RF sources on these sections. The peak power for Alternative 2 is 100 (160) kW for the LB (HB) sections. The cavity couplers are designed to withstand a factor of four increase in peak power. For this section of the machine, due to the high RF power requirements, the technology chosen for the power source is a klystron-based system. The primary reason for this choice is cost. Furthermore, klystron technology is mature and very reliable for operation with typical lifetimes on the order of >20 yrs with less than 1% faults per year. As in Alternative 1 each cavity will be powered by a single RF source. For Alternative 2 we assume identical klystron systems throughout the 650 MHz region. This choice will provide a practical uniformity along the 650 stations while providing a more than adequate overhead on RF power for the cavities at the LB region.

There is no distinction between Alternatives 1 and 2 at the level shown in Figure 2. Hence, Figure 2 applies also to Alternative 2.

Table 3: Linac configuration and performance parameters for Alternative 2.

	Front End	SC Linac					
Kinetic Energy (out)	2.1	800					MeV
H- Beam Current (peak)	10	10					mA
Chopping Fraction	0.5	0.5					
H- Beam Current (averaged over pulse)	5	5					mA
Pulse Length	215	215					μsec
Total Particles	6.72E+12	6.72E+12					
Pulse Repetition Rate	20	20					Hz
Beam Duty Factor	0.43	0.43					%
RF Duty Factor	100	4.8					%
Cavity β_g		0.09	0.19	0.40	0.61	0.92	
RF frequency	162.5	162.5	325	325	650	650	MHz
Cells/cavity	-	2	2	2	5	5	
Cavity effective length	-	0.20	0.20	0.42	0.75	1.12	m
Cavity gradient	-	9.7	10.0	11.4	17.5	20.0	MV/m
Cavities/cryomodule	-	8	8	5	3	6	
Number of cryomodules	-	1	2	7	11	3	
Accelerating cryomodule length	-	6.0	5.2	6.5	4.3	9.6	m
Inter-module spacing	-	0.3	0.5	0.5	1.0	0.8	m
Focusing elements (Quad. (NC) / Sol. (SC))	18	8	8	21	22	6	
Total length		6	10.4	45.5	47.3	28.8	m
Beam power	-	17.9					kW
Beam transverse emittance (rms, normalized)	-	0.3					mm-mr
Beam longitudinal emittance (rms)	-	1.1E-06					eV-s
Installed RF peak power (total)		7.7					MW
Cavity bandwidth	-	110					Hz
Heat load (Full DF @ 2K)	-	260					W
Linac wall-plug power (@operational duty factor)		3.1					MW
Length of linac	17.2	153					m

Description of the associated conventional construction

The siting of Alternative 2 is shown in Figure 1. The total enclosure length of Alternative 2 is 170 m to accommodate the full 800-MeV linac. The conventional construction activities required for Alternative 2 are identical to Alternative 1.

Potential schedule for construction, including interruption to operations

The schedule for construction and commissioning of Alternative 2 is the same as for Alternative 1.

Alternative 3: Hybrid Pulsed NC and SC Linac

Alternative 3 is an 800-MeV H- linac constructed by adding a 400-MeV superconducting linac, optimized for low-duty factor pulsed operations, at an average current of 20 mA, to the existing 400-MeV linac. The existing linac and associated support equipment will be relocated to the Tevatron infield in the same location established for the Reference Design for reasons described later in this section.

The beam transfer line between the linac and the Booster, and modifications to the existing Booster, Recycler, and Main Injector are identical to those described in the Reference Design (Alternative 1).

Technical Description and Performance Characteristics

The configuration and performance characteristics of the Alternative 3 linac are described in Table 4. The overall operations scenario is dictated by the requirement of providing 6.7×10^{12} protons per pulse to the Booster, within the maximum pulse length that can be provided by the RF system in the 805 MHz portion of the existing linac. The maximum pulse length is desirable in order to maximize the number of injected turns into the Booster for the purpose of facilitating phase-space painting. This pulse length is determined by the capabilities of the RF power systems in the existing linac and is nominally 75 μsec; we have de-rated to 54 μsec to provide a 40% operating margin. The corresponding beam current is 40 mA (peak)/20 mA (chopped). This lies within the capabilities of the existing 400-MeV linac.

The Alternative 3 configuration is shown schematically in Figure 3 – note that this figure is not to scale. The configuration starts with a front end incorporating a pulsed ion source, a 2.1 MeV, 201.25 MHz, Radio Frequency Quadrupole (RFQ), and a 10.4 m long MEBT. This configuration is very similar to the Reference Design with the exception of the RF frequency, which must be matched to the existing linac. The MEBT accommodates the fast chopper required to create a 44.7 MHz bunch structure for injection and capture in the Booster. The LEBT and MEBT will be relocated from the PIP2IT facility; the existing IS will be relocated and the RFQ will be newly fabricated with a design based on the PIP2IT RFQ, but scaled to 201.25 MHz and re-optimized for 40 mA operations. The MEBT broadband chopper incorporated into Alternatives 1 and 2 should performance satisfactorily at 201.25 MHz. The front ends for Alternatives 3 and 4 are identical.

The existing NC linac consists of a drift tube (DTL) section operating at 201.25 MHz and a cavity coupled (CCL) section operating at 805 MHz. The transition between the two sections occurs at 116.5 MeV. Longitudinal matching is provided by two non-accelerating 805 MHz modules at this point. The DTL section was commissioned in 1970; the CCL section is significantly younger, having been commissioned in 1992. The utilization of a 2.1 MeV RFQ in the front end will require the construction of a new DTL tank-one for beam acceleration from 2.1 to 10.4 MeV (the existing RFQ provides beam at 750 keV). This replacement is also a desirable modification from the reliability standpoint – the existing DTL tank-one was installed as a prototype nearly 50 years ago and represents a known reliability risk. The subsequent four DTL tanks in the existing linac will be reutilized (following relocation).

Table 4: Linac configuration and performance parameters for Alternative 3.

	Front End	Exist NCLinac	SCLinac	
Kinetic Energy (out)	2.1	400	800	MeV
H- Beam Current (peak)	40	40	40	mA
Chopping Fraction	0.5	0.5	0.5	
H- Beam Current (averaged over pulse)	20	20	20	
Pulse Length	54	54	54	μsec
Total Particles	6.7E+12	6.7E+12	6.7E+12	
Pulse Repetition Rate	20	20	20	
Beam Duty Factor	0.11	0.11	0.11	%
RF Duty Factor	0.21	0.21	0.71	%
Cavity β_g	-	Variable	0.81	
RF frequency	201.25	201.25/805	805	MHz
Cells/cavity (CCL)	-	16	6	
Cavity Length (CCL)	-	1.4-2.1	0.90	m
Cavity Gradient (CCL)	-	7.5	16	MV/m
Cavities/Module (CCL)	-	4	4	
Number of Modules (DTL/CCL)	-	5/7	8	
Accelerating Module Length (DTL/CCL)	-	7.4-19/5.7-8.4	6.3	m
Inter-Module spacing (DTL/CCL)	-	0.9/0.3-0.4	1.6	m
Focusing Quadrupoles	18	120/28	16	
Beam Power	-	-	17.9	kW
Beam Transverse Emittance (rms, normalized)	-	-	2	mm-mr
Beam Longitudinal Emittance (rms)	-	-	6.30E-05	eV-s
Installed RF Peak Power (total)	3.3	84.8	13.9	MW
Cavity Bandwidth	-	-	507	Hz
Heat Load (Full DF @ 2K)	-	-	164	W
Linac Wall-plug Power	-	2.6	1.1	MW
Length of Linac	16.9	142.0	63.2	m

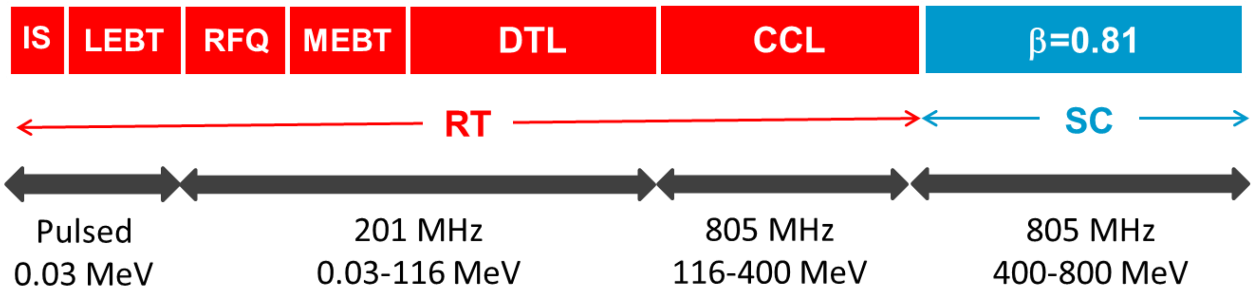

Figure 3: Configuration of the Alternative 3 Linac (not to scale). The room temperature section is red, the superconducting section is blue.

RF power in the existing DTL is provided by 201.25 MHz triodes driven by associated modulators. Five such stations are required. The triodes are a long-identified Linac vulnerability – a single vendor exists and Fermilab is one of only two customers. As a risk mitigation strategy Fermilab has accumulated a two-year supply of triodes and has also developed a 201 MHz klystron replacement in collaboration with a different vendor (CPI). A prototype klystron exists and has been tested. Replacement klystrons could be delivered from the vendor two years following a go ahead from Fermilab. The triodes do not represent a viable long-term solution for the DTL whereas klystron technology is well developed and CPI is a well-established U.S. company with five-plus decades of experience, and with a diverse product portfolio. Also it is well-known that klystron technology requires considerably less maintenance than equivalent tube amplifiers and klystron lifetimes are substantial higher than vacuum tubes, providing higher reliability and lower operations costs. Hence Alternatives 3 and 4 would utilize new klystrons as the RF power source in this section. The current Linac modulators have been recently upgraded and will support the switch from triode to klystron without further modifications.

The existing CCL is powered by seven 10-MW (peak) klystrons, modulators, and pulse transformers. These systems are currently 25 years old, but appear adequate to continue service for a substantial number of years into the future. Hence, Alternative 3 will continue to use these systems.

The superconducting linac in this alternative is based on the high-beta section of the Spallation Neutron Source (SNS) linac at Oak Ridge National Laboratory. We can adopt this design directly because the SNS was constructed with an RF frequency identical to that used in the Fermilab linac (805 MHz). We assume gradient performance equal to the best of the modules currently operational at SNS. This seems a reasonable assumption since the SNS cryomodules were constructed roughly 15 years ago and our understanding of superconducting technologies has advanced significantly since then. The assumed gradient is 16 MV/m and a total of 32 cavities deployed across eight cryomodules are required to reach 800 MeV. The assumed Q_0 is 1×10^{10}, which is roughly a factor of two improvement over SNS. The Q_0 has limited impact on other operational parameters because of the low duty factor at which this linac would operate.

As at the SNS we would plan to have a single RF source associated with each cavity, for a total of 32 stations. The peak power required to drive a cavity under the assumed operating conditions is 270 kW. Applying a 60% overhead, as is done in the Reference Design, leads to a requirement of about 440 kW for each source. This is beyond the reach of solid state or single-beam inductive output tubes. 805 MHz klystrons, as utilized in SNS, are the adopted solution. Because of the low duty factor the average power required from each station is only 3.5 kW.

The superconducting linac is operated at 2K in order to provide good cavity performance including the suppression of microphonics. The cryogenic load is the sum of the static and dynamic heat loads. At 2K the static heat load of the SNS cryomodule is 20 W. The dynamic heat load is determined by the cavity gradient, the cavity Q_0, and the duty factor. For the operating conditions associated with Alternative 3 this amounts to 0.6 W/cryomodule. The total heat load for 8 cryomodules operating at 2K is thus 164 W and is dominated by the static heat load. As in the Reference Design we provide 100% overhead on this number in specifying the cryoplant capacity as 330 W at 2K.

The realization of this alternative requires the relocation of the existing Linac to the Tevatron infield. The total physical length of the Alternative 3 linac is 222 meters, from ion source to exit of the superconducting linac – about 40 meters longer than the Reference Design. The equipment that will be relocated includes:

- Accelerating modules
- Modulators
- Waveguide
- Focusing elements with power supplies
- Vacuum pumps with power supplies
- Instrumentation

In addition to relocation, the existing Linac will be upgraded to 20 Hz operations. This will be incorporated into the controls and timing systems, which will be identical to the Reference Design. Modifications to the quadrupole power supplies in the DTL and potentially also in the CCL will also be required.

Description of the associated conventional construction

The siting of Alternative 3 is shown in Figure 1. The same siting is used for all options, with only the length of the linac enclosure varying. The total enclosure length of Alternative 3 is 222 m to accommodate the full 800-MeV linac.

The primary conventional construction requirements for Alternative 3 includes:

- Site preparation work, including the re-routing of the current Main Ring road to accommodate the newly required cooling pond;

- Construction of a ~300 m linac enclosure of 15' × 15' cross section that accommodates the 800-MeV linac, the interface to the beam transfer line, and room for an eventual extension of the linac to 1000 MeV;
- Construction of a new linac gallery and access hatch to the west of the linac enclosure;
- Construction of a service center building at the north end of the gallery to provide access to the linac enclosure;
- Construction of a refrigerator and compressor building to house the required cryoplant;
- Construction of a new ~2 acre cooling pond in the area formerly occupied by the Main Ring ponds;
- Associated utilities and HVAC.

The beam transfer line enclosure from the linac to Booster is common to all alternatives, as is the reconfiguration of the Booster injection area.

Commentary on the siting of Alternatives 3 and 4

Providing a path to >2 MW on the LBNF target is a primary motivation for PIP-II within the P5 report and also serves as a strong motivator for the researchers who have joined the DUNE Collaboration. It is known that achieving >2 MW will require replacement of the existing Booster[3]. However, it is highly unlikely that the existing Linac and Booster enclosures can accommodate the beam intensities required to support this performance due to inadequate shielding. More specifically the current Accelerator Safety Envelope for the linac is 3.54E17 protons per hour, with an operational limit established at 5% below this. The required throughput in PIP-II is 4.8E17 pph. It is likely this could be accommodated through a combination of strategically placed additional passive shielding and active controls. So we believe that in principle the existing Linac enclosure could be utilized in PIP-II. However, in the 2-MW era a total of 9.0E17 pph is required to support LBNF operations, and the total Linac/Booster throughput is raised to 18.0E17 pph if we were to construct an RCS at 20 Hz to take full advantage to the 20 Hz capabilities of the PIP-II linac. This factor of ~5 increase beyond the current safety envelope cannot be achieved without a complete restructuring of the Linac and Booster enclosures, hence we would be constructing a new rapid cycling synchrotron (RCS) on the Tevatron infield. As a consequence, if we were to implement PIP-II in the existing linac enclosure the entire linac would have to be moved again at the time of implementation of 2 MW. This may save money in the short term (~$7.0M; see construction cost discussion below) but it is very inefficient, both in terms of total cost and in terms of interruption to operations, in the long term. Based on these considerations we decided to relocate the linac to a new enclosure better adapted to the needs of 2 MW in Alternatives 3 and 4 as part of the PIP-II Project.

[3] See discussion of >2 MW in the evaluation section.

Potential schedule for construction, including interruption to operations

The schedule for construction has the same duration as the PIP-II Reference Design (Alternative 1) – FY2020-2025. The construction of the linac enclosure plus the required service buildings and galleries can take place coincident with ongoing accelerator operations, with the exception of the final connection into the Booster. Major portions of the linac and support systems can be installed and commissioned without beam at any time – the exception being the 10-400 MeV portion of the existing Linac. Deinstallation of the existing Linac followed by its reinstallation at the new site is expected to take ~12 months. The plan would be to execute this work during the shutdown anticipated for the LBNF connection to the Main Injector, currently scheduled over December 2022 – November 2024. The long duration of that shutdown should provide ~6 months of commissioning of the newly configured linac prior to the start of operations.

Alternative 4: Normal Conducting Linac

Alternative 4 is an 800-MeV H- linac constructed using the present 400 MeV warm linac with additional 805 MHz CCL cavities appended to achieve the full energy goal. As mentioned in Alternative 3 above, this design plan uses the relocation of the existing Linac, and associated support equipment, to the Tevatron infield in the same location established for the Reference Design. The idea is simply to use as much of the present Linac as possible and replicate the necessary number 805 cavities presently installed in the Linac. Alternative 4 offers the least inherent technical risk of the alternates being considered.

Technical description and performance characteristics

Because this alternative, up to 400 MeV, is identical in configuration to Alternative 3 this section will focus on the additional CCL section. Table 5 provides the configuration and parameters for Alternate 4. The table, as mentioned above, is for the purpose of comparison and does not necessarily provide optimized numbers – for example the present Linac has run at higher beam currents (up to 50 mA) in the past and may be further optimized.

Table 5: Linac configuration and performance parameters for Alternative 4

	Front End	Exist NCLinac	New CCLinac	
Kinetic Energy (out)	2.1	400	800	MeV
H- Beam Current (peak)	40	40	40	mA
Chopping Fraction	0.5	0.5	0.5	
H- Beam Current (averaged over pulse)	20	20	20	
Pulse Length	54	54	54	μsec
Total Particles	6.7E+12	6.7E+12	6.7E+12	
Pulse Repetition Rate	20	20	20	
Beam Duty Factor	0.11	0.11	0.11	%
RF Duty Factor	0.21	0.21	0.71	%
Cavity β_g	-	Variable	Variable	
RF frequency	201.25	201.25/805	805	MHz
Cells/cavity (CCL)	-	16	16	
Cavity Length (CCL)	-	1.4-2.1	2.1	m
Cavity Gradient (CCL)	-	7.5	7.5	MV/m
Cavities/Module (CCL)	-	4	4	
Number of Modules (DTL/CCL)	-	5/7	8	
Accelerating Module Length (DTL/CCL)	-	7.4-19/5.7-8.4	8.5 - 9.5	m
Inter-Module spacing (DTL/CCL)	-	0.9/0.3-0.4	.4	m
Focusing Quadrupoles	18	120/28	20	
Length of Linac	16.9	142.0	74.1	m
Beam Power	-	-	17.9	kW
Beam Transverse Emittance (rms, normalized)	-	-	2	mm-mr
Beam Longitudinal Emittance (rms)	-	-	6.30E-05	eV-s
Installed RF Peak Power (total)	3.3	84.8	60.0	MW
Cavity Bandwidth	-	-	-	Hz
Heat Load (Full DF @ 2K)	-	-	-	W
Linac Wall-plug Power	-	-	3.8	MW

The Alternative 4 configuration is shown schematically in Figure 4 (as for the other alternatives this figure is not to scale). As with Alternative 3 the configuration starts with a front end incorporating a pulsed ion source, a 2.1 MeV, 201.25 MHz, Radio Frequency Quadrupole (RFQ), and a 10.4 m long MEBT. A new DTL tank 1 matched to the 2.1 MeV injector is followed by the existing Linac 4 DTLs and seven CCLs. An additional five full length CCLs and one shorter CCL would then be added to reach the 800 MeV extraction energy.

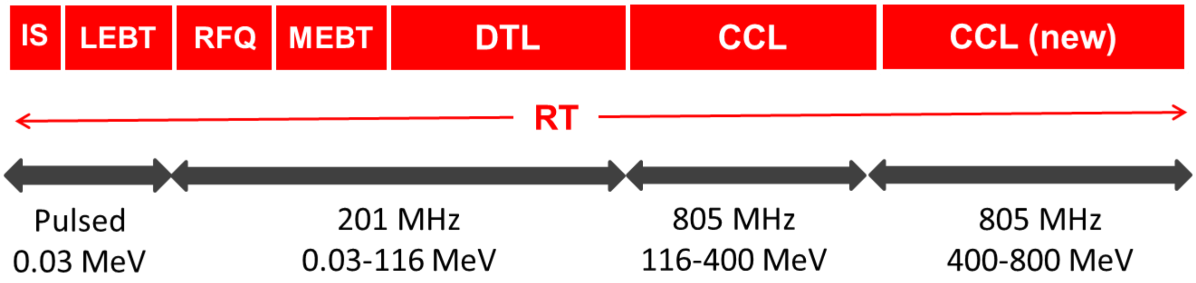

Figure 4: Configuration of the Alternative 4 linac (not to scale). As indicated by the red color the entire linac operates at room temperature.

Alternative 4 RF power systems are as described in Alternate 3 above. The additional 6 CCL would simply replicate the 10 MW klystrons that have been in use since 1993 with minor updates to accommodate obsolescence and lessons learned.

<u>Description of the associated conventional construction</u>

The siting of Alternative 4 is the same as the other alternatives as shown in Figure 1 with only the length of the linac enclosure varying. The total enclosure length of Alternative 4 is 217 m to accommodate the full 800-MeV linac.

The primary conventional construction requirements for Alternative 4 are the same as Alternative 3 without the need for construction of a refrigerator and compressor building.

Again, the beam transfer line enclosure from the linac to Booster is common to all alternatives, as is the reconfiguration of the Booster injection area.

<u>Potential schedule for construction, including interruption to operations</u>

The Alternate 4 schedule is the same as Alternate 3 through the end of the 400 MeV section. However, due to having no need for cryogenics a reduction in both installation time and commissioning is expected. As much as possible of the additional hardware associated with the 400 to 800 MeV CCL section would be built and installed prior to beam shutdown, depending upon the actual timing of the shutdown.

Cost Estimates

Construction Cost Estimates

The construction cost estimate for each alternative is organized as a "Total Project Cost to DOE". It includes all activities associated with the development, construction, and installation of the 800-MeV linac plus required modifications to Booster/Recycler/and Main Injector with offsets for international in-kind contributions. All estimates follow the methodology developed for the Reference Design cost estimate, and reutilize information developed for the Reference Design to the extent possible. The cost estimate is formulated as follows:

- Each alternative estimate covers the period from FY2016 through the completion of construction in FY2025. Note that substantial R&D costs ($10's of millions) applicable to Alternatives 1 and 2 prior to FY2016 are excluded from these estimates;
- The scope includes: the 800-MeV linac, beam transfer line, and required modifications to the Booster, Recycler, and Main Injector; the scope includes fabrication and installation; the scope does not include the acquisition of spare components or parts, or beam commissioning;
- Estimates are developed as if everything is constructed and managed by Fermilab staff;
- The estimate comprises materials & services (M&S) in FY2013 dollars, and effort in person-years by skill type;
- M&S estimates are complete for all major systems, conventional facilities, project management, and R&D;
- Estimates of effort are completed for all major systems, construction management, project management, R&D, and EDIA; person-years are translated into SWF (salary, wages, and fringes) at Fermilab FY2013 labor rates;
- All items that are expected to be provided via international in-kind contributions are then removed from the estimate;
- Published Fermilab overhead rates are applied;
- An escalation factor of 18.2% (FY2013 to FY2020 at 2.4%/year) is applied;
- An across-the-board 35% contingency is applied as an assessment of the degree of inherent risk.

The above process provides a "point estimate" for the Total Project Cost to DOE (TPC). At CD-0 an upper end to the cost range was developed for the Reference Design based on guidance from DOE G 413.3-21. The Reference Design was judged to have a design maturity in class 3-4 as described in that document. A corresponding + 26% was applied to the point estimate to define the upper end of the cost range. We have applied the same factor to Alternatives 3 and 4 in recognition of the mature designs of the 805 MHz acceleration systems utilized from 400-800 MeV (based on SNS for Alternative 3 and the existing CCL modules for Alternative 4).

Cost estimates developed by this process for all alternatives are summarized in Table 6. The upper end of the cost range for the Reference Design (Alternative 1) is $650 M as described in the Mission Need Statement. Characterizations of the bases of estimate are given in Appendix I.

Table 6: Total Project Cost estimates for the four alternatives (dollar amounts in millions)

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Project Management	$25.8	$25.8	$25.8	$25.8
Accelerator Physics	$3.9	$3.9	$4.2	$3.9
R&D	$38.5*	$38.5*	$37.1*	$31.8
Front End	Include in R&D	Include in R&D	$5.4	$5.4
Cavities & Cryomodules	$61.8*	$58.4*	$15.3	$10.7
325 MHz (SSR)	$24.5*	$24.5*	NA	NA
650/805 MHz (Elliptical; CCL)	$35.9*	$32.6*	$14.7	$10.7
Warm Magnets	$1.3*	$1.3*	$0.7	$0.0
RF Power	$52.1*	$56.3*	$30.1	$18.5
Cryogenics	$23.2*	$23.2*	$17.9	NA
Controls	$13.5*	$13.5*	$13.5	$12.5
Instrumentation	$7.4*	$7.3*	$5.9	$0.7
Beam Transfer Line	$7.2	$7.2	$7.2	$7.2
Electrical Systems	$3.2	$3.0	$1.2	$1.0
Infra, LCW, Safety, Vacuum	$8.7	$8.5	$8.7	$3.1
Booster/Recycler/Main Injector	$30.6	$30.6	$30.9	$32.0
Civil Construction	$71.3	$69.1	$74.2	$72.8
Existing Linac Relocation	NA	NA	$2.1	$2.1
Sub-Total	$347.2	$345.4	$279.6	$227.5
International Contributions*	$107.7	$69.3	$1.5	$0.0
Sub-Total	$239.5	$276.1	$278.1	$227.5
Overheads	$83.9	$91.4	$99.4	$78.6
Contingency (35%)	$113.2	$128.6	$132.1	$107.1
Escalation (18.2%)	$79.5	$90.3	$92.7	$75.2
Point Estimate	**$516.1**	**$586.4**	**$602.3**	**$488.4**
Upper Cost Range	**$650.3**	**$738.9**	**$759.0**	**$615.3**

*Areas of anticipated international in-kind contributions. The value of international contributions is subtracted from the system estimate within the row labeled International Contributions.

As can be seen from the table the cost-to-DOE comparison is dominated by variations in the magnitude of the international (Indian) contributions. Without international contributions the point estimates would be:

Alternative 1: $740M

Alternative 2: $736M

Alternative 3: $607M

Alternative 4: $488M

The civil construction costs for all alternatives lie within about 4% of Alternative 1. Variations in cost are related primarily to variations in the linac length with Alternative 4 being the longest. However, Alternative 4 benefits from not requiring a building to house a cryoplant.

<u>Commentary on siting of Alternatives 3 and 4</u>

From a civil construction perspective, Alternatives 3 and 4 require additional conventional construction to accommodate the complete linac enclosure and gallery space as compared to providing an ~70 m extension if we were to utilize the currently existing enclosure. However, because the existing enclosure resides in a highly developed area there are both savings and additional costs associated with moving to the Tevatron infield. These include:

- Site preparation: The in-place solution incurs an additional $3.7M costs associated with relocation of parking lots and roads, and additional wetland impact;
- Utilities: The in-place solution incurs an additional $0.7 M costs associated with the relocation of utilities ($1.0M) accompanied by an offset (-$0.3M) due to reduced need for new infrastructure;
- Enclosures: The in-place solution reduces cost by $7.7 M through reutilization of linac and transfer line enclosures.

The net result is that Alternatives 3 & 4 as presented on the Tevatron infield add about $3.3 M in base civil construction costs as compared to extending the existing linac enclosure. Incorporating overheads, contingency, and escalation results in an incremental cost of about $7.0 M as viewed at the point estimate level.

Linac Annual Operating Costs

The existing accelerator complex at Fermilab consists of 16 km of accelerators and beamlines, two high power target stations, several low power target stations, and 130 buildings. The accelerators are:

- An 8-GeV Proton Source
    - A 400-MeV linear accelerator (“Linac”), 0.15 km

  - An 8-GeV synchrotron (“Booster”), 0.5 km
- An 8-GeV proton accumulator ring (“Recycler”), 3.3 km
- A 120-GeV synchrotron (“Main Injector”), 3.3 km
- An 8-GeV synchrotron (“Delivery Ring”), 0.5 km
- Transfer lines and fixed target beam lines, 8 km

The complex schedules beam delivery 40+ weeks annually, with >80% uptime during these scheduled periods. Annual shutdowns for maintenance and upgrades occupy the remaining weeks of the year. Currently the DOE operations support for the complex is ~$85M on an annual basis (FY16 dollars). With the construction of the PIP-II linac, support for the existing 400 MeV Linac (~$5M) would be replaced with operating costs for the new linac.

Annual operating cost estimates have been developed for all alternatives. The estimates are incremental in the sense that they are associated with the linac itself, not the downstream accelerators, nor do they include substantial shared costs associated with common infrastructure. Our expectation is that the latter should be comparable to current costs and will be identical for all alternatives.

The linac annual operating cost comprises four components:

- Consumables/spares. These include items that have a predictable lifetime and require periodic replacement. Modulator tubes are an example.
- Cryogens. This includes LN2, LH2, and GH2 utilized in support of cryogenic operations.
- Electric power. Costed at current rates ($37.6/MW-hr).
- M&O costs. These include hands-on maintenance labor and supporting M&S. This cost is further allocated between building maintenance, cryoplant maintenance, and linac maintenance.

M&O estimates are based on extrapolations from currently incurred costs for the existing linac and the cryogenic facilities at Fermilab. Annual electricity costs are based on estimates of the wall-plug power for each alternative and the current cost of electricity, assuming operations of 5600 hours/year. Costs are collected in FY2016 dollars and then inflated to FY2025 (the first year of operations). Linac Annual Operating Costs are summarized in Table 7. Included in the final row is the anticipated cost for operating the balance of the complex ($80M today) extrapolated to 2025 dollars.

Table 7: Annual linac operating cost estimates for the four alternatives (dollar amounts in FY2025 millions; M&O=Maintenance and Operations). The final row displays the operating costs for the balance of the Fermilab accelerator complex including shared infrastructure.

	Alternative 1	**Alternative 2**	**Alternative 3**	**Alternative 4**
Consumables	$0.5	$0.8	$0.7	$0.6
Cryogens	$0.4	$0.4	$0.2	NA
Electric Power	$1.0	$1.0	$1.2	$1.3
M&O/Bldg	$1.0	$1.0	$1.3	$1.4
M&O/Cryo	$1.9	$1.9	$1.7	NA
M&S	$0.5	$0.5	$0.5	
SWF	$1.4	$1.4	$1.1	
M&O/Linac	$2.9	$2.9	$3.8	$3.6
M&S	$0.1	$0.0	$0.1	$0.1
SWF	$2.9	$2.9	$3.7	$3.6
Annual Linac Operating Cost	**$7.8**	**$8.0**	**$8.9**	**$6.9**
Existing Complex	**$102.5**			

Performance with Respect to Evaluation Criteria

Evaluation criteria for the four alternatives have been established by the DOE/OHEP as follows:

- Deliver more than 1 MW of proton beam power from the Main Injector over the energy range ~60 GeV to 120 GeV, at the start of LBNF operations;
- Sustain high reliability operations of the Fermilab accelerator complex;
- Support the current 8-GeV program, including Mu2e, g-2, and short-baseline neutrino experiments;
- Provide an upgrade path for a second generation Mu2e experiment at 100 kW;
- Provide a platform for extension of beam power to LBNF of greater than 2 MW;
- Provide a platform for extension of capability to high beam-power, high duty-factor operations.
- Extent of interruption to ongoing accelerator operations during construction;
- Technical risk;
- Potential for international contributions;
- Cost to DOE including operation of the accelerator.

Note that these evaluation criteria are not weighted, nor are they designed to produce an aggregate score that would identify a preferred alternative. This section provides analysis and commentary of each option for each evaluation criteria. The commentary includes both quantitative and subjective comparisons, with an emphasis on identifying characteristics that distinguish between the alternatives rather than providing a comprehensive evaluation of each alternative with respect to each criteria. For example, in cases for which all options have common characteristics, either technical or cost, we do not attempt to defend these characteristics in this document. The underlying basis for such characteristics is generally contained in the Reference Design Report and accompanying cost estimate.

>1 MW to LBNF

As shown in Table 1, all alternatives are designed to provide 1.2 MW of beam power from the Main Injector at 120 GeV and 1.0 MW of beam power at 60 GeV. Because the needs for the long baseline neutrino power are satisfied by a low-duty-factor proton source, the superconducting linacs of Alternatives 1, 2, and 3 have no inherent advantage over the normal conducting linac of Alternative 4 as measured against this criteria. Hence, we judge the probability of achieving this performance to be essentially independent of the alternative selected, subject to comments listed below under reliability and technical risk.

All options offer a substantial period of time for commissioning significant parts of the system during the period associated with the 23-month interruption to accelerator operations for connection of LBNF into the accelerator complex. Alternatives 1 and 2 could allow a substantial fraction of this period for commissioning of the complete linac in advance of the initiation of LBNF operations, depending upon the exact timing of the LBNF shutdown; Alternatives 3 and 4 would offer a more limited, but still substantial period of complete linac commissioning following relocation of the existing 400-MeV linac to its new enclosure. Thus, we would judge Alternatives 1 and 2 to have a modestly higher probability of achieving 1 MW performance at the initiation of LBNF operations than Alternatives 3 and 4. (See further discussion under Interruption to Operations below.)

High Reliability Operations

As noted in the Annual Operating Costs discussion the Fermilab Accelerator Complex consists of 16 km of accelerators and beamlines, two high power target stations, several low power target stations, and maintenance of 130 buildings on the site. The complex schedules beam delivery 40+ weeks annually, with >80% availability during these scheduled periods (depending on the program). Annual shutdowns for maintenance and upgrades occupy the remaining weeks of the year. For purposes of this report, we will discuss the availability of the complex in support of the long baseline neutrino program.

During FY14 and FY15, the complex had 84 weeks of scheduled beam delivery and 20 weeks of scheduled shutdown. In addition, there were short scheduled down periods for maintenance and repair during the beam delivery periods. Integrating over the Linac, Booster, Recycler, Main Injector, transfer lines, and the high power target station, the complex averaged 86.3% availability in FY14 and 84.7% availability in FY15, where availability is defined as beam up time /scheduled beam up time. We would like to sustain this level of availability for operation of the accelerator complex.

Many elements of the Proton Source are approaching 50 years of operation. The Proton Improvement Plan (PIP) was developed to ensure reliable operation of the Proton Source. The Proton Source group was asked to develop and implement a plan to meet the targets for proton source throughput, while maintaining good availability and acceptable residual activation. The plan addressed hardware modifications to increase repetition rate and improve beam loss while ensuring viable operation of the Linac through 2023, and the Booster through 2030. PIP should enable Linac/Booster to:

- Deliver 2.3E17 protons per hour @ 15 Hz
- Maintain Linac/Booster availability > 85%

with residual activation at acceptable levels.

The PIP program began in 2012 and has completed 22 of the 33 major work packages, with 3 more anticipated complete by the end of 2016. Major goals included the increase of the beam repetition rate from 7.5 Hz to 15 Hz (complete), elimination of major obsolescence issues, elimination of major reliability issues, and a doubling of the maximum throughput to >2e17 protons per hour. PIP is scheduled to complete in 2020.

Among the four alternatives the front end (IS, LEBT, RFQ, MEBT), transfer line, Booster, Recycler, and Main Injector are common. Therefore, it is the section from downstream of the MEBT to the start of the transfer line that we need to consider for this Analysis of Alternatives. The alternatives discussed should match or exceed the availability of the current Linac. To set the scale, the 400 MeV Linac availability has been >96% over the FY14 and FY15 time period. The RF systems in the Linac account for 70% of all Linac downtime.

Alternatives 1 and 2 are to all intents and purposes the same from the availability perspective. We anticipate that availability will be quite high, based on the experience at SNS. After initial commissioning and operation, the SNS Superconducting Linac has achieved 98% availability over a 5 year period[4].

The existing 400 MeV Linac has demonstrated high reliability. In addition, the upgrades in progress (as part of the ongoing PIP program) or planned (in the PIP-II relocation scheme) are designed to address known reliability issues in the RF systems. Some specific elements in the PIP program are to replace the original 200 MHz modulators with a modern Marx modulator. As part of the PIP-II relocation scheme, we would include the replacement of the 200 MHz 7835 tube based power amplifiers with a PIP developed 200 MHz klystron. In addition, relocation to a new gallery would address reliability concerns associated with aging infrastructure. With these upgrades in mind, we will take steps to ensure that the availability for Alternatives 3 and 4 would be on par with Alternatives 1 and 2.

In conclusion, we judge that all 4 alternatives will be able to “Sustain high reliability operations of the Fermilab accelerator complex” and that for this evaluation criteria all alternatives would be labeled as “Low Risk”.

Current 8-GeV Program

The 8-GeV program currently encompasses the short-baseline neutrino (SBN) experiments MiniBoone and MicroBoone, and will be expanded over the next several years to include ICARUS-T600, and the Short-Baseline Near Detector. The SBN program relies on 8-GeV protons delivered directly from the 8-GeV Booster to the Booster Neutrino Beam (BNB) target.

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[4] Y. Kang, *et al*., “Status and Performance of ORNL Spallation Neutron Source Accelerator Systems”, Proceedings of IPAC2016, Busan, Korea, May 2016.

Additional elements of the 8-GeV program will come online over the next several years: the Muon g-2 experiment and the muon-electron conversion experiment (Mu2e). Both of these experiments operate with 8-GeV beams from the Booster, although the Recycler Ring, and the proton Delivery Ring in the case of Mu2e, are utilized to prepare the proper beam time structure for targeting. At the time of initiation of PIP-II operations the SBN program is expected to be fully operational, Muon g-2 will be completed, and Mu2e should be nearing the end of its initial run.

The 8-GeV program is designed to run in parallel with the long-baseline neutrino program (NuMI/NOνA, followed by LBNF/Dune). All protons required by these programs are supplied by the Booster. The Proton Improvement Plan currently nearing completion has already established Booster beam operations at 15 Hz, thereby enabling the simultaneous operations of the NuMI beamline and the 8-GeV programs described above. These integrated programs require 60% of the Booster cycles to be dedicated to providing protons to the Recycler/Main Injector complex in order to support NuMI operations at 700 kW with the remaining 40% of Booster cycles dedicated to delivery of protons to the 8-GeV program.

Because the 8-GeV program operates at the margin of the long-baseline program modest improvements in Booster performance, in particular an increase in the repetition rate, can have a significant impact. It is for this reason that the Reference Design (Alternative 1) incorporates a 20 Hz linac accompanied by a corresponding increase in the Booster repetition rate.

Table 8 displays how the incorporation of 20 Hz capability into the Reference Design provides approximately a factor of two increase in the beam power available to the 8-GeV program. This factor is realized only if the Main Injector is operating at 120 GeV in support of LBNF. Alternatively the 20 Hz capability can be utilized to sustain 1 MW operations of LBNF at energies as low as 60 GeV. However, at this energy nearly all Booster cycles are devoted to LBNF leaving little capability for an 8-GeV program. For intermediate energies the beam power available at 8 GeV varies approximately linearly between 60 and 120 GeV. The ultimate allocation of beam between LBNF/DUNE and the 8-GeV program is expected to be determined via the Fermilab program planning process as the PIP-II era approaches.

The above analysis applies equally to all alternatives, including the upgrade to 20 Hz operations included in Alternatives 3 and 4.

Table 8: Booster 8-GeV performance in PIP and the PIP-II Reference Design (Alt. 1)

	PIP	PIP-II Reference Design	
Linac Protons per Pulse	4.7×10^{12}	6.7×10^{12}	
Booster Protons per Pulse	4.3×10^{12}	6.5×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Beam Power @ 8 GeV	83	166	kW
Beam Power to RR/MI (120 GeV operations)	46	83	kW
Beam Power to RR/MI (60 GeV operations)	NA	142	kW
Beam Power to 8 GeV Program (120 GeV operations)	37	83	kW
Beam Power to 8 GeV Program (60 GeV operations)	NA	24	kW

Upgrade Path for Mu2e

The Mu2e experiment is currently under construction at Fermilab with a start of commissioning scheduled for 2020. The experiment is shooting for a single event sensitivity of 2.5×10^{-17}, a factor of 10,000 beyond current experimental limits. It is anticipated that roughly five years of operation will meet this programmatic goal, meaning the mid-2020s is the appropriate time for consideration of a second generation effort.

The Mu2e experiment will utilize 8-GeV beams delivered from the Booster and processed through the Recycler and Delivery Ring (DR) to create a time structure appropriate to the experiment. The essential feature of this pattern is that it repeats with a period characteristic of the muon lifetime. Within Mu2e the time structure is a repetitive pattern of proton beam delivered onto a production target for ~200 nsec, followed by beam off for the balance of the 1.7 μsec revolution period of the DR. This pattern can be characterized as having a modest (10%) duty factor at the microscopic (μsec) level, and high (33-100%) duty factor at the macroscopic (sec) level. The total 8-GeV beam power delivered to the Mu2e experiment is about 8 kW.

Following the initial run of Mu2e opportunities will exist for a second generation experiment: if no signal is observed there will be a strong incentive to increase the sensitivity of the experiment; if a signal is observed there will be a strong motivation to operate with different target materials in order to characterize the underlying physical mechanism. In either case a proton beam of both higher power and more flexible timing structures is desirable[5]. These motivations are acknowledged within the P5 report.

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[5] K. Knoepfel, et al. Feasibility Study for a Next-Generation Mu2e Experiment, Fermilab-Conf-13-254, arXiv:1307.1168.

The objective of a second generation Mu2e experiment will be to provide a substantial (factor of ~10) increase in the single event sensitivity – primarily via an increase in the number of stopped muons – while maintaining small backgrounds. Figure 5 shows the number of stopped muons in the Mu2e detector as a function of proton beam kinetic energy at fixed beam power.[6] As can be seen the current operating energy of 8 GeV is not optimal and hence one can think of more suitable energies in the PIP-II era. In particular a proton energy of 800 MeV, as supplied by the PIP-II linac, is seen as providing equal performance (per kW) as the 8-GeV beam to be utilized in the first generation.

The number of stopped muons per kW provides a fairly straightforward figure of merit (FOM) for Mu2e experimental performance. However, another FOM related to the material damage suffered in the (superconducting) production solenoid is also of fundamental importance: the number of stopped muons per DPA (displacement per atom) in the solenoid coils. This is shown in Figure 6 (also from reference 3). Note, that sustained performance of the production solenoid requires maintaining a DPA below about 5×10^{-5}. The combined information of these two figures is displayed in Figure 7 and can be summarized as follows:

- An experimental exposure of three years at 100 kW is a reasonable goal for a second generation Mu2e.
- The optimum proton beam energy for the Mu2e experiment lies in the range 2-3 GeV where a single effect sensitivity of about 1.2×10^{-18} (a factor of 20 improvement over the first generation Mu2e) can be realized.
- Proton beam energies of 800-1000 MeV are modestly worse, providing single event sensitivities of about 2×10^{-18}, but still a factor of ~12 better than the first generation Mu2e.
- There are several consideration in play, not shown in the figures. The capability of providing proton pulses <100 nsec wide, a duty factor of 90% or better, and proton extinction below 1×10^{-13} are required to support next generation goals. Beyond this, operations with beam energies below the antiproton production threshold (5.6 GeV) eliminate a significant experimental background.

[6] A Study of the Energy Dependence of Radiation Damage in Superconducting Coils for a Next Generation Mu2e at PIP-II, Fermilab-Conf-16-095-APC-E, April 2016

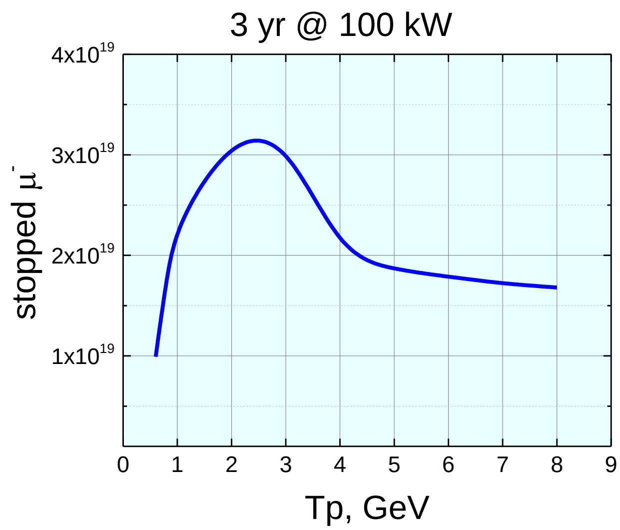

Figure 5: The number of stopped muons in the Mu2e detector as a function of proton energy, at fixed integrated beam power.

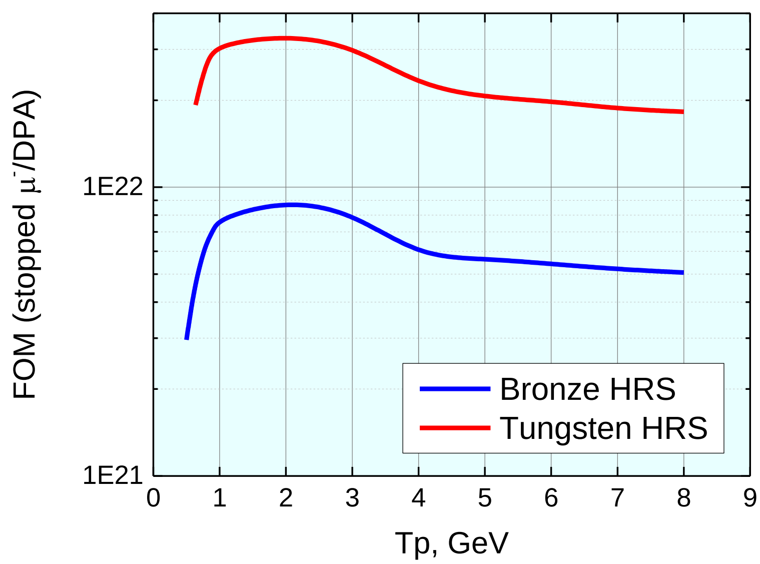

Figure 6: An ad hoc figure-of-merit (FOM) as a function of proton beam energy for bronze and tungsten heat and radiation shields (HRS). The FOM is defined as the number of stopped muons divided by a measure of material damage in the coils of the superconducting production solenoid, quantified as displacements per atom (DPA).

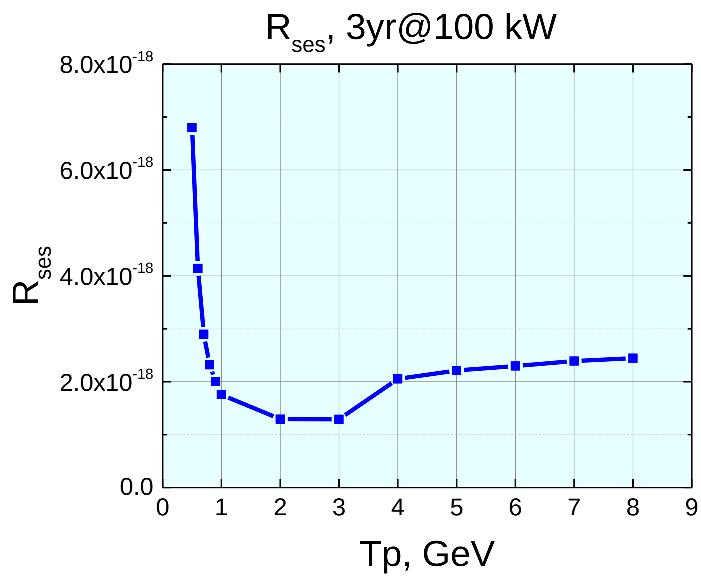

Figure 7: An estimate of the single event sensitivity, using input from Figure 5, that may be achieved with a second generation Mu2e experiment that has been upgraded to handle 100 kW of beam power at a given beam energy.

The above analysis points toward a target beam power of about 100 kW at an energy of 800-4000 MeV, with an appropriate time structure for the experiment. Such a scenario has been developed for the Reference Design, consistent with simultaneous operations of LBNF. This scenario is based on utilization of the wideband chopper integrated into the front-end MEBT and is reliant on a cryoplant capable of supporting CW operations (a proposed India in-kind contribution). The scenario looks like this:

- The RFQ operates at 10 mA peak (3.8×10^8 H^-/bunch) as designed.
- Four bunches are transmitted through the MEBT every 1.6 μsec, providing an average current of 0.15 mA. This beam is delivered to the Mu2e production target at 800 MeV. The pulse width on the target is ~60 nsec.
- Every 50 msec (20 Hz) the pattern is interrupted for 3 msec to provide beam to the Booster for the LBNF program.
- The total beam power delivered to the Mu2e target is 110 kW.

This scenario is shown schematically in Figure 8. Note that this is only one example of many configurations that can be achieved with PIP-II: both the pulse duration and repetition rate can be varied to meet the needs of the experimental program. Also note that from the RF perspective this scenario represents CW operations.

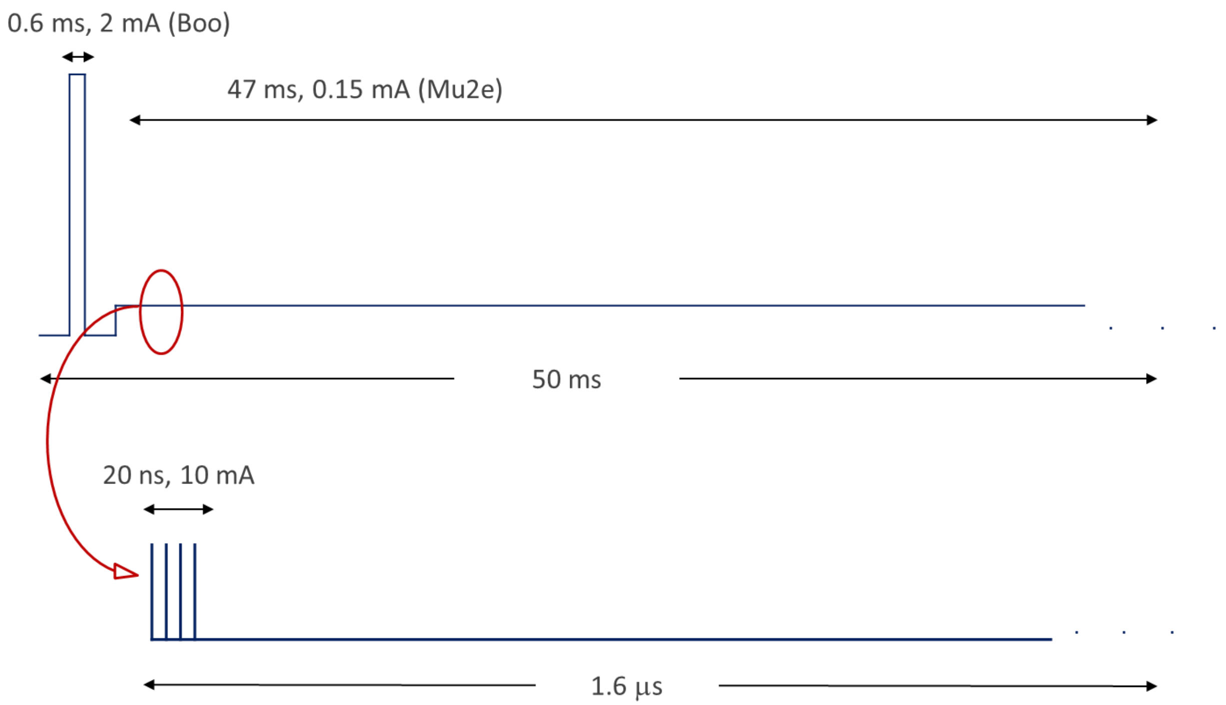

Figure 8: Possible beam time structure for a second generation Mu2e experiment operating simultaneously with LBNF. The upper diagram shows the beam structure over 50 msec, corresponding to one 20 Hz cycle of the linac. The bottom diagram shows the structure within a 1.6 μsec cycle of beam to Mu2e.

The scenario outlined above allows the Reference Design (Alternative 1) to provide an effective source of protons for a second generation Mu2e operating at 100 kW. By delivering 800-MeV beam directly to the Mu2e target it avoids any conflicts with LBNF for utilization of Booster acceleration cycles, hence this scenario allows simultaneous LBNF operations at the full power specification for both experiments. It is likely desirable that the H- be stripped of their electrons to provide protons on the Mu2e target. In addition the Mu2e production target system and solenoid will have to be rebuilt to accommodate the 800-MeV beam energy and higher beam power.

Alternative 2 is constructed of CW-capable acceleration modules. Hence, the primary needs to accommodate this scenario in Alternative 2 will be upgrading of the RF sources and provision of a cryoplant capable of supporting CW operations. The upgrade to the RF sources is straight-forward and could probably be accomplished for a few times $10M. Assuming that India will deliver the CW-capable cryoplant in Alternative 2 this represents the limit of conversion costs.

Alternatives 3 and 4 could be used to supply 8 GeV beam to the Mu2e experiment via the Recycler and Delivery Ring as will be used in the initial experiment. Upgrade capabilities are severely limited in this mode of operation due to: 1)Shielding limits operations of Delivery Ring to beam powers below about 10 kW. These limitations, which are inherent in the civil construction of the facility, are not easily rectified. 2)The accelerator timeline associated with simultaneous operations of Mu2e and LBNF limit Mu2e to about 15 kW based on PIP-II intensities. 3)Space-charge effects in the Delivery Ring and their impact on slow extraction are expected to limit beam power to less than 20 kW. The sum of these effects is that Mu2e operations is likely to be restricted to somewhere within the range 10-20 kW if implemented using Alternatives 3 and 4. Moving to the higher beam powers achievable with Alternatives 1 and 2 would require much more extensive modifications. The copper linac in both scenarios would have to be replaced by a CW-capable linac and supporting infrastructure. The anticipated cost is many times $100M.

In summary, Alternative 1 accommodates an upgrade to Mu2e that would provide more than a factor of 10 increase in the single event sensitivity, without any impact on LBNF operations. Alternative 2 could accommodate such an upgrade at a cost likely to be significantly under $100M. Alternatives 3 and 4 cannot be made to accommodate a significant (> factor of two) upgrade to Mu2e in any practical sense – accommodation would require substantial (complete in Alternative 4) replacement of the linear accelerator systems.

Platform for >2 MW to LBNF

The strategy for the delivery to LBNF of >2 MW beam power will be developed in consideration of the following:

- Slip-stacking in the Recycler is not possible at intensities beyond PIP-II due to uncontrollable beam instabilities during the slip-stacking process. The Recycler can still serve as a proton accumulator for protons from an 8-GeV source, but accumulation will be limited to a “box-car” configuration.
- The Booster cannot be upgraded to support intensities beyond 2×10^{13} protons per pulse as required in the absence of slip-stacking in the Recycler. The ultimate limitations are beam loss driven by the high (longitudinal and transverse) machine impedances, poor magnetic field quality, poor vacuum, and transition crossing. These effects are likely to make the machine un-maintainable. In addition inadequate radiation shielding of the Booster will limit intensities. Hence, the Booster will have to be replaced as the source of 8-GeV protons to the Recycler/Main Injector complex.
- The Booster can be replaced with a higher intensity 8-GeV accelerator. Candidates include either a modern rapid cycling synchrotron (RCS) or an extension of the PIP-II linac to 8 GeV.

- In any scenario an extension of the PIP-II 800-MeV linac to energies somewhere between 1-2 GeV will likely be required to mitigate space-charge forces at injection into a new RCS. The upper end of this range would be required for an RCS with characteristics of modern machines, for example the RCS in the J-PARC facility. The lower end of the range could be achieved if current R&D into circular accelerators incorporating either non-linear (integrable) optical systems or highly super-periodic lattices bear fruit over the next decade.

The strategy for >2 MW to LBNF is likely to be determined sometime near the end of PIP-II construction. Nonetheless, we present two example scenarios here providing 2.4 MW from the Main Injector at 60-120 GeV. This power level requires the delivery of 1.5×10^{14} protons from the Main Injector every 1.2 seconds at 120 GeV, and every 0.6 seconds at 60 GeV. Accumulation of this quantity of beam would require box-car stacking in the Recycler of six beam pulses containing 2.5×10^{13} protons each (assuming a source with the same circumference as the existing Booster) over a period of as low as 0.6 seconds. This implies a repetition rate of at least 10 Hz in the source. Alternatively one could consider injecting directly into the Main Injector a long (~10 msec) H- pulse from an 8 GeV linac. Such a configuration would create substantial challenges in the injection stripping process. These two possibilities are outlined in Table 9.

Table 9: Two scenarios for achieving 2.4 MW from the Main Injector based on replacement of the existing Booster with either a RCS or an 8-GeV pulsed linac.

	RCS	**Linac**	
Proton Source			
Particle Type	p	H-	
Beam Kinetic Energy	8.0	8.0	GeV
Protons per Pulse	2.5×10^{13}	1.5×10^{14}	
Beam Pulse Length	0.0016	10	msec
Pulse Repetition Rate*	10	1.67	Hz
Pulses to Recycler	6	NA	
Pulses to Main Injector	NA	1	
Beam Power at 8 GeV (Total)	320	320	kW
Beam Power to Main Injector**	160/320	160/320	kW
Beam Power Available to 8 GeV Program**	160/0	160/0	kW
Main Injector			
Beam Kinetic Energy**	120/60	120/60	GeV
Main Injector Protons per Pulse	1.5×10^{14}	1.5×10^{14}	
Main Injector Cycler Time**	1.2/0.6	1.2/0.6	sec
LBNF Beam Power**	2.4/2.4	2.4/2.4	MW

* Minimum pulse rate to support 2.4 MW at 60 GeV. Facility design could be higher.

** First number refers to 120 GeV MI operations; second to 60 GeV

The replacement of the Booster with a facility capable of supporting in excess of 2 MW to LBNF will represent a major project and decisions concerning strategy will be made during the development phases of the project. The strategy will depend on the choice among the four alternatives considered for PIP-II. In particular, Alternatives 3 and 4 could not be pared with the linac shown above as the total protons per pulse lies well beyond their capabilities.

In all alternatives an increase of a factor of four in the per pulse intensity delivered from the linac is required into the RCS. This could be obtained relatively straightforwardly in Alternatives 1 and 2 by a combination of increases in the pulse length and beam current. This flexibility does not exist in Alternatives 3 and 4 as increases in the pulse length are limited by the room temperature technologies. The total required beam charge implies at 50 mA (chopped, 100 mA peak) beam pulse with a 75 μsec pulse width. The 75 μsec is achievable with existing hardware. While 50 mA operations has been shown in the past, recent experience has not gone beyond 38 mA. If 50 mA (peak) could be achieved such a solution could be adopted, however it would require abandoning the bunch-to-bucket injection scheme in favor of an adiabatic capture scheme. Alternatively, if it were deemed desirable to limit the linac beam intensities (or the Main Injector beam intensity) one could consider reducing the Main Injector cycle time, and increasing the linac repetition rate back up to 20 Hz, as accommodated by all PIP-II alternatives.

No specific scenarios have been developed for beam power approaching 3 MW. However, in considering 3 MW we first note that the 8 GeV beam power (in the RCS scenario) is 0.32 MW. This means in principle one could deliver up to 4.8 MW at 120 GeV or 2.4 MW at 60 GeV without modifications to the RCS. The most straight forward way to get from 2.4 to ~3 MW at 120 GeV would be to reduce the Main Injector cycle time to 1.0 sec. This would require upgrades to the Main Injector RF and magnet power supply systems. With the intensities listed above this would provide a beam power of 2.9 MW at 120 GeV and would leave 128 kW of beam power available to an 8 GeV program. Providing comparable performance at 60 GeV and/or increasing the available beam power for an 8-GeV program could be accomplished by increasing the RCS repetition rate to 20 Hz accompanied by a reduction in the MI 60-GeV cycle time to 0.5 sec.

To summarize, Alternatives 1 and 2 provide a relatively robust platform for providing in excess of 2 MW to LBNF by serving as an injector to a replacement to the existing Booster. Alternatives 3 and 4 have considerably less flexibility in terms of the range of approaches that could be taken in achieving this beam power from the Main Injector, and also rely on substantial hardware that will be ~60 years old at the initiation of 2 MW operations. Hence these alternatives probably carry more technical risk than Alternatives 1 and 2.

Platform for High Beam Power, High Duty Factor Operations

The 2013 "Snowmass" particle physics community study[7] identified many promising research opportunities that require high proton beam power (100-5000kW) and high bandwidth control of proton beam pulse trains. These opportunities span physics research programs based on muons, kaons, and neutrons. The most likely initial utilization of high-beam-power, high-duty-factor capabilities is a second generation muon-to-electron conversion experiment as described earlier.

Recent advances in high-bandwidth instrumentation motivate detector concepts with time resolutions approaching 10 pico-seconds and very high dynamic range – more than an order of magnitude higher performance than the present state of the art. The combined capability of high-power, high-bandwidth beams with high-bandwidth instrumentation can deliver unprecedented detector sensitivities through much better rejection of out-of-time backgrounds and precise

[7] Planning for the Future of U.S. Particle Physics, The Snowmass 2013 Proceedings, http://www.slac.stanford.edu/econf/C1307292/

determination of event kinematics through time-of-flight techniques. Examples of these concepts include searching for new physics in next generation muon decay experiments that require extinction between beam pulses in a high frequency train at less than the 10^{-11} level, and searches for new physics such as low-mass dark matter with decay-in-flight experiments that require very narrow beam pulses (< 100 pico-seconds) within a high frequency pulse train. This pulse train flexibility can only be satisfied by superconducting linacs and hence only Alternatives 1 and 2 could provide such a platform. To quantify the capability, the superconducting linacs in Alternatives 1 and 2 are based on a source capable of delivering up to 10 mA of beam and sculpting a high-frequency pulse train, an RF system capable of accelerating 2 mA of beam, and a cryogenic system capable of sustaining CW operations. At 800 MeV the total beam power would be 1.6 MW, with up to 8 MW if 10 mA could be accelerated. This is an immense amount of beam power – certainly beyond the capability of a single experimental target station to deal with. However, a feature of both Alternatives 1 and 2 is the ability to provide variable time structures simultaneously to different experimental areas, making it somewhat easier to capitalize on the opportunity. In all such scenarios the beam power to LBNF is maintained.

The detailed beam and experiment configurations that explore the rich research landscape identified in the Snowmass study will be determined by the scientific imperatives of the coming decade. The combination of high beam power and high-bandwidth control of beam pulse trains with advances in high-bandwidth detector instrumentation can provide unprecedented capability to pursue these imperatives. Both Alternatives 1 and 2 can provide this. The only way to achieve these capabilities in Alternatives 3 and 4 would be to replace the room temperature linac portions with superconducting linacs.

Interruption to Accelerator Operations

The construction, installation, and commissioning of PIP-II will require an interruption to operations (aka "shutdown") to complete the following major tasks:

- Civil construction to connect the beam transfer line enclosure to the Booster enclosure;
- Installation of a new injection region into the Booster;
- Modifications to the Booster resonant power supply circuit to support 20 Hz operations;
- Installation of upgrades to the Booster collimation systems, as necessary;
- Installation of new RF power systems in the Main Injector;
- Installation of a new γ_t-jump system in the Main Injector;
- Installation of new slip-stacking cavities in the Recycler;
- Relocation of existing 400 MeV linac components and systems (Alternatives 3 and 4 only);

- Linac commissioning: In Alternatives 1 and 2 complete commissioning of the 800 MeV linac can be carried out without any disruption to operations. In Alternatives 3 and 4 commissioning of the new front end and hardware commissioning without beam of the downstream 400 MeV can be carried out without any disruption of operations. Commissioning of the 10-400 MeV linac can only take place after relocation and installation in the new location.
- Linac to Booster beam transfer line commissioning: In Alternatives 1 and 2 commissioning of the majority of the length of the beamline can be carried out without any disruption to operations. In Alternatives 3 and 4 commissioning of the beamline cannot commence until the entire linac is installed and commissioned, a substantial period after the start of the shutdown.
- Booster Commissioning: In all alternatives commissioning of the Booster takes place following commissioning of the beam transfer line. This happens within the shutdown, but could be initiated substantially earlier in Alternatives 1 and 2 than in 3 and 4.
- Main Injector/Recycler Commissioning: In all alternatives this follows Booster commissioning, but can only take place following completion of the shutdown.

In order to maximize the probability of having a functioning accelerator complex at the end of the LBNF shutdown, it would be desirable to have all PIP-II installation and commissioning activities possible completed in advance of the shutdown. The extent to which this is achievable will depend upon the actual scheduling of the LBNF shutdown. A notional sequence of events leading up to and including the shutdown is shown in Figure 9 – we have combined Alternatives 1&2 and Alternatives 3&4 in this graphic because there are no substantial differences within these two groupings. The sequence displayed in the figure corresponds to a shutdown that comes late enough to allow the completion of a substantial portion of linac component fabrication, installation, and commissioning prior to the start of the shutdown. This sequence is likely not achievable with the LBNF shutdown as currently planned for December 2022 – November 2024 (duration of 23 months).

As noted in Figure 9 activities that are reliant on installation of the 10-400 MeV section of the PIP-II linac proceed at different times within Alternatives 1&2 and Alternatives 3&4. This is because of the need to relocate the existing linac in Alternatives 3&4. The following conclusions can be drawn from looking at the figure:

- In principal all alternatives should be able to complete installation and commissioning activities by the completion of the LBNF shutdown, with the exception of Recycler/Main Injector commissioning which can only begin following completion of the LBNF shutdown.
- Commissioning of the Booster could commence roughly ten months earlier in Alternatives 1&2 than in 3&4. This enhances the probability that the accelerator complex will perform at-or-near the 1.2 MW level at initiation of LBNF operations.

- Early Booster availability would allow for operations of the (8-GeV) short baseline neutrino program for ~7 months prior to completion of the LBNF shutdown in Alternatives 1&2 – the period defined as “reinstallation” on the LBNF schedule. It is currently planned that LBNF reinstallation will be scheduled for day shifts, Monday-Friday. This would allow for SBN operations at night and over weekends during this period. Due to the late start in Booster beam commissioning support for SBN operations during the shutdown will be much more limited (and perhaps non-existent) in Alternatives 3&4.
- For these advantages to be realized in Alternatives 1 and 2, the LBNF shutdown would have to be scheduled late enough to allow the fabrication, installation, and commissioning of a significant portion of linac components in advance of the shutdown. This is not consistent with the current thinking on the LBNF schedule, so this advantage may or may not be realized in practice.

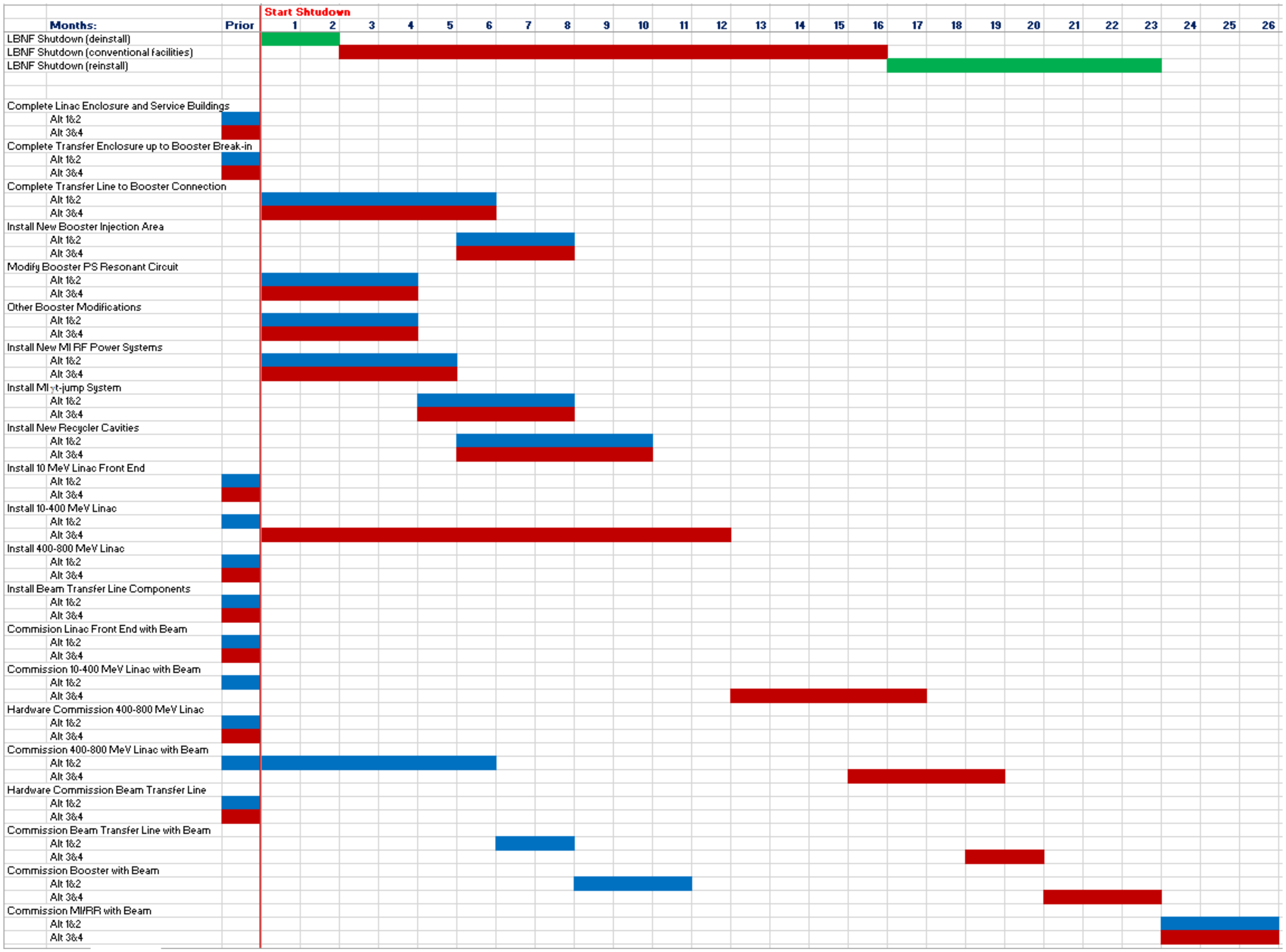

Figure 9: Sequence of activities leading up to and through the shutdown required to integrate PIP-II into the existing accelerator complex for Alternatives 1&2 and Alternatives 3&4. This shutdown will run coincident with the LBNF shutdown.

Technical Risk

The technical risks associated with the PIP-II Reference Design (Alternative 1) have been identified as:

- Front End;
- Operations of a superconducting linac in pulsed mode at low current;
- Achievement of a 50% increase in Booster/Recycler/Main Injector beam intensity;
- Development of solid-state RF sources;
- Development of superconducting RF cavities and cryomodules;
- Development of requisite capabilities of vendors and international partners.

These technical risks are being mitigated through the PIP-II R&D program which has three primary components: Front end development at the PIP-II Injector Test facility, superconducting RF development, and beam dynamics studies and simulations within the existing accelerators. The first two of these are undertaken in collaboration with India.

A comparison of the different alternatives according to these identified risks is given below. A high level Technical Readiness Level (TRL) evaluation of the alternatives at the system level is presented in Appendix 2.

<u>Front End</u>

The front end is required to deliver the requisite beam characteristics and quality, including the correct time structure, for acceleration in the linac. The front end configurations are substantially the same in all four alternatives: an ion source, LEBT, RFQ, and MEBT. In all alternatives the MEBT integrates a wideband chopper that removes bunches delivered from the RFQ in order to create a time structure matched to the RF frequency at Booster injection. The primary differences in the four alternatives are in the beam current delivered by the front end, varying from 2 to 20 mA (after chopping). These currents all lie within the range of current experience. Thus, we see no substantial difference in technical risk between the four alternatives.

<u>Operations in Low Current/Pulsed Mode</u>

Alternative 1 is based on a CW linac operated initially in pulsed mode. This results in an unnaturally low beam current that has ramifications for control of the resonant frequencies in the cavities. In particular, for optimal coupling, the cavity bandwidth in Alternative 1 is about 60 Hz. This needs to be compared to the expected cavity detuning from microphonics (~20 Hz) and Lorentz Force Detuning (LFD, ~300 Hz). These numbers have been minimized by careful design of the cavities to desensitize to these effects, however the ratio of LFD/cavity bandwidth still lies beyond present-day experience. Hence active compensation will be required and is a target of the

PIP-II R&D program[8]. Further mitigations beyond active compensation could include operating at a higher current (up to 10 mA peak is consistent with the RFQ performance) with a commensurate increase in RF power, or maintaining RF continuously in the cavities to obviate the LFD (consistent with the capabilities of the cryoplant to be provided by India).

Alternative 2 mitigates these issues by raising the beam current modestly (factor of 2.5) with a concomitant increase in bandwidth, moving the ratio of detuning to bandwidth into the range of current experience.

Alternative 3 with its still higher beam current removes this as a serious technical issue and the issue is not faced at all in Alternative 4 due to the absence of a superconducting linac in the acceleration chain.

Beam Intensity Increase in Booster/Recycler/Main Injector

The Booster, Recycler, and Main Injector are required to support a ~50% increase in beam intensity for PIP-II. This increase is enabled through the reduction in space-charge forces at Booster injection through the increase in the injection energy. However, a number of other beam physics issues require attention, most specifically transition crossing in the Booster and Main Injector, and slip-stacking in the Recycler. These areas are under study in the PIP-II R&D program; however, because all alternatives utilize the same Booster/Recycler/Main Injector configuration there is no substantive difference between the alternatives in this regard.

Solid-State RF Sources

Solid state RF sources are selected for all RF systems in Alternatives 1 and for 162.5 & 325 MHz systems in Alternative 2. These selections are based both on versatility in low-peak-power (<100 kW) applications and on the interests of our Indian collaborators who will be providing these sources. While solid state RF sources are in use at a variety of accelerators around the world today, this technology cannot yet be characterized as "off-the-shelf". Development of robust and reliable sources is a primary element of the PIP-II R&D program.

Alternatives 3 & 4 utilize klystrons for both the warm and cold linacs. In both cases the requirements are the same as sources currently in operations at Fermilab and SNS. Hence, there is very little risk associated with these sources.

Development of Superconducting RF Cavities and Cryomodules

Alternatives 1 & 2 require development of five different SCRF cavity/cryomodule configurations, operating at three different frequencies. This represents a significant R&D effort that builds on a very significant investment in SCRF infrastructure at Fermilab over the prior

[8] W. Schappert et al, Progress at FNAL in the Field of the Active Resonance Control for Narrow Bandwidth SRF Cavities, IPAC2015, Richmond, VA. http://accelconf.web.cern.ch/AccelConf/IPAC2015/papers/wepty036.pdf

decade, and is being undertaken by the India Institutions and Fermilab Collaboration (IIFC). At the end of the R&D program prototype cyromodules will have been fabricated and tested at all three frequencies (two of these – HWR and SSR1 – with beam at PIP2IT), and dressed cavities for the two remaining configurations will have been tested. By the end of the R&D period we expect this risk to be retired.

Alternative 3 also requires a single configuration superconducting cryomodule to accelerate the beam from 400 to 800 MeV. This cryomodule can be identical to the high-beta cryomodules in operation at SNS. Because of the decade of experience beyond SNS now available, we assume that the average accelerating gradient in PIP-II will equal the best gradients available in SNS. We would build a single prototype cryomodule to validate the design and assembly procedure.

Alternative 4 has no superconducting RF cavities. The 400-800 MeV linac represents a straight-forward extension of the room temperature cavity coupled linac technology employed in the existing 116-400 MeV linac.

<u>Development of Requisite Capabilities of Vendors and International Partners</u>

An important goal in the R&D phase is to develop vendors with capabilities that will allow them to deliver components that meet the requirements and specifications of PIP-II during the construction phase. For Alternatives 1 & 2 these products are primarily superconducting cavities and RF sources. The primary mitigation to the risk associated with these components is the development of multiple qualified vendors. Multiple companies in Europe have a demonstrated ability to deliver elliptical accelerating structures of high quality for incorporation into particle accelerators. A focus of the R&D phase has been to develop equivalent capabilities in North American vendors. Following the withdrawal of this product line by Advance Energy Systems (AES) the sole potential North American vendor is Pavac, based in Vancouver, British Columbia. Orders placed with Pavac are expected to validate their capabilities. The production of spoke resonator cavities has been undertaken by a local company (Roark) with good success to date.

In parallel India is developing capabilities for superconducting cavity development within the context of the IIFC, and utilizing domestic industries. India will be delivering dressed cavities of all four cavity types associated with 325 and 650 MHz operations for incorporation into prototype cryomodules or stand-alone testing as appropriate.

India is also in the lead on the development of solid-state RF amplifiers for PIP-II (Alternatives 1 & 2). These are again under development with Indian domestic suppliers. The mitigation against failure to develop qualified vendors is the existence of vendors in the U.S. and Europe for 325 MHz systems, and a reversion to tube-based amplifiers (most likely Induction Output Tubes) at 650 MHz.

Alternative 3 requires a single superconducting cavity type that has already been used in the SNS. This cavity was developed and supplied by a European vendors at the time of SNS construction. It is safe to assume this vendor could provide the same cavity again. Klystrons are utilized for the RF amplifiers, again with capabilities existing in several U.S. and European vendors.

In summary, Alternatives 3 and 4 have less inherent risk than Alternatives 1&2 in the following areas: Operations of a superconducting pulsed linac at low current (Alternative 1), development of solid-state RF sources, development of superconducting RF cavities and cryomodules, and development of requisite capabilities in vendors and collaborators. However, the mitigation of these risks is the primary goal of the PIP-II R&D program currently being undertaken with India. Substantial resources have been invested into this program over the last decade and successful completion should result in comparable technical risks between all alternatives.

Potential for International Contributions

Fermilab has been collaborating with four Indian institutions (BARC/ Mumbai, IUAC/ New Delhi, RRCAT/Indore, and VECC/Kolkata) for nearly a decade. The Indian Institutions and Fermilab Collaboration was formed to engage in R&D aimed at high intensity proton linacs based on superconducting RF technologies, with an expectation of a significant Indian contribution to the PIP-II construction phase. India is engaged in this collaboration for the purpose of developing domestic capabilities, both at their government laboratories and in industry, to support longer term national goals based on the construction of high intensity superconducting proton linacs.

All work to date within the IIFC has been in the context of the PIP-II Reference Design (Alternative 1). This work covers essentially all areas associated with the linac – there is no engagement in the existing accelerators. The existing framework for cooperation envisions India providing approximately half of the technical components to the linac– a substantial sum as indicated in Table 6 [9]. More specifically this in-kind contribution encompasses (Alternative 1):

- Half of all superconducting cavities within the 325 MHz and 650 MHz sections of the linac. This includes assembly of cavities into He jackets and testing in India prior to shipment to Fermilab. In addition, Indian institutions are in the lead on development of prototype SSR2 and LB650 cavities during the R&D phase.
- All RF sources within the 325 MHz and 650 MHz sections of the linac. These sources will all be based on solid-state RF amplifiers.

[9] Project Annex I to 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 for High Intensity Proton Accelerators, signed January 2015.

- All (warm and cold) focusing magnets in the 325 MHz and 650 MHz sections of the linac. In addition India is delivering all magnets for the MEBT section of the PIP-II Injector Test facility.
- A 2000 W (at 2K) cryoplant. India will procure two such plants – one to be delivered to Fermilab and the other to BARC. This plant will allow PIP-II to initiate operations in CW mode if required by the experimental program.
- LLRF, RFPI, Controls, and Instrumentation electronics designs and associated boards.

Because of the technology alignment with domestic priorities Indian interest is limited to superconducting CW linacs as reflected in the signed documents. We assume, although we have not discussed specifically, that this would extend to the superconducting linac in Alternative 2 – although not the 650 MHz RF sources, which are likely beyond the capabilities of solid-state devices. Hence, we would expect a reduced, but still significant Indian in-kind contribution to Alternative 2. This expectation is not without risk however.

It is highly unlikely that an Indian contribution would be forthcoming to Alternatives 3 & 4 – DAE investment to date has been exclusively in SRF cavities and RF sources operating at 325, 650, and 1300 MHz and their planning for future domestic accelerators is based on this frequency set. There would probably also be some diplomatic fallout in pursuing either of these options following the substantial investment in the Alternative 1 & 2 technologies made by India over the last decade. To mitigate this fallout to the extent possible we have assumed a reasonable completion of the joint R&D program in all scenarios.

A partnership with INFN (Italy) has recently been initiated with the potential to lead to an in-kind contribution of LB650 dressed cavities. The assumption in the cost estimates presented in this report is that all LB650 dressed cavities will be coming from Italy and/or India in both Alternatives 1 and 2.

Cost to DOE

The costs to DOE are shown in Table 6. As described earlier the Indian in-kind contribution dramatically impacts this table. However, there is a cost risk associated with the Indian contribution that is not explicitly incorporated into this table as constructed.

Summary

The following table provides a concise summary of the analysis and performance of Alternatives 1-4. Details are found in the body of the report above.

Alternative/Criterion	Reference Design	Pulsed SC Linac	NC/SC Pulsed Linac	NC Pulsed Linac	Comments
Beam Power to LBNF (MW)	1.2	1.2	1.2	1.2	For MI operations at 120 GeV
Accelerator Complex Reliability (Risk)	Low	Low	Low	Low	Alternatives 3 and 4 ranked low based on PIP investments.
Beam Power to 8-GeV Program (kW)	83	83	83	83	For MI operations at 120 GeV
Upgrade Mu2e 100 kW	Y	Y	N	N	For > factor two increase in beam power and accelerator upgrade <$100M
Platform for LBNF > 2 MW	Y	Y	Y*	Y*	Requires Booster replacement in all alternatives. *Alternatives 3 and 4 have less flexibility, and more technical risk, in achieving >2 MW
Platform for high power, high duty factor	Y	Y	N	N	For accelerator upgrades <$100M
Interruption to operations	Minimal*	Minimal*	Minimal	Minimal	Assuming the PIP-II shutdown corresponds to the LBNF shutdown. *Alternatives 1 and 2 have the potential for an additional 7 months of operations to SBN during nights and/or weekends – whether realized will depend upon the exact timing for the LBNF shutdown.
Technical Risk	Moderate	Low	Low	Low	Primary risk in Alternative 1 is resonance control. Otherwise

Alternative/Criterion	Reference Design	Pulsed SC Linac	NC/SC Pulsed Linac	NC Pulsed Linac	Comments
					Alternatives 3 and 4 have less inherent risk, but risk is equalized at the completion of R&D.
Potential International Contributions	Yes	Yes	No	No	Pursuit of Alternative 2 would result in some reduction of the Indian in-kind contribution of RF sources. No international contributions are anticipated in Alternatives 3 and 4.
Cost to DOE (construction point estimate)	$516	$586	$602	$488	Point estimate, FY2020 $M. The cost risk associated with Indian deliverables that is not incorporated into Alternatives 1 and 2.
Cost to DOE (annual operating)	$8	$8	$9	$7	Linac only, incremental costs; FY2025 $M

Appendix I – Cost Basis of Estimate

The cost estimates presented in Table 6 originate with the estimate prepared for the Independent Project Review of the PIP-II Reference Design (Alternative 1) conducted in June 2015. The estimate methodology is described in the Construction Cost Estimate section of this report. Here we characterize the bases of the cost estimates as presented in Table 6. Estimates are largely developed as either level-of-effort, engineering estimates based on similar components fabricated and utilized in Fermilab accelerators, actual costs of components, engineering estimates based on prototypes, or parametric estimates.

Table A1: Characterization of the bases of estimate for all alternatives

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Project Management	LOE: Based on NOvA and NSLS-II experience			
Accelerator Physics	LOE: Based on experience to date. Additional 2 FTE-years added to Alt 3 for new beam dynamics modeling			
R&D	EngEst: Based on PIP2IT and IIFC deliverables package		EngEst: Assumes completion of PIP2IT and minimal commitments to IIFC	
Front End	See R&D		EngEst/Act: Based on recent fabrication (RFQ) and quantity takeoffs (DTL tank 1).	
Cavities & Cryomodules 325 MHz (SSR) 650/805 MHz (Elliptical; CCL) Warm Magnets	Proto/Act: Bill of materials with actuals incurred to date EngEst: Based on BOMs		EngEst/Act: Bill of materials with extrapolation of actuals from similar procurements	
RF Power	Para: SSRFA and klystron based on $/Watt EngEst: Support infrastructure based on quantity takeoffs		Proto/Act: 201 MHz klystron based on prototype. 805 MHz klystron based on actuals at SNS and Fermilab	
Cryogenics	EngEst/Act: Based on 2 K heat load, quantity take offs of major components, recent experience in procurements associated with the newly installed cryoplant at the CMTF.			NA
Controls	EngEst/Act: Based on similar systems currently in service at Fermilab and elsewhere.			

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Instrumentation	EngEst: Based on similar systems currently in service at Fermilab and elsewhere.			Act: Relocation of existing equipment
Beam Transfer Line	EngEst: Based on similar components in service at Fermilab.			
Electrical Systems	EngEst: Based on similar components in service at Fermilab.			
Infra, LCW, Safety, Vacuum	EngEst: Based on similar components in service at Fermilab.			
Booster/Recycler/Main Injector	EngEst: Based on extrapolation from similar components in service at Fermilab			
Civil Construction	Para: Parametric estimates based on pre-conceptual facilities layouts.			
Existing Linac Relocation	NA		EngEst: Based on recent experience in accelerator maintenance/reconfiguration shutdowns.	

<u>Key</u>

LOE (Level of Effort): A fixed number of people assigned for the duration of a task
EngEst (Engineering Estimate): Best estimate by an engineer, generally based on quantity takeoffs.
Proto (Prototype): Estimate based on experience with construction of prototype systems or components.
Act (Actual): Extrapolation from actual procurements of identical or similar items
Para (Parametric): Estimate based on a standard translation of performance to cost (e.g. $/Watt, $/sqft)

Appendix II – Technical Readiness Levels

The section Performance with Respect to Evaluation Criteria/Technical Risk examines the four alternatives from the perspective of major technical risks assessed at the level of integrated systems. These risks have largely been identified by the PIP-II management team, incorporating advice from various advisory committees, and they provide the context for the R&D program. A complimentary approach is to assess the Technical Readiness Level. This approach is aimed more directly at the component/sub-system level with a goal of identifying an overall readiness to construct.

Below we display our evaluation of the TRL by sub-system for each of the four alternatives, with TRL levels as defined in DOE G 413.3-4A: Technology Readiness Assessment Guide. Technical Readiness is evaluated on a scale of 1 to 9, with 9 representing the highest readiness level (System Operations).

Table A2.1: Technical Readiness Level assessment for Alternative 1

Alternative 1/Subsystem	Estimated TRL	Justification	Major Risk	Probability	Impact
Ion Source/LEBT	8	Demonstrated at Injector Test, meets requirements	Technical	Low	
RFQ	8	Demonstrated at Injector Test, meets requirements	Technical	Low	
MEBT	5	Most at higher level (7), the chopper requires beam demonstration	Technical	Medium	Change in baseline injection plan in Booster
HWR	7	Similar technology demonstrated in ion accelerators	Technical	Low	
SSR1	6	Spoke cavity technologies developed (different frequency)	Cost	Medium	Cost
SSR2	6	Spoke cavity technologies developed (different frequency)	Cost & Schedule	Medium	Cost & Delay
LB650	7	Similar technology (different frequency) has been demonstrated	Cost & Schedule	Medium	Cost & Delay
HB650	7	Similar technology (different frequency) has been demonstrated	Cost & Schedule	Medium	Cost & Delay
325 MHz RF SSA	4	Demonstrated in laboratory, moving to system test at Injector Test	Schedule	Medium	Delay
650 MHz RF SSA	7	75 kW demonstrated at 505 MHz (INDUS-2), moving to 650 MHz	Schedule	Medium	Delay
Booster Injection	8	Similar technology operational at SNS, need to adapt to FNAL environment	Cost	Low	Cost (but small compared to SRF costs)
Cryogenics	8	Similar systems demonstrated at FNAL	Cost	Low	

Table A2.2: Technical Readiness Level assessment for Alternative 2

Alternative 2/Subsystem	Estimated TRL	Justification	Major Risk	Probability	Impact
Ion Source/LEBT	8	Demonstrated at Injector Test, meets requirements	Technical	Low	
RFQ	8	Demonstrated at Injector Test, meets requirements	Technical	Low	
MEBT	5	Most at higher level (7), the chopper requires beam demonstration	Technical	Medium	Change in baseline injection plan in Booster
HWR	7	Similar technology demonstrated in ion accelerators	Technical	Low	
SSR1	6	Spoke cavity technologies developed (different frequency)	Cost	Medium	Cost
SSR2	6	Spoke cavity technologies developed (different frequency)	Cost & Schedule	Medium	Cost & Delay
LB650	7	Similar technology (different frequency) has been demonstrated	Cost & Schedule	Medium	Cost & Delay
HB650	7	Similar technology (different frequency) has been demonstrated	Cost & Schedule	Medium	Cost & Delay
325 MHz RF SSA	4	Demonstrated in laboratory, moving to system test at Injector Test	Schedule	Medium	Delay
650 MHz Klystrons	8	Similar technology (different frequency) in service world-wide	Cost	Low	
Booster Injection	8	Similar technology operational at SNS, need to adapt to FNAL environment	Cost	Low	Cost (but small compared to SRF costs)
Cryogenics	8	Similar systems demonstrated at FNAL	Cost	Low	

Table A2.3: Technical Readiness Level assessment for Alternative 3

Alternative 3/Subsystem	Estimated TRL	Justification	Major Risk	Probability	Impact
Ion Source/LEBT	8	Demonstrated at Injector Test, meets requirements	Technical	Low	
RFQ	7	Demonstrated at Injector Test, need to develop at 201 MHz	Cost	Low	Cost (but small compared to other costs)
MEBT	5	Most at higher level (7), the chopper requires beam demonstration	Technical	Medium	Change in baseline injection Plan in Booster
201 MHz DTL	9	Operational at Fermilab	Moving existing systems	Low	
805 MHz CCL	9	Operational at Fermilab	Moving existing systems	Low	
HB805 SRF	8	Operational at SNS, adapt to FNAL environment	Cost	Low	Cost
201 MHz Klystron	5	Prototype tested	Cost	Medium	Cost
805 MHz Klystron	8	Operational at SNS, adapt to FNAL environment	Moving existing systems	Low	
Booster Injection	8	Similar technology operational at SNS, need to adapt to FNAL environment	Cost	Low	Cost (but small compared to SRF costs)
Cryogenics	8	Similar systems demonstrated at FNAL	Cost	Low	

Table A2.4: Technical Readiness Level assessment for Alternative 4

Alternative 4/Subsystem	Estimated TRL	Justification	Major Risk	Probability	Impact
Ion Source/LEBT	8	Demonstrated at Injector Test, meets requirements	Technical	Low	
RFQ	7	Demonstrated at Injector Test, need to develop at 201 MHz	Cost	Low	Cost (but small compared to other costs)
MEBT	5	Most at higher level (7), the chopper requires beam demonstration	Technical	Medium	Change in baseline injection Plan in Booster
201 MHz DTL	9	Operational at Fermilab	Moving existing systems	Low	
805 MHz CCL	9	Operational at Fermilab	Cost	Low	Cost
201 MHz Klystron	5	Prototype tested	Cost	Medium	Cost
805 MHz Klystron	9	Operational at FNAL	Moving existing systems	Low	
Booster Injection	8	Similar technology operational at SNS, need to adapt to FNAL environment	Cost	Low	Cost (but small compared to other costs)