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Report from the Fermilab Proton Intensity Upgrade Central Design Group

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1 Executive Summary

This document is the primary output of the Proton Intensity Upgrade Central Design Group (PIU CDG) which was convened in the summer of 2022. The Group was asked to study options and provide recommendations for upgrading the Fermilab Accelerator Complex including increased reliability and capability and a focus on increasing the proton intensity to the LBNF beamline. Several approaches and combinations of approaches were examined for capability, cost, schedule, risks, and necessary R&D:

1. Shortening the Main Injector (MI) cycle time and making reliability improvements to the complex.
2. Building a new Rapid Cycling Synchrotron (RCS) to replace the Booster (3 configurations).
3. Building a new Superconducting RF (SRF) Linac to replace the Booster (3 configurations).

The Main Injector reliability improvements and cycle time reduction could be executed in stages over the course of the 2020's, simultaneous with PIP-II construction, and would enable beam delivery rates higher than the PIP-II design at the start of LBNF/DUNE experiment operations in 2031. The Booster replacement options would require a few-year shutdown and commissioning period and come online in the late 2030's time frame. The Booster replacement options are ultimately capable of producing higher beam power for LBNF, 2.4 MW vs. 2.1 MW of the MI cycle time reduction, as well as increasing the capacity, capability, and reliability of the complex overall.

It is recommended that the Main Injector cycle time shortening and reliability improvement work be carried out through the 2020's simultaneous with the establishment of a Project to build either an RCS or SRF Linac based Booster replacement. Under this approach, known as the Accelerator Complex Evolution (ACE) plan, higher power will be available to LBNF than would come from PIP-II alone, already at the start of LBNF/DUNE experiment operations. Coming later, the Booster replacement will provide even more power and considerably enhanced capabilities for a broader physics program. It will also be a robust and reliable platform for the future. The Booster replacement will provide an R&D platform for a multi-TeV collider and could potentially serve as the injector for such a machine.

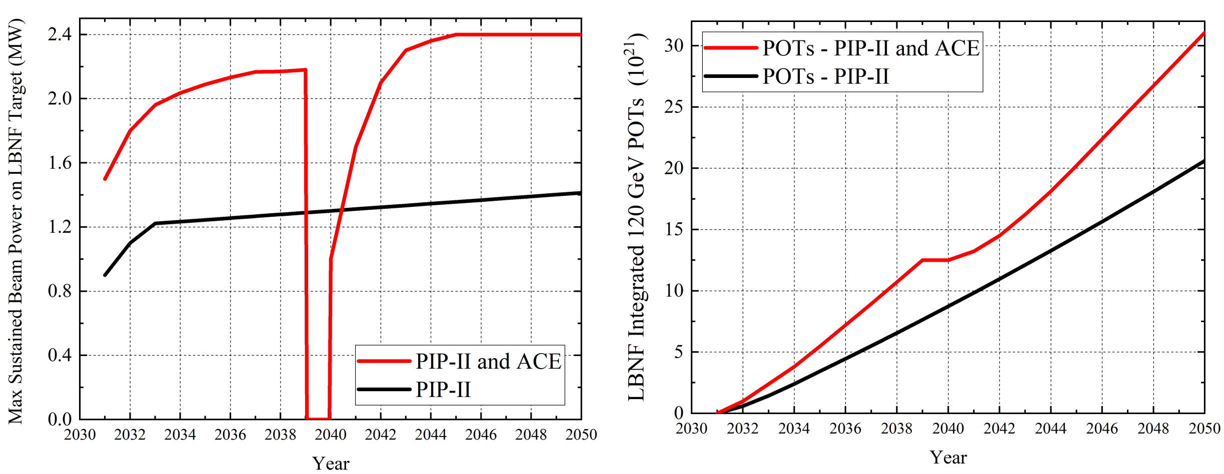


Figure 1: Maximum sustained beam power [left] and integrated number of 120 GeV protons on the LBNF neutrino target [POTs, right] under two scenarios: no upgrade beyond PIP-II (black line), PIP-II with ACE (Main Injector cycle time reduction and reliability improvements followed by either an RCS or an SRF linac Booster replacement, red). The integrated POT number assumes 44 weeks of operation per year and expected machine commissioning progress, overall efficiency and availability of the Fermilab accelerator complex. This plot includes the need for Mu2e to use approximately 25% of Booster cycles through 2033 and the fact that the horns and targets being delivered by the LBNF/DUNE-US Project will be capable of a maximum intensity of 1.2MW. Reaching higher power will require design effort and funding for those systems between the present time and 2030.

The timeline for power and POT delivery is laid out in Figure 1 compared to the timeline if no improvements were made beyond those of the PIP-II Project.

Taking the roughly estimated cost of the Main Injector cycle time reduction and reliability improvements and combining it with the cost ranges of the mid-capability RCS or SRF Linac option produces an expected cost range of $1,000M to $2,500M for the ACE plan to be executed over the 2020's and 2030's. Note this is the full cost and does not take into account international contributions which were substantial for the PIP-II Project.

The first component of the ACE plan, the Main Injector modifications, are critical to improve the complex's reliability. The Main Injector cycle time reduction will significantly boost power to LBNF in a timely way, but this extra power at 120 GeV is at the expense of power available at 8 GeV. The Booster replacement is needed to provide the extra power and flexibility at all energies. Overall the ACE program will provide proton spigots to serve experiments exploring neutrinos, the dark sector, dark matter, CLFV, as well as free-energy for new ideas.

The Fermilab Booster has served the accelerator complex for 50 years, but it is not capable of serving the laboratory for the next 50 years. A Booster replacement will be needed for its superior capacity, capability, and reliability. The ACE plan delivers a timely, higher POT to LBNF than PIP-II alone could provide, and a Booster Replacement that will provide the needed capacity, capability, and reliability for a broad and diverse program of experiments.

Looking ahead toward the vision of a multi-TeV collider based at Fermilab, the Booster replacement could provide an essential first step towards an accelerator complex capable of serving as the front end of such a collider.

Contents

2 Introduction

This document is the primary output of the Proton Intensity Upgrade Central Design Group (PIU CDG) which was convened in the summer of 2022 and asked to study options for increasing proton intensity after the completion of the PIP-II Project. The Charge to the group from the Fermilab Director, Lia Merminga, and the composition of the group are both provided in Appendix A. The need for increasing proton intensity beyond that envisaged in the PIP-II era comes, most pressingly, from the DUNE experiment. The primary oscillation measurements of DUNE are expected to be statistics limited for many years and the competition with the HyperK experiment drives the need to integrate as many 120 GeV protons on the LBNF target as possible, as fast as possible.

In addition to the DUNE experiment, an upgraded and reliable proton intensity could facilitate a number of new experiments and improve the results from some older ones. A set of such potential experiments is noted in Section 4 and a group of proton spigots defined that could serve them. A workshop series focused on ACE begins with a first workshop to be held in June, 2023 (https://indico.fnal.gov/e/aces2023). The workshops will define a diverse set of experiments and a testbed for R&D for multi-TeV colliders, and machine parameters to accomplish this broad program as well as to serve as a front end for a multi-TeV collider.

The charge to the PIU CDG assumes that the Fermilab Booster will need to be replaced in order to provide 2.4 MW to LBNF and, therefore, requests that the group examine Superconducting RF Linac and Rapid Cycling Synchrotron Booster replacement options. In the course of these investigations it was found that >2 MW could be delivered to LBNF by reducing the Main Injector cycle time in the near term. This cycle time reduction is expected to be realizable on a short timescale and can be accomplished over a series of summer shutdowns with no need for any disruptive long downtime of the accelerator complex. It is also expected that the Main Injector cycle time reduction could be accomplished over the 2020's and be completed in time for first beam to LBNF or even by the end of the long shutdown (early CY29).

This discovery of a timely way to send >2MW to LBNF has led to the first recommendation of this group, to pursue the reduction of the Main Injector cycle time in the near term and concurrently improve its reliability. In parallel a replacement of the Booster should be pursued for the long term reliability and capability of the complex. The Booster [1] is an early example of a rapidly-cycling synchrotron (RCS). Built in the 1960s, it features a design in which the combined-function dipole magnets also serve as vacuum chambers. Such a design is quite cost-effective, and it does not have the limitations associated with the eddy currents in a metallic vacuum chamber. However, it has a large impedance, and a small aperture. In the present Booster, the transition energy is at about 4.2 GeV (kinetic) and the beam loss occurring during transition crossing is one of the main intensity limitations [2]. Further, the passive shielding of the Booster tunnel will not be adequate for high power operations and the long-term reliability of critical accelerator components cannot be guaranteed. Nonetheless, the new capability provided by PIP-II and modest upgrades to the present Booster, combined with improvements downstream, particularly to the Main Injector, have the potential to support >2 MW to LBNF through the 2030's. Motivated by Fermilab's desired long term future physics program including d diverse set of smaller experiments and eventually a multi-TeV collider, investigation into a Booster replacement should begin soon, with the goal of starting operation in the late 2030s.

In this document we describe the Main Injector cycle time reduction, the consequent need to make the Accelerator Complex more reliable, and ways to achieve that increased reliability in Sec 3. The desired experiments and resultant proton spigots that the HEP community may wish to build at Fermilab are described in Sec. 4 and Sec. 5 describe the compatibility of the current complex and Booster replacement configurations with a future multi-TeV collider program at the lab. The document then goes on to lay out six configurations that could serve as Booster replacements, three involving an RCS and three using an SRF linac. These six configurations are broken out into their elements in Sec. 7 where each element's costs, risks, and R&D needs are described. Sec. 8 then brings the elements back together and describes the total costs, risks, and necessary R&D for each of the six configurations. The work is summarized in Sec. 9.

3 Upgrading the Complex Prior to Booster Replacement

The PIP-II upgrade [3] will increase the 8 GeV proton flux out of the Booster by a factor of two from the present values by a) increasing the charge accelerated per Booster pulse from 4.5×10^{12} to 6.5×10^{12} protons; b) raising the pulse rate from 15 Hz to 20 Hz. Additionally, upgrades to the Recycler and the Main Injector will enable acceleration of up to 1.5 times the present number of particles, 7.5×10^{13} protons per pulse to 120 GeV with a 1.2 second cycle time remaining unchanged from the present operation. These improvements will enable the 120 GeV LBNF beam power of 1.2 MW as well as a substantial increase of the beam flux for the 8 GeV physics program.

Further advances in the 120 GeV proton flux to LBNF could be achieved by a combination of

- Shortening of the MI cycle time.
- Increase of the MI beam pulse intensity.
- Measures to improve overall accelerator efficiency by beam loss mitigation and enhancements of reliability.

The working group considered two potential upgrades to the accelerator complex that could be implemented before any replacement of the Booster and which hold the promise of increased power to LBNF/DUNE to as much as the full 2.4 MW. These two upgrades are reduction in the Main Injector Cycle Time and the PIP-II Accumulator Ring (PAR). They are described in the next two subsections. The combined costs of the two is very roughly estimated to be in the $200M ballpark.

3.1 Shortening the Main Injector Cycle Time

The two-fold increase of the 8 GeV beam throughput by the Booster in the PIP-II era opens a path to utilizing these 'excess' protons via more rapid acceleration in the Main Injector. If the MI cycle time can be decreased from the current 1.2 s then a proportional power gain can be obtained without the need for higher beam intensity. Such an approach offers significant advantages over the intensity upgrades: i) it can be implemented in stages as an incremental update making maximum use of investments into the accelerator complex by the PIP-II project; ii) it is associated with much less risk from the beam physics side as the beam intensity per pulse remains the same; iii) the increase of beam power through pulse rate at constant charge per pulse is more forgiving for target system design.

Assuming the use of the accelerator chain up to the Main Injector without changes after PIP-II, the minimum cycle time attainable in the MI will be determined by the slip-stacking procedure in the Recycler: 13 booster ticks are required for the 12 injections and an additional one for slipping. The Booster repetition rate of 20 Hz results in the minimum beam forming time of 0.65 s.

Scenario	**Present**	**PIP-II**	**A**	**B**	**C**
MI cycle time (s)	1.33	1.2	0.9	0.7	0.65
Booster intensity (10^{12})	4.5	6.5			
Booster ramp rate (Hz)	15	20			
Booster cycles for 8 GeV	6	12	6	2	1
Available 8 GeV power (kW)	29	83	56	24	12
MI 120 GeV power (MW)	0.86	1.25	1.66	2.14	2.3

Table 1: Main Injector 120 GeV power for different cycle time scenarios.

It has been investigated whether the MI cycle time could be reduced to 0.65 s from 1.2 s which would lead to an 85% power increase at constant intensity. For this to be feasible, the following must be considered:

Magnets The design ramp rate for Quadrupoles and Dipoles is 240 GeV/s and this will need to be increased to 500 GeV/s. There is a concern that the increased voltage driving the magnets may lead to partial discharge eroding the epoxy. However, this is still to be investigated.

Electrical power The Kautz road substation capacity needs to be increased to include two additional transformers and harmonic filters. Each service building will need to be expanded as 2 dipole and 1 quadrupole power supplies need to be added.

Regulation and control

RF accelerating system Following the PIP-II upgrades to the RF system, the maximum per pulse intensity is limited to 120×10^{12} protons. If the MI cycle time is reduced, then new power amplifiers would not be required as only the cycle time is reduced. However, in order to maintain the same RF bucket area, the maximum voltage must be increased. Currently there are 20 RF cavities providing 4.8MV max voltage (energy gain per turn). With 0.65 s cycle about 9MV would be needed to maintain minimum bucket area This could be done by either adding extra cavities or replacing the cavities with ones that can produce a high voltage.

Beam dynamics One of the significant advantages of shortening the cycle is that the power is increased with the beam intensity remaining the same. This means the beam physics remains mostly the same. Attention must be paid to the eddy currents which produce a sextupole field. Doubling the ramp rate will double the size of the sextupole field; however, this is not expected to be a significant impact.

3.2 The PIP-II Accumulator Ring (PAR)

A PIP-II proton accumulator ring (PAR) is proposed to be built simultaneously with PIP-II. It could effectively serve several purposes: a) meeting the needs of delivering high intensity bunched beams for possible future rare processes experimental program by accumulating long low current PIP-II pulse of H^- particles into few short high intensity 0.8-1 GeV proton bunches with $O(100$ kW$)$ average beam power, b) improvement of the Booster operation for neutrino program with > 2 MW out of the Main Injector due to elimination of very challenging H^- charge-exchange injection system from the Booster – that can be more easily done in PAR. As the result, a single turn 2μs injection from PAR to the Booster would be greatly superior to the 0.55ms long pulse injection directly from the PIP-II linac and, therefore, will significantly reduce the beam losses in the Booster and allow higher intensity operation and potentially better reliability; c) staging for a potential future 1 GeV upgrade of the Booster injector energy.

PAR is a low cost accumulator ring to be located adjacent to the PIP-II Booster transfer line (BTL) near the planned Booster injection point. The H^- charge-exchange injection into PAR will feature a number of modern design improvements over H^- charge-exchange injection system into the Booster, including the extraction unstripped H- to an external absorber rather than increasing activation in the ring and better control of large-angle Coulomb-scattering losses off the injection foil. This compact ring is designed to fit alongside the BTL to allow easy transfer of beam to and from the BTL as well as to a rare processes physics program to be located in the middle of the PAR. The PAR will accumulate the PIP-II beam with one of two planned RF systems. The bunched beam will then be extracted to either the Booster in a single turn injection or to a beam dump experiment. The PAR extraction rate for the Booster beam cycles would remain at 20 Hz with the required accumulation time. The rate for the other PAR users would be limited by the injection and pulsed extraction systems. The baseline design is 100 Hz operation with 100 kW to 200 kW beam power. More design parameters will be provided in Sec. 3.2.3.

3.2.1 PAR Layout

The footprint of PAR is constrained by the Booster in the west, the Booster transfer line (BTL) in the south and PIP-II in the east. Working with the PIP-II civil engineers and Proton Source personnel, a suitable location for PAR was found that met all the constraints of the existing infrastructure and PIP-II plans. The limited spacing for PAR requires that the tunnel be smaller than the present Booster circumference. However, a desire to keep the PAR as a Booster loader required that we have a nearly identical harmonic number. To accommodate the Booster injection needs, a folded accelerator and lattice design was developed. More details on the PAR lattice will be presented in the following subsection. The PAR will cross the present Main Ring tunnel twice, which is unavoidable. The crossing will be similar to the BTL but the rings will not be at the same elevation.

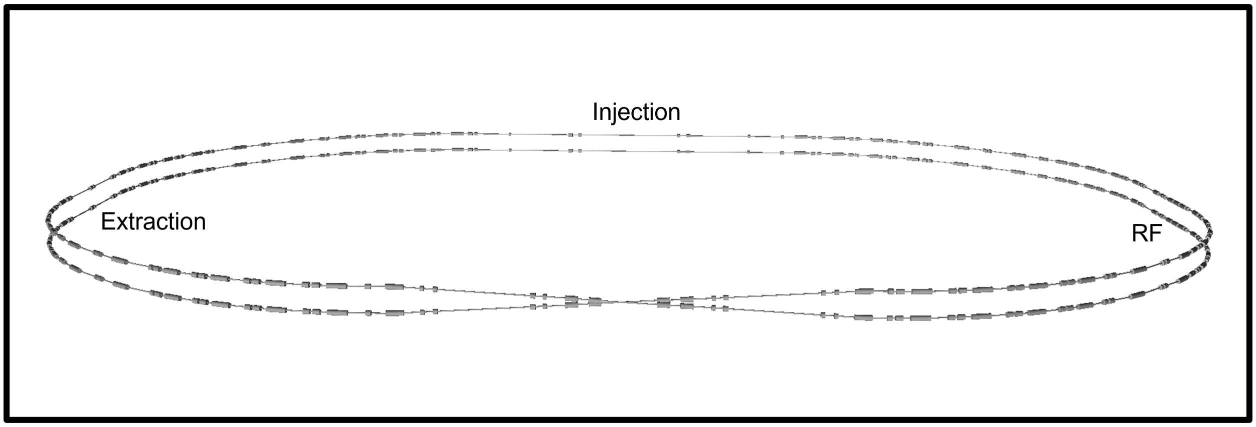


Figure 2: Schematic view of the PAR. A folded figure-8 design has the necessary injection region, two extraction regions, and two RF systems, all in an approximately 244 m circumference tunnel.

The placement of PAR will enable the commissioning of PIP-II to the BTL and Booster to be independent from the commissioning of PAR. The independence is achieved by having a fast switching magnet near the last BTL dipoles. The pulser magnet will either kick beam into the transfer line to PAR or remain on the BTL to Booster trajectory. This method of beam transfer is only required for the commissioning period of the PAR. Once commissioned, the pulsed magnet system is replaced with DC dipoles magnets and injection to the Booster will pass through PAR. One dipole bends beam to the PAR and another would bend the extracted PAR beam onto the BTL to a Booster trajectory before the BTL pass through beam pipe.

The present civil construction plan for PAR has a service building located near the injection and extraction area to house the power supplies required for the pulsed systems. The exact placement has yet to be determined but will be chosen to satisfy the needs of the planned DS physics program and other potential PAR users.

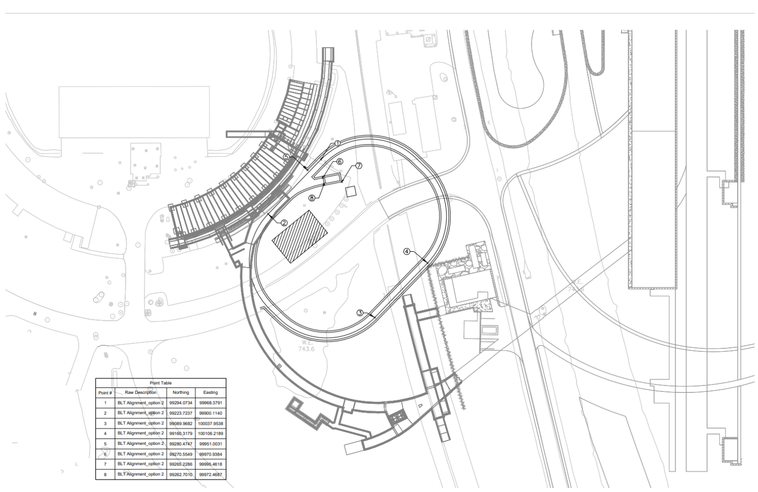
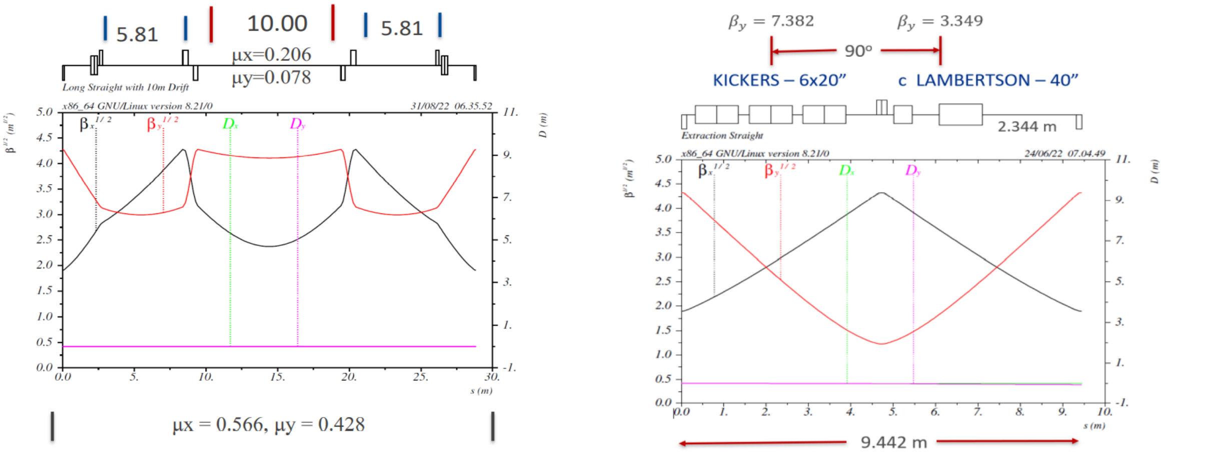


Figure 3: The location PAR is adjacent to Booster and Booster Transfer Line.

3.2.2 PAR Lattice Concepts

The PAR lattice, shown in Figure 4, is well developed and meets the desired spacing and lattice parameters. Although PAR only accumulates beam, it has two separate RF systems. One RF system to accommodate bunches beam destined for the Booster. The second RF system has a lower harmonic for super bunch(es) for beam dump experiments. The PAR lattice has a 10 meter long injection region to handle the waste

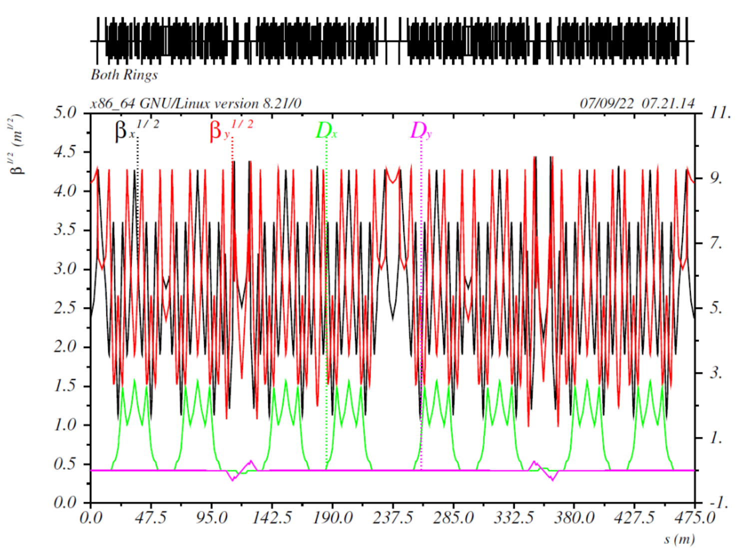


(a) The PAR injection lattice with a 10 meter straight. (b) The PAR extraction lattice with 3 sets of short kickers.

Figure 4: PAR injection and extraction lattices

beam from the H- stripping at high cycle rates. For comparison, PAR's 10 meters is 3 meters longer than the planned PIP-II Booster injection region making it possible to safely extract unstripped H- particles. Additionally, PAR has two separate extraction lines to allow independent operations. The lattice has zero dispersion in the RF regions to reduce concerns over possible Synchro-betatron coupling instabilities. The beta and dispersion functions are well matched to Booster and PAR needs. Space is available for collimation in PAR, including immediately downstream of injection.

The PAR lattice has been adjusted to utilize magnetic elements that already exist at the lab and this reduces the PAR cost. For example, FNAL quads have been identified that meet the length, strength and aperture requirements for PAR. Corrector magnets that were once used in the Booster and are now in storage are acceptable for PAR. The bend elements are being optimized to reduce manufacturing and design costs. The present design has a 3.125 inch aperture which matches the wide bore Booster RF cavity design.



Element	Length in	Count
Quad	14.5	64
Quad	11.3	22
Quad	8.2	16
Dipole	35	64
Dipole	42	16
Dipole	20	24
V-H Trim	8	96
ORBMPs	14	4
Kickers	20	12

Table 2: PAR lattice and associated magnet table

PIP-II Accumulator Ring (PAR) Parameters - Booster Use		
Parameter Name	Value	Units
Booster Synchrotron Circumference	474.2	m
Booster Synchrotron Radius	75.47	m
Accumulator Circumference	485.49/2	m
Aperture	3 -.125	in
PAR Injection Energy (kinetic)	800	MeV
PAR Injection Energy (Total)	1738	MeV
PAR Extraction Energy (kinetic)	800	MeV
Revolution Frequency	519822	Hz
Revolution Period	1.924	us
RF Properties		
h (matching with Booster RF)	~84	Fundamental
fRF	44.705	MHz
Bucket Length	22.37	ns
Number of Booster type RF Cavities	4	
Peak RF Voltage/Cavity	50 - 60	kV
Total RF Voltage	0.2	MV
Bucket Area	0.074	eVs
Synchrotron Oscillation Period	1.27E+04	Hz
PIP2 beam Intensity	6.70E+12	ppCycle
PIP2 Bunch Intensity	8.27E+10	p/bunch

(a) PAR parameters for the Booster injection operation

PAR – Accumulator for storage for DS Physics Search		
Option 1		
h - Harmonic Number (additional RF system)	4	
fRF	2.079	MHz
Bucket Length	480.93	ns
Number of Recycler type 2.05 MHz RF Cavities	2	
Peak RF Voltage/Cavity	5	kV
Peak RF Voltage	0.01	MV
Bucket Area	1.66	eVs
Synchrotron Oscillation Period	6.10E+02	Hz
Scaled Bunch Intensity	1.82E+12	p/bunch
Option 2		
h (additional RF system)	5	
fRF	2.599	MHz
Bucket Length	384.75	ns
Number of Recycler type 2.5MHz RF Cavities	2	
Peak RF Voltage/Cavity	5	kV
Peak RF Voltage	0.010	MV
Bucket Area	1.19	eVs
Synchrotron Oscillation Period	6.82E+02	Hz
Average Bending Radius	77.2682102	m
Average Dipole B-Field	0.063	Tesla

(b) PAR parameters for high intensity beam dump HEP experiments

Figure 5: PAR Parameters

3.2.3 PAR Parameters

PAR has been designed around a list of key parameters which are presented in Figure 5. As work continues on the PAR design, these parameters will be adjusted. However, it should be noted that they have not changed significantly over the past year. The PAR beam pipe aperture is 28% larger than the Booster dipole aperture. This will allow for low loss accumulation and higher beam flux for the dump experiments. This aperture is also the same as the new wide bore Booster RF cavities. A larger aperture will make the RF cavity the aperture restriction which will require a new RF cavity design and testing program. This aperture is well suited for the delivery of several hundred kW of beam power to a DS program. Additionally, this aperture allows PAR to use existing FNAL magnets which are in storage - significantly reducing cost. The baseline power that might be delivered to the DS dump experiment is estimated to be 125 kW. This will require 100 Hz operation with 1E13 ppp. The intensity limit is based upon a conservative value for space charge at 800 MeV. A future upgrade to the PIP-II linac to 1 GeV will allow for the PAR base intensity to be increased to 1.5E13 ppp. The higher energy and intensity will increase the delivered power to the DS program to 240 kW. A DS physics program would be competitive at these power numbers and provide a new beam based DS program here at FNAL.

PAR delivery to the Booster will be a single turn 2 μs injection. This single bucket to bucket transfer will greatly simplify the Booster loading and reduce losses in the Booster. Single turn loading will also result in no need to flatten the Booster bend field with correctors as needed to accommodate the approximate 600 us injection loading time. Additionally, the Booster RF system will be simplified because the RF phase locking between PAR and Booster is achieved in a simple injection. Additionally, the Booster acceleration and feedback curves will be similar to present operations.

3.2.4 PAR Budget

The PAR cost table is preliminary but has been based on PIP-II civil construction and recent hardware purchases in line with this document's approach of estimating costs from recent or current projects. A key goal in the design of PAR was to deliver a capable machine at the lowest cost. Magnets, RF cavities, kickers, and engineering designs are mostly copies of existing systems. The present plan has a single service

PAR cost breakdown	Cost ($M)
Tunnel enclosure	23.4
Permanent magnets (includes labor)	7
Support stands	1.4
Correctors (reused)	0.1
Power supplies (guess)	1
44 MHz RF (reuse 4+2 spares legacy Booster cavities with modifications)	4
2.5 MHz RF (2 + 1 spare) (See Table 5)	1
Vacuum (re-use Booster vacuum pumps ?)	2.5
BPM electronics ($0.1M) + detectors ($0.65M)	0.75
Injection ORBUMP + PS (See Table 4)	5.13
Extraction kickers: 16 (½ m kickers) + 4 spares = 20 kickers (See Table 3)	3
Extraction lambertsons (2+1 spare @0.17M/lambertson) + PS (2x PS @ $0.5M each)	1.5
Total	50.8

Table 1: PAR cost estimate (18 Jul 2022)

Figure 6: PAR's budget table as of July 2022.

Site Preparation			
Site Work	1	Lot	$ 2,000,000
Utilities	1	Lot	$ 2,500,000
		Site Preparation Total	$ 4,500,000
Enclosure			
	Length (ft)	**Width (ft)**	**Square Feet**
Beamline Enclosure	800	10	8,000
Absorber Enclosure	40	16	640
Shielded Hatch	20	12	240
Exit Stairs	100	5	500
Main Ring Crossing	140	12	1,680
		Total Square Feet	11,060
		Cost/SF	$ 1,391 (
		Enclosure Cost	$ 15,381,000
Service Building			
	Length (ft)	**Width (ft)**	**Square Feet**
PAR Service Building	50	50	2,500
		Cost/SF	$ 1,391 (
		Service Building Cost	$ 3,477,000
Summary			
Site Preparation			$ 4,500,000
Enclosure			$ 15,381,000
Service Building			3,477,000
		Construction Total	**$ 23,358,000**

Figure 7: Cost table for PAR civil construction

building to house the extraction and injection power systems. Yet to be determined is the location for the PAR RF hardware. Because PAR crosses the MR tunnel near the RF region, a possible placement of PAR hardware can be in an existing Tev/MR building. The folded ring design saves on civil construction costs but does require some additional lattice design effort to accommodate the folded lattice. Costs for construction are in line with PIP-II estimates, but details need to be worked out for the MR crossings and penetrations. Additional costs are expected for vacuum systems but are still uncertain until an inventory of existing surplus older Booster vacuum systems is completed. The PAR kickers will follow the same design as the present Booster but will require a 3.125 inch aperture versus the present 2.5×3 inch rectangular aperture.

4 Potential Experiments and Proton Spigots

4.1 The Potential Experiments

An incomplete listing of possible experiments that could make use of PIP-II beam or later beam from a Booster Replacement is given in Figure 8. Note that DUNE is not included in this table as providing beam to DUNE is considered compulsory and not optional. Note also that the experiments are grouped by desired proton energy and these groupings are indicated by color. This listing is generated from whitepapers written for the Snowmass process and gathered together in [4]. The list is inevitably incomplete but it is hoped that it at least spans the different proton energies, powers, and time structures that might be required. The experiments then allow for the definition of proton spigots that are described in the next two sections.

4.2 The PIP-II Era Proton Spigots

The PIP-II era proton complex beam delivery capabilities are collectively designated as "Spigot 0" or S0. These are proton beamlines that could support experiments using the PIP-II era proton complex infrastructure, although not necessarily restricted to the PIP-II era timeline. Indeed when considering the 2.4 MW PIU scenarios, we will take note of any area in which S0 capabilities are lost or enhanced.

The specific beam delivery capabilities in the S0 category are further enumerated as S0A-S0F, by energy and pulse structure. A categorization of PIP-II era experiment and facilities into those S0 subcategories is provided:

S0A: 0.8 GeV PIP-II Linac, experiments which require CW Linac.

The S0A subcategory is for experiments which require continuous or near-continuous beam. directly from the PIP-II linac. Although the PIP-II linac delivers 800 MeV H- ions, experiments which require protons or use lower energy beams can also be considered. Beam energies up to 1 GeV can also be considered part of this subcategory. Linac experiments, pulsed or CW, at energies above 1 GeV in the PIU era would be considered part of Spigot 1 (S1).

Configurations C1c, C2b, C2c (defined in Sec. 6) modify the PIP-II linac for higher current and pulsed-only operation (element E1c), and consequently do not support S0A experiments in the PIU era.

S0A Experiments:

- Mu2e-II (100 kW)
- mu2eg, mu3e
- REDTOP run-II (1 MW)
- neutron-antineutron oscillation experiments (with neutron production target)

S0B: 0.8 GeV PIP-II Linac, experiments which can use pulsed linac beam.

The S0B subcategory is for experiments which use high duty-factor and/or low-current beams but are distinguished from S0A in that they do not necessarily require the PIP-II linac to operate in a CW mode.

S0B Experiments:

- Surface muon programs including muonium
- REDTOP run-II (100-200 kW)
- EDM storage ring (with polarized proton source upgrade, extraction at 232 MeV)
- Proton irradiation facility (0.8 GeV version)

S0C: 0.8 GeV PIP-II Accumulator Ring program.

Experiment	Experiment type	Proton Beam			Uses existing or new beamline?	Spigot
		Energy [GeV]	Power [kW]	Time Structure		
Proton Storage Ring: EDM and Axion Searches	Precision tests Dark Matter	0.232	1e11 polarized protons per fill	Fill the ring every 1000s	new	S0B
Physics with Muonium	Precision tests	0.8	1e(13+/-1) POT per second	CW	new	S0B
REDTOP Run I	Precision tests	1.8 - 2.2	0.03-0.05	slow extraction	Muon Campus	S0E
REDTOP Run II	Precision tests	0.8 - 0.92	200	CW,	new	S0A, S0B
REDTOP Run III	Precision tests	1.7	>1,000	CW,	new	S1
Ultra-cold Neutron Source for Fundamental Physics Experiments, Including Neutron-Anti-Neutron Oscillations	Precision tests	0.8-2	1,000	quasi-continuous	new	S0A
CLFV with Muon Decays	CLFV	Not critical 0.8 to a few GeV	100 or more	continous beam on the timescale of the muon lifetime i.e. proton pulses separated by a microsecond or less. The more continuous the better	new	S0B
Mu2e II	CLFV	1 to 3	100	pulse width 10s of ns or better separated by 200 to 2000 ns. Flexible time structure and minimal pulse-to-pulse variation	new	S0A, S1
Fixed Target Searches for new physics with O(1 GeV) Proton Beam Dump	Dark Sector, Neutrino	0.8 to 1.5 GeV	100 or more	<O(1 micro s) pulse width for neutrino measurements, <O(30 ns) pulse width for dark matter searches, 10^{-5} or better duty factor	new	S0C, S2
PRISM-like Charged Lepton Flavor Violation	CLFV	1 -3 GeV	up to 2 MW	15ns pulses at a rep rate of about 1 kHz	new	S0C, S2
Proton Irradiation Facility	R&D	Energy is not very important	1e18 protons in a few hours	Pulsed beam (duty factor not specified)	new	S0B
SBN	Neutrino	8	32	20Hz	BNB	S0D & S3
Mu2e	CLFV	8	8	<10^{-10} extinction	Muon Campus	S0E
Fixed Target Searches for new physics with O(10 GeV) Proton Beam Dump	Dark Sector, Neutrino	8	up to 115	Beam spills less than a few microsec with separation between spills greater than 50 microsec	BNB	S0D & S3
Muon beam dump	Dark Sector	8 (producing 3 GeV muons)	3e14 muons in total on target for the whole run	CW	Muon Campus	S0E
Muon Collider R&D	R&D	8 - 16GeV	4e13 to 1.2e14 protons per bunch	5 - 20 Hz rep rate and bunch length 1-3 ns	new	S3
Muon Missing Momentum	Dark Sector	few 10s of GeV	10^{10} muons per experimental runtime	Pulsed beam (duty factor not specified)	new	S0F
High Energy Proton Fixed Target	Dark Sector, Neutrino	O(100 GeV)	1e12 POT/s therefore ~20 kW	CW via resonant extraction. "IF we could up the duty factor that woul dbe even better"(?)	Switchyard or new	S0F
Test-Beam Facility	R&D	120, lower energies would also be beneficial	10 to 100 kHz on the testing apparatus	Pulsed beam (duty factor not specified)	Switchyard or new	S0F
Tau Neutrinos	Neutrino	120	1200 or higher	MI time structure	LBNF	LBNF

Figure 8: Potential experiments for the PIP-II and Booster Replacement Eras. The running of DUNE is assumed and not part of this table. The experiments are grouped by desired proton energy and these groupings are indicated by color. Data drawn from [4]

The PIP-II CDR does not currently include any accumulator ring (AR) to serve 800 MeV low-duty factor experiments. However, an AR could be a modest extension of the PIP-II linac complex and experiments enabled by that capability should be distinguished from S0A and S0B.

Section 3.2 above provides an outline to the AR design known as PAR, which we can consider as a reference design for the evaluation of PIP-II era capabilities, including a cost analysis in Section 7.10. More compact and/or higher power scenarios have been discussed in [5, 6].

Beam energies up to 1 GeV can also be considered part of this category. Beam energies above 1 GeV would be considered part of the Spigot 2 (S2) in the PIU era.

S0C Experiments:

- PIP2-BD dark sector search (compatible with PAR)
- AMF/PRISM charged-lepton flavor violation experiments (<400kW with 20ns pulses, not compatible with PAR, compatible with C-PAR or similar high-power short-pulse ring)

S0D: 8 GeV Booster Experiments

The S0D subcategory is for experiments which use low duty-factor 8 GeV beam directly extracted from the Booster (such as SBN program). Any experiments which use low-duty factor but require rebunching or other longitudinal manipulation in the Recycler should instead by considered part of S0E. The S0D beamline is limited in beam power and rep. rate beyond PIP-II era capabilities, but the Spigot 3 (S3) is for Booster Replacement Era experiments which require similar pulse structure but higher beam power.

S0D Experiments:

- Current SBND program
- SBND Dark Matter program

S0E: 8 GeV Recycler & Delivery Ring Experiments.

The S0E subcategory is for experiments which make use of either the Recycler Ring or Delivery Ring. In particular we consider experiments which require rebunching or other longitudinal manipulation in the Recycler (such as g-2 or mu2e), experiments which require use of the Delivery Ring for use of secondary beams (such as g-2), experiment which require use of the Delivery Ring for slow-extraction (such as mu2e), and experiments which require use of the Delivery Ring for deceleration (such as REDTOP run I). PIU upgrades are not expected to enhance the capabilities of the Delivery Ring.

S0E Experiments:

- Current g-2 program
- Current mu2e program
- REDTOP run I

S0F: 120 GeV Main Injector Slow-Extraction program.

The S0F subcategory is for experiments which require slow-extracted beam at 120 GeV. Experiments which require slow-extracted protons with energies between 60-120 GeV can also be considered part of this category, although that is not a present capability.

The beam power available by slow-extraction is primarily limited by particle losses on the extraction septum during the slow-extraction process. Although it may be possible to make (modest) upgrades to the Main Injector to improve slow-extraction performance, those upgrades are largely independent of the upgrades necessary for the fast extracted beam power.

S0F Experiments:

- Current SpinQuest program
- Current and next test beam program

- DarkQuest dark matter spectrometer experiment
- M3 muon missing-momentum experiment

Omitted from this list is the 60-120 GeV Main Injector Fast-Extraction program (i.e. O(100) GeV Low Duty-Factor) for the long baseline neutrino program, which is taken to be a fixed point in our planning. It is also important to note that S0C describes a capability that leverages the PIP-II era upgrades but requires a modest extension of the proton facility in the form of an accumulator ring as described in Sec. 3.2.

4.3 The Booster Replacement Era Proton Spigots

The new Booster Replacement Era experiments and facilities are classified into three categories designated as Spigots (S1, S2, and S3). The PIP-II era Spigots (S0A-S0F) can be assumed to continue as long as they are valued, except where stated otherwise. The Spigot classification allows for a common basis to compare the breadth of the experimental program supported by each accelerator upgrade configuration. Section 8.1 gives the proton beam power available to each Booster Replacement Era Spigot.

A categorization of Booster Replacement Era experiments and facilities into spigots is provided:

S1: O(1) GeV High Duty-Factor Beamline

The S1 category is for experiments which require high-duty factor GeV-scale proton or H- beams. In particular, we consider an energy extension of the PIP-II linac. Many of the PIP-II era experiments listed in S0A or S0B can also be supported at a higher energy. There is some margin for optimization of the beam energy, between 0.8 and 2 GeV. Although a CW extension of the PIP-II linac would feature considerably more beam power for S1, but pulsed linac extensions of the PIP-II linac can also be considered.

S1 Experiments:

- REDTOP run-III (requires 1.7 GeV)
- May be compatible with S0A & S0B experiments

S2: O(1) GeV Low Duty-Factor Beamline

The S2 category is for experiments which require low-duty factor GeV-scale proton beams. The primary scenario under consideration is for the GeV-scale linac (consistent with S1) to be collected in one or more intense accumulator rings (AR) and extracted in short pulses for experiments. Although RCS configuration C1b requires such an AR to facilitate injection, the other configurations would have to add element E4 in order to support S2 capabilities.

The optimization of the AR for the experimental program is beyond the scope of this document. The performance of the AR will depend strongly on the injection energy and consequently beam power for experiments will scale nonlinearly with energy. In order to reach MW-class S2 program (requiring 2-GeV CW linac E1a), the development of laser H^- stripping technology may also be necessary. We can consider 2 GeV as a reference energy, with the understanding that there may be some margin for optimization.

In any subsequent AR optimization the pulse structure requirements and preferred parameters for experiments should be considered carefully. With the three currently proposed users - the PIP2-BD dark sector search, the AMF CLFV experiment, and facilitated injection into the RCS – the necessary beam parameters overlap but are not identical.

S2 Experiments:

- PIP2-BD dark sector search (C-PAR and RCS-AR scenarios)
- AMF/PRISM charged-lepton flavor violation experiments (with 20ns pulses)
- Enhanced performance versions of most S0C experiments

S3: O(10) GeV Low Duty-Factor Beamline

The S3 category is for experiments and beamlines operating with a low-duty factor, high-power proton beam at 6 GeV or higher. Experiments and beamlines that do not require low-duty factor operation but are compatible with low-duty factor operation may also be included in this category (such as an irradiation facility).

In particular, we consider two types of accelerator configurations which would provide for beams in this category: direct extraction from of an O(10) GeV RCS (configurations C1a, C1b, C1c), or extraction from an accumulator ring supported by an O(10) GeV linac (configurations C2a, C2b, C2c). In either the RCS or high-energy AR case, the same ring would also deliver beam to the Recycler and Main Injector. Consequently, the key figure is the "available" beam power, which is defined to be the beam power available to this beamline concurrent with 2.4 MW 120 GeV operation of the Main Injector.

We consider 8 GeV as a reference energy, but higher beam energy could have implications for the Main Injector program. For an 8 GeV beam, much of the existing MI transfer line infrastructure can be re-purposed and the Recycler Ring could be kept operational as desired. At 9-12 GeV however, the space-charge tune-spread and geometric emittance could be substantially reduced in the Main Injector (and in any high-energy AR).

S3 Experiments:

- SBN-BD KPIPE sterile neutrino search, kaon decay at rest, intermediate energy dark sector search
- Muon collider front end R&D (see Section 5)
- Proton irradiation facility (8 GeV version)
- Muon beam dump experiment
- Enhanced performance for most S0D experiments

The one type of PIU-era experimental beamline not listed here is any potential O(10) GeV high-duty factor program. Such a program would be entirely parasitic on the S3 program and would only be readily available in PIU accelerator configurations which feature an 8-GeV linac (C2a-C2c). Presently, there are no active collaborations proposing to use such a beamline at Fermilab. Such as beamline might be applied to a high-duty factor kaon-decay program, such as the KOTO experiment which is served by 30 GeV protons slow-extracted from the J-PARC Main Ring [7, 8].

5 Compatibility with Future Colliders

Future colliders are an essential component of a global strategic vision for particle physics, for instance for the detailed study of the properties of the Higgs boson and for the exploration of mass scales above those accessible at the HL-LHC (∼10 TeV partonic collision energy). The prime candidates under consideration for an e^+e^- Higgs Factory are the FCC-ee at CERN, CepC in China and the ILC in Japan. The leading energy frontier concepts for the ∼10 TeV mass scale are FCC-hh, SPPC, and ∼10 TeV muon colliders (MuC). During the Snowmass'21 process, several options for future colliders in the U.S. were explored [9, 10]. In order to develop the concepts and designs for a future collider in the U.S., a concerted national accelerator R&D program focused on future colliders has been proposed [9] .

While one goal of the PIU described in this document, is to double the neutrino flux (from the PIP-II regime) for the LBNF/DUNE experiment by increasing the 120 GeV proton beam power on target to 2.4 MW or more, corresponding proposed upgrades of the Fermilab accelerator complex will also increase proton beam intensity available for other present and future Fermilab experiments. In addition, a Booster Replacement is a necessary ingredient as a front-end for a future multi-TeV collider at Fermilab and can be used as a platform for nearer term muon collider R&D. As evident from the Snowmass'21 proceedings, the US HEP community has aspirations for a future energy frontier collider at Fermilab beyond the LBNF/DUNE project time-frame. A high energy MuC of up to 10 TeV (5 TeV beams) could fit within the Fermilab site boundaries. Depending on the nature of pursued new physics, it would provide the energy reach equivalent to a 50 - 200 TeV proton-proton collider. We discuss here the requirements of a proton driver for a Muon Collider facility, as well as the R&D program required in developing the collider design.

In 2021, CERN launched a muon collider design study to assess the feasibility of building a high energy muon collider, identify critical challenges, and develop an R&D program aimed at addressing them. An International Muon Collider Collaboration (IMCC) was formed to conduct the study. The near-term goal of the study is to establish whether an investment into a full Conceptual Design Report and a demonstration program are scientifically justified for the next European Strategy for Particle Physics Update. US physicists made key contributions to many areas of the IMCC design study through the Snowmass process. The R&D program described in this document is well aligned with IMCC priorities and timelines.

5.1 PIU towards a Muon Collider Facility

Effective production of muons for the collider would require a source of high energy, high intensity proton pulses, which we label a Muon Collider proton driver (MuC-PD). A ∼2 MW 10 Hz MuC-PD is required in a typical scenario, which implies 200 kJ pulses of 1.56×10^{14} protons at 8 GeV [11]. In the PIU configurations considered (see Sec. 6), the RCS and linac-based upgrades could provide ≈ 0.3—1.6 MW of 8 GeV protons. These may be further upgraded at a later stage toward the proton intensities required by a muon collider. Table 3 compares key parameters to be provided by the PIU scenarios to the needs of a future Muon Collider proton driver (MuC-PD). It's clear that the latter requires higher power beams of shorter bunches.

5.1.1 Linac-PIU scenarios

An 8 GeV linac-based proton driver can be a viable option to support the muon collider R&D and to provide a facility for the multi-MW beams needed for the future collider. However, substantial upgrades would be required to support the MuC facility [12]. It's important to emphasize that this scheme is similar to the Project-X scenario previously envisioned [13]. The scheme consists of a linac feeding an accumulator ring followed by a compressor that merges the accumulated protons into a few short bunches to deliver to the MuC facility. If the Linac-PIU option is selected, then the needed linac will have already been constructed, with an accumulator ring, but a compression ring will have to be added to generate the required beam structure of a few ns-long proton bunches. Subsequent increases in beam current or beam energy can also be considered to improve proton driver beam power.

In Table 4, parameters for three possible MuC-PD scenarios are considered. In the MuC-PD1 scenario, the proton energy is set to the PIU energy of 8 GeV and 20 Hz pulses of 60×10^{12} protons are used to obtain a 1.5 MW source. In the MuC-PD2 scenario, the intensity per pulse is set to the PIU value of 40×10^{12} protons and the proton energy is increased to 12 GeV to obtain a 20 Hz 1.5 MW source. In the MuC-PD3 scenario the proton energy is increased to 16 GeV and the pulse intensity increased to 120×10^{12}, while the pulse rate is reduced to 5-10 Hz to obtain 1.5-3.0 MW. This higher intensity scenario matches MuC-PD driver parameters in Ref. [11] and requires further upgrades from PIU scenarios.

The MuC-PD1 is especially well-suited as an upgrade (or overdesign) of the linac-based PIU scenarios, and is similar to the Project X version. It can incorporate both the 8 GeV linac and accumulator ring (AR). However, it will require considerable upgrades since the linac peak current has to double and the existing AR has to be modified or an additional ring provided in order to serve as a compressor ring (CR). The MuC-PD2 and MuC-PD3 scenarios can use the existing linac, however, additional acceleration must be provided, possibly by upgrading the AR to carry out acceleration as well. For both cases, an additional ring has to be built for bunch compression.

5.1.2 RCS-PIU scenarios

The RCS-PIU scenario can also be a viable option to support both R&D and a facility for the multi-MW beam needed for a Muon Collider.

The RCS designs must consider known intensity limitations. An important constraint in accelerator rings is the space charge tune shift, which in a simplified geometry can be written as:

$$\Delta\nu_{SC} = -\frac{3N_p r_p F}{2\epsilon_{N,95}\beta\gamma^2 B_f}$$

where N_p is the number of protons in the ring, classical radius of the proton $r_p = 1.535 \times 10^{-18}$ m, F is a transverse form factor of 0.5 (for KV, 1 for a Gaussian beam), $\epsilon_{N,95}$ is the 95% normalized beam emittance ($\epsilon_{N,95} = 6\pi\epsilon_{N,rms}$), and B_f is the bunching factor. (This overly simplified formula ignores the dispersion-dependent beam size ($\eta\delta p/p$), $x - y$ asymmetry, and assumes KV shape for the beam.) At injection parameters of $N_p = 1.56 \times 10^{14}$, $E = 2$ GeV (PIU RCS injection energy), $\epsilon_{N,95} = 40\pi$ mm-mrad (MI acceptance), $B_f = 0.4$, we obtain $\Delta\nu_{SC} = -0.38$. This is significantly larger than desirable. However, if the acceptance can be increased, say, to $\sim 80\pi$ mm-mrad, (or the beam energies increased), the RCS would be readily capable of the beam intensity required for a MuC-PD.

It is important to emphasize that in the past an RCS scenario has been considered for a Fermilab based MuC facility [11]. If the RCS option is selected, the following features should be considered: (1) upgradability to 16 GeV beam energy, for instance, upgrading the RCS magnets if necessary or allowing for a second RCS; (2) siting to accommodate the footprint of a proton compressor ring (CR).

More specifically, MuC-PD1 and MuC-PD2 can use the existing infrastructure but the RCS has to be upgraded to deliver higher charge (MuC-PD1) or higher energy (MuC-PD2). A higher charge will typically require larger apertures (100 mm) while a higher energy will require stronger magnets. It is likely that MuC-PD2 can be achieved with a power supply upgrade rather than a magnet replacement. Both scenarios will require the addition of a CR. The third MuC-PD scenario has a more ambitious set of parameters, in which the higher energy will permit pulse compression scenarios with higher intensity. The MuC-PD3 scenario is achievable from upgrades to the existing RCS-PIU scenarios, requiring the addition of one more ring that combines acceleration to 16 GeV and a CR. Another possibility will be extending the linac acceleration to 4 GeV, followed by an accelerator ring to ramp up to 16 GeV, followed by bunch compression. This scenario will require a complete replacement of the PIU RCS, building a new RCS in the existing tunnel with stronger magnets.

Parameter	PIU scenarios	MuC-PD scenarios
Energy	8 GeV	8-16 GeV
Rep. rate	10-20 Hz	5-20 Hz
Avg. beam power	0.3-1.6 MW	1-4 MW
Proton structure	25-40 e12 over 2 μs ring	40-120 e12 in four 1-3 ns bunches

Table 3: Key specifications of the PIU scenarios and parameters needed for a Muon Collider proton driver.

5.1.3 Booster/MI upgrade scenarios without Booster Replacement

Scenarios that limit accelerator upgrades to the existing Booster and MI would not preclude construction of a subsequent Muon Collider facility. But, such scenarios also do not make progress towards the multi-MW

		MuC-PD1	MuC-PD2	MuC-PD3
MuC-PD parameters	Energy	8 GeV	12 GeV	16 GeV
	Pulse intensity	60 e12	40 e12	120 e12
	Rep. rate	20 Hz	20 Hz	5-10 Hz
	Avg. beam power	1.5 MW	1.5 MW	1.5-3.0 MW
Linac-PIU scenarios	Linac rep. rate	20 Hz	20 Hz	10 Hz
(8 GeV Linac + AR)	Linac proton rate	12 e14/s	8 e14/s	6 e14/s
	Acceleration in AR? *	No	Yes	Yes
	New CR ring? *	No	Yes	Yes
RCS-PIU scenarios	RCS upgrade?	Int. Upgrade	Energy Upgrade	Replace RCS
(8 GeV RCS)	RCS norm. emit.**	40 π mm mrad	24 π mm mrad	80 π mm mrad
	New CR ring? *	Yes	Yes	Yes

Table 4: High level parameters for three different Muon Collider proton drivers, either linac- or RCS-based. We note that the Linac-PIU may be especially well suited to MuC-PD1 and MuC-PD3, and the RCS-PIU may be especially well suited to MuC-PD2. *In MuC-PD2 and MuC-PD3 the AR is modified for acceleration and a new CR ring is constructed, whereas in MuC-PD1 the AR is used for proton compression. **The RCS 95% normalized emittance corresponding to $\Delta\nu_{SC}$ = -0.2 and 2 GeV beams is given for comparison, however, injection energy upgrade or improvement in space-charge mitigation performance are possible alternatives.

power needed for a MuC. Therefore, the next major complex upgrade would then be optimized for a Muon Collider proton driver. More details on the MuC R&D are provided in the next section.

5.2 PIU and Muon Collider R&D program

Any of the PIU scenarios outlined above would allow us to perform crucial muon collider R&D. They will also enable partial or full demonstration of technology for proton bunching, muon production, capture, ionization cooling and acceleration. The primary goal of the Muon Collider R&D program is to demonstrate technology for producing bright muon beams and accelerating them to the nominal energy. Muons are created as a tertiary beam, where the baseline production scheme utilizes an intense proton beam hitting a dense target. This produces pions, which are captured in a solenoidal decay channel where they decay to muons. Because of the complexity of the muon production, cooling and acceleration, R&D on the following components is critical to demonstrate feasibility of a Muon Collider facility:

- Proton beam accumulation and compression: A multi-bunch proton beam from proton accelerators needs to be accumulated into a single bunch in the accumulator. The bunch length will then be compressed in the compressor ring. Because a useful proton beam energy for pion production is 5-20 GeV, the proton beam size and density are constrained by space-charge effects. Studies of the maximum achievable density and shortest bunch length are needed [14].

- Pion production target: A MW or higher power proton beam hitting a target deposits a great amount of instantaneous beam power in the target material. There is currently no target design that can survive the power deposition from the MuC-PD proton beam. This R&D item will study new target materials and demonstrate novel target design concepts [15].

- Pion & muon capture: Pions and kaons produced at the target are collected and transported to a decay volume. The muons produced in the volume are moderated and captured in RF buckets in the capture channel. The capture channel is located near the target in order to capture as many pions and muons as possible, and on a timescale compatible with the muon lifetime at rest (2.2 μs). Demonstration of high radiation tolerance and high capture efficiency requires dedicated R&D [16].

- Muon cooling: In order to have high brightness muon beams for collisions (and to fit into the acceptance of a downstream accelerator complex), the muon phase space has to be significantly reduced via the ionization cooling process. Performance of the ionization cooling system is central to the design of the accelerator complex. This R&D item will study cooling system designs with the goal of minimizing the beam emittance while maintaining high transmission efficiency [17–19].

- Muon acceleration: The muon beam needs to be rapidly accelerated in order to minimize muon loss by decay. The space charge effect needs to be studied and overcome, in particular in the initial acceleration stages. The R&D effort will include studies of rapid acceleration schemes and compensation of the space-charge effects [20, 21]. Rapid-cycling magnets with the parameters needed for muon acceleration must be developed.

The extent of the MuC R&D program will depend on the intensity of the available proton beam at the target. If the intensity is between 10^{13} and 10^{14} protons per bunch, MuC technology can be fully demonstrated with the designed beam parameters shown in Tab. 3. Specifically, one can perform detailed muon ionization cooling and acceleration studies with a high intensity beam. This is important as space charge and beam loading effects in the high accelerating gradient RF cavities can potentially degrade the performance, and, therefore, should be carefully evaluated. A high intensity beam would allow for a complete demonstration of the muon ionization cooling performance and transmission efficiency in muon acceleration. If the available proton beam intensity is less than 10^{13} per bunch (e.g. if upgrade of the current booster is chosen) the extent of the R&D program would be limited. Assuming that the energy of the proton beam is in the optimal range for muon production, a muon beam can still be produced and studied. Validation of the key MuC components can be performed, but without fully addressing collective effects. These collective effects can potentially be studied in the proton beam if contributions from hadronic interactions are small. If the proton beam energy is outside of the optimum range for muon production, the proton beam can still be used for hardware R&D, such as target irradiation studies, performance tests of high gradient RF cavities in strong magnetic fields [22,23], and radiation tolerance tests of high field superconducting magnets [24,25] and SRF cavities [26]. Table 5 provides a summary of the R&D extent without and with Booster replacement.

R&D item	**PIP-II era Booster (Low intensity beams)**	**Linac-PIU or RCS-PIU (high intensity beams)**
Beam preparation and bunching	- Validate AR, CR concepts with Booster beam - No space charge tests	- Validate with high intensity proton beam - Study performance with space charge effect
Targetry	- Study performance with sub-MW proton beams.	- Study reliability and stability of components. - Validate/evaluate target material, design.
Muon capture	- Study performance with low intensity muon beams.	Study with intense muon beams: - Space charge effect - Capture efficiency - Component tests in extreme radiation environments.
Muon cooling	- Validate concept - Study performance with low intensity muon beams.	- Study beam phase space and transmission efficiency using intense muon beams.
Muon acceleration	- Study system performance with low intensity muon beams.	- Study space charge and beam loss mechanisms during acceleration with intense muon beams.
Hardware components	- Study system performance with low intensity proton beams.	- Use proton and muon beams to investigate critical devices.

Table 5: Key R&D studies achievable with various proton beam scenarios.

5.3 Synergistic plan for the MuC R&D facility

The MuC R&D facility can be a multiple users facility because it is capable of providing various kinds of beams for new physics projects, some of which were discussed during the Snowmass Community Planning

Exercise. We mention a few examples below.

A high power MuC target test will generate a very large number of pions and kaons. Pions and kaons in an energy range between 4 and 12 GeV could be used for the **nuSTORM** and **ENUBET** facilities. On the other hand, stopped pions on the target can be a source of polarized muons which can be exploited for new rare process and precision experiments. A few hundred MeV pions will be used for the testing of MuC R&D components.

After a muon cooling channel, the muons can be accelerated up to a desired energy and used in the so-called **Neutrino Factory** designed to store a monochromatic muon beam in a storage ring to provide neutrinos from decaying muons. The muon beam after cooling can also be decelerated to below 40 MeV/c. This beam can be used for a lepton flavor violation experiment. The MuC R&D facility itself can be an integral part of the Advanced Muon Facility (**AMF**).

The time structure and bunch intensity of the muon beam must be optimized for each application, however. In general, the neutrino applications are not sensitive to the beam timing where the focus is on high flux and better control/understanding of neutrino beam systematics. The muon beam time structure is important for many muon physics applications, however. Often a short bunch length and high muon bunch intensity lead to a better physics reach.

6 Description of the Six Main Configuration Options

The PUI CDG put together 6 configurations for a booster replacement that can each deliver 2.4 MW to the LBNF beamline. Three of these feature a Rapid Cycling Synchrotron (RCS), labelled C1a,b,c and three feature a superconducting RF Linac, labelled C2a,b,c. The physical layout of the three RCS configurations is shown in Fig. 9 and the physical layout of the three SRF Linac configurations is shown in Fig. 10.

6.1 Common Elements of the Six Main Configuration Options

Besides the requirement of providing 2.4 MW to the LBNF beamline, the six configurations have several features in common. They all start with PIP-II, though some require modest upgrades to the PIP-II linac as detailed in the sections below and in Sec. 7.1. All six configurations require that the protons are fed from PIP-II to a new linac that takes their energy up to 2 GeV (described in Sec. 7.1). Coming out of the 2 GeV linac the protons are accelerated to 8 GeV in ways that are different for each of the six configurations and are described in the sections below. Each of the six configurations injects 8 GeV protons into the Main Injector following stacking in the Recycler. From that point on the six configurations are again identical and require some Main Injector upgrades detailed in Sec. 7.7 and an upgraded LBNF target station as detailed in Sec. 7.8.

6.2 Configuration C1a: 10 Hz Rapid Cycling Synchrotron (RCS) with Metallic Vacuum Chamber

The present Fermilab proton Booster is an early example of a rapid-cycling synchrotron (RCS). Built in the 1960s, it features a design in which the combined-function dipole magnets serve as vacuum chambers. Such a design is quite cost-effective, and it does not have the limitations associated with the eddy currents in a metallic vacuum chamber. However, an important drawback of that design is a high impedance, as seen by a beam, because of the dipole magnet laminations. More recent RCS designs (e.g. J-PARC) employ large and complex ceramic vacuum chambers in order to mitigate the eddy-current effects and to shield the beam from the magnet laminations. Such a design, albeit very successful, is quite costly because it requires large-bore magnets and large-bore rf cavities. As our first configuration (C1a), we will consider an RCS concept with a thin-wall metallic vacuum chamber as a compromise between the chamber-less Fermilab Booster design and the large-bore design with ceramic chambers [27].

The RCS designs also feature several design improvements relative to the current Fermilab Booster. The H^- injection straight section accommodates a higher H^- injection energy, which in turn allows space-charge forces at injection to be significant suppressed. The H^- injection region (like J-PARC and SNS) allows for extraction of H^- or H_0 particles left unstripped by the injection foil into a diagnostic line with a beam dump, rather than increasing ring activation with an inline absorber. The lattice geometry also accommodates primary-secondary collimation systems without placing aperture-restricted bending sections between scatterers and absorbers or restricting the available phase-advance. The lattice optics are carefully designed with a low momentum compaction factor to avoid transition-crossing and with dispersion-free RF regions to avoid synchro-betatron coupling. Like J-PARC, the RCS can use second-harmonic RF to length proton bunches and mitigate space-charge effects.

As a result of metallic vacuum chamber eddy current limits, we consider the RCS ramp rate limited to 10 Hz with a beampipe diameter limited to 44 mm. The space-charge associated with the required beam intensity within that beampipe aperture can be managed with a 2 GeV injection energy. Therefore, as part of C1a we also consider a 2-GeV extension of the PIP-II linac. We assume a pulsed extension of PIP-II linac, but a CW-capable 2-GeV extension of the PIP-II linac can also be considered to deliver additional beam to Spigot 1 or Spigot 2 beamlines.

6.3 Configuration C1b: 20 Hz RCS with Ceramic Vacuum Chamber, Larger Magnets, and Accumulator Ring

In our second and third configurations (C1b and C1c) we consider two configurations similar to C1a. The difference is the RCS uses a ceramic vacuum chamber allowing it to ramp with a faster ramp rate and

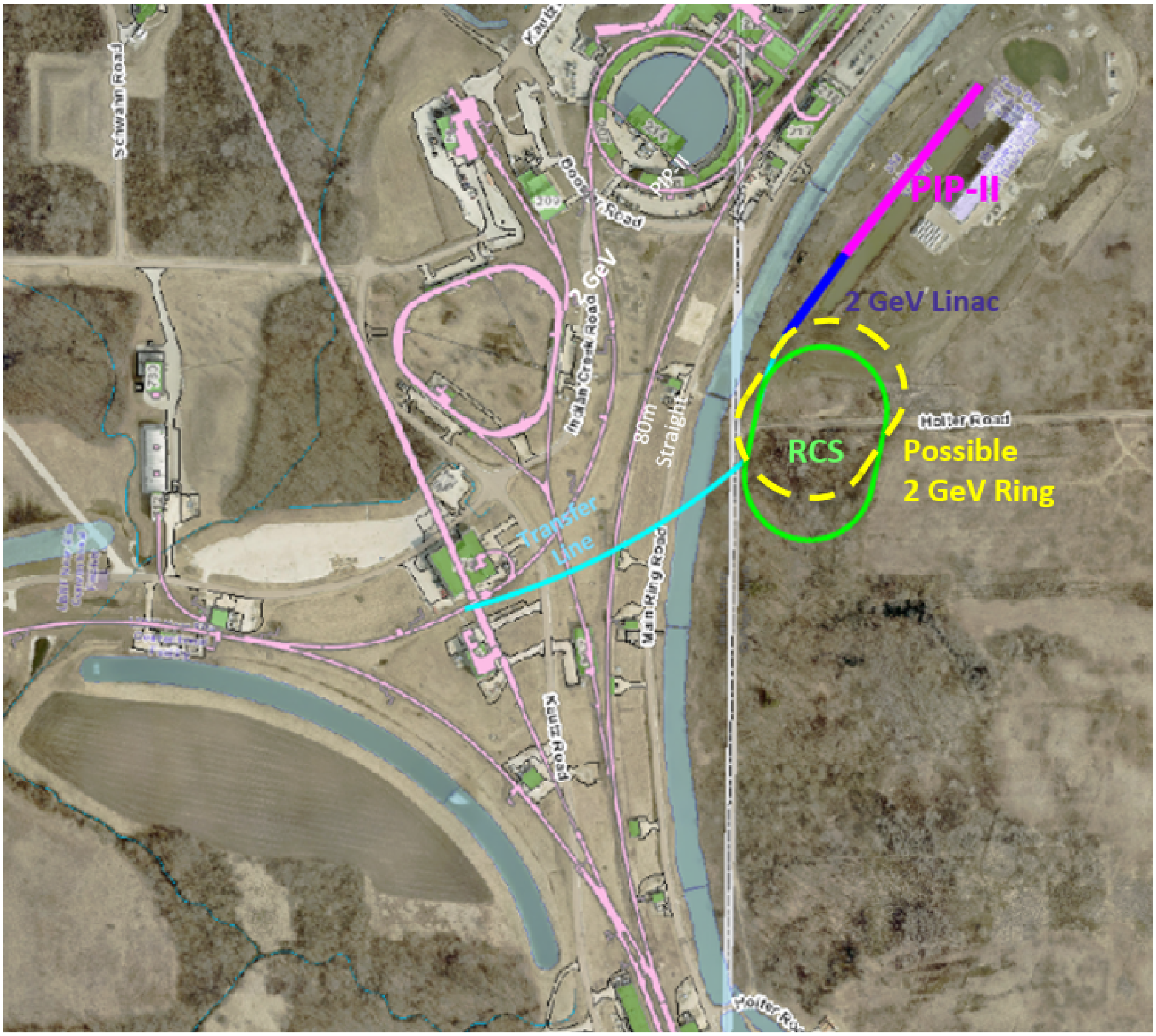


Figure 9: Schematic overview of a possible PIU scenario layout for an RCS accelerator. The PIP-II Linac leads into an extension that accelerates the beam to 2 GeV. A transport line injects that beam into the 8 GeV RCS accelerator. 8 GeV beam from the RCS is transported through a new transfer line into the Booster to MI transport (MI-8) for injection into the Recycler Ring at RR-10. The transfer line is 300 m long and is followed by 220 m of transport using the MI-8 line. The 2 GeV beam could instead be directed into an accumulator ring (shown in yellow) and transferred to the RCS after accumulation. The 2 GeV ring could also provide beam to a 2 GeV experimental program.

feature larger apertures. The ceramic vacuum chambers must be carefully engineered to simultaneously provide a high-frequency conductive path in the longitudinal direction (to control impedances) and a low-frequency resistive path along the transverse direction (to control eddy currents). The J-PARC RCS provides a precedent for such designs and clearly the direct vacuum chamber costs will constitute less than 5% of total RCS costs. However, the vacuum chambers would need to be designed to different specification and likely be manufactured and assembled by different US-based suppliers. To mitigate risk associated with vacuum chamber manufacturing and impedance-limitations to performance, we consider a 100mm diameter aperture for the C1b and C1c configurations (compared to the 44mm diameter aperture for C1a or the 200mm diameter aperture for J-PARC RCS). The elevated costs for the 20 Hz RCS configurations primarily reflect this change in magnet aperture.

In [28], 20 Hz RCS design configurations are considered in detail. However, not all design differences between [28] and [27] are intrinsic to the high-level parameters. Therefore, we consider C1b & C1c with ring circumferences and lattice designs identical to C1a for the purposes of providing a straightforward understanding of the differences in cost.

In present operation and anticipated for the PIU-era operation, the Fermilab Recycler is used to accumulate batches from the Booster (or RCS) while the Main Injector ramps. In this way, the Main Injector cycle time is not extended by the batch accumulation time. However, the 20 Hz RCS accumulation time of 0.2-0.25 s is shorter than the 10 Hz RCS accumulation time of 0.5 s, and consequently the 20 Hz RCS is capable of delivering 2.4 MW beam to DUNE/LBNF without accumulating in the Fermilab Recycler. This means that C1b & C1c scenarios (as well as C2b & C2c scenarios) hedge against any limitations in the performance of the Fermilab Recycler that may be encountered in the PIU era.

No longer limited by eddy currents, versions of the C1b and C1c configurations with ramp rates higher than 20 Hz, energies higher than 8 GeV, or higher beam intensities can also be considered. For this document, we did not perform a cost-estimate for those possible overdesigns, but rather used a set of parameters that would reliably deliver beam to the MI/RR for the 2.4 MW DUNE/LBNF program while also providing a significant increase in beam power available to Spigot 3 beamlines. For Muon Collider Proton Driver scenarios in particular (see Section 5), the capacity of C1b and C1c configurations for overdesign or subsequent upgrade is a critical feature (relative to the C1a configuration).

With a 2 mA injection current and 25×10^{12} (or more) proton intensity, the H- injection times into the rings are at least 2 ms (compared to ∼0.1ms in current operation and ∼0.6ms for PIP-II era Booster) which presents two challenges. The first challenge is that the circulating proton beam scatters off the carbon foil used for H^- injection leading to degradation of foil lifetime and increased activation due to downstream scattering. Calculations of foil temperature are provided in [28]. For the SNS accelerator, this phenomenon is the dominant source of ring activation and a limiting factor for operational beam power. The second challenge, especially for the 20-Hz resonant-circuit RCS, is that the bend field changes by 0.5-4% over the course of the injection time, which must be compensated to avoid a 5-20 mm orbit distortion (and a corresponding loss of aperture).

Configurations C1b & C1c represent two solutions to the challenge posed by the long duration of the H^- injection process, especially for the 20 Hz RCS. In C1b, the beam is injected instead into a fixed-energy (2-GeV) accumulator ring (AR) which completely eliminates the challenge associated with the change in bend field over the injection duration. After accumulation in the 2-GeV AR, the beam can be transferred and promptly begin acceleration. The challenge associated with protons scattering off the H^- injection foil is not eliminated, but the optics of the AR can be better optimized for injection (large betas at foil location, large phase-advance through downstream collimators) allowing up to 2-5 factor reduction in uncontrolled foil-scattering losses. The RCS optics would consequently be freely optimized for other accelerator performance characteristics such as the reduction of machine resonances, elimination of transition-crossing, and accommodation of RF accelerating cavities.

To facilitate cost-comparison, we consider a 2-GeV AR (element E4) with a circumference equivalent to the RCS, similar configuration of magnets, and a 100mm diameter aperture. These parameters also ensures that the physical dimensions of the 2-GeV AR are consistent with RCS performance requirements and will simultaneously allow for a robust 2-GeV experimental program (Spigot S2). We also assume that the 2-GeV AR is housed in a separate tunnel from the RCS, to avoid field distortions in the AR, shared tunneled activation limits, and ambiguous beam-loss monitor data. The possibility of housing the AR in the same tunnel as the RCS (like the Fermilab Recycler and Main Injector) is considered an item for potential cost-reduction R&D.

6.4 Configuration C1c: 20 Hz RCS with Ceramic Vacuum Chamber, High Current Linac, without Accumulator Ring

Another approach to the challenge posted by the long duration of the H^- injection process is to increase the linac current to at least 5 mA. The injection duration is shortened commensurately with the increase in linac current, as is the activation caused by circulating protons scattering off the injection foil. The reduction in foil-particle interactions also keeps the peak foil temperature less than 1900 K, thus enabling reliable foil performance.

To achieve 5 mA linac current at 2 GeV, the PIP-II linac must be modified and (in this document) we consider the scenario in which the linac operates in pulsed rather than CW mode. From source to 2 GeV the linac would deliver 2 ms flattop pulses every 20 Hz. This rules out any of the PIP-II era experimental programs that explicitly require CW running (Spigot S0A), such as mu2e-II or REDTOP run II. Configurations C2b and C2c described below also use a 5 mA linac upgrade. (A hybrid operational linac mode with high current pulsed and low current CW components might mitigate this, see section 7.1.5.)

6.5 Configuration C2a: Superconducting Linac with Slight PIP-II current upgrade and XFEL RF sources

In this configuration, a superconducting RF linac is used to reach 8 GeV—similar to how PIP-II uses an SRF linac to reach 0.8 GeV, and its extension would be used to reach 2 GeV. The path from 2→8 GeV via an SRF linac is based on well-established 1.3 GHz SRF cryomodules in order to draw on extensive experience both at Fermilab and in the broader global accelerator community and take advantage of the substantial cost reduction and industrialization efforts in ILC and XFEL development. This technology was developed by international partners for the ILC [29], went through pioneering operational studies in TTF/FLASH [30], and had its first major implementation in the European XFEL (17.5 GeV via 800 cavities in 100 cryomodules) [31]. The design was recently adjusted for CW operation for SLAC's LCLS-II and LCLS-II-HE (8 GeV from 440 cavities in 55 cryomodules).

A schematic overview of the linac configurations is shown in Fig. 10. The linac configurations are based on the following elements: the PIP-II linac; an extension of PIP-II with additional cryomodules to 2 GeV; an optional 2 GeV accumulator ring to create a spigot for a 2 GeV pulsed experimental program; a 2→8 GeV SRF Linac; an 8 GeV accumulator ring; an injection line to the Recycler/Main Injector; as well as a number of transfer lines in between elements.

The linac options–C2a, C2b, and C2c–are three slightly differing ways of extending the PIP-II SRF linac to higher energies. C2a is the most basic configuration, using cryomodules and RF sources that were developed for previous SRF projects. All configurations provide some proton power at 8 GeV beyond what is needed for the Main Injector/Recycler, which could be used for an 8 GeV physics program. C2b and C2c provide substantially higher 8 GeV proton power than C2a, but they call for a higher beam current of 5 mA from PIP-II and—for C2c—more challenging higher duty factor RF sources for the 2→8 GeV linac.

More details of the different elements of the linac configurations, including the pulsed 2→8 GeV linac and the accumulator ring, are presented in Section 7.6.

6.6 Configuration C2b: Superconducting Linac with Significant PIP-II current upgrade and some RF R&D

C2b is identical to C2a, except it assumes an upgrade of the beam current from PIP-II to 5 mA (from 2.7 mA) to allow for more power to an 8 GeV physics program. More details are presented in Section 7.6.

6.7 Configuration C2c: Superconducting Linac with Significant PIP current upgrade and significant RF R&D

C2c is identical to C2b but with higher duty factor RF sources for the 2→8 GeV linac to allow for more power to an 8 GeV physics program. More details are presented in Section 7.6.

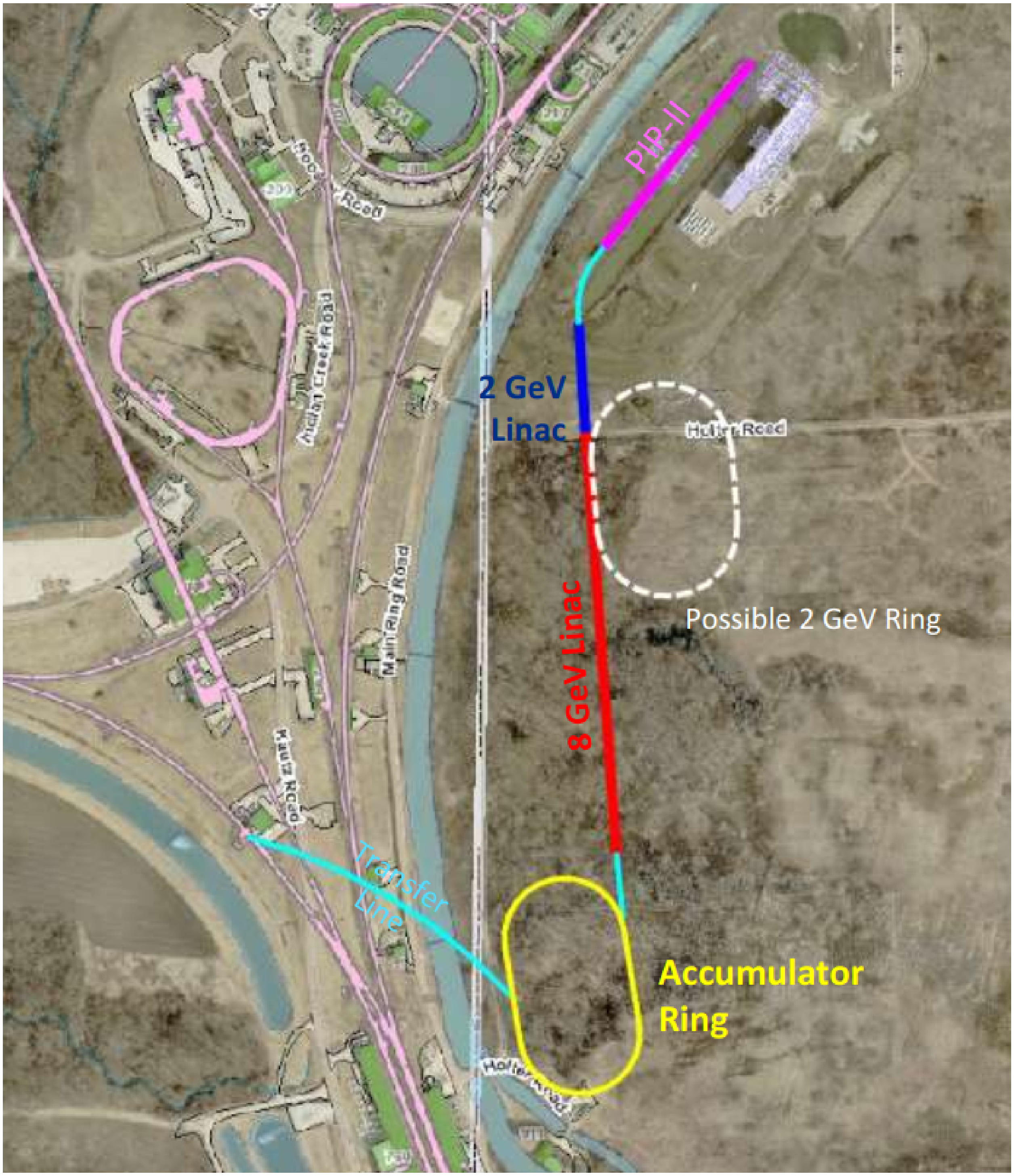


Figure 10: Schematic overview of a possible layout for an 8 GeV Linac PIU scenario. Following the PIP-II linac, a transport directs the beam into a 2 GeV linac extension (100 m) which is followed by an 350m Linac that accelerates the beam to 8 GeV. This is followed by a short transport that injects the 8 GeV beam into an Accumulator Ring. A transfer line (320 m long) would transport the accumulated 8 GeV protons into the Recycler Ring at RR-62, or the Main Injector at MI-62. A 2 GeV storage Ring could be added to accumulate beam from the 2 GeV linac for use in low-energy intensity frontier experiments.

6.8 R&D for the Configurations

There are a number of critical R&D issues that affect the performance, cost and/or schedule risks associated with each proposed configuration. These R&D items are a mix of work needed to determine if the concept is feasible and work needed to reduce project risk. They are listed below.

- Metallic vs ceramic vacuum chamber: what is the highest sustainable magnet ramp rate with a metallic vacuum chamber (and no forced cooling)? (C1a)
- Is it possible to place a new RCS and an Accumulator in the same tunnel? (C1a,b,c)
- How is the ceramic vacuum chamber fabricated and what is the cost? (C1b,c)
- Is the XFEL RF system suitable? (C2a)
- Is RF system development needed for beyond XFEL capabilities? (C2b,c)
- Are High Efficiency RF Amplifiers needed capable of CW operations? (C2a,b,c)
- Is stripping injection feasible at 8 GeV? (C2a,b,c)
- What are the Horn and Target upgrades for $>$ 2 MW operation? (C1a,b,c C2a,b,c)

7 The Elements of the Six Configurations, including the Cost and Risks of Each

The 6 configurations described in Sec. 6 are presently characterized by different degrees of development and knowledge on viable technical solutions. The associations of Cost and Risks to each solution is driven by SME (Subject Matter Expert) inputs about the maturity of each solution, supported, in some case (e.g. PIP-II 2 GeV extension) by the extensive availability of DOE 413.3b Project documentation and in other cases (e.g. 20 Hz RCS with Ceramic Vacuum Chambers) by parametric extrapolations from similar - but not identical - projects in the US or around the world.

When viewed through the lens of a DOE 413.3b Project, the six main configurations discussed here are obviously at a pre-CD0 (Approve Mission Need) stage. As such, typical elements informing a Cost Estimate typical of a “projectized” approach (such as Extensive Technical Specifications, Interfaces, Preliminary or Final Design Reviews, etc.) are clearly missing at this time. Nevertheless, similarities with other accelerator construction https://www.overleaf.com/project/62a68ff25fb2aa7a3c6c0fa5projects in the DOE complex (SNS, EIC, LCLS-II, PIP-II) or around the world (XFEL, J-PARC) allow reasonable extrapolations to determine cost ranges for the configurations discussed here.

The estimating group of the PIU CDG adopted the following approach to come up with Cost Range determinations for the elements of the 6 configurations:

- Determine a Work Breakdown Structure (WBS) for each element to L2 (or, when feasible, to L3 and lower) to ensure full scope identification. These WBSs were compared, for completeness, to existing Projects’ WBSs.
- Obtain from SMEs a point cost estimate for each element of the WBS, based on adoption of known and documented costs (e.g. PIP-II 2 GeV extension), extrapolations from similar activities (e.g. 8 GeV Linac cost from LCLS-II/XFEL) or parametric extrapolations from similar projects (e.g. RCS cost from EIC/JPARC.)
- Avoid individual estimates of Project Office/Management Cost or Contingency allocation.
- Obtain from SMEs an assessment of maturity of the estimate for each WBS element (CLASS concept, see below) following the DOE G 413.3-21 Cost Estimating Guide.

As stated in the DOE order G 413.3 -21, widely accepted cost estimate classifications are found in the Association for Advancement of Cost Engineering International (AACEI), Recommended Practice (RP) No. 17R-97 and RP No. 18R-97”. In addition, ”Five suggested cost estimate classifications are listed in Figure 11 along with their primary characteristics and Figure 12 lists the secondary characteristic and the estimate uncertainty range, as a function of the estimate CLASS.”

For the cost range estimates of the 6 configurations described in this paper, all estimated elements were treated as ”pre-CD0”, with CLASS estimates ranging from CLASS 5 to CLASS 3 and the expected accuracy shown in Table 6. An interesting observation is that all Civil Construction and Conventional Facilities estimates were assigned CLASS 5 (most uncertain) and several beam-line elements such as SRF Cryomodules were assigned Class 3 (least uncertain).

	Low	High
CLASS 5	-50%	+100%
CLASS 4	-30%	+50%
CLASS 3	-20%	+30%
CLASS 2	-15%	+20%
CLASS 1	-10%	+10%

Table 6: Accuracy used for Cost Ranges in the Estimate Exercise

Cost Estimate Classification	Primary Characteristics	
	Level of Definition (% of Complete Definition)	Cost Estimating Description (Techniques)
Class 5, Concept Screening	0% to 2%	Stochastic, most parametric, judgment (parametric, specific analogy, expert opinion, trend analysis)
Class 4, Study or Feasibility	1% to 15%	Various, more parametric (parametric, specific analogy, expert opinion, trend analysis)
Class 3, Preliminary, Budget Authorization	10% to 40%	Various, including combinations (detailed, unit-cost, or activity-based; parametric; specific analogy; expert opinion; trend analysis)
Class 2, Control or Bid/Tender	30% to 70%	Various, more definitive (detailed, unit-cost, or activity-based; expert opinion; learning curve)
Class 1, Check Estimate or Bid/Tender	50% to 100%	Deterministic, most definitive (detailed, unit-cost, or activity-based; expert opinion; learning curve)

Figure 11: Definition of the 5 classes of cost estimate.

	Primary Characteristic	*Secondary Characteristic*		
ESTIMATE CLASS	**DEGREE OF PROJECT DEFINITION** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 70%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	70% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

Notes: [a] The state of process technology and availability of applicable reference cost data affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.

Figure 12: Characteristics of the 5 classes of cost estimate.

7.1 Elements E1a, E1b, and E1c: 2 GeV PIP-II Extensions and PIP-II Modifications

Both the RCS and 8 GeV linac upgrade options require increasing the beam energy at injection to approximately 2 GeV. The RCS option will benefit from the reduced space charge at the increased energy, while the high energy linac option will need the beam with an approximate energy of 2 GeV to take advantage of higher frequency, $\beta = 1$, high-gradient cavities that can be grouped and fed from a single, high-power klystron.

7.1.1 Lattice of the 2 GeV extension

The simplest solution for the 2 GeV upgrade is to extend the PIP-II HB650 section. The nominal HB650 lattice cell that includes two room-temperature quadrupoles per cryomodule was used for the extension lattice. The design of the 2 GeV extension was developed under the assumption that the BTL stays in place. Note that the HB650 cavity is suitable for both pulsed and CW operations. The maximum energy gain per cavity, 19.81 MeV, in the extension cavities was left unchanged. This assumption can be overly conservative for pulsed operations.

Figure 13 shows a solution that consists of nine new HB650 cryomodules installed in the tunnel extension, two upgraded HB650 cryomodules installed upstream of the BTL that increase the beam energy from 800 MeV to 1 GeV, and one buncher cryomodule, which includes two HB650 cavities. The buncher rematches the longitudinal beam phase space from the PIP-II linac to the extension. This lattice accelerates the beam to an energy of 2.07 GeV. The beam is accelerated with a minimal impact on the transverse and longitudinal beam emittances. The linac tunnel extension is approximately 90 meters long. Table 7 shows the main lattice parameters. Figures 14 and 15 show the evolution of the beam emittances and energy along the extension.

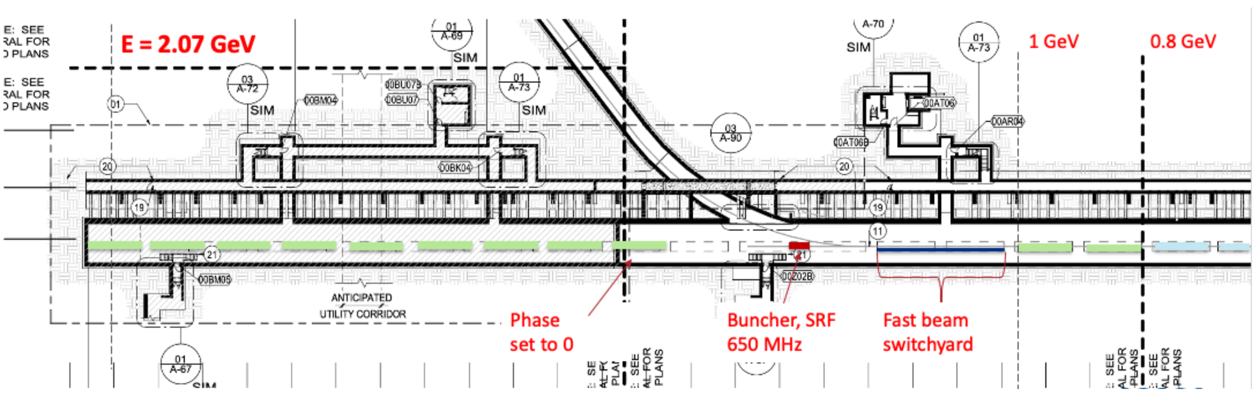


Figure 13: Layout of the 2 GeV extension with beam running from right to left. Cryomodules included in the upgrade are shown in light green, while the PIP-II baseline cryomodules are light blue.

Parameter	Value	Unit
Initial beam energy	0.8	GeV
Final beam energy	2.07	GeV
Normalized beam emittance, r.m.s./99%, X,Y	0.27 / 2.8	mm mrad
Normalized beam emittance, r.m.s./99%, Z	0.34/ 3.6	mm mrad
HB650 cryomodules before BTL	2	
HB650 cryomodules after BTL	9	
HB650 2-cavity buncher	1	
Quadrupoles	22	

Table 7: Main parameters of the 2 GeV linac extension

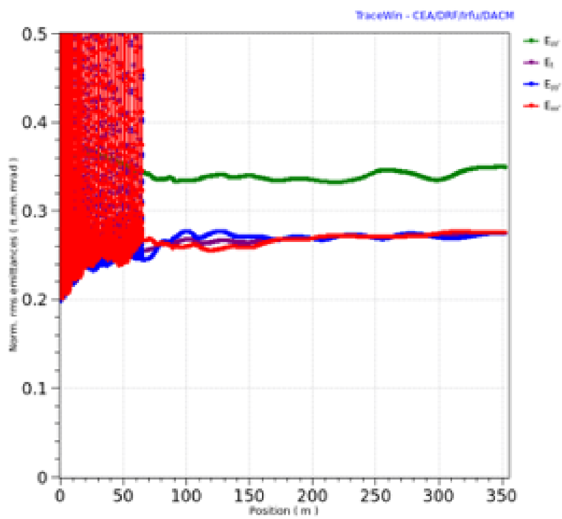


Figure 14: Evolution of the beam emittances along the linac with 2 GeV extension.

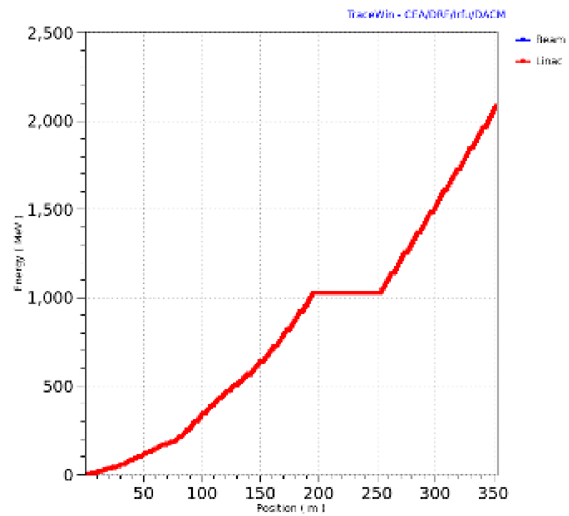


Figure 15: Evolution of the beam energy along the PIP-II linac and 2 GeV extension.
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Other solutions that can accelerate the beam to a higher energy were developed. For example, HB650 cryomodules can be installed starting directly after the BTL line, bringing the number of cryomodules downstream of BTL to eleven. The first two cavities of the first cryomodule after BTL will be used as a buncher while other cavities of the first three cryomodules after BTL will be zero-phased. This solution accelerates the beam to 2.3 GeV within the same footprint. However, the longitudinal beam emittance, affected by the on-crest acceleration, increases by roughly 30%-40%. It is not clear if this longitudinal emittance growth is acceptable. Therefore, the more conservative solution with the buncher will be used.

7.1.2 Operational regimes of the 2 GeV extension linac

The beam current in the extension is determined by the PIP-II linac. Presently, the maximum beam current in the PIP-II linac is specified at 2 mA. The beam current can be increased to ∼5 mA if the RF amplifiers are upgraded to a higher power. Increasing the beam intensity in PIP-II beyond 5 mA will require modifications to the front end, adjustment of cavity coupling, further upgrade of the amplifiers to a higher power, and, therefore, is not considered in this write-up. Modifications required to run PIP-II with an intensity of 2.5 mA, 2.7 mA, and 5 mA are described below.

In this document we consider three operational options for the extension: 2 mA CW, 2 mA pulsed, and 5 mA pulsed. We do not consider the 5 mA CW option for the extension due to its high cost and the expected low demand for this beam. Neither do we differentiate between different combinations of pulse length and rep. rate due to their similar principal requirements. Note that the difference in cost between the 2 mA and 5 mA pulsed options is small. Therefore, we do not consider pulsed options with intermediate intensities, e.g., 2.5 mA or 2.7 mA, and assume their complexity and cost will be similar.

Table 8 shows parameters of the extension linac for different operational modes and includes PIP-II parameters for comparison. This study assumes that the two new cryomodules upstream of BTL with all their supporting systems will be procured as part of the 2 GeV extension upgrade. However, the cryomodules will be connected to the PIP-II cryo system. The amplifiers for these two cryomodules will be connected to the PIP-II cooling and electrical distribution systems.

7.1.3 Cost estimate for the 2 GeV extension

Table 9 shows the cost estimate for the options listed in Table 8. The estimate was obtained by either scaling the corresponding PIP-II budgets or as an independent estimate for scope that is not part of PIP-II, e.g., the cryoplant, cryomodules, and RF amplifiers. The number of cavities and cryomodules, the average combined

Parameter	PIP-II	2 mA, CW	2 mA, Pulsed	5 mA, Pulsed	Unit
Accelerator energy	0 - 0.8	0.8 - 2.0	0.8 - 2.0	0.8 - 2.0	GeV
Pulse beam current	2	2	2	5	mA
Beam pulse rate	20	CW	10 - 20	10 - 20	Hz
Beam pulse length	0.55	CW	1 - 2	1 - 2	ms
RF pulse rate	CW	CW	10 - 20	10 - 20	Hz
RF pulse length	CW	CW	4 - 5	3 - 4	ms
Number of CMs	23	11+1b	11 + 1b	11+1b	
Number of cavities	119	68	68	68	
CM cryogenic load @2K	1835	1460	200 - 300	200 - 300	W
Max. amplifier RF power	70	70	70	140	kW
Average RF power	3370	3360	160-400	250 - 650	kW

Table 8: 2 GeV Linac extension options and their main parameters.

RF power, the maximum power rating of amplifiers, the cryogenic heat load, and the length of the beam pipe were used as scaling factors for corresponding systems. In estimating the cost, it was assumed that all the scope will be procured by DOE. The L2 WBS structure was adapted from PIP-II with a single change: the cryogenic system was separated into a WBS L2 element. The cost estimate includes WBS L2 and L3 management of corresponding activities.

The cost estimate assumes that the extension project includes all elements required to build and operate the 2 GeV extension. This might not be an optimal solution if the 8 GeV linac is chosen for the power upgrade. The overall design of the facility will have to be optimized globally. For example, there can be one centralized cryoplant facility, serving both the 2 GeV extension and the high energy linac.

7.1.4 Schedule

Figure 16 shows a tentative high-level schedule for the 2 GeV extension. The schedule assumes that the upgrade will reuse PIP-II designs for accelerator systems and cryomodules, significantly reducing the design effort. Also, the schedule assumes that CD-2 and CD-3 will be obtained at the same time, taking advantage of the successful completion of PIP-II and reduced technical risks. It will take the project approximately six years after the start of construction to reach CD-4. The critical path for the schedule goes through the procurement of the cryoplant and CF cryoplant building. Therefore, construction of the cryoplant and the cryoplant building should start as early as possible.

Connection of the 2 GeV extension to the PIP-II linac will have to be orchestrated carefully to minimize impact on the operational schedule. The PIP-II tunnel includes a stub to simplify the connection. A temporary, 20-ft-thick wall will be installed in the stub to shield personnel working in the extension tunnel. Equipment upstream of the wall, including two new HB650 CMs and the bunchers, will be installed and connected during shutdowns. The temporary shielding wall will be installed at the location where the lattice has the beam pipe and room temperature elements, reducing the installation effort once the temporary wall is removed. Additional analysis is required to develop the installation sequence and schedule to estimate the required shutdown time. It feels, however, that the interruption to connect the extension can be shorter than six months and will fit into the schedule without increasing the project duration.

7.1.5 Compatibility of PIP-II linac with upgrades and required modifications

High duty factor/CW multi-user operations of PIP-II

The PIP-II linac is designed to be CW-compatible:

- The PIP-II Front End (except for the fast MEBT chopper), HP RF, SRF, cryogenics, shielding, safety systems, utilities, and infrastructure are designed to operate in the CW regime and are compatible with multi-user CW operations without modifications.
- Initially, the PIP-II linac will accelerate pulsed beam with a pulse length of 550 μs. Several systems require a design review or upgrade to enable safe acceleration of a high duty factor or CW beam for

WBS Element	**Description**	**2 mA CW**	**2 mA Pulsed**	**5 mA Pulsed**	**CLASS Estimate**
X	**Project**	**412,635**	**326,450**	**346,997**	
X.01	Project Management	35,000	27,000	27,000	
X.01.01	Project Management	35,000	27,000	27,000	
X.02	SRF	82,700	82,700	82,700	CLASS 3
X.02.01	SRF Project Management	3,500	3,500	3,500	
X.02.02	SRF HB650 Cryomodules	79,200	79,200	79,200	
X.03	Cryogenic Systems	68,015	54,152	54,300	CLASS 4
X.03.01	CS Management	3,500	3,500	3,500	
X.03.02	CS Cryoplant	53,500	39,637	39,784	
X.03.03	CS Cryogenic Distribution System	11,015	11,015	11,015	
X.04	Accelerator Systems	93,261	55,181	75,581	CLASS 4
X.04.01	AS Management	3,000	3,000	3,000	
X.04.02	AS MPS	2,000	2,000	2,000	
X.04.03	AS HPRF and RF Distribution	71,694	33,614	54,014	
X.04.04	AS LLRF	2,991	2,991	2,991	
X.04.05	AS Magnets/PS	2,540	2,540	2,540	
X.04.06	AS Vacuum	1,500	1,500	1,500	
X.04.07	AS Controls	5,136	5,136	5,136	
X.04.08	AS Safety Systems	1,000	1,000	1,000	
X.04.09	AS Instrumentation	3,400	3,400	3,400	
X.05	Installation and Commissioning	48,963	40,477	40,477	CLASS 4
X.05.01	I&C Management	3,100	3,100	3,100	
X.05.02	I&C Building Infrastructure	20,979	12,494	12,494	
X.05.03	I&C Linac Installation	2,540	2,540	2,540	
X.05.04	I&C Beam Commissioning	3,150	3,150	3,150	
X.05.05	I&C Accelerator Physics	2,025	2,025	2,025	
X.06	Conventional Facilities	84,696	66,940	66,940	CLASS 5
X.06.01	CF Project Management	5,964	5,964	5,964	
X.06.02	CF Cryoplant Building	22,000	22,000	22,000	
X.06.03	CF Utility Plant	9,200	4,750	4,750	
X.06.04	CF Linac and Gallery Extension	47,532	34,226	34,226	

Table 9: Cost estimate for the 2 GeV Linac extension for three operational scenarios listed in Table 8.

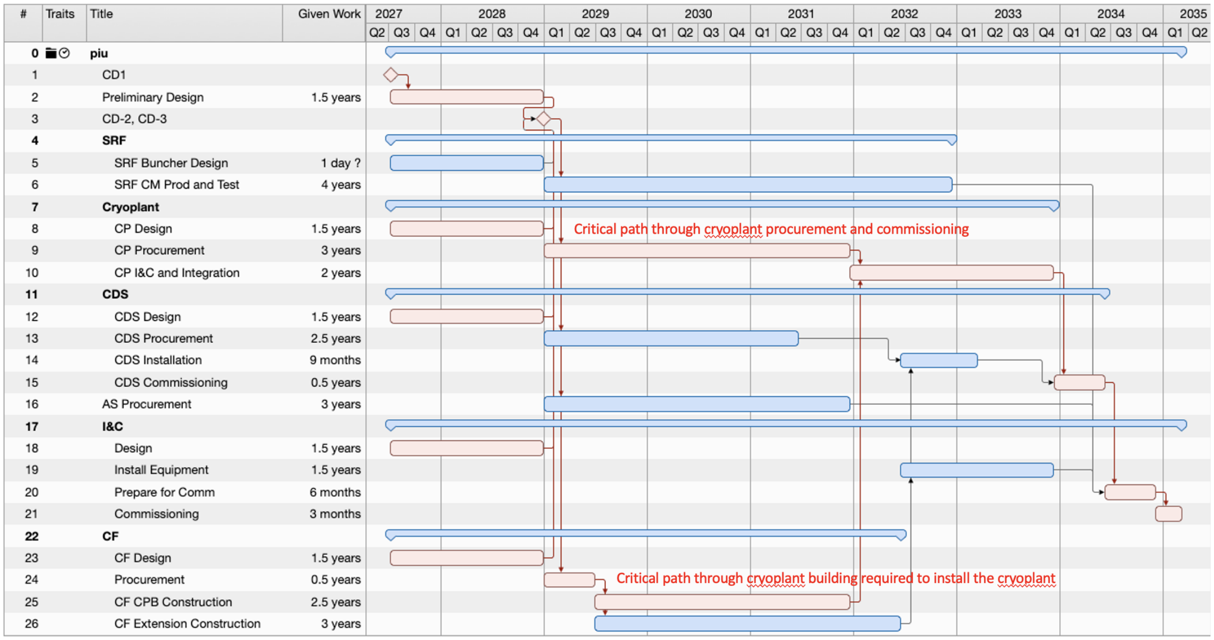

Figure 16: Schedule of the 2 GeV extension.

multi-user operations:

- Impacts on timing, beam intensity instrumentation, and MPS systems need to be understood.
- A new, high duty factor fast MEBT chopper is required.
- RF separators and beam switchyards are required to distribute the beam to multiple users.

The cost of these modifications needs to be fully understood but is expected to be less than 10% of the total cost of the 2 GeV extension.

With these modifications, the PIP-II linac will be able to support pulsed and CW multi-user operations with a beam current up to 2 mA. In this regime, short beam pulses can be provided to the LBNF and 8 GeV programs, while the rest of the beam can be provided to low-energy programs at 1 GeV.

Important considerations for operations with a beam current higher than 2 mA

The beam physics design of PIP-II is compatible with a beam current of 5 mA. To deliver a 5 mA beam to users, the ion source and RFQ have to produce and accelerate approximately 10 mA of beam current. Approximately 40% of the beam is chopped in the MEBT to produce bunch patterns suitable for the injection into the Booster or RCS. 10 mA is about the maximum that the front end, including the MEBT chopper, are designed for. Increasing the beam current beyond 5 mA will require a review and, possibly, redesign of the front end and the chopping scheme that will require significant effort and time.

A moderate increase in the beam intensity above 2 mA can be achieved without an upgrade of the amplifiers by utilizing design margins. Power specifications for the amplifiers were derived under a conservative assumption of losses in the transmission line, cavity detuning, amplifier controllability margin, and cavity coupling errors occurring simultaneously. With these margins added up, the ratio of the RF power at a cavity coupler to the amplifier power specification, $R_{c/a}$, should not exceed 0.75. Because the probability of needing these margins simultaneously is small, the overall margin can be reduced. In this study, we assumed that

- amplifiers do not require an upgrade if the ratio $R_{c/a}$ does not exceed 0.8.
- amplifiers might not need an upgrade if the ratio $R_{c/a}$ is in the range between 0.8 and 0.85 and there are only a few of these cavities. The situation can be mitigated by reducing the cavity voltage at a cost of a small reduction in the final beam energy.

- amplifiers will need an upgrade if $R_{c/a}$ exceeds 0.85.

As shown below, PIP-II RF amplifiers will have to be upgraded if the beam current exceeds 2.5 mA. LB650 amplifiers will have to be upgraded first with other types following suite as the beam current increases. The increased power rating of the amplifiers will increase the load on the electrical and cooling systems. To avoid costly and time-consuming modifications of the PIP-II electrical and cooling infrastructure, several upgrade options exist: 1) use new higher-efficiency amplifiers, 2) pulse the RF and/or beam, and 3) provide beam with a different peak intensity to different users to reduce average power consumption. In this study, we assume that HWR, SSR1, SSR2, and LB650 cavities always operate in the CW RF regime even if the beam is pulsed. The Lorentz force detuning in SSR1, SSR2, and LB650 cavities presently is deemed too large, making pulsing RF in those cavities difficult. Although this issue can be resolved later, in this study, we assume that RF can be pulsed only in HB650 cavities.

Cavity power couplers have to be compatible with the increased RF power. Upgrading couplers will require removal of cryomodules from the tunnel and can be prohibitively labor-intensive and expensive. PIP-II cavity power couplers were tested up to the forward power required to accelerate the 2 mA beam. To ensure safe operations, the couplers were tested at this power with full reflection, providing roughly a factor of two margin in the field and average power. Below we compare the peak field and power at the couplers to the test values used to qualify the couplers.

Three feeders, A, B, and C, provide 18 MVA of electrical power to PIP-II amplifiers. Each feeder is rated at 6 MVA. Feeders A and B feed the HB650 amplifiers together, while feeder C provides power to all other amplifiers. It is assumed that the combined rating of the feeders has to be higher than the peak electrical load even though the average power can be lower. Additional analysis of the load waveform will be required to understand whether this requirement can be relaxed. Note that the load can be redistributed between the feeders at a cost which is presently unknown but likely negligible in comparison to the overall cost of the upgrade.

PIP-II provides 8240 GPM of processed chilled water to cool amplifiers. Below we calculate the amount of water required for different scenarios assuming 23 GMP per each 20 kW of the amplifier rating (before combining).

Operations with a beam current of 2.5-2.7 mA

The maximum beam intensity that the PIP-II linac will be able to accelerate without needing an upgrade of the amplifiers is approximately 2.5 mA. Eleven LB650 amplifiers will have the ratio $R_{c/a}$ between 0.8 and 0.83. The ratio $R_{c/a}$ is below 0.8 for all other amplifiers. Thus, we can assume that the PIP-II linac can be operated with 2.5 mA without upgrading amplifiers.

Increasing the beam intensity to 2.7 mA will require an upgrade of ten LB650 amplifiers. The cost of this upgrade is estimated roughly at $15M, with the labor constituting roughly a quarter of the cost but having a high uncertainty. Seven more LB650 amplifiers with the ratio $R_{c/a}$ between 0.8 and 0.85 are candidates for the upgrade as well. The ratio $R_{c/a}$ does not exceed 0.77 for all other amplifiers.

Calculations show that the RF field and power losses in cavity couplers do not exceed test values for both beam intensities.

The electrical power required to accelerate the 2.5 mA beam is 5.5 MW and 5.0 MW for feeders A/B combined and C respectively. For the beam current of 2.7 mA, the electrical load becomes 5.6 MW and 5.2 MW. The required water flow is 5960 GPM and 6200 GPM for the 2.5 mA and 2.7 mA cases respectively, smaller than the capacity of the PIP-II cooling system.

Operations with a beam current of 5 mA

We consider both pulsed and CW options for the 5 mA operation of the PIP-II linac. However, as mentioned above, we assume that the 2 GeV extension is expected to operate only in a pulsed regime with a 5 mA beam.

Acceleration of a 5 mA beam requires upgrading nearly all of the PIP-II amplifiers. A small portion of the PIP-II amplifiers can be relocated downstream. The following distribution of amplifiers is assumed:

- HWR: at least four new 162.5 MHz, 15 kW, CW amplifiers will be required to power the last four HWR cavities.
- SSR1: Sixteen existing SSR2 20 kW, CW amplifiers can be reused to power all of the SSR1.

- SSR2: Five existing SSR2 20 kW, CW amplifiers can be reused to power the first five SSR2 cavities. Thirty new 325 MHz, 40 kW, CW amplifiers will be required to power the rest of the SSR2 cavities.
- LB650: Sixteen existing 650 MHz, 70 kW amplifiers can be reused to power LB650 cavities. Twenty new 650 MHz, 100 kW amplifiers will be required to power the rest of the LB650 cavities.
- HB650: Modifications to HB650 amplifiers will depend on the operational mode.
  - For pulsed PIP-II operations, it is prudent to choose the same amplifiers that will be used for the 2 GeV extension. Thus, twenty-four new 650 MHz, 140 kW pulsed amplifiers will be required.
  - For CW beam PIP-II operations, twenty-four new 650 MHz, 120 kW, CW amplifiers can be used to accelerate the beam to 800 MeV. Alternatively, thirteen 100 kW and eleven 120 kW, 650 MHZ, CW amplifiers can be used to accelerate the beam. The cost and power consumption of these options will be similar.
  - Amplifiers for the two new HB650 cryomodules installed upstream of the BTL will support the operational mode, pulsed or CW, selected for the PIP-II linac.

Calculations show that the RF field in the couplers of SSR2 cavities can exceed the maximum field that the couplers were tested to by roughly 7%. In the CW regime, average RF losses in couplers of some SSR2 and LB650 cavities can exceed losses observed during the coupler test by up to 20%. The increased field and power dissipation increase the risk of a coupler failure. The increased RF losses in couplers will not be an issue for a pulsed regime or a regime when the 5 mA beam is sent in short pulses and a lower beam current, e.g., 2 mA, is accelerated through the rest of a cycle.

The peak electrical power required to accelerate the 5 mA beam is 10.0 MW and 9.8 MW for feeders A/B and C respectively.The average power will reduce to 0.4 MW and 7.5 MW when the machine is operated in the pulsed regime with short 5mA pulses. An additional feeder with other required electrical gear will have to be added to the facility at a cost of several million dollars for either option.

The required water flow for the pulsed regime is approximately 6000 GPM. This requirement is met by the PIP-II design without modifications. For the 5 mA CW operations, the flow requirement is approximately 10700 GPM, significantly exceeding the available cooling capacity. The cooling requirements can be significantly reduced if more efficient amplifiers are used for the upgrade. For example, increasing the efficiency of amplifiers from 44% to 51% will reduce the required flow of chilled water from 10700 GPM to the available 8240 GPM. Additionally, amplifiers capable of maintaining high efficiency dynamically over a broad range of the output RF power can be used to accelerate short 5 mA pulses for LBNF interleaved with a 2 mA high duty factor beam for low energy programs.

The cost of the upgrade, including labor, required to operate PIP-II with a 5 mA beam in the pulsed regime is estimated at $60M. The upgrade to enable 5 mA CW operations will cost $85M, assuming availability of high efficiency amplifiers.

Simultaneous acceleration of H- and proton beams

A modest modification of the front end to add a proton source will allow PIP-II to simultaneously accelerate H- and proton beams. This can provide additional capabilities and enhance operational flexibility of the machine by eliminating the need for a new fast MEBT chopper in some operational regimes and simplifying separation of H- and proton beams.

Summary of modifications required to operate PIP-II in a multi-user mode and with a higher current.

Here we summarize the discussion of the compatibility of the PIP-II linac with the upgrades and required modifications:

- A design review or upgrade of several PIP-II systems mentioned above will be required to enable safe acceleration of a high duty factor beam for multi-user operations. Also, RF separators and beam switch yards will be required to supply beam to multiple users.
- PIP-II will be able to accelerate the beam with an intensity of 2.5 mA in the CW regime without modifications.

- PIP-II will be able to accelerate the beam with an intensity of 2.7 mA in the CW regime after an upgrade of ten LB650 amplifiers. The estimated cost of this upgrade is $15M.
- Pulsed operations with a beam current of 5 mA will require an upgrade of most of the PIP-II amplifiers. An additional feeder to deal with the peak power load will have to be added. The cost of these modifications is approximately $60M.
- CW operations with a 5 mA beam current will significantly increase the average electrical load and heat generated by the amplifiers. Presently, neither the PIP-II cooling system nor the electrical system have sufficient capacity to support 5 mA CW operations, assuming the efficiency of amplifiers is kept at 44%. These issues can be addressed by using amplifiers with improved efficiency for the upgrade. The efficiency has to be increased from 44% to 51% to match the capacity of corresponding PIP-II systems. As a compromise, PIP-II can be operated with short 5 mA pulses interleaved with a near-CW 2 mA beam for low energy programs. To take advantage of this operational regime, amplifiers capable of maintaining high efficiency dynamically over a broad range of the output RF power will be required. Assuming these issues are resolved, the cost of this upgrade is estimated at approximately $85M.

Taking the 2 GeV extension costs and class info from Table 9 and combining it with the costs of PIP-II modifications outlined above results in Table 10 where the cost ranges for the three 2 GeV extensions and associated PIP-II modifications is presented.

	2 mA CW	**2 mA Pulsed**	**5 mA Pulsed**
Cost point estimate [$M]	413	326	407
Cost range [$M]	280-645	223-507	280-627

Table 10: Cost point estimate and range for the 2 GeV Linac extension with PIP-II modifications for the three operational scenarios listed in Table 8.

7.2 Element E2: 10Hz RCS

The RCS is based on the design in [27]. The ring is designed as a racetrack (two long straight sections and two 180° arcs). One straight section is for the normal conducting RF cavities and the other is use for injection, extraction and collimation. Normal conducting RF cavities are chosen over SRF cavities as a sweep of the RF frequency is required. A FODO lattice is used in which the F and D quads have the same strength and are connected serially with the dipoles. For 10 Hz operation, a metallic vacuum chamber is sufficient and allows a smaller aperture. The parameters are shown in Table 11.

The cost estimate for the 10Hz RCS was obtained from a parametric comparison with the BNL Electron Ion Collider (EIC) estimates at CD-1 level provided to PIU-CDG by the EIC Management Team. In the parametric estimate the EIC estimates were re-scaled by the number of magnets in the respective FODO cells, the difference in accelerator total length and a rescaling of infrastructure such as vacuum pipes and power supplies. The (NC)RF system estimate was based on FNAL Booster cavities and tuners. In addition we obtained a bottom-up estimate for conventional facilities using the PIP-II tunnel sizing parameters and including wet-land mitigation. In estimating the cost, it was assumed that all the scope will be procured by DOE. In-Kind contributions will provide an opportunity to reduce cost. The WBS structure was adapted from the EIC WBS. The cost estimate includes WBS L2 and L3 management of corresponding activities but not the overall Project Office cost.

Table 12 shows the breakdown of component classes and point cost estimates. Taking the 10Hz RCS cost and class info from Table 12 enables the cost range to be calculated in Table 13.

7.3 Element E3: 20Hz RCS

The 20 Hz RCS design is very similar to that of the 10 Hz design. In order to achieve the higher cycle rate of 20 Hz, the vacuum chamber must be replaced with a ceramic chamber. A minimum aperture of 100 mm is required such that the eddy-current effects are not detrimental.

Parameter	
Number of RF cavities	16
Number of 2nd harmomic RF cavities	10
Beam pipe material	metallic
Power supplies for magnets	667
Aperture (diameter)	44
Max field strength (dipole)	0.87375
Magnet inductance [mH]	25
Injection Energy [GeV]	2
Extraction Energy [GeV]	8
Injection length (uninterrupted length)	17
RF voltage [MV]	1.6
Rf frequency [MHz]	50.33-52.81
Circumference [m]	553.2
Dipole length [m]	2.13216
Number of dipoles	100
Number of quads	132

Table 11: The broad parameters for a 10 Hz RCS option.

Table 12: Cost estimate for the 10 Hz RCS

WBS Element	**Description**	**Cost**	**CLASS Estimate**
Y	Project	306M	
Y.02	RCS Magnets	75M	CLASS 4
Y.03	RCS Power (Magnets)	60M	CLASS 4
Y.04	RCS Power (RF)	30M	CLASS 4
Y.05	RCS Power (Vacuum)	5M	CLASS 4
Y.06	RCS Vacuum	5M	CLASS 4
Y.07	RCS Instrumentation and Controls	10M	CLASS 4
Y.08	(NC)RF	30M	CLASS 5
Y.09	Conventional Facilities	78M	CLASS 5
Y.10	Beam Extraction	13M	CLASS 4

	10Hz RCS
Cost point estimate [$M]	306
Cost range [$M]	193 - 513

Table 13: Cost point estimate and range for the 10Hz RCS.

The cost estimate for the 20Hz RCS extension was obtained from a parametric comparison with the BNL Electron Ion Collider (EIC) and the following considerations related to the specifics of the 20 Hz RCS:

- Magnet Aperture due to Ceramic Beam Pipe. A beam pipe of 100mm diameter was assumed to be sufficient to minimize eddy-current heating effects. The cost of the magnet materials (assumed to be 50% of the magnets total cost) was scaled quadratically by the ratio of (100mm/44mm).
- Magnets Power Supplies were scaled according to the cost of the magnets to accommodate the faster ramping rates.
- The Ceramic Beam Pipe cost was extrapolated from the JPARC cost.

Table 14: Cost estimate for the 20 Hz RCS

WBS Element	**Description**	**Cost**	**CLASS Estimate**
Y	Project	513M	
Y.02	RCS Magnets	179M	CLASS 5
Y.03	RCS Power (Magnets)	143M	CLASS 4
Y.03	RCS Power (RF)	30M	CLASS 4
Y.03	RCS Power (Vacuum)	5M	CLASS 4
Y.04	RCS Vacuum	25M	CLASS 5
Y.05	RCS Instrumentation and Controls	10M	CLASS 4
Y.06	(NC)RF	30M	CLASS 5
Y.07	Conventional Facilities	78M	CLASS 5
Y.08	Beam Extraction	13M	CLASS 4

Table 14 shows the breakdown of component classes and point cost estimates. Taking the 20Hz RCS cost and class info from Table 14 enables the cost range to be calculated in Table 15.

	20Hz RCS
Cost point estimate [$M]	513
Cost range [$M]	297 - 926

Table 15: Cost point estimate and range for the 20Hz RCS.

7.4 Element E4: 2 GeV Accumulator Ring

The cost estimate for the 2 GeV Accumulator Ring was obtained from a parametric comparison with the BNL Electron Ion Collider (EIC), presented in Section 7.2, and a comparison to the cost of the Spallation Neutron Source Accumulator ring, escalated to present day. In addition, the following considerations related to the specifics of the 2 GeV Accumulator were included:

- As for the case of a 20 Hz RCS, a ceramic beam pipe of 100mm diameter was assumed to be sufficient to minimize eddy-current heating effects. The cost of the magnet materials (assumed to be 50% of the magnets total cost) was scaled quadratically by the ratio of (100mm/44mm).
- The cost of RF elements (Cavities and Power Supplies) was reduced by a factor of 1/4 to accommodate only the needs for beam handling, but not beam acceleration.
- The cost of Magnets was scaled from the 20 Hz RCS according to the ratio of momenta.
- Magnets Power Supplies cost was scaled according to the cost of the magnets between the 10Hz RCS and the 2 GeV AR .

WBS Element	Description	Cost	CLASS Estimate
Y	Project	289M	
Y.02	RCS Magnets	90M	CLASS 5
Y.03	RCS Power (Magnets)	72M	CLASS 4
Y.03	RCS Power (RF)	8M	CLASS 4
Y.03	RCS Power (Vacuum)	5M	CLASS 4
Y.04	RCS Vacuum	5M	CLASS 5
Y.05	RCS Instrumentation and Controls	10M	CLASS 4
Y.06	(NC)RF	8M	CLASS 5
Y.07	Conventional Facilities	78M	CLASS 5
Y.08	Beam Extraction	13M	CLASS 4

Table 16: Cost estimate for the 2 GeV AR

- All other cost estimates were kept identical to the 10 Hz RCS estimate.

Table 16 shows the breakdown of component classes and point cost estimates. Taking the 2 GeV AR cost and class info from Table 16 enables the cost range to be calculated in Table 17.

	2GeV AR
Cost point estimate [$M]	289
Cost range [$M]	166 - 524

Table 17: Cost point estimate and range for the 2GeV Accumulator Ring.

7.5 Element E5: 8 GeV Accumulator Ring

The cost estimate for the 8 GeV Accumulator Ring was obtained from the 10Hz RCS estimate presented in Section 7.2 and the following considerations related to the specifics of the 8 GeV Accumulator:

- The cost of RF elements (Cavities and Power Supplies) was reduced to 1/4 to accommodate only the needs for beam handling, but not beam accelerations
- All other cost estimates were kept identical to the 10 Hz RCS estimate.

WBS Element	Description	Cost	CLASS Estimate
Y	Project	262M	
Y.02	RCS Magnets	75M	CLASS 5
Y.03	RCS Power (Magnets)	60M	CLASS 4
Y.03	RCS Power (RF)	8M	CLASS 4
Y.03	RCS Power (Vacuum)	5M	CLASS 4
Y.04	RCS Vacuum	5M	CLASS 5
Y.05	RCS Instrumentation and Controls	10M	CLASS 4
Y.06	(NC)RF	8M	CLASS 5
Y.07	Conventional Facilities	78M	CLASS 5
Y.08	Beam Extraction	13M	CLASS 4

Table 18: Cost estimate for the 8 GeV AR

Table 18 shows the breakdown of component classes and point cost estimates. Taking the 8 GeV AR cost and class info from Table 18 enables the cost range to be calculated in Table 19.

	8GeV AR
Cost point estimate [$M]	262
Cost range [$M]	150 - 476

Table 19: Cost point estimate and range for the 8GeV Accumulator Ring.

7.6 Elements E6a, E6b, and E6c: 8 GeV SRF Linac Options

7.6.1 Overview of 2→8 GeV Cryomodule Design

Following the LCLS-II design, each cryomodule will have 8 cavities and a quadrupole magnet. Incorporating some of the features of the LCLS-II design such as larger chimneys on the cavities will also allow support for relatively high 2K RF heat load (this will be important for high duty factor operation, as in E6b described below). In terms of experience at Fermilab in the LCLS-II type cryomodule, Fermilab was the lead lab for cryomodule design and produced roughly half of the cryomodules for LCLS-II and is now producing roughly half of the cryomodules for LCLS-II-HE (Fermilab also developed the nitrogen-doping treatment used in LCLS-II cavities [32]). As part of ILC development, Fermilab also assembled and operated a 31.5 MV/m average gradient cryomodule (very similar to the specifications seen in this document), in collaboration with international partners including DESY and INFN [33]. As a result of LCLS-II, ILC, and other projects using this type of cryomodule, relevant state-of-the-art production and testing facilities exist already, both at Fermilab and at other labs. In addition, thanks to these previous projects, the linac option can take advantage of existing vendors for crucial parts such as cavities, couplers, and RF sources. Key components have been industrialized, including existing technical drawings and procurement specifications.

7.6.2 Additional Technical Considerations

The sections below describe the parameters chosen for the linac option fairly briefly, omitting important additional technical considerations that were evaluated as part of the development of the plans described here. Please see Ref. [12] for discussions on a number of important subjects, including foil heating during injection from the linac to a ring, beam losses at injection, laser assisted injection, SRF cavity performance, and stripping of H^- prior to injection in the ring due to magnetic fields, electric fields, intrabeam scattering, and blackbody radiation. Some of the specific parameters for the linac option have been modified since Ref [12] was written — updated parameters appear in this document.

7.6.3 Number of 1.3 GHz Cryomodules

The number of LCLS-II type cryomodules needed to achieve 6 GeV of energy gain depends on the accelerating gradient, the transit time factor (which describes how well matched the cavity design is to the $\beta = v/c$ of the particles), and the synchronous phase. For the baseline design, a gradient of 31.5 MV/m was chosen. The gradient was chosen to be fairly high to reduce the length of the tunnel and number of cryomodules needed, and within a range that has been demonstrated before (including at Fermilab). A simple estimate of the number of cryomodules needed would be 6000 MeV / (8 cavities/module × 31.5 MeV/m × 1.038 m/cavity) = 22.9 modules. However, taking into account that the transit time factor for 1.3 GHz cavities with $\beta = 1$ starts at ~ 0.9 at 2 GeV (though it quickly improves, as seen in Fig. 17) and that the optics call for the cavities to operate with a synchronous phase of $-10°$ (see Fig. 18), 25 cryomodules gives a maximum energy gain of 5978 MeV, and 26 cryomodules gives a maximum energy gain of 6225 MeV. To provide risk mitigation for scenarios including reduced performance in some cavities and challenges with RF/resonance control at high gradients, it was decided to include 27 cryomodules in the linac. The extra cavities are assumed to be installed in the linac and ready to operate if needed, but not typically powered for baseline operations (or else powered but at a lower gradient).

The choices of cryomodule type and number of cryomodules are summarized in Table 20. The couplers, Q_0, RF sources, and cryogenic choices are based on previous pulsed machine designs including E-XFEL and ILC.

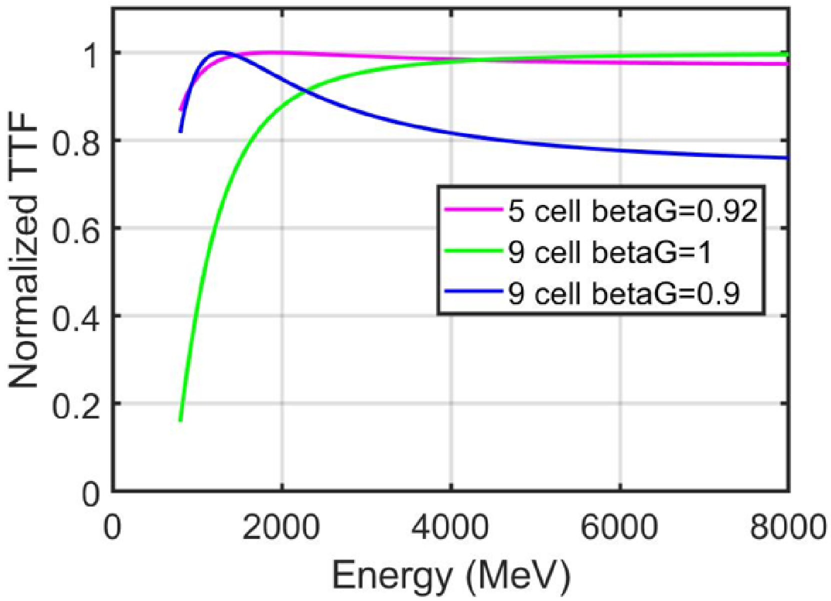

Figure 17: Transit time factors for a $\beta = 0.92$ 650 MHz 5-cell cavity (as in PIP-II and the 2 GeV extension), a $\beta = 1$ 1.3 GHz 9-cell cavity (as in E-XFEL and LCLS-II), and a potential $\beta = 0.9$ 1.3 GHz 9-cell cavity.

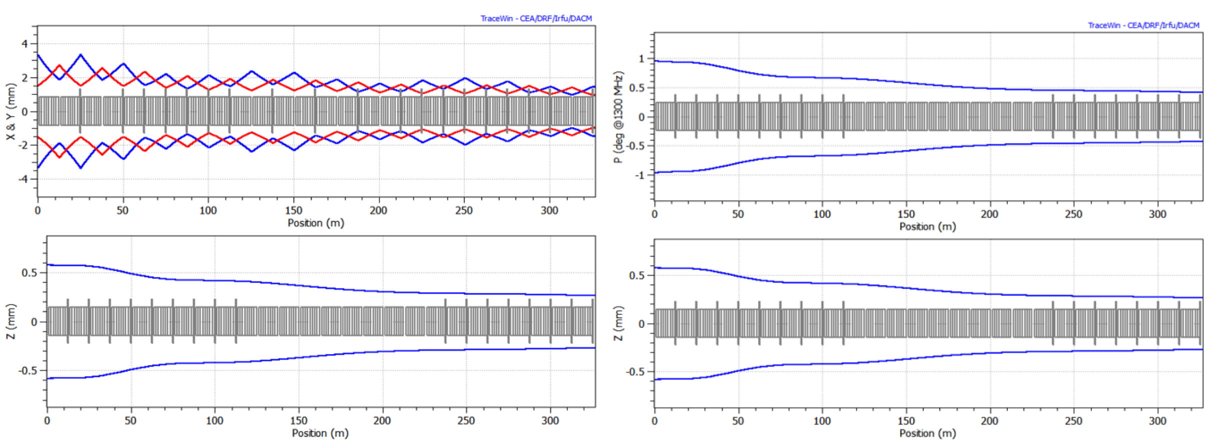

Figure 18: Optics for the 2→8 GeV linac based on a 31.5 MV/m accelerating gradient.

Parameter	Value
Cryomodule Type	LCLS-II-HE
Cavity Type	TESLA 1.3 GHz 9-cell
Coupler Type	TTF-III
Cavities per CM	8
Total number of CMs	27
Operating gradient (MV/m)	31.5 [SRF R&D goal: 34]
Q_0	1×10^{10} [SRF R&D goal: 2×10^{10}]
RF Source Type	Pulsed klystron / modulator
RF distribution	Waveguide with phase shifters
Cryoplant Type	2 K with cold compressors
Cryogenic distribution type	E-XFEL-like (connected CMs)

Table 20: Summary of basic parameters for 2→8 GeV linac cryomodules

7.6.4 Three Options for the 2→8 GeV Linac

There are different ways to reach 2.4 MW of protons on target for LBNF/DUNE with the linac. We consider 3 options in this document: one basic option and two options that deliver significantly more power of 8 GeV protons, either by increasing the current from PIP-II and/or by increasing the RF duty factor. The three options are summarized below:

- E6a - Basic option: slight PIP-II current upgrade, uses E-XFEL RF sources
- E6b - High current PIP-II option: significant PIP-II current upgrade, requires some RF R&D
- E6c - Highest power option: significant PIP-II current upgrade, requires significant RF R&D

Option E6a meets the requirements for LBNF/DUNE without any major R&D developments for the RF sources, just using what has been demonstrated with XFEL sources. For Options E6b and E6c, PIP-II should be upgraded to allow for higher current operation, requiring upgrades to its RF sources. For Option E6c, significant upgrades are needed for the RF sources to allow for higher duty factor operation (longer pulses, higher repetition rate).

For option E6a, a beam current of 2.7 mA is specified during the pulses. As discussed in the previous sections, this may require replacing the RF sources for the LB650 cryomodules in PIP-II to allow them to reach higher peak power.

The three options will have impacts on the extra beam power available for the physics program out of the 8 GeV "spigot" (this is in addition to the 8 GeV beam power for the Recycler/Main Injector for LBNF/DUNE). Option E6a provides a relatively small amount of extra power for the 8 GeV program, $\sim$ 160 kW. Options E6b and E6c provide significantly more (more details below). With option E6c, which combines higher duty factor RF and higher beam current, MW-scale beam power is provided at 8 GeV which could serve for example a muon collider.

Table 21 presents some important parameters for the RF system in the three scenarios E6a, E6b, and E6c. All parameters were based on a Q_0 of 1×10^{10}, except for the bottom line, which shows how the 2K heat load would change for a Q_0 of 2×10^{10}. If SRF R&D successfully increases Q_0 to 2×10^{10}, some other parameters would change as well (for example the optimal loaded Q), but they are not shown in the table. Some key assumptions that were made for the RF sources for all three options: 1) power overhead of 25%, 2) maximum average power per RF source is < 150 kW, 3) input power is the same for filling and acceleration.

Option E6a is based on the capabilities of the European XFEL multi-beam klystron RF system. Options E6b and E6c include a pulse width of 3.0 msec, which is beyond the capability of XFEL RF system: these options require RF source R&D. Option E6c parameters are roughly based on the higher average power, lower pulsed power SBK CPI VKL7796, but further R&D could be done to increase parameters further. To accommodate the higher average RF power, some modifications should be done for the input coupler. Designs and tested prototypes already exist for a high power 1.3 GHz coupler [34, 35].

Option	E6a	E6b	E6c
Beam current, mA	**2.7**	**5.0**	**5.0**
Flat-top pulse length, msec	**1.5**	**2.0**	**2.0**
Rep. rate, Hz	**10**	**10**	**20**
Opt. loaded Q, $\times 10^6$	4.5	4.5	4.5
Filling time, msec	0.6	1.0	1.0
Pulse width, msec	2.1	3.0	3.0
Duty factor, %	2.1	6.0	6.0
Input pulsed power/cavity, filling, kW	330	170	170
Input pulsed power/cavity, acceleration, kW	110	170	170
Input average power/cavity, kW	3.6	5	10
RF source pulsed power/CM, MW	3.3	1.7	1.7
RF source average power/CM, kW	37	50	100
No. of CMs/RF source (150 kW limit)	3	3	2
RF source pulsed power, MW	10	5	3.4
RF source average power, kW	110	150	200
Cryo-load for baseline Q_0 of 1×10^{10}, W	617	754	1360
Cryo-load for SRF R&D Q_0 of 2×10^{10}, W	390	456	762

Table 21: Summary of RF parameters for the linac

For option E6b and E6c, PIP-II CMs would operate with CW RF up through the LB650s. The HB650s (from both PIP-II and the 2 GeV extension) would be operated pulsed with 5 mA beam current and 20 Hz rep rate, with half of the beam current going to the 8 GeV linac (operated at 10 Hz), and half going to a 2 GeV program (10 Hz to this program).

Table 22 presents some important parameters for the beams from the 8 GeV linac in the three scenarios. All three get to 2.4 MW for LBNF/DUNE. For Option E6b and E6c, there are also configurations that successfully reach 2.4 MW for LBNF/DUNE without use of the Recycler to accumulate batches. For Option 1, the Recycler is needed to achieve 2.4 MW of beam power to LBNF/DUNE.

Option	E6a	E6b	E6c
Beam current, mA	**2.7**	**5**	**5**
Flat-top pulse length, msec	**1.5**	**2**	**2**
Rep. rate, Hz	**10**	**10**	**20**
Max Pulse Charge, 10^{-6} C	4.05	10	10
Number of batches	6	6	6
Batches / pulse	1	2	1
Charge / batch, 10^{-6} C	4	4	4
Required pulse at current, ms	1.49	1.62	0.8
Required proton / batch, $\times 10^{12}$	25	25	25
Required MI intensity, $\times 10^{12}$	150	150	150
Accumulation time, s	0.5	0.2	0.25
MI cycle time, s	1.2	1.2	1.2
MI power, kW	2400	2400	2400
Available Cycles for 8 GeV	50.0%	75.0%	75.0%
Available Power at 8 GeV, kW	162	570	1200
Potential MI power, kW	2400	2800	3200

Table 22: Summary of parameters for the beams from the 8 GeV linac.

In Options E6b and E6c, the 2.0 ms linac pulse delivers more than what is necessary to fill the MI over 6 batches. Accordingly, the minimum pulse length needed to fill at that current is given. But for the 8 GeV program, we assume the full 2.0 ms pulse is delivered and that the AR can handle that charge. Options E6a, E6b, E6c have a significant variation in 8 GeV beam power, owing first to the difference in linac current and next to the difference in the linac pulse rate. The potential MI power is the beam power at 120 GeV, if we limit the Main Injector to 200 e12 protons but set aside power limits on DUNE/LBNF beamline.

The beam power associated with option E6c begins to overlap with beam power requirements of the Muon Collider proton driver (see section 5). To support these scenarios, higher linac beam current and/or duty factor could be increased even further.

7.6.5 Cost Estimates for the 2→8 GeV Linac

Table 23 shows the point cost estimate for the 2→8 GeV Linac. The cost estimate is obtained by scaling corresponding E-XFEL actual costs and LCLS-II-HE and PIP-II budgets. The main scaling factors are the number of 1.3 GHz cryomodules, RF power/ sources needed by cryomodule and the cryogenic heat load. A rough comparison with the LCLS-II actual costs is done as a sanity check. The point estimates seem to be reasonable for this stage of the cost estimate exercise.

There are cost saving opportunities; mainly value engineering for conventional facilities should be considered in the future. A few examples are:

- Use of a single cryoplant and common conventional facilities for PIP-II 2 GeV CW and Linac 8 GeV pulsed Linacs
- The klystron gallery can be eliminated with a few modifications to the tunnel that add additional service areas (like the E-XFEL)
- The high bay area can be eliminated, by planning to use the PIP-II high bay to move CMs into the 8 GeV Linac

WBS Element	**Description**	**E6a Cost Estimate**	**E6b Cost Estimate**	**E6c Cost Estimate**	**CLASS Element**
Y	Project	457M	457M	473M	
Y.02	SRF	108M	108	108	CLASS 3
Y.03	Cryo System	33M	33M	33M	CLASS 4
Y.03	Accelerator Systems	61M	61M	77M	CLASS 4
Y.03	Linac Inst./Comm.	50M	50M	50M	CLASS 4
Y.04	Conventional Facilities	205M	205M	205M	CLASS 5

Table 23: Cost estimate for the 2-8 GeV Linacs

One may notice that some of the WBS elements in the cost estimate for the 2→8 GeV Linac are smaller than those for the CW 0.8→2 GeV Linac. A key factor in this is that the 2→8 GeV Linac is designed to run only in pulsed mode, not CW. As a result, the RF source cost per cavity can be much smaller, as a single high power source can have its power distributed across multiple cryomodules instead of having an individual source per cavity. The cryogenic dissipation can also be much smaller than it would be if the cavities were run in CW mode, made smaller by the off-time in the duty cycle. The linac can also be shorter than it would be if it were run CW, as the cavities can be run at higher gradients without overwhelming the cryogenic systems with excess load (the dissipation scales with the square of the accelerating gradient — the smaller duty cycle helps to counteract this increase in the cryogenic load).

Option	**E6a**	**E6b**	**E6c**
RF, MW	1.8	2.5	5.0
Cryogenics, MW	0.6	0.75	1.4
Total, MW	**2.4**	**3.2**	**6.3**

Table 24: Power Requirements for the 8 GeV linac.

Taking the Linac costs and class info from Table 23 enables the cost ranges to be calculated in Table 19.

	E6a	E6b	E6c
Cost point estimate [$M]	457	457	473
Cost range [$M]	290-766	290-766	301-790

Table 25: Cost point estimate and range for the 2-8 GeV Linac for the three scenarios listed in Table 23.

7.7 Element E7: Main Injector and Recycler Upgrades

The Recycler and Main Injector must also be able to take an increase in beam intensity and each machine will require some upgrades. During the commissioning of the Recycler as a proton stacker, an instability caused by the electron cloud was observed. The instability could be mitigated by changing to a longer bunch length, however, it is expected to return in the future. Simulations suggest the limit for the Recycler is a bunch intensity of 1×10^{11} which would equate to a beam power of 1.4 MW. The potential for electron cloud instability depends on the material of the vacuum chamber or more specifically, its Secondary Electron Yield (SEY). The Recycler beam pipe is made from 316L stainless steel which has a max SEY of around 2 and reduces to around 1.2 after being exposed to a significant amount of beam. To reduce the SEY further, the beam pipe could be coated with a lower SEY material such that the SEY is below 1. It should be noted that while the cost of re-coating or replacing all of the RR beam pipe is not substantial compared with other upgrades, a significant amount of time is required to carry out the work on the order of a year.

The current RF system for the Main Injector would need to be replaced. Following the PIP-II upgrades, each RF cavity will have two power amplifiers (PA) which would allow up to 120×10^{12} protons per pulse to be accelerated. Assuming the MI is ramping at 1.2s, this would be an equivalent beam power of 1.8 MW. Above this, the RF cavities would need a larger PA. This would be difficult to retrofit and so a new RF cavity design would also be needed.

WBS Element	Description	Cost	CLASS Estimate
Y	Project	40M	
Y.02	RR beam pipe recoating	10M	CLASS 4
Y.03	MI RF upgrade	30M	CLASS 4

Table 26: Cost estimate for MI/RR upgrades

Table 26 shows the breakdown of component classes and point cost estimates. Taking the cost and class info from Table 26 enables the cost range to be calculated in Table 27.

	MI RR Upgrades
Cost point estimate [$M]	40
Cost range [$M]	28 - 60

Table 27: Cost point estimate and range for the upgrades needed to the Main Injector and Recycler.

7.8 Element E8: LBNF Target Station Upgrades

The LBNF beam was designed with the intention that it eventually operate at 2.4 MW. Many portions of the facility are already capable of 2.4 MW, and some are designed to be upgraded from the initial 1.2 MW facility. Already capable of 2.4 MW are those that are very expensive to replace, those that expect to last for the life of the facility, and cases where the 2.4 MW capability was most convenient to implement at the start. Areas to be upgraded are those where the cost, complexity, or schedule of the 2.4 MW component would be significantly greater than the 1.2 MW component, and the component is either consumable or the upgrade is fairly modular in nature and can be implemented without significant downtime.

This section describes the LBNF beam facility's various components and their readiness for 2.4 MW. Concepts and designs, as they exist, are described for various components. Major components which require significant additional preparation that must start well before realization are target materials R&D, target design, and horn design. The major outstanding risks are the target materials and a conceptual design for a Horn A, which must surround the target. If the beam-induced heating and stress are too great to allow that geometry, then a re-optimization of target-horns lattice must be performed. Significant geometry changes to the beamline would requires extensive re-engineering and reconfiguration.

The LBNF project has been planning under the assumption that 2.4 MW proton beam is achieved through increasing the proton beam intensity from 7.5×10^{13} protons per pulse, to 1.5×10^{14} protons per pulse. This assumption was based on the variety of upgrade scenarios proposed which each increased the pulse intensity. However, the Main Injector cycle time reduction proposes a very minimal proton intensity increase, with a dramatic reduction in the time between pulses (also nominally achieving 2.4 MW). There are some implications of the upgrade that would be different in this scenario. These differences are noted throughout this section and summarized. Another consideration is that a reduction of the Main Injector cycle time may potentially deliver 2.4 MW beam earlier than anticipated, reducing the opportunity to incorporate lessons learned from 1.2 MW operation, and marginally increasing risk.

7.8.1 LBNF Beam Components and Status for 2.4 MW

LBNF Primary Beamline The LBNF Primary Beamline consists of all the technical devices, utilities, and conventional facilities from the Main Injector extraction to the entrance of the target station, including service buildings. All components were designed to be compatible with the nominal 2.4 MW parameters, including technical components (magnets, vacuum, instrumentation), power supplies, instrumentation, utilities, and conventional facilities. The instrumentation may need some minor upgrade based on the particular parameters of the equipment and the beam.

The reduction of the Main Injector cycle time significantly increases the pulse rate of the primary beamline. While it was designed to operate at as short a cycle time of 0.7 s, that was specifically for 60 GeV operation. The beamline would be required to deliver 120 GeV protons at that cadence. Compared to 1.2s cycle at for 120 GeV beam, the faster operation would approximately double the voltage required for the power supplies and greatly increase the peak power. The rms power and thus the heat to be removed from the bus and magnets would increase by about 25%. The main magnets are of the same type as the Main Injector, and should be able to operate at 120 GeV at that cadence, but a power supply upgrade would be necessary, which would require more surface conventional facilities, feedthroughs, cabling, and utilities. Design studies must be performed to understand the scope of the upgrade that will be required.

LBNF Target Complex The LBNF Target Complex consists of all the technical devices, utilities, and conventional facilities of the target hall from the entrance of the proton beam to the end of the target shield pile, and the support and storage buildings surrounding the target hall. All conventional facilities and many utilities were designed to be compatible with 2.4 MW operation, including additional water cooling of the target shield pile. Several of the beamline devices and their utilities will require augmentation.

The LBNF target was specifically designed to be limited to near 1.2 MW in order to optimize physics performance, and needs to be redesigned for 2.4 MW. The target undergoes the greatest concentrations of radiation damage and thermal shock; mitigations to these effects can affect physics performance, leading to a specific power limit. This limit depends both on beam power and per-pulse intensity. Furthermore, the target is known to be a consumable with a conservative lifetime of one year. The 2.4 MW target must deal with both greater energy deposition from higher beam power and thermomechanical shock from higher pulse intensity. A crucial next step for the target is to initiate materials R&D to specifically qualify materials for the next target through an irradiation campaign (and for the materials of the entrance and exit windows).

This materials R&D qualification presently has a time-cycle of roughly five years, and needs to be complete during the target design process. The target and windows themselves must then be designed for the specific beam conditions to optimize the physics performance of the LBNF beam. Notably, the 1.2 MW target itself has been an in-kind contribution (design and fabrication) from UKRI-STFC, who are also interested in the R&D for the 2.4 MW target. An accelerated approach to the target, as demanded by the Main Injector cycle time reduction, would reduce the anticipated gains from operational experience and validation prior to the

2.4 MW upgrade. Additional stress cycles are not expected to be an issue for fatigue. The target protection baffle may require redesign in either its dimensions, or adding water cooling.

LBNF has a suite of three horns (Horn A, Horn B, and Horn C). Horn A entirely surrounds the target, Horn B lies closely downstream, and Horn C is ten meters further downstream. The horns are subject to heating and stresses from both the 300 kA pulsed currents and the beam energy deposition. The electromagnetic heating and stresses at 2.4 MW will be no more than 1.2 MW, as the currents are the same and the horns were designed to operate with a cycle time as short as 0.7 s. The beam energy deposition will be roughly twice as large, and potentially greater with a different target geometry. Horn C is unlikely to be affected. Horn B is an item of study, and can likely be accommodated by modest improvement of cooling or reductions in heating. Horn A is the greatest item of concern because of its proximity to the target. Horn A may require substantial modification to survive the higher beam power. Furthermore, it is not yet proven that a Horn A can entirely surround the target and operate at 300 kA. If that situation proves intractable, a different geometry of targets and horns may be required, which would require greater modification of the target-horn system. Changes like that could greatly increase the downtime of an upgrade and the cost involved. The striplines are also areas of significant stress, but fortunately do not see much beam heating. A reduction in the Main Injector cycle time would involve lesser beam stresses from the individual pulses, but greater average heating from the horn electrical pulses. The horn power supply is designed for a cycle time as short as 0.7 s, so it would only require minor upgrades in its charging supply if the cycle is further shortened.

Beam windows for exiting the primary beamline and entering the nitrogen volume of the target hall must be reconsidered for 2.4 MW. The primary beam window is expected to be tolerant of 2.4 MW beam, especially under a reduction of the Main Injector cycle time where the per-pulse intensity will be less. The upstream decay pipe window is designed to be fully replaceable with a higher-power window that has less mass in its center region. Further analysis is required, as some recent analyses have suggested the present 1.2 MW design would be tolerant of 2.4 MW beam. This issue is further relaxed for a Main Injector cycle time reduction which involves lower intensity beam pulses.

The cooling systems for the target and horn will require upgraded capability for 2.4 MW. The RAW systems which provide the ultimate heat rejection will need increased capacity. Furthermore, the helium cooling system for the target may require wholesale replacement to operate at higher pressures and velocities for the 2.4 MW. UKRI-STFC is also consulting on the design and procurement of this system.

Construction and integration of these devices must be starting while the 1.2 MW LBNF systems are being assembled and installed, as well as spare devices. Adequate physical facilities are needed in terms of floorspace, crane capacity and height, and test equipment. The proposed Target Systems Integration Building (TSIB) will be used maximally in pursuit of these upgrades.

LBNF Absorber Complex The LBNF Absorber Complex consists of all the technical devices, utilities, and conventional facilities from the exit of the target hall, through the decay volume and absorber, as well as the buildings surrounding the absorber. All conventional facilities, devices, utilities were designed to be compatible with 2.4 MW operation, including the absorber itself. Some pieces of instrumentation may need to be re-evaluated with the new beam parameters, though an increased power achieved through a reduction of the Main Injector cycle time will generally have lighter requirements. Some RAW upgrades will be needed for higher beam power.

7.8.2 Long-Lead R&D & Design

The most pressing R&D and Design work to start is on the target materials, the target design, and the Horn A design. For a mid-later 2030s start of 2.4 MW beam, it had been initially proposed to start target materials research in 2024, and target/horn pre-conceptual design in 2025. If the higher power upgrade is advanced to an earlier date, then it is even more urgent to start these studies.

Target materials R&D is a set of irradiations and experiments to qualify particular materials for inclusion in the target and surrounding devices that directly lie on the beam axis (such as windows). The sequence of experimentation leads to a timeframe of $\sim$ 5 years minimum for results:

- Initial selection of materials from design considerations, and sourcing of those materials for experiments. These materials must then be fabricated into representative specimens for the various experiments.

- High-intensity, high-energy proton irradiation is performed on a set of specimens to directly emulate the radiation damage and gas production of an actual target.
- As an adjunct, multiple-ion and electron irradiation can be performed to produce similar (though not identical) radiation damage on an accelerated timeframe, and with less inconvenience.
- In-beam pulsed irradiated of specimens, such that the induced thermomechanical stresses are similar to actual stresses.
- Bench tests on irradiated and unirradiated specimens.
- Materials science investigations and micromechanics of irradiated and unirradiated specimens.

There is serialization to some of the tests above. Combined with the complications of handling and shipping irradiated materials between laboratories of different capabilities, a five-year timescale is typical for a complete cycle of experimentation. Ideally, this cycle is complete prior to conceptual or preliminary design of a target and its associated windows. Acceleration of this R&D is possible with the realization of the proposed High-Power Targetry laboratory at Fermilab, which would offer the ability to perform many of the investigations locally. A further realization of an irradiation facility at Fermilab could further compress the timescale for these cycles.

The combined pre-conceptual design of a target and the first horn is necessary to demonstrate that the basic geometry can be retained for higher power. The target is challenging as the average power deposited will at least double, and the heat must be conducted away with helium. Pulsed beam also increases stresses, which may require a larger target radius, further increasing energy deposition. The horn inner conductor is directly heated by the beam shower and the 300 kA excitation. The conductor is cooled by a direct water spray which is already challenging at 1.2 MW. It is anticipated that marginal changes to the designs and cooling systems can accommodate the 2.4 MW power, however, the studies have not been performed to demonstrate this. If the nominal geometry cannot be maintained, a reconfiguration could be required which could have significant impacts on performance, schedule, and cost. Also notable is that a power increased achieved by reducing the Main Injector cycle time would involve twice as many current pulses as the nominal parameters, but the beam pulses would be less intense.

7.8.3 Risk of Reconfiguration

The risk of reconfiguration is a major uncertainty remaining in the LBNF 2.4 MW upgrade, and it depends on the ability to engineer a target and horn that are survivable, with high confidence, for their design lifetimes. The present state of knowledge suggests that modifications to the target and Horn A are possible to accommodate 2.4 MW without major reconfiguration, though detailed designs have not been produced. If detailed designs show that the horn must be moved further from the target, then significantly more substantial design exercises must be performed.

Reconfiguration would entail several mostly serial design steps, and implementation could result in an extended beam outage. The engineering constraints must first be understood in a general sense to establish the boundary conditions. Then, a physics optimization procedure is performed requiring very substantial particle simulation quantities to develop an optimized target-horn geometry. Detailed engineering designs of those devices must then be performed, and iterated through simulation. Construction would take several more years. Finally: installation could take an extended period if shielding or utilities need reconfiguration, leading to an extended beam outage. Many of these activities are substantially minimized or eliminated if the reconfiguration can be avoided.

7.8.4 Considerations for a Main Injector Cycle Time Reduction

A reduction in the Main Injector cycle time, as a route to 2.4 MW (or near), generally places less stress on LBNF beam devices. Items such as windows, targets, and horns undergo less stress per pulse, while having greater pulses. The impact of greater-stress pulses is generally greater than more frequent pulses.

Reducing the Main Injector cycle time is more challenging for powered devices which must pulse more frequently, and particularly for those whose excitation is proportional to beam energy (such as the primary beam magnets). These devices are well-designed for the stresses involved, however, there will be significantly greater average heating, and a greater amount of power required (average power and voltage in some cases). For the primary beamline, this could have a significant effect upon the power supplies.

An additional consideration of a Main Injector cycle time reduction is that it potentially offers an accelerated timeline to higher beam power. That accelerated timeline will require a greater amount of work to occur for upgrades, while the initial devices are still being built. This parallel work will require greater resources to be available, compress the timeline of R&D, and reduce the ability to integrate operational experience to validate the 1.2 MW design features. Reducing the validation will lead to greater risk or conservatism in design decisions.

LBNF is designed to be upgradable to 2.4 MW with a nominal set of beam parameters. The scope of the upgrades is understood for the nominal parameters; A power increase achieved by reducing the Main Injector cycle time potentially introduces additional scope, while simplifying some upgrades. Uncertainty does exist in how upgrades to the target and horns themselves are to occur. This uncertainty must be addressed by performing target materials R&D as soon as possible, and starting conceptual design of the target and first horn to eliminate the possibility of reconfiguration, and settle design envelopes.

The cost of the LBNF target station upgrades is very roughly estimated at $50M. This is a Class 5 estimate and so has an estimated cost range of $25M to $100M.

7.9 Elements E9a and E9b: Transfer Lines for RCS and SRF Linac Options

Connecting the various machines are several transfer beamlines. The model for a typical transfer line is the 8 GeV line which transports protons from the current Booster to the Main Injector. The beamline consists of 3 basic sections: the extraction lattice, the middle FODO transport lattice, and the injection lattice. The extraction lattice includes powered quadrupoles, dipoles, and correctors. The FODO transport lattice consists of a repeating set of permanent magnets. The injection lattice consists of powered quadrupoles, a Lambertson magnet, and kicker magnets.

A general cost estimate for each section of the transfer line can be provided since the cost does not change significantly with beam energy. The power requirements do not change significantly with the injection and extraction lattices for 1-2 GeV and 8 GeV transfer lines. Since the middle FODO lattice is made of repeating sets of permanent magnets, the cost can be estimated per length.

The cell length of a ring is usually optimized and so, this cell length can be assumed well optimized also for the transfer line. Another assumption can be taken on the focusing structure and phase advance of each cell [36]. Often a 90 deg FODO cell is used since it has a good ratio of minimum and maximum beam sizes, features equal apertures, provides good locations for trajectory correction and beam instrumentation, and it provides the ideal phase advance for injection and extraction equipment.

For a transfer line into the Main Injector, the cell length is 32m which would require 1 quadrupole magnet per 16m in the transfer line. In the case of the RCS where the cell length is 8 m, there would be 1 quadrupole magnet every 4 m.

If bending is required, dipole magnets will also be needed in some of the cells. The number of dipoles per cells depends on how much bending strength is needed.

Regarding the cost of the transfer lines, the cost of the extraction lattice and the injection lattice is already included in the machines (the linac, the RCS, and the AR). So this leaves the cost of the FODO lattice and the cost of civil construction to be explained. Table 28 shows the point cost estimate for the transfer line FODO lattices plus the civil engineering leading towards the AR and the MI. These transfer line costs do not include the cost of the bending magnets. These can be added to the cost once the tunnel layouts are specified.

For the RCS and SRF Linac layouts shown in Figs. 9 and 10 the lengths of the various transfer lines and the resulting costs are detailed in Table 29.

7.10 Elements S1, S2, S3: Booster Replacement Era Spigots

The three new proton spigots available in the Booster Replacement Era are described in sec 4.3. With the definition of the 6 Booster Replacement configurations C1a,b,c and C2a,b,c it is clear that proton Spigots S1 and S3 come for free as part of all 6 configurations and spigot S2 comes free with C1b, but to enable

Table 28: Cost per unit length of Transfer Line FODO Lattice plus Civil Engineering

WBS Element	**Description**	**Transfer Line Cost for RCS/AR ($k per 16m)**	**Transfer Line Cost for MI ($k per 16m)**	**CLASS Estimate**
Y	Project	2,654	1,218	
Y.02	Power Supplies	80	20	CLASS 5
Y.03	Vacuum	146	36	CLASS 5
Y.04	Instrumentation and Controls	288	72	CLASS 5
Y.05	Magnets	1,400	350	CLASS 5
Y.06	Civil Engineering	740	740	CLASS 5

Table 29: Costs of the transfer lines for the RCS and SRF Linac configurations. Lengths are extracted from Figs. 9 and 10

Machine	**Transfer Line**	**Length**	**Cost per 16m**	**Cost (CLASS 5 Range)**
E9a (RCS)	2GeV line into RCS	60m	$2.65M	$10.6M
	RCS to existing 8GeV MI line	300m	$1.22M	$23.2M
	Total			$33.8M ($16.9M-$67.6M)
E9b (SRF Linac)	PIP-II to 2GeV Linac	80m	$2.65M	$13.3M
	8GeV Linac to Accumulator	80m	$2.65M	$13.3M
	Accumulator to MI	270m	$1.22M	$20.7M
	Total			$47.2M ($23.6M-$94.5M)

S2 in configurations C1a, C1c, and C2a,b,c a 2 GeV accumulator must be added. Table 30 summarizes the spigots available to each booster replacement configuration and the cost of adding them if not already part of the configuration.

Table 30: The additional costs of adding the three proton spigots S1, S2, S3 to each of the 6 Booster Replacement configurations C1a,b,c and C2a,b,c

	S1 O(1) GeV High Duty-Factor	**S2** O(1) GeV Low Duty-Factor	**S3** O(10) GeV Low Duty-Factor
C1a	included	$289M ($166M-$524M)	included
C1b	included	included	included
C1c	included	$289M ($166M-$524M)	included
C2a	included	$289M ($166M-$524M)	included
C2b	included	$289M ($166M-$524M)	included
C2c	included	$289M ($166M-$524M)	included

Note that an experiment that uses a proton spigot will likely have it's own beamline elements (e.g. a target). There is no consideration of such elements in this document.

8 The Cost of the Six Main Configuration Options

The point cost estimates and costs ranges are described for each element in Sec. 7. The 6 Booster replacement configurations are built from different combinations of these elements and the cost estimates can be similarly built from the cost estimates of the elements. Fig. 19 Shows the costs of the elements of the six configurations and those costs summed to produce total configuration costs. Each cell of the matrix of Fig. 19 contains the point estimate cost (large, bold font) and the estimated lower and upper bound of the cost range (small, pale font). The cost of adding Spigots 1, 2, and 3 are also indicated if they are not already part of the configuration. The total cost and cost range of each configuration is presented on the bottom line assuming each configuration needs a Spigot 2 (source of low duty factor beam at 1 GeV for experiments). If Spigot 2 is not needed by any experiment and a 2 GeV accumulator is not needed for the accelerator chains then the configuration cost may be smaller and is show on the second to last row. All costs in Fig. 19 are in millions of FY22 US Dollars (i.e. no escalation for future years).

The configuration cost point estimates vary from $843M for configuration C1a to $1,553M for C2c. Given the cost estimation paradigm employed in this document most elements of costs fall into Classes 4 or 5 and so the configuration costs ranges are broad. At the low end is the range for C1a, $543M to $1,386M, and at the upper end lies the range for C2c, $963M to $2,647M.

	C1a: 10 Hz RCS, Metallic Vacuum Pipe	C1b: 20 Hz RCS, Ceramic Vac, with 2 GeV AR	C1c: 20 Hz RCS, Ceramic Vac, High Current Linac, No AR	C2a: 8 GeV SRF Linac, small current increase, XFEL RF	C2b: 8 GeV SRF Linac, high current, some RF R&D	C2c: 8 GeV SRF Linac, high current, significant RF R&D
E1a: 2mA CW PIP-II, 2mA CW extension	280 413 645	280 413 645				
E1b: 2mA CW PIP-II, 2mA, 2ms, 20Hz exten.				223 327 507		
E1c: 5mA, 2ms, 20Hz PIP-II; 5mA, 2ms, 20Hz exten.			280 407 627		280 407 627	280 407 627
E2: 10 Hz RCS	193 306 513					
E3: 20 Hz RCS Ceramic Vaccuum Pipe		297 513 926	297 513 926			
E4: 2 GeV Accumulator Ring		166 289 524				
E5: 8 GeV Accumulator Ring				150 262 476	150 262 476	150 262 476
E6a: 8 GeV SRF Linac, XFEL RF				290 457 766		
E6b: 8 GeV SRF Linac, RF R&D					290 457 766	
E6c: 8 GeV SRF Linac, High Current						301 473 790
E7: MI & RR Upgrades	28 40 60	28 40 60	28 40 60	28 40 60	28 40 60	28 40 60
E9a: Beam Transfer Lines for RCS Options	17 34 68	17 34 68	17 34 68			
E9b: Beam Transfer Lines for SRF Linac Options				24 47 94	24 47 94	24 47 94
Spigot 1: ~ 1 GeV High duty factor beam	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0
Spigot 2: ~ 1 GeV Low duty factor beam (add E4)	166 289 524	0 0 0	166 289 524	166 289 524	166 289 524	166 289 524
Spigot 3: ~ 10 GeV Low duty factor beam	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0
Grand Total with Spigot 2	684 1,082 1,810	788 1,289 2,223	788 1,283 2,205	881 1,422 2,427	938 1,502 2,547	949 1,518 2,571
Grand Total without Spigot 2 (if optional)	518 793 1,286	788 1,289 2,223	622 994 1,681	715 1,133 1,903	772 1,213 2,023	783 1,229 2,047

Figure 19: The costs of the elements of the six configurations and those costs summed to produce total configuration costs. Each cell of the matrix contains the point estimate cost (small, pale font) and the estimated lower and upper of the cost range (large, bold font). The cost of adding Spigots 1, 2, and 3 are also indicated if they are not already part of the configuration. The total cost and cost range of each configuration is presented on the bottom line assuming each configuration needs a Spigot 2 (source of low duty factor beam at 1 GeV for experiments). If Spigot 2 is not needed by any experiment and a 2 GeV accumulator is not needed for the accelerator chains then the configuration cost may be smaller and is shown on the second to last row. Note that E8, the LBNF Target Station Upgrade is not included in this cost table as it is assumed that work will have already been finished as part of the Main Injector Cycle Time reduction. All costs are in millions of FY22 US Dollars (i.e. no escalation for future years).

8.1 The Proton Power available to each Booster Replacement Era Spigot

In Table 31 and Table 32, the beam power that can be delivered to each Spigot for several configurations is given.

		Configuration Beam Power		
		C1a	C1b	C1c
Spigot 1	dedicated	~2000 kW	~2000 kW	0 kW
	parasitic on S2	3920 kW	3785 kW	160 kW
	parasitic on S2, S3	4000 kW	4000 kW	240 kW
Spigot 2 (with E4)	dedicated	~2000 kW	~2000 kW	160 kW
	parasitic on S3	~2000 kW	~2000 kW	400 kW
Spigot 3	dedicated	160 kW	720 kW	720 kW
	parasitic on LBNF	320 kW	960 kW	960 kW

Table 31

		Configuration Beam Power		
		C2a	C2b	C2c
Spigot 1	dedicated	0 kW	0 kW	0 kW
	parasitic on S2	135 kW	0 kW	0 kW
	parasitic on S2, S3	215 kW	400 kW	400 kW
Spigot 2 (with E4)	dedicated	135 kW	0 kW	0 kW
	parasitic on S3	215 kW	400 kW	400 kW
Spigot 3	dedicated	160 kW	570 kW	1200 kW
	parasitic on LBNF	320 kW	760 kW	1600 kW

Table 32

The differences in beam power available for Spigot 1 and Spigot 2 can be seen as a direct function of associated 2-GeV linac. The 2 mA CW 2-GeV linac, Element E1a, is used with configuration C1a and C1b, providing up to 4 MW of CW beam power, up to 2 MW of which would be shared with Spigot 2 (if there is a 2-GeV accumulator ring and it is rated appropriately for that beam power). The 2.7 mA pulsed 2-GeV linac, Element E1b, is used with configuration C2a to provide 215 kW beam power at 2 GeV, only 135 kW of which is available with interfering with the higher energy program (to be used for either Spigot 1 or Spigot 2). It should be noted that in the case of C2a, the PIP-II linac is still CW up to 0.8-GeV, leaving multi-MW beam power still available at only a slightly lower beam energy (Spigot S0A, S0B, S0C). The 5 mA pulsed 2-GeV linac, Element E1c, is used with configuration C1c, C2b, and C2c, providing up to 400 kW of beam power at 2-GeV. In the case of C2c, the higher energy program can potentially use all of the 2-GeV beam power leading to a powerful Spigot 3 program. In the case of C1c and C2b, roughly half of the beam power is available to be shared between the Spigot 1 program and any Spigot 2 program. In the case of the 5 mA pulsed 2-GeV linac, the PIU experimental program comes at the expense of the 0.8-GeV experimental program - Spigot S0A excluded in that case, while S0B and S0C would only be available parasitically.

Providing Spigot 2 requires element E4, the 2 GeV Accumulator Ring, which is included in configuration C1b, but entails a marginal cost of approximately 282 m$ for the other five configurations. In all configurations C1c, C2a, C2b and C2c, the Spigot 2 beam power is limited by the beam available from the linac. With configuration C1a or C1b, the Spigot 2 beam power is limited only by the capabilities of the 2-GeV Accumulator Ring, up to about 2 MW depending on the design. The optimization of a multi-MW 2-GeV Accumulator Ring is somewhat outside the scope of this document. In many cases, Spigot 2 experimenters value short-pulse structure as much or more than raw beam power.

The beam power available for Spigot 3 is directly dependent on the configuration. Configuration C1b, C1c, and C2b provide 570-720 kW relative to the 160 kW available with configuration C1a and C2a. The marginal cost of C1c relative to C1a is 228 m$. The marginal cost of C2b relative to C2a is only X m$, although some R&D will be needed for C2b for the longer linac pulse length. The largest Spigot 3 beam power is 1.2 MW available from C2c, where a marginal cost of C2c relative to C2b is X m$ and relative to C2a is X m$, with a more significant amount of R&D needed for the higher linac rep. rate.

9 Summary

Several approaches to improving the Fermilab Accelerator complex have been examined for capability, cost, schedule, risks, and necessary R&D:

1. Shortening the Main Injector (MI) cycle time and making reliability improvements to the complex.
2. Building a new Rapid Cycling Synchrotron (RCS) to replace the Booster (3 configurations).
3. Building a new Superconducting RF (SRF) Linac to replace the Booster (3 configurations).

The Main Injector cycle time reduction and reliability improvements could be executed in stages over the course of the 2020's, simultaneous with PIP-II construction, and would enable beam delivery rates higher than the PIP-II design at the start of LBNF/DUNE experiment operations in 2031. The Booster replacement options would require a few-year shutdown and commissioning period and come online in the late 2030's time frame. The Booster replacement options are ultimately capable of producing higher beam power, 2.4 MW vs. 2.1 MW of the MI cycle time reduction.

It is recommended that the Main Injector cycle time shortening and reliability improvement work be carried out through the 2020's simultaneous with the establishment of a Project to build either an RCS or SRF Linac based Booster replacement. Under this approach, known as the Accelerator Complex Evolution (ACE) plan, higher power should be available to LBNF than would come from PIP-II alone if the necessary high-power targetry R&D can be accelerated. A Booster replacement would provide even more power and considerably enhanced capabilities for a broader physics program. It would also be a robust and reliable platform for the future, including a proton source for energy machine research

The timeline for power and POT delivery is laid out in more detail in Figure 20 and compared to the timeline if no improvements were made beyond those of the PIP-II Project.

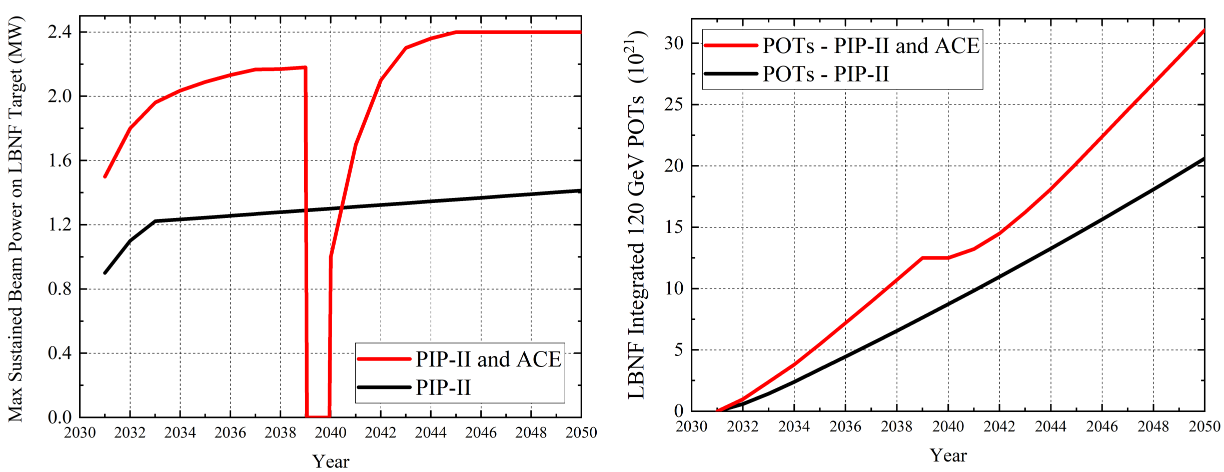

Figure 20: Maximum sustained beam power [left] and integrated number of 120 GeV protons on the LBNF neutrino target [POTs, right] under two scenarios: no upgrade beyond PIP-II (black line), PIP-II with ACE (Main Injector cycle time reduction and reliability improvements followed by either an RCS or an SRF linac Booster replacement, red). The integrated POT number assumes 44 weeks of operation per year and expected machine commissioning progress, overall efficiency and availability of the Fermilab accelerator complex. This plot includes the impact of providing approximately 25% of Booster cycles through 2033 to Mu2e and the fact that the horns and targets being delivered by the LBNF/DUNE-US Project will be capable of a maximum intensity of 1.2MW. Reaching higher power will require design effort and funding for those systems between the present time and 2030.

Taking the roughly estimated cost of the Main Injector cycle time reduction and reliability improvements and combining it with the cost ranges of the mid-capability RCS or SRF Linac option produces an expected cost range of \$1,000M to \$2,500M for the ACE plan to be executed over the 2020's and 2030's. Note this is the full cost and takes no account of international contributions which were substantial for the PIP-II Project.

It should be noted that the first component of the ACE plan, the Main Injector cycle time reduction, only serves the goal of power to LBNF and the extra 120 GeV power is at the expense of power available at 8 GeV. The amounts of beam available at 8 GeV and 120 GeV will be tunable and are not locked in by the ACE plan. The Booster replacement is needed to provide the extra power and flexibility at all energies.

The Fermilab Booster has served the accelerator complex for 50 years, but it is not capable of serving the laboratory for the next 50 years. A Booster replacement will be needed for its superior capacity, capability, and reliability. The ACE plan delivers both higher POT to LBNF than PIP-II alone could provide and a Booster Replacement that will provide even higher rates of POT accumulation in addition to a modern and flexible Fermilab Accelerator Complex.

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11 Appendix A: Committee Composition and Charge

Chairs	Steve Brice(ND) (Co-Chair)	Brenna Flagher(PPD) (Co-Chair)	
SRF Linac Subgroup	Sam Posen(APS-TD) (Lead) Donato Passarelli(APS-TD)	David Neuffer(AD) Arun Saini(APS-TD)	Slava Yakovlev(SQMS) Grigory Eremeev(APS-TD)
Rings Subgroup	Rob Ainsworth(AD) (Lead) Jeff Eldred(AD)	Sasha Valishev(AD) Jonathan Jarvis(AD)	Kiyomi Seiya(AD)
Cost Subgroup	Giorgio Apollinari(APS-TD) (Lead) Steve Dixon(PIP-II)	Richard Marcum(OPSS) Mayling Wong-Squires(AD)	Tug Arkan(APS-TD)
PIP-II 2GeV Extension Subgroup	Eduard Pozdeyev(PIP-II) (Lead) Jerry Leibfritz(PIP-II)	Brian Chase(AD) Slava Yakovlev(SQMS)	James Steimel(PIP-II)
LBNF Target and Horns Subgroup	Bob Zwaska(AD) (Lead)	Frederique Pellemoine(AD)	Jonathan Lewis(LBNF)
Scrutiny Subgroup	Sergei Nagaitsev(AD) Pushpa Bhat(PPD) Mary Convery(LBNF)	Vladimir Shiltsev(AD) Sergey Belomestnykh(APS-TD)	Mike Syphers(NIU) Bill Pellico(ET)

Table 33: The composition of the Proton Intensity Upgrade Central Design Group, indicating subgroups and subgroup leaders. Each individual's division is indicated in parentheses.

Fermilab Proton Intensity Upgrade Central Design Group (CDG)

CHARGE

Dear Brenna and Steve,

We are asking that you chair the Central Design Group (CDG) for the Fermilab Proton Intensity Upgrade, the upgrade of the accelerator complex and LBNF to multi-MW capability. The 2014 P5 Report noted PIP-II will establish a platform for "subsequent upgrades to multi-MW capability." This is an essential upgrade to the Fermilab Accelerator Complex in order to achieve 2.4 MW of beam power for LBNF/DUNE, reduce the time for LBNF/DUNE to achieve first results, and sustain high-reliability operation of the Fermilab Accelerator Complex, and potentially enable other science possibilities.

The Proton Intensity Upgrade should include the extension to the PIP-II linac to higher energy, the Booster Replacement (BR), upgrades to the Recycler Ring and Main Injector for multi-MW capability, and high-power target R&D.

The primary outputs from this group will be project plans for the multi-MW upgrade of the accelerator complex that will be an important input to the next P5 process.

This group should stay in close coordination with the Fermilab Science Priorities Working Group (charged with preparing Fermilab for the next P5) in order for the science case and facilities concepts to be developed self-consistently. The prioritized list of physics opportunities based on the "Physics Opportunities for the Fermilab Booster Replacement" white paper will be an important input to your work.

The CDG should provide the following outputs by September 2022:

- A draft Mission Need Statement (MNS) for the Proton Intensity Upgrade, including the Booster Replacement (BR)
- A description of the most promising technologies for the BR (these would serve as input for a future alternatives analysis and development plan), including
    - Strengths and risks of each accelerator design concept (Syphers white paper and other options)
    - Cost, schedule, risks, and a targeted R&D program for each option
    - Opportunities provided by each technology
    - Note: In accordance with recommendations from the Fermilab Physics Advisory Committee (PAC), the final decision on the technology choice will be weighted in favor of the fastest, most cost-effective path to 2.4MW.
- A Reference Design for the entire Proton Intensity Upgrade with both BR options analyzed
- A preliminary project plan for the entire Proton Intensity Upgrade (for each BR options) that includes:
    - Parametric Cost and schedule estimates based on and scaled from relevant past projects, preliminary risk assesment and a targeted R&D program
    - Lists of potential domestic and international partners

Make sure to establish regular touch points with the Science Priorities Working Group, chaired by Jim Amundson, and develop a consistent plan that enables the science priorities identified by that working group.

Thank you,

Lia, Joe, and Kevin June 19, 2022

Figure 21: The charge to the Proton Intensity Upgrade Central Design Group from Fermilab Director Lia Merminga

12 Appendix B: A Worked Example of Parametric Estimation

This appendix details the parametric extrapolations used for an initial point estimate of a specific RCS options for the ACE program: Element E2, the 10 Hz Rapid Cycling Synchroton (RCS). The parametric estimates of the cost of the other elements were all made in a directly analogous way.

When viewed through the lens of a DOE 413.3b Project, the six main configurations discussed in this document are at pre-CD0 (Approve Mission Need) stage. They have been estimated at "cost/schedule range" levels. The cost ranges (in some cases running up to +100% of a preliminary point estimate) will ultimately be inclusive of Project's elements such as Estimate Uncertainties and Risk Contingency that cannot be properly estimated at this early stage.

The preliminary point estimates are not supported, at this time, by all necessary elements typical of a "projectized" approach (such as Extensive Technical Specifications, Interfaces Definition, Preliminary or Final Design Reviews, Basis of Estimates, Estimate Uncertainties or Risks Uncertainties, Contingencies, etc.). However, similarities with other accelerator construction projects in the DOE complex (SNS, EIC, LCLS-II, PIP, PIP-II) or around the world (XFEL, JPARC) allow parametric extrapolations to determine an initial point estimate and from there reliable cost ranges for the configurations considered in this paper. Such parametric estimate approach follows order DOE G 413.3 – 21 as indicated in the following excerpt from the order.

> **5.2 Parametric Estimating Techniques**
>
> A parametric model is a useful tool for preparing early conceptual estimates when there is little technical data or engineering deliverables to provide a basis for using more detailed estimating methods.[10] A parametric estimate comprises cost estimating relationships and other cost estimating functions that provide logical and repeatable relationships between independent variables, such as design parameters or physical characteristics and cost, the dependent variable. Capacity factor and equipment factor are simple examples of parametric estimates; however, sophisticated parametric models typically involve several independent variables or cost drivers. Parametric estimating is reliant on the collection and analysis of previous project cost data in order to develop the cost estimating relationships.

Figure 22: A quote from DOE Order G 413.3 – 21

In general, the cost estimating group of the PIU CDG adopted the following approach to come up with Cost Range determinations for the elements of the 6 configurations discussed in the ACE report:

- Determine a Work Breakdown Structure (WBS) for each element to L2 (or, when feasible, to L3 and lower) to ensure full scope identification. These WBSs were compared, for completeness and where appropriate, to existing 413.3b Projects WBS.
- Obtain from Subject Matter Experts (SMEs) a point cost estimate for each element of the WBS, based on adoption of known and documented costs (e.g. PIP-II for the 2 GeV extension), extrapolations from similar activities (e.g. 8 GeV Linac cost from LCLS-II/XFEL) or parametric extrapolations from similar projects (e.g. RCS cost from EIC/JPARC)
- Avoid estimates of Project Office/Management Cost or Estimate Uncertainties of Risk Contingency needs
- Obtain from SMEs an assessment of maturity of the estimate for each WBS element (CLASS concept, see below) following the DOE G 413.3-21 Cost Estimating Guide.

As stated in the DOE order G 413.3 -21 widely accepted cost estimate classifications are found in the Association for Advancement of Cost Engineering International (AACEI), Recommended Practice (RP) No. 17R-97 and RP No. 18R-97". Five suggested cost estimate classifications are identified and their primary characteristic listed in terms of estimate CLASSES (see Chapter 7).

For the cost range estimates of the 6 configurations described in this paper, all estimated elements were treated as "pre-CD0" with CLASS estimates ranging from CLASS 5 to CLASS 3.

For the specific case of "Element E2: 10 Hz RCS" the PIU CDG Cost Group identified the following WBS at L2:

WBS Element	
Y.02	RCS Magnets
Y.03	RCS Power (Magnets)
Y.04	RCS Power (RF)
Y.05	RCS Power (Vacuum)
Y.06	RCS Vacuum
Y.07	RCS Instrumentation & Control
Y.08	(NC)RF
Y.09	Conventional Facilities
Y.10	Beam Extraction

Table 34: WBS elements for Element E2, the 10Hz RCS

The parametric approach to estimate "Element E2: 10 Hz RCS" was heavily based on input obtained from the Electron Ion Collider (EIC) 413.3b Project presently under execution at BNL. The EIC entertains the construction of an electron RCS housed in the RHIC tunnel.

A private communication from Dr. Ferdinand Willeke (EIC Technical Director-BNL) provided to the PIU CDG the following information in July 2022:

> The RCS is 400 MeV to 18 GeV electron synchrotron with a repetition rate of 1 Hz (100 ms ramp) It is going to be installed in the existing RHIC tunnel and has therefor only minor civil construction cost. It's circumference is 3887 m (about 200 n.c. magnets, FODO cells with 2 sextupole families). Vacuum system is copper. The latest cost table - following EIC CD-1 approval - is below. Minor escalation effects (few % point over the course of 4 years execution) were not corrected for.

Rapid Cycling Synchrotron		$113,332,905
RCS Magnets - BNL		$36,444,260
RCS Magnets - TJ		$18,502,136
RCS Power Supplies		$37,126,850
RCS Vacuum		$14,052,672
RCS Instrumentation		$7,206,986

> TJ builds the dipoles, BNL build quads, sextupoles and correctors.
>
> There is also $10 M for 2 5cell SRF cavities. EIC needs about 60 MV circumferential voltage. Cost for conventional systems magnet cooling systems is also not in the table and needs to be added at $10M. In addition there are injector cost estimated at $50M (electron source, 400 MeV linac estimated at $37M and transfer lines/kickers estimated at $13M).
>
> The estimates include "Installation and Commissioning" of the various elements and "Beam-line services" (new cable trays, mechanical integration such as supports and alignments, new vacuum/electrical lines when necessary, etc .)

The following parametric extrapolations were used for the ACE estimate of the "E2: 10 MHz RCS":

Y.02 Magnets: EIC RCS used a total ∼200 magnets, FODO cells with 2 sextupole families. FNAL RCS uses ∼242 magnets (100 dipoles, 130 quads; 12 skew-quadrupoles (pages 247 and 249 of [27]) and ∼362 corrector magnets (98 sextupoles ; 66 vertical correctors, 66 horiz correctors, 132 sextupole correctors) which are typically shorter (∼20% in length) and less complicated than main-ring magnets. In this case the parametric extrapolation assumed that the total number of magnets from EIC RCS to FNAL RCS will increase from ∼200 to ∼300.

- EIC RCS Estimate \$50M ⟶ FNAL RCS Estimate: \$75M

Y.03: RCS Power (Magnets): Extrapolation from EIC: 1/8 vacuum pumps due to smaller circumference than EIC, but 4x magnets (doubled the EIC power supplies to accommodate for more magnets but less vacuum pumps).

- EIC RCS Power Supplies Estimate \$37M ⟶ FNAL RCS Estimate: \$60M

Y.04 RCS Power (RF): Power for 16 cavities for 1st harmonic, 10 cavities for 2nd harmonic (pg 254), FNAL Booster experience of ∼\$22M (PIP - 22 refurbished cavities + refurbised drive system), PIP estimated \$1M per cavity's brand new drive system, escalated to 2022 and rounded up to \$30M.

- EIC RCS N/A ⟶ FNAL RCS Estimate: \$30M

Y.05 RCS Power (Vacuum): FNAL RCS is 1/8 circumference of EIC. Cost of Power Supplies for vacuum System based on SME estimate: power supplies for total 164 vacuum pumps (one vacuum pump per 132 half cell, per RF cavity, and 6 additional pumps forbare vacuum beampipe), \$5M.

- EIC RCS N/A ⟶ FNAL RCS Estimate: \$5M

Y.06 RCS Vacuum: Each of the 132 half cells, and each RF cavity, has a vacuum system (pump, instruments, valves). Plus estimate 6 pumps for the bare beampipe. Total 164 vacuum systems. For the 316LN SS beam pipe , electropolished and hydrogen degassed, then coated (inner surface) with TiN; (pg 249-251). Copper is 25 percent more expensive than SS, 1/8 circumference of EIC. \$14M /1.25/8 x 3(electropolishing, degassing, TiN coating)

- EIC RCS Vacuum Estimate \$14M ⟶ FNAL RCS Estimate: \$5M

Y.07 RCS Instrumentation & Control: Rounded up from EIC estimate

- EIC RCS I&C Estimate \$7.2M ⟶ FNAL RCS Estimate: \$10M

Y.08 (NC)RF: 16 cavities for 1st harmonic, 10 cavities for 2nd harmonic (pg 254), FNAL Booster experience of ∼\$22M (PIP - 22 refurbished cavities + refurbised drive system), PIP estimated \$1M per brand new cavity, escalated to 2022 and rounded up to \$30M.

- EIC RCS N/A ⟶ FNAL RCS Estimate: \$30M

Site Work	**\$13,848,900**
6MW Feeder from Master Substation	\$2,000,000
Utilities (ICW, chilled water, DWS, Sanitary Sewer, data/com)	\$4,512,186
Site Preparation (roads and restoration)	\$4,936,714
Wetland Mitigation	\$2,400,000
Utility Plant	**\$16,758,701**
Building	\$5,547,699
Equipment (towers, pumps, controls)	\$8,867,745
Process Side Equipment	\$2,343,257
Enclosure	**\$28,303,335**
10' wide x 8' high x 1968' long	\$28,303,335
Beam Transfer Line	**\$11,936,874**
10' wide x 8' high x 830' long	\$11,936,874
Service Building	**\$6,934,624**
50' wide x 250' long high bay building with 25 ton crane	\$6,934,624
Direct Cost Total	**\$77,800,000**

Y.09 Conventional Facilities: Bottom-up estimate in FY22$ based on PIP-II CF contract placement and assuming a tunnel with the following specs: Length of tunnel - 600m, Standard main injector style tunnel - 10' wide x 8' high, 1 Utilities Building, Power, cooling (6 MW, 10,000 GPM), Wetland mitigation – assume all footprint (14 Acres) will require mitigation at 1.5 times (i.e. need to "purchase" 20 Acres of "wetland credit")

- EIC RCS N/A $\longrightarrow$ FNAL RCS Estimate: $78M

Y.10 Beam Extraction: Rounded up from EIC estimate after removal of 400 MeV Injector system, estimated at ~37M.

- EIC RCS Beam Ext. (incl. 400 Mev Inj.) $50M $\longrightarrow$ FNAL RCS Estimate: $13M

With the previous bottoms-up (Y.09) or parametric (EIC, PIP) estimates, the Point Cost Estimate for the "E2: 10 Hz RCS" is contained in the following table (which is identical to Table 12):

WBS Element	Description	Cost
Y.02	RCS Magnets	75M
Y.03	RCS Power (Magnets)	60M
Y.04	RCS Power (RF)	30M
Y.05	RCS Power (Vacuum)	5M
Y.06	RCS Vacuum	5M
Y.07	RCS Instrumentation and Controls	10M
Y.08	(NC)RF	30M
Y.09	Conventional Facilities	78M
Y.10	Beam Extraction	13M
Total		306M

Table 35: Cost estimate for the 10 Hz RCS (identical to Table 12)

The following CLASSES were assigned to the maturity of the above Point Cost Estimates by FNAL SMEs. High & Low from the Cost Range estimates were then summed linearly to determine an overall Cost Range for the "E2:10 Hz RCS". The result of this table is the costs range identical to Table 15 and to the E2 Element in Fig 19.

WBS Element	Description	Cost	Class	Low	High
Y.02	RCS Magnets	75M	CLASS 4	52.5	112.5
Y.03	RCS Power (Magnets)	60M	CLASS 4	42	90
Y.04	RCS Power (RF)	30M	CLASS 4	21	45
Y.05	RCS Power (Vacuum)	5M	CLASS 4	3.5	7.5
Y.06	RCS Vacuum	5M	CLASS 4	3.5	7.5
Y.07	RCS Instrumentation and Controls	10M	CLASS 4	7	15
Y.08	(NC)RF	30M	CLASS 5	15	60
Y.09	Conventional Facilities	78M	CLASS 5	39	156
Y.10	Beam Extraction	13M	CLASS 4	35	75
Total		306M		193	513

Table 36: Cost range for the 10 Hz RCS (result identical to Table 15)