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PIP-II STATUS AND STRATEGY

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Abstract

Proton Improvement Plan-II (PIP-II) is the centerpiece of Fermilab's plan for upgrading the accelerator complex to establish the leading facility in the world for particle physics research based on intense proton beams. PIP-II has been developed to provide 1.2 MW of proton beam power at the start of operations of the Long Baseline Neutrino Facility (LBNF), while simultaneously providing a platform for eventual extension of LBNE beam power to >2 MW and enabling future initiatives in rare processes research based on high duty factor/higher beam power operations. PIP-II is based on the construction of a new 800 MeV superconducting linac, augmented by improvements to the existing Booster, Recycler, and Main Injector complex. PIP-II is currently in the development stage with an R&D program underway targeting the front end and superconducting RF acceleration technologies. This paper will describe the status of the PIP-II conceptual development, the associated technology R&D programs, and the strategy for project implementation.

OVERVIEW

The Proton Improvement Plan-II (PIP-II) is a high-intensity proton facility being developed to support a world-leading neutrino program over the next two decades at Fermilab. PIP-II is an integral part of the U.S. Intensity Frontier Roadmap as described in the Particle Physics Project Prioritization Panel (P5) report of May 2014 [1]. PIP-II is focused on upgrades to the Fermilab accelerator complex capable of providing a beam power in excess of 1 MW on target at the initiation of Long Baseline Neutrino Facility [1, 2] operations and is a part of a longer-term concept to achieve multi-MW capabilities at Fermilab. PIP-II is anticipated to be a Department of Energy project following the critical decision (CD) process and guidelines of DOE Order 413.3b [3]. At the present time, PIP-II is still in the development phase and is not a formal construction project.

Design Criteria and Considerations

The existing Fermilab accelerator complex could be upgraded using a number of different approaches in order to achieve beam power in excess of 1 MW on the LBNF target. The challenge is to identify solutions that provide an appropriate balance between minimizing near-term costs and maintaining the flexibility to support longer-term physics goals. In order to constrain consideration to a modest number of options the following criteria are applied to possible solutions:

- support the delivery of at least 1 MW of proton beam power from the Main Injector to the LBNF target at energies between 60-120 GeV.
- provide support to the currently envisioned 8 GeV program, including the Mu2e and g-2 experiments, as well as the suite of short-baseline experiments [4, 5].
- provide a platform for eventual extension of beam power to LBNF to more than 2 MW.
- include a future capability to support rare processes experiments with high duty factor and high beam power.

The ideal facility meeting the above criteria would be a modern 8 GeV superconducting linac for injection either into the Main Injector or Recycler as described in the Project X RDR [6], or the pairing of an ~2 GeV SRF linac with a modern Rapid Cycling Synchrotron. These options provide performance that would significantly exceed the first design criteria, and would meet all subsequent criteria, but also significantly exceed the likely available funding.

Design Approach

The goal of Proton Improvement Plan-II is to enhance the capabilities of the existing accelerator complex at Fermilab to support delivery of 1.2 MW beam power to the LBNF production target, while simultaneously providing a platform for subsequent upgrades of the accelerator complex to multi-MW capability. High-level goals, and supporting beam performance parameters, for PIP-II and their comparison to current Proton Improvement Plan (PIP) [7] parameters are given in Table 1. The central element of PIP-II is a new 800 MeV superconducting linac accelerating H- ions and located in close proximity to the existing Booster as shown in Figure 1. This siting offers several advantages in terms of minimizing cost while retaining options for future development; in particular, the site affords direct access to significant electrical, water, and cryogenic infrastructure.

The concept for PIP-II is described in a Reference Design Report [8] and includes the following scope:

- An 800 MeV superconducting linac (SC Linac), constructed of CW-capable accelerating structures and cryomodules, operating with a peak current of 2 mA and a beam duty factor of 1.1%.
- Beam transport from the end of the SC Linac to the new Booster injection point, and to a new 800 MeV beam dump.
- Upgrades to the Booster to accommodate 800 MeV injection, and acceleration of 6.5×10^{12} protons per pulse.

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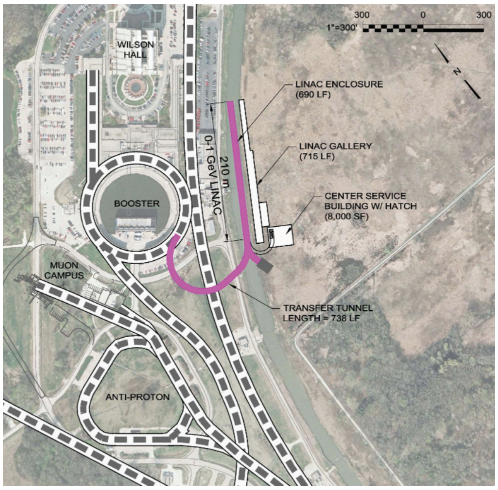

Figure 1: Site layout of PIP- II. New construction is predominantly in the Tevatron infield. Grey dashed areas represent existing underground enclosures.

- Upgrades to the Recycler to accommodate slip-stacking of 7.7×10^{13} protons delivered by twelve Booster batches.
- Upgrades to the Main Injector to accommodate acceleration of 7.6×10^{13} protons per pulse to 120 GeV with a 1.2 second cycle time, and to 60 GeV with a 0.7 second cycle time.

The linac energy is selected to support a 50% increase in Booster beam intensity, accompanied by a 30% reduction in the space-charge tune shift as compared to the current operations. This choice is conservative and will ensure lower fractional beam loss required at the higher operating intensities and higher injection energy. The linac is constructed nearly entirely of components that are capable of operating in CW mode with the cryogenic system being the primary exception. For the chosen parameters, the incremental cost in constructing the linac from CW compatible components is minimal.

800 MeV LINAC STATUS

Figure 2 shows the layout of the SC Linac, The β values represent the optimal betas where the corresponding cavity delivers the maximum accelerating voltage. A room temperature (RT) section accelerates the beam to 2.1 MeV and creates the desired bunch structure for injection into the SC Linac. The RFQ and the first SC section (HWR) operate in the CW mode. To reduce the required cryogenic power the other accelerating structures operate in the pulsed mode. However they are designed and built to be CW compatible in order to accommodate future upgrades. Operation with a peak current of up to 10 mA is supported by the ion source, LEBT and RFQ. The bunch-by-bunch chopper located in the MEBT removes undesired bunches leaving the beam current at up to 2 mA (averaged over a few μs) for further acceleration. There is also a "slow" chopper in the LEBT with rise and fall times of about 100 ns allowing for the formation of a macro-structure in the beam timing. Together the LEBT and MEBT choppers form the desired bunch structure.

Table 1: PIP-II High Level Performance Goals

Performance Parameter	PIP	PIP-II	Units
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Pulse Length	0.03	0.55	ms
Linac Pulse Rate	15	20	Hz
Linac Upgrade Potential	NA	CW	
Booster Protons(Extracted)	4.2	6.5	10^{12}
Booster Pulse Rate	15	20	Hz
Booster Beam Power	80	160	kW
8 GeV Beam Power to LBNF	N/A	80-120	kW
Beam Power to 8 GeV Program	30	80-40	kW
MI Protons (Extracted)	4.9	7.6	10^{13}
MI Cycle Time @ 120 GeV	1.33	1.2	sec
MI Cycle Time @ 60 GeV	N/A	0.7	sec
Beam Power @ 60 GeV	N/A	1	MW
Beam Power @ 120 GeV	0.7	1.2	MW
Upgrade Potential @ 80-120 GeV	N/A	2.4	MW

The choice for the LEBT energy of 30 keV is a compromise between considerations of beam space charge effects that may increase the transverse emittance at low energy and RFQ adiabatic bunching, where the longitudinal emittance improves with decreasing the injection energy. This choice balances the final warm front end emittances among the three degrees of freedom. The RFQ energy of 2.1 MeV is chosen to be below the neutron production threshold for most materials, thereby simplifying the RFQ and MEBT maintenance. At the same time, this energy is sufficiently large to mitigate space charge effects in the MEBT at currents as high as 10 mA.

Recent developments in 1300 MHz ILC technology at Fermilab [9] and elsewhere have made it a preferable choice for the possible future extension of the SC Linac to higher energy. That forces the choice of accelerating frequencies to be subharmonics of the ILC frequency of 1300 MHz, and, consequently, yields 162.5, 325 and 650 MHz as frequencies for PIP-II. This choice results in a comparatively smooth frequency increase in the course of acceleration, accommodating bunch compression due to adiabatic damping.

R&D STRATEGY

The R&D Strategy is designed to mitigate technical and cost risks by validating the choices made in the facility design and by establishing fabrication methods for major subsystems and components, including the qualification of suppliers. There are 5 key aspects to the strategy:

1. Development and operational test of PIP-II Front End covering the first 20 MeV (PXIE).

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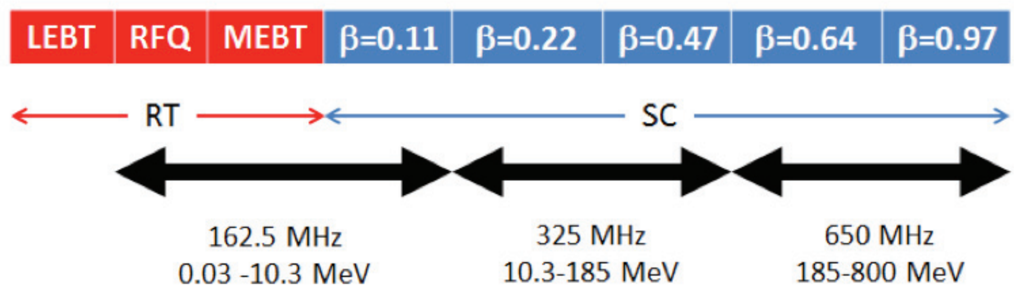

Figure 2: The SC Linac technology map. Items in red are at room temperature, items in blue are superconducting. β values represent the optimal values for each cavity type.

2. Development and demonstration of cost effective superconducting radio frequency acceleration systems at three different frequencies (162.5 MHz, 325 MHz, 650 MHz) and with RF duty factors ranging from 10% to 100%.

3. Development of a Booster injection system capable of accepting beam pulses from the SC Linac.

4. Development of system designs capable of supporting a 50% increase in the proton beam intensity accelerated and extracted from the Booster/Recycler/Main Injector complex.

5. Development of requisite capabilities at international partner institutions to successfully contribute to SC Linac construction.

The PXIE program will develop and perform an integrated system test of the room temperature front end [10] and the first two superconducting cryomodules [11]. The status of the commissioning of the LEBT is summarized at this conference in Ref. [12]. The RFQ will be commissioned during 2015, with the MEBT to follow in 2016. Initial power testing of the HWR and SSR1 cryomodules is expected in 2017, with beam passing through the cryomodules in 2018.

The SRF program in support of PXIE aims to have dressed and tested cavities of all types by 2018. As noted, HWR and SSR1 cryomodules will be tested with beam at PXIE. A HB650 cryomodule (5-cell elliptical cavities operating at 650 MHz, β_{opt} = 0.97, β_g = 0.92) , consisting of 6 cavities, will be tested with full RF power by 2018. This cryomodule is being developed by the India Institutes Fermilab collaboration. The LB650 (5 cell elliptical cavities operating at 650 MHz, β_{opt} = 0.64, β_g = 0.61) and SSR2 (single spoke cavities operating at 325 MHz, β_{opt} = 0.47) dressed cavities will undergo a complete test as part of the R&D program.

With all of the cavities, except those in the HWR cryomodule, operating in pulsed mode, Lorentz force detuning is an important aspect of the resonance control. R&D on the resonance control using active frequency control with fast piezo-based tuners is underway [13].

The modifications to the existing machines at Fermilab to support PIP-II have been identified. A new injection insert for the Booster (to handle the higher 800 MeV energy H^- ions) is required. Preliminary designs have begun [14]. Investigations into the RF design requirements for the Booster, the Recycler, and the Main Injector are underway but not at the stage where results are available for report. Given the high beam intensities, it is important to understand beam stability, transverse and longitudinal emittance growth, and beam losses. Beam dynamics studies on these topics are underway.

There is some flexibility with regard to trading off R&D scope for project risk (and associated contingency) at CD-3 (formal construction start); however, the expectation is that any deliverable associated with the PXIE program, SRF program, or Booster/MI/RR modifications, not completed in advance of CD-3, will need to be completed during the construction phase. The priority for retirement of these risks is as follows:

1. Completion and operation of the PXIE room temperature section.

2. Successful operation, with beam, of a HWR cryomodule in close proximity to the MEBT absorber.

3. Successful rf testing of an SSR1 and HB650 cryomodule; establishment of potential vendor and partner institutional capabilities to supply cavities of each type meeting performance requirements.

4. Demonstration of rf sources capable of meeting requirements at all frequencies.

5. Successful operation of SSR1 cryomodule with beam.

Expected completion of all elements is in 2019.

CONCLUSION

Fermilab's plan for upgrading the accelerator complex is built around a new 800 MeV superconducting linac and modifications to the existing machines. With these upgrades, the complex will be capable of providing a beam power in excess of 1 MW at the start of LBNF operations. In addition, PIP-II establishes a flexible platform for future development of the Fermilab complex. In this paper, we have presented the design criteria, layout, technology choices, and R&D program necessary to complete this work.

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