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BEAM COMMISSIONING AND INTEGRATED TEST OF THE PIP-II INJECTOR TEST FACILITY*

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Abstract

The PIP-II Injector Test (PIP2IT) facility is a near-complete low energy portion of the Superconducting PIP-II linac driver. PIP2IT comprises the warm front end and the first two PIP-II superconducting cryomodules. PIP2IT is designed to accelerate a 2 mA H- beam to an energy of 20 MeV. The facility serves as a testbed for a number of advanced technologies required to operate PIP-II and provides an opportunity to gain experience with commissioning of the superconducting linac, significantly reducing project technical risks. Some PIP2IT components are contributions from international partners, who also lend their expertise to the accelerator project. The project has been successfully commissioned with the beam in 2021, demonstrating the performance required for the LBNF/DUNE. In this paper, we describe the facility and its critical systems. We discuss our experience with the integrated testing and beam commissioning of PIP2IT, and present commissioning results. This important milestone ushers in a new era at Fermilab of proton beam delivery using superconducting radio-frequency accelerators.

INTRODUCTION

The Proton Improvement Plan II (PIP-II) is an essential enhancement to the Fermilab accelerator complex [1] that will provide the world's most intense high-energy neutrino beam to the Deep Underground Neutrino Experiment (DUNE) in South Dakota [2]. PIP-II high-level goals are to 1) reduce the time required for DUNE to achieve its goals by delivering the proton beam power to the LBNF target in excess of 1 MW in the energy range between 60 GeV to 120 GeV, and 2) sustain high reliability, multi-user operations of the Fermilab complex.

PIP-II consists of 1) a Superconducting (SC) 800 MeV H- linac, 2) an approximately 300-meter-long beam transfer line that takes the beam to the Fermilab Booster, and 3) accelerator upgrades required to deliver 1.2 MW of the beam power on the LBNF target at 120 GeV.

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The front end of the linac plays a critical role in the accelerator. It generates the beam, defines beam parameters, accelerates the beam to an energy compatible with downstream accelerating structures, and generates a required bunch pattern.

Fermilab and the PIP-II project constructed the PIP-II Injector Test Facility (PIP2IT) as a testbed for PIP-II technologies to test critical PIP-II front end systems, validate the design of SC cryomodules, and demonstrate feasibility of bunch-by-bunch chopping.

PIP2IT included a nearly complete copy of the PIP-II front end and the first two PIP-II cryomodules. Figure 1 shows the layout of PIP2IT with its main components. PIP2IT was commissioned in two phases. Phase 1 up to the end of the 2.1 MeV MEBT was commissioned with beam from 2015 to 2018 [3]. The HWR and SSR1 cryomodules were added in 2019-2020, leading to the second phase of commissioning of the whole accelerator between June 2020 and April 2021. In April 2021 the PIP2IT beam commissioning was stopped. The PIP2IT hardware was disassembled and moved to storage to be installed later in the PIP-II tunnel. The area used by PIP2IT was reconfigured for PIP-II cryomodule testing.

This paper focuses on the second phase of PIP2IT commissioning.

GOALS OF PHASE 2 COMMISSIONING

The main goals of the PIP2IT test were:

- Conduct integrated commissioning of PIP2IT
- Demonstrate beam with LBNF/DUNE parameters at the end of SSR1 CM
- Validate beam optics and measure beam parameters. Test beam tuning procedures
- Test PIP-II technical systems to inform design decisions
- Gain experience with installation, testing, and operation of PIP2IT equipment
- Integrate in-kind contributions
- Include lessons learned in the design of technical systems and operational procedures

Note that equipment testing was a critical part of PIP2IT, having same priority as the beam commissioning.

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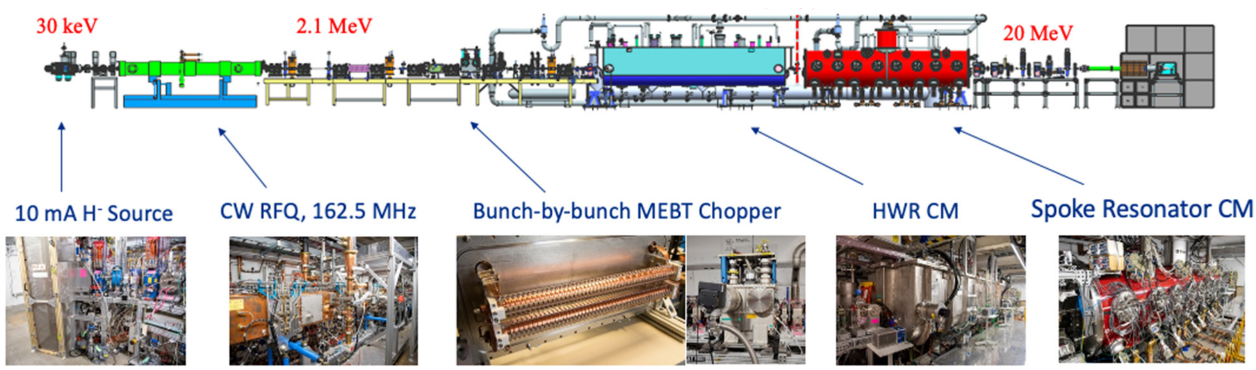

Figure 1: PIP2IT layout with its major components. The length of the facility is approximately 35 meters.

PIP2IT SYSTEMS

Ion Source, LEBT, RFQ, and MEBT Transport

PIP2IT included one DC, H- multi-cusp ion source that can generate up to 15 mA of H- beam current. The 1.5 m long LEBT section transports the 30 keV H- beam to the RFQ. The RFQ was designed and manufactured at Berkeley National Laboratory. The RFQ is a brazed 4-vane 162.5 MHz structure with stabilizing Pi-rods. The RFQ is designed to accelerate the beam with the current of 10 mA from 30 keV to 2.1 MeV with the accelerating efficiency exceeding 95%. The RFQ demonstrated CW operations with an average RF power of ~100 kW. The MEBT transport comprised quad magnets and three copper bunchers. The MEBT vacuum environment was divided into “regular” and particulate-free areas. A small-aperture insertion divided the areas to reduce the flow of gas emitted from the MEBT beam absorber towards the HWR cryomodule. The test results for the ion source, LEBT, RFQ, and MEBT obtained during Phase 1 commissioning were reported in [3].

Fast MEBT Chopper

The fast, bunch-by-bunch MEBT chopper is a critical PIP-II system required to meet operational and user requirements. Because the RFQ frequency (162.5 MHz) is not a harmonic of the Booster RF (~44 MHz), some linac bunches will miss Booster buckets during the injection. The fast MEBT chopper removes these bunches at a low energy, reducing losses at the Booster injection. Also, future users require pre-programmed arbitrary bunch patterns. To satisfy these requirements, the PIP-II front end includes a fast, bunch-by-bunch chopper. A prototype of the chopper was installed and tested at PIP2IT. The system consisted of two synchronized traveling-wave (TW) kickers and a 20-kW absorber for the disposed chopped beam.

The chopper can remove individual bunches at 162.5 MHz. The chopper kicker voltage follows the input gate signal provided by the beam pattern generator that can generate arbitrary chopping patterns as shown in Fig. 2. The demonstration of the chopper operation and measurement of the extinction factor, described below, was a critical milestone for the project.

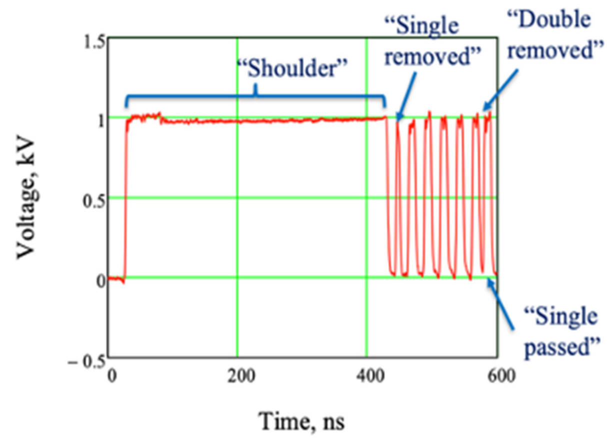

Figure 2: The fast MEBT chopper can create flexible bunch patterns by removing individual bunches at 162.5 MHz.

SRF Cryomodules

Two cryomodules were added to PIP2IT in 2019: the HWR cryomodule developed at Argonne [4] and the SSR1 Prototype cryomodule developed at Fermilab [5].

HWR Cryomodule

The HWR cryomodule is designed to accelerate the beam from 2.1 MeV to ~10 MeV. It includes eight 162.5 HWR cavities and eight focusing solenoids. Each solenoid package includes horizontal and vertical correctors and BPMs.

The cryomodule was delivered to Fermilab and installed at PIP2IT in 2019. It was cooled down in February of 2020. After the cooldown, it was discovered that the first two cavities could not be tuned to 162.5 MHz without exceeding the specified maximum stress for the tuner. In addition, HWR cavity 3 developed a high-resistance short in the coupler bias circuit. To avoid damaging the coupler, the project decided to not operate cavity 3. Therefore, HWR cavities 1-3 were not used for the beam acceleration, although HWR cavities 1 and 2 were tested in the SEL regime without the beam.

The field conditioning of cavities 1-2, 4-8 revealed no issues. The cavities were able to meet the operational field requirement with a 10% margin (see Fig. 3). The cavity Q_0 was deduced from the dynamic heat load. The measured Q_0 was 1.3E10, meeting the requirement, 0.85E10. This value was similar to the number measured at Argonne, 1.5E10.

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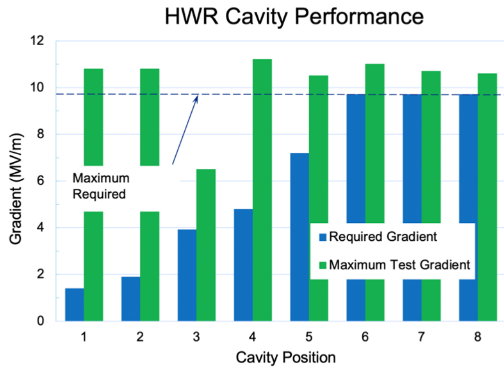

Figure 3: HWR cavity performance

During later operations, HWR cavity 6 quenched under seemingly benign conditions. After the quench, the cavity exhibited stronger emission at the operational field. The operational field of the cavity was reduced to ~8 MV/m. Sometime later, the temperature of the HWR cavities was allowed to drift to 80K-100K during cryoplant maintenance, causing gas migration inside the cryomodule. This event reduced the offset of field emission to ~9.5 MV/m in cavity 8. Surprisingly, this excursion of the cavity temperature and gas migration pushed up the offset of field emission in cavity 6, allowing its operation at ~9 MV/m.

SSR1 Prototype Cryomodule

A single SSR1 Prototype cryomodule was developed by Fermilab and delivered to PIP2IT in the end of 2019. The cryomodule comprised eight single-spoke resonators and four solenoids with correctors and BPMs. The cooldown of the cryomodule provided a great deal of useful information, revealing some opportunities for improvement.

The SSR cavities were conditioned to the maximum field in SSR1 cavities, 10 MV/m, plus 15% margin, 11.5 MV/m total. Figure 4 shows the demonstrated field in the SSR1 cryomodule. Cavities 2, 3 and 7 exhibited some field emission that limited their operational field.

Figure 4: SSR1 Prototype cavity performance

The Q_0 derived from the measured dynamic heat load was 0.35E10. The measured Q_0 number is lower than the requirement, 0.85E10. The lower-than-expected Q_0 was correlated to the magnetic field measured inside the cryomodule. This field was attributed to weak magnetization of some components. A better choice of material and magnetic field hygiene will be implemented for production cryomodules. Note that this nonconformance is not dangerous because of the small dynamic heat load contributed by SSR1 and small number of SSR1 cryomodules (2) in the PIP-II beam line.

LLRF System

The LLRF system was a result of fruitful collaboration of several laboratories: Fermilab, Berkeley, JLab, SLAC, and BARC. After testing the system with cavities, the LLRF system demonstrated excellent performance, easily meeting the PIP-II requirement (see Table 1) for both types of cavities. 14 cavities out of 16 tested met the requirement for the maximum microphonics detuning of 20 Hz. Microphonics will be further investigated at PIP-II.

Table 1: Amplitude and phase stability in HWR and SRR1 cavities vs. PIP-II requirement. The measured data was taken with beam.

Parameter	PIP-II Requirement	HWR (mean)	SSR1 (mean)
Amplitude	0.06%	0.01%	0.02%
Phase	0.06°	0.009°	0.01°

Instrumentation

PIP2IT included a broad variety of instrumentation:

- LEBT: Allison scanner, DCCT, toroid, electrical isolated electrodes
- MEBT: toroid, ACCT, DCCT, BPMs, Allison scanner, prototype laserwire, RWCM, prototype wire scanner, scraper and RPU bias electronics, electrical isolated electrodes
- HWR & SSR1: BPM electronics
- HEBT: ACCT, BPMs, wire scanners, ToF BPM, RWCM, insertable Faraday cup, Fast Faraday cup, dump electronics, BLM detectors.

BPMs proved to be a versatile diagnostic system that can provide a wealth of information about the beam and accelerator. To fully take advantage of the opportunities provided by BPMs, PIP-II optimized the design of the BPM, phase distribution, and data acquisition systems. The length of all PIP-II BPM cables will be calibrated, enabling measurement of the absolute beam phase and energy.

BEAM COMMISSIONING

Initial Commissioning and Tuning

The Phase 2 of PIP2IT operations started in June of 2020 with reestablishing the beam in MEBT.

Challenges Due to Inoperative HWR Cavities

As mentioned earlier in this paper, the first three HWR cavities were not used for the beam acceleration, causing a significant concern. However, beam simulations showed that beam commissioning still was possible, although the loss of beam energy and quality was unrecoverable. To avoid delaying the start of commissioning and tests informing PIP-II designs, the project made a prudent decision to proceed with the commissioning, regardless of the issues with the HWR cavities, and fix the cavities later.

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SRF Linac Tuning

The commissioning of the SRF portion started with passing the 2.1 MeV beam without acceleration to the dump at the end of HEBT.

The optimal acceleration phase for each cavity was set by the typical cavity phasing procedure, in which the cavity phase was changed, and the response of a downstream BPM was recorded. At a lower energy, the procedure gave an asymmetric and sometimes hard-to-interpret response due to beam debunching. The procedure was improved by measuring the difference in the phase of two downstream BPMs and scanning over a smaller range of phases. The phasing procedure was applied sequentially to each accelerating cavity.

The cavity voltage was calibrated with the beam at the beginning of the run. The phase scan was performed for each cavity at a reduced amplitude, and the energy variation was recorded. All other cavities were turned off. This measurement gave the difference between the RF and beam calibrations, which typically was within $\pm 10\%$ and did not exceed $\pm 20\%$.

The beam energy was measured by fixed beamline BPMs and a movable BPM placed after the SSR1 cryomodule. The beamline BPMs were successfully used to measure the increment of the beam energy after each cavity that was added up to obtain the energy profile shown in Fig. 5. Unfortunately, the length of BPM cables was not calibrated before the run, making the absolute energy measurement impossible. In contrast to its successful use in Phase 1, the movable BPM frequently gave large errors in the measured energy value, especially when the last operational cavity was far away from the movable BPM.

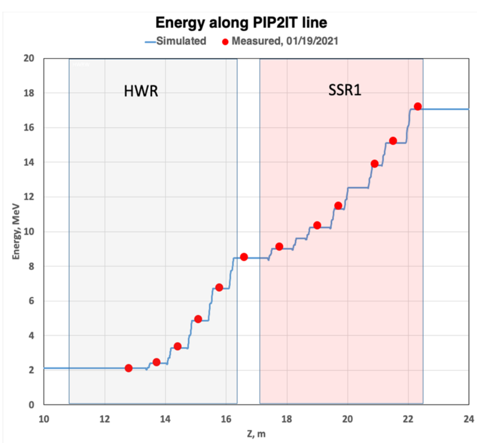

Figure 5: Simulated and measured beam energy along the PIP-II beam line.

Beam with PIP-II Design Parameters Demonstrated

The commissioning of PIP2IT started with 10 µs long pulses that were safe to operate under any conditions. Once the operation of the fast chopper was established, the chopped beam was used for nearly all the commissioning activities. After the MPS was tested with short pulses, the pulse length was increased gradually to the nominal Booster 550 µs pulse length.

In March of 2021, the PIP2IT facility demonstrated the beam with PIP-II design parameters shown in Table 2. PIP2IT was operated for several hours in this mode showing stable operations.

Table 2: Beam with DUNE Design Parameters

Parameter	Demonstrated Value
Energy	16 MeV
Beam current	2 mA
Pulse length	550 µs
Pulse rep. rate	20 Hz
Bunch pattern	Chopped Booster pattern

Beam Measurements & Operational Challenges

Chopper Performance

Figure 6 shows the bunch pattern of the PIP2IT accelerated beam measured after the SSR1 cryomodule. The measured extinction factor was 5E-4 (relative to the full bunch intensity), exceeding the requirement of 1E-3.

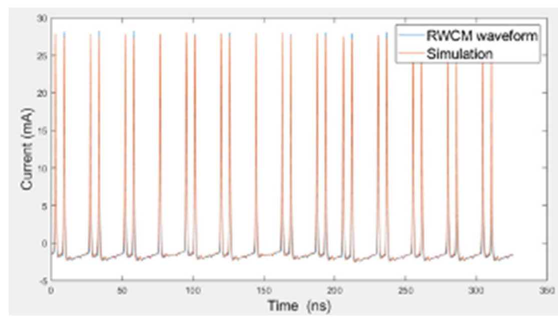

Figure 6: Chopped beam pattern measured after the SSR1 CM at 16.5 MeV. Minimum separation between bunches was 6.15 ns.

Measured Beam Parameters

Table 3 shows measured beam parameters in comparison to expected/required values. The expected beam energy and quality could not be achieved due to inoperative HWR 1-3 cavities. Also, we suspect that the reduced longitudinal beam quality and significantly increased sensitivity to errors due to the inoperative HWR cavities caused some losses in the machine.

Table 3: Measured Beam Parameters

Parameter	Required	Measured
Energy (MeV)	22	17.1
Current (mA)	2	2
Transmission	99%	>98%
Trans. emittance (rms., norm., µm)	0.25	0.23
Long. emittance (rms. µm)	0.4	0.3
Bunch extinction ratio	1E-3	5E-4

Orbit Correction Using Bayesian Optimization

Software for orbit correction based on Bayesian optimization was developed and applied to orbit correction at PIP2IT. Figures 7 and 8 show the beam orbit before and

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after the correction. The test was successful, showing fast and reliable convergence of this method. The method can be applied to optimization of other parameters, such as envelopes, assuming appropriate diagnostics exists.

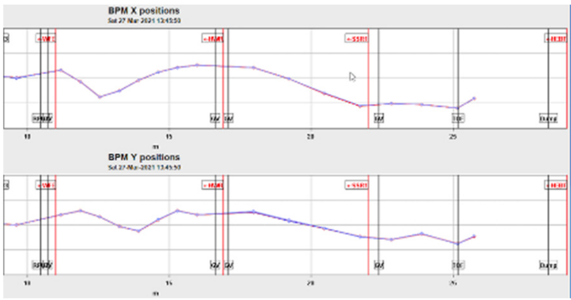

Figure 7: Orbit in PIP2IT before correction. The plots show the horizontal (upper) and vertical (lower) orbit in the cryomodule and HEBT area.

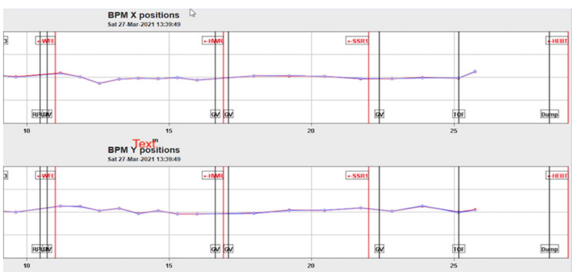

Figure 8: Orbit in PIP2IT after correction using software based on Bayesian optimization.

Hysteresis-like Behavior in SC Magnets

Hysteresis-like behavior was observed in superconducting correctors and solenoids. Based on the orbit response, we estimated the remnant field of a few percent of the maximum field. The effect was observed in all HWR and SSR1 correctors. The residual field stayed without a noticeable change for ~30 min. The effect could be reduced with the demagnetization procedure. A similar effect was observed in solenoids but not studied. The effect can introduce discrepancy with a machine model, complicate machine tuning, and require iterative optics/orbit correction.

The likely source of the residual field is a persistent SC current in the conductor. The new SSR solenoid/corrector package will be wound with a conductor with a smaller filament size (10 µm vs 40 µm) that can reduce the residual magnetization.

Stability and Repeatability of Linac Phasing

The high sensitivity of the linac cavity phasing to small variation in the MEBT energy became obvious during operations. Variations in the beam energy in MEBT smaller than 0.5% resulted in phase errors of $\pm 100°$ at the first operational HWR cavity (#4), requiring retuning of the linac. The exact cause for these changes was not identified. The changes typically were triggered by shutdowns of amplifiers and electronic racks likely causing the RFQ LLRF system to come back to a slightly different state. We will address the energy and phase changes in MEBT during commissioning of PIP-II. The effect also can be mitigated by feedback using two MEBT buncher cavities and two BPMs (phase) to correct the phase/energy error.

IN-KIND CONTRBUTIONS

PIP2IT provided an opportunity to integrate and operate equipment developed by the India's Department of Atomic Energy (DAE) as part of PIP-II In-Kind contributions. The following system were integrated into PIP2IT and tested:

- 7 kW amplifiers
- SSR1 cavity
- MEBT magnets

Based on the hands-on operational experience with the in-kind systems, the project was able to provide feedback on the design of the systems to the Indian Partner.

SUMMARY AND PATH FORWARD

Integrated commissioning of PIP2IT has been completed successfully in April 2021. Beam with parameters required for LBNF/DUNE has been demonstrated. Performance of key systems met PIP-II requirements. Design of accelerator systems was validated with and without beam. All the planned hardware tests (43) were completed. Test results and lessons learned guide the development of PIP-II designs. DAE in-kind contributions were successfully integrated and operated at PIP2IT providing valuable experience.

After the commissioning was completed, a significant portion of PIP2IT equipment was moved to storage. This equipment will be re-installed and recommissioned at PIP-II.

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The successful construction and commissioning of the PIP2IT facility would not be possible without contributions and support of many scientists, engineers, technicians, and operations and business support personnel. We would like to thank all those who directly or indirectly contributed to the project's success. We would like to thank our partners who provided their expertise and in-kind contributions to the project. We are grateful to our DOE collaborators for their contributions to the project. We are thankful to the management of Fermilab for enabling and supporting the project.

REFERENCES

[1] E. Pozdeyev *et al.*, "The Proton Improvement Plan-II (PIP-II): Design, physics and technology advances, first tests", to be published.

[2] Fermilab, `https://lbnf-dune.fnal.gov`

[3] L. R. Prost *et al.*, "PIP-II Injector Test Warm Front End: Commissioning Update", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2943-2946. `doi:10.18429/JACoW-IPAC2018-THYGBF2`

[4] Z A Conway, *et al.*, "a new 2 Kelvin Superconducting Half-Wave Cavity Cryomodule for PIP-II", *IOP Conf. Ser.: Mater. Sci. Eng.*, 2015. `doi:10.1088/1757899x/101/1/012019`

[5] D. Passarelli *et al.*, "Test Results of the Prototype SSR1 Cryomodule for PIP-II at Fermilab", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 4461-4465. `doi:10.18429/JACoW-IPAC2021-THPAB343`