PIP-II INJECTOR TEST: CHALLENGES AND STATUS*

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Abstract

The Proton Improvement Plan II (PIP-II) at Fermilab is a program of upgrades to the injection complex. At its core is the design and construction of a CW-compatible, pulsed H- superconducting RF linac. To validate the concept of the front-end of such machine, a test accelerator known as PIP-II Injector Test is under construction. It includes a 10 mA DC, 30 keV H- ion source, a 2 m-long Low Energy Beam Transport (LEBT), a 2.1 MeV CW RFQ, followed by a Medium Energy Beam Transport (MEBT) that feeds the first of 2 cryomodules increasing the beam energy to about 25 MeV, and a High Energy Beam Transport section (HEBT) that takes the beam to a dump. The ion source, LEBT, RFQ, and initial version of the MEBT have been built, installed, and commissioned. This report presents the overall status of the Injector Test warm front end, including results of the beam commissioning through the installed components, and progress with SRF cryomodules and other systems.

THE PIP-II PROJECT

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 a Department of Energy project following the critical decision (CD) process and guidelines of DOE Order 413.3b [3]. The project does anticipate in-kind contributions from international partners, with significant contributions from India. At the present time, PIP-II received designation of CD-0 ("Mission Need") in November 2015. A Reference Design Report was completed in 2015 [4].

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.
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.

In this paper we will describe the first step in this strategy, the development and operational test of the front end (PIP-II Injector Test or PI-Test).

The PI-Test program will develop and perform an integrated system test of the room temperature front end [5] and the first two superconducting cryomodules [6]. The hardware layout is shown in Figure 1.

PIP-II INJECTOR TEST

PI-Test will install and test hardware with the following scope:

- A H^- source capable of up to 10 mA at 30 keV
- A Low Energy Beam Transport (LEBT) using un-neutralized transport in the downstream part of the line and beam chopping
- A Continuous Wave RadioFrequency Quadrupole (RFQ) operating at 162.5 MHz and capable of delivering 5 mA at 2.1 MeV
- A Medium Energy Beam Transport (MEBT) with an integrated wide band chopper capable of generating arbitrary bunch patterns at 162.5 MHz
- Two low β superconducting cryomodules, utilizing half wave (HWR) and single spoke resonators (SSR1), capable of accelerating 2 mA of beam to 25 MeV
- Beam dump capable of accommodating 2 mA at full beam energy
- Associated utilities and shielding

The Ion source and LEBT were commissioned in 2015. The RFQ was commissioned during 2016 [8], with the full Medium energy beam transport to follow in 2017. Initial

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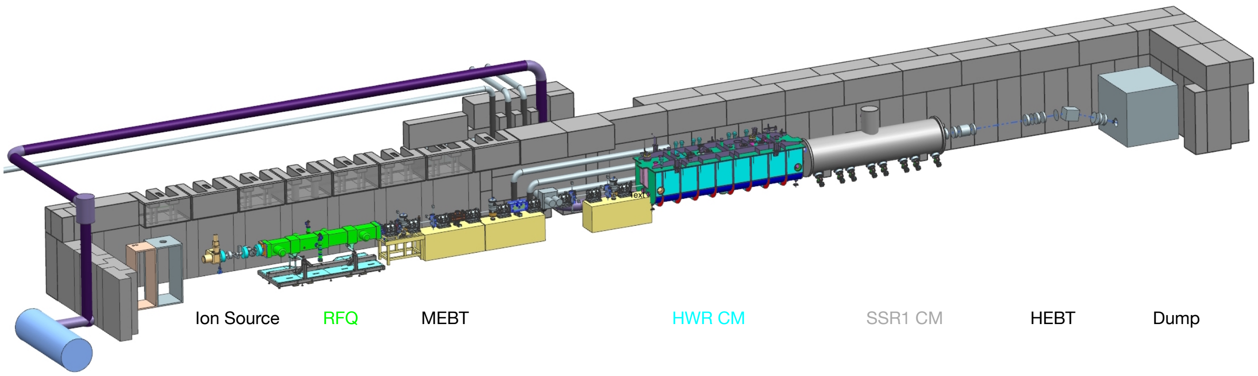

Figure 1: Hardware layout of the PI-Test. From the left, the Ion Source and LEBT, the RFQ (green), the MEBT, the HWR Cryomodule (light blue), the SSR1 Cryomodule, the HEBT (not fully designed) and beam dump. In the background, the cryogenic distribution system pipes and concrete blocks for shielding are shown.

power testing of the HWR and SSR1 cryomodules is expected in 2018, with beam passing through the cryomodules in 2019.

Associated with the hardware scope is a set of beam deliverables, necessary to meet the goals of the PIP-II Reference Design. In the LEBT region, vacuum management between the un-neutralized section and the RFQ and performance of the beam chopper have already been demonstrated. In the MEBT, the performance of the beam chopper, the absorber, and vacuum system are the deliverables. The validation of a 162.5 MHz bunch chopper, able to pass programmable bunch patterns. PI-Test should demonstrate extinction of the chopped bunch at the 10^{-4} level without generating significant emittance growth. The absorber for the eliminated bunches has to demonstrate reliability and long lifetime, effectively absorbing 60% of the beam coming from the RFQ. The absorber is situated upstream of the first SRF cryomodule, so vacuum management to prevent performance degradation is essential. The optimal distance between the MEBT absorber and the HWR entrance will be determined, based on vacuum performance and hardware.

Both pulsed and CW operation of the SRF cryomodules are foreseen. An active area of research is the understanding of the resonance control and Lorentz Force Detuning in pulsed operation [9], especially for the SSR1 cryomodule.

Installation Status

As of September 2016, PI-Test has installed and commissioned the following hardware:

- the 30 keV H^- ion source and Low Energy Beam Transport,
- the 2.1 MeV RFQ,
- the first phase of the MEBT consisting of 2 doublets and dipole correctors, a buncher cavity, diagnostics, and a beam dump.

Figure 2 shows the LEBT and RFQ as installed. The LEBT has been operational since 2014, the RFQ and MEBT phase 1 were installed in the period between October 2015 and March 2016. All associated controls, instrumentation, machine protection, low level RF and power sources have been installed and commissioned. In the following section, performance of the installed components will be described.

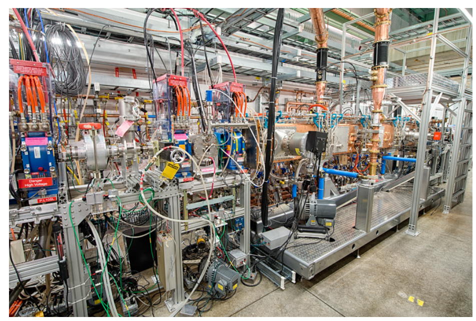

Figure 2: The Low Energy Beam Transport Section and the RFQ as installed. The beam travels from left to right in this picture.

Performance

LEBT The ion source is a non-cesiated, filament driven 15 mA DC source, providing 30 keV H^- ions. With the addition of a modulator to the extraction electrode, PI-Test can provide pulsed beam from 5 μsec to 16 msec in length. A water cooled Allison scanner, based on examples from LBNL and SNS, is mounted on the vacuum chamber. Figure 3 shows an example measurement from the scanner, taken with a 3.7 mA DC beam. Three solenoids form the focussing elements in the LEBT, with a chopper between solenoids #2 and #3. The upper plate of the chopper serves as the beam absorber. A biased diaphragm in solenoid #2 serves as a potential barrier, with full neutralization upstream and un-neutralized transport downstream [5]. Up to 10 mA, both DC and pulsed, has been transported to the entrance of the RFQ, though settings have been optimized for injection of 5 mA into the RFQ.

The input emittance is 0.13 mm (rms, normalized) at 5 mA and the neutralization scheme has been realized. More than 20% of the beam is lost (via scraping) upstream of solenoid

#1. Drifts of the Twiss parameters have been observed over various time scales (hour, day, and longer term). Software stabilization loops have been implemented to minimize the effect of drift at the entrance to the RFQ.

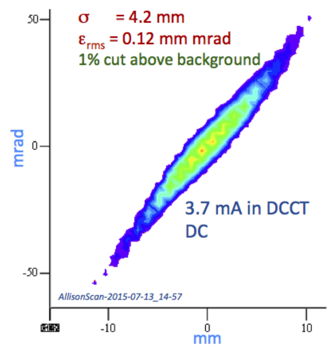

Figure 3: An example beam emittance measure in the LEBT for a 3.7 mA DC beam.

RFQ The PI-Test RFQ is a 162.5 MHz, 4.45 m long, four-vane CW structure constructed of four longitudinal modules. Acceleration from 30 keV to 2.1 MeV requires a 60 kV vane-to-vane voltage. As it operates in CW at high power, a brazed copper structure has been chosen [10]. 32 π mode rods provide quadrupole mode stabilization and 80 fixed tuners are used to correct for local field perturbations. The RFQ was designed and fabricated in collaboration with Lawrence Berkeley National Laboratory.

The RFQ is powered by two separate 75 kW 162.5 MHz amplifiers. It was successfully conditioned with 120 kW input power, initially at 5% duty factor and also at CW operation. At this level of operation, the vane potential has been estimated to be 66 kV, 10% above the specification [8]. The two amplifiers are driven by a single LLRF controller, with separate gain and phase matching circuits. The LLRF control has demonstrated good regulation over a wide variety of pulse widths, from 100 µsec to 5 msec, by making use of both phase feedback and beam compensation loops. Voltage and phase regulation performance are shown in Figure 4.

Beam commissioning with the RFQ began in March of this year. It took less than an hour to achieve > 90% transmission efficiency and 4 mA to the end of the MEBT phase 1. Since March, PI-Test has considered the RFQ commissioned for pulsed beam operation and has concentrated on measurements and understanding of the beam diagnostics and beam parameters, working with beams from 1-10 mA. Transmission efficiency is measured to be 98% ± 3%, where individual toroid calibration uncertainties dominate the systematic uncertainty. The output energy (documented below) is well within the specification and output emittance measurements are underway.

MEBT The MEBT is an approximately 10 m section between the RFQ and the first SRF cryomodule, with space allotted for diagnostics, transverse and longitudinal focussing,

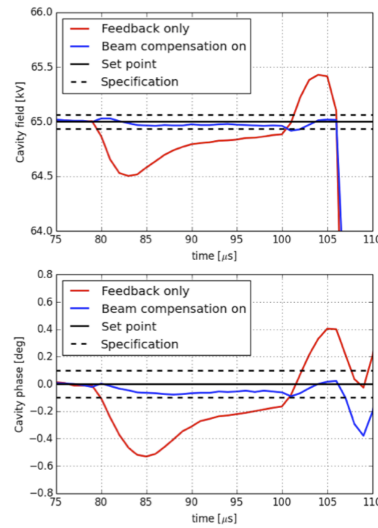

Figure 4: RFQ LLRF voltage and phase performance for a 25 µsec pulse. Black solid line is the set point, black dashed is the specification. The red curve is feedback only, the blue includes beam loading compensation. The pulse starts at approximately 79 µsec in time. The feedback and compensation loops lose control as the beam exits.

and a wide band beam chopper. Transverse focussing is provided by 7 quadrupole triplets, with 2 quadrupole doublets to match the beam from the RFQ to the triplet section. Longitudinal focussing is provided by 3 162.5 MHz buncher cavities. The MEBT includes a vacuum transition section from < 10^{-6} to UHV necessary for SRF operation.

The wide band chopper is the key element. It allows for a pre-determined pattern (programmed into the LLRF) of 162.5 MHz bunches to be directed to a beam absorber with minimal distortion to remaining bunches. While chopping in an MEBT has been demonstrated in other accelerators (e.g., [11]), bunch by bunch chopping is more demanding. The PIP-II concept of Booster injection [4] requires successful demonstration at PI-Test.

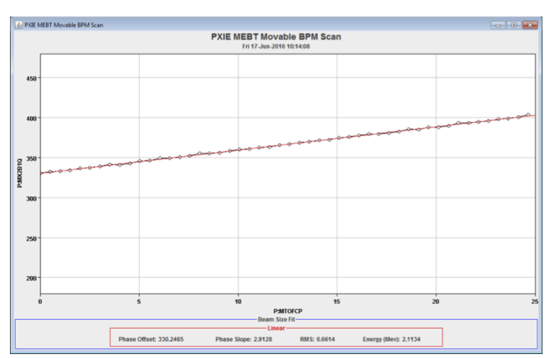

Figure 5: The measured RF phase vs position for the Time-of-Flight BPM. The slope is inversely proportional to the beam velocity.

The MEBT will be built out in phases, allowing tests and measurements along the way. The first phase included the 2 doublets and the first bunching cavity plus a variety of diagnostics, with the focus being on characterization of the beam coming out of the RFQ. The diagnostics included a variable position BPM, allowing for beam energy measurement via time-of-flight. As shown in Figure 5, the beam energy can be measured by fitting the change in RF phase measured with the BPM vs the BPM position. The absolute phase is arbitrary, the slope is inversely proportional to the beam velocity. Using the measured slope, the beam energy from the RFQ is 2.11 MeV ± 0.5%, well within the specification of 2.1 MeV ± 1.0%. The dominant uncertainty is the understanding of BPM longitudinal position. Transverse beam size is measured with scrapers, quadrupole current scans associated with transverse beam size measures lead to transverse emittance. At the time of this conference, final results are not ready for presentation as we work through understanding of the calibrations and settings.

The second phase of the MEBT allows for testing of the chopper prototypes. There are two designs under consideration, one a helical structure at 200 Ω impedance and one a planar array structure at 50 Ω impedance (see Figure 6). During this phase, the choppers will be both be installed and run to measure orbit deflections. The absorber will be installed in phase 3.

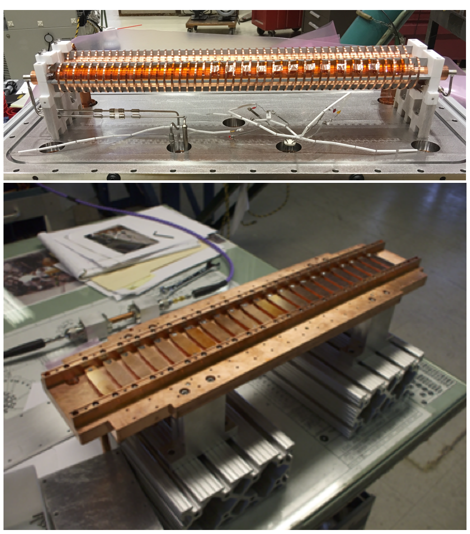

Figure 6: Prototype elements for the kickers in the MEBT chopper. On top is the helical 200 Ω structure, on bottom is the planar 50 Ω structure.

SRF Cryomodules

HWR The half wave resonator cryomodule accelerates the beam from 2.1 MeV to 10 MeV in 8 cavities resonating at 162.5 MHz, interspersed with superconducting solenoids. The cavities use a double conical structure to reduce peak fields and cryogenic loads while providing a high shunt impedance at an optimal β of 0.11. Each cavity will be individually powered by a solid state amplifier of up to 7 kW. The solenoids have return coils and transverse steering coils without additional magnetic shielding. All components have been designed for CW beam operation. PIP-II plans to operate the cavities with CW RF and pulsed beam. The cavities and solenoids have met design specifications and a dummy assembly procedure has begun. The HWR design and fabrication has been done by collaborators at Argonne National Laboratory. Construction is proceeding on schedule with delivery from ANL expected in the spring of 2018.

SSR1 The single spoke resonator cryomodule accelerates beam from 10 MeV to 25 MeV in cavities resonating at 325 MHz, interspersed with 4 superconducting solenoids in the following order: C S C C S C C S C C S C. Each cavity will be individually powered by a solid state amplifier of up to 20 kW. Horizontal and vertical dipole correctors are located inside each solenoid along with a four-electrode beam position monitor.

Ten cavities have been fabricated, including 2 from Indian collaborators. All 10 bare cavities have been tested and passed performance specifications for Q0 and gradient, as shown in Figure 7. One cavity has been fully dressed and tested with prototype tuner and coupler and again has met all specifications.

Resonance control in the context of Lorentz Force detuning (LFD) is a key issue for the single spoke resonator cavities. The design calls for narrow bandwidth (1/2 bandwidth on order 30 Hz) operating in pulsed mode, while LFD can cause shifts of more than twice that frequency. To minimize power overheads, the PIP-II cavities will require active compensation for both LFD and microphonics. An active R&D program is underway to understand the requirements and demonstrate hardware and software approaches for active compensation. Some promising results are presented in other papers at this conference [9].

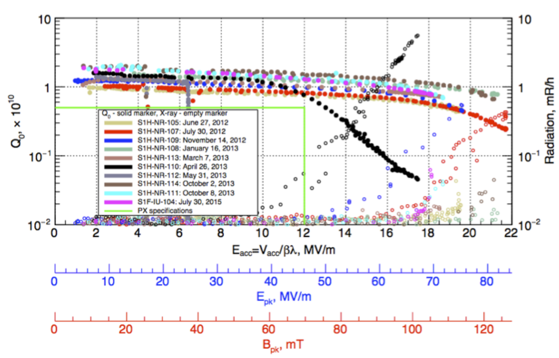

Figure 7: Prototype elements for the kickers in the MEBT chopper. On top is the helical 200 Ω structure, on bottom is the planar 50 Ω structure.

CONCLUSION

The focus through the last year has been the installation, commissioning, and characterization of the 2.1 MeV RFQ. CW RF operation has been demonstrated, and pulsed beam operation has met the goals. 10 mA pulsed beam has been accelerated through the RFQ and MEBT phase 1, with >97% transmission and energy of 2.11 MeV ± 0.5%.

Over the next year, PI-Test will focus on extending the MEBT to full length, with tests of pulsed and CW beam. A major focus will be the characterization and performance of the bunch by bunch chopping system, including the understanding of the vacuum transition into the UHV section for the SRF cryomodules. It is anticipated that the cryogenic distribution system and the HWR and SSR1 cryomodules will be ready for installation in 12-18 months, with full operation of the 25 MeV CW beam to follow in late 2018.

PI-Test is making good progress at addressing the necessary questions to advance the PIP-II project. A set of R&D deliverables has been developed and scheduled to address technical risk in agreement with the requirements of the critical decision process.

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