DESIGN OF PIP-II MEDIUM ENERGY BEAM TRANSPORT*

A. Saini#, C. Baffes, A. Chen, V. Lebedev, L. Prost, A. Shemyakin, FNAL, IL 60510, USA

Abstract

The Proton Improvement Plan-II (PIP-II) is a proposed upgrade for the accelerator complex at Fermilab. The central piece of PIP-II is a new superconducting radio frequency (SRF) 800 MeV linear accelerator (linac) capable of operating in both continuous wave (CW) and pulse regimes. The PIP-II linac comprises a warm front-end that includes a H- ion source capable of delivering 15-mA, 30-keV DC or pulsed beam, a Low Energy Beam Transport (LEBT), a 162.5 MHz, CW Radio-Frequency Quadrupole (RFQ) accelerating the ions to 2.1 MeV and, a 14-m Medium Energy Beam Transport (MEBT) before beam is injected into SRF part of the linac. This paper presents the PIP-II MEBT design and, discusses operational features and considerations that lead to existing optics design such as bunch by bunch chopping system, minimization of radiation coming to the warm front-end from the SRF linac using a concrete wall, a robust vacuum protection system etc.

MEBT REQUIREMENTS

Important requirements for any MEBT is to transport the beam from exit of a RFQ to the entrance of a main accelerating section with a minimal emittance dilution. In addition, a MEBT also facilitates a beam diagnostic before injecting it to the main accelerating section. The PIP-II MEBT is envisioned to exhibit not only above features but also a chopping system that would provide a capability of removing any bunch out of a true-CW beam coming out from a RFQ. This is one of the several eminent features of the PIP-II linac design [1] that enables not only to optimize injection into the Booster ring but also to customize the beam temporal pattern for other potential users. Thus, the chopping system is the most critical part of the MEBT and, its implementation drives overall design concept of the MEBT. Some of the beam requirements in the MEBT is shown in Table 1.

Table 1: MEBT Beam Parameters [1]

Parameter	Value	Units
Energy	2.1	MeV
Input beam current	0.5 – 10	mA
Output beam current *	0 – 2	mA
Transverse emittance**, in/out	0.2/0.23	μm-rad
Longitudinal emittance**, in/out	0.28/0.31	μm-rad

* Averaged over 2 μs

** Specified for 5 mA of input beam current

Furthermore, the design also needs to address potential diffusion of particles and outgassing, from the chopping system, to the first SRF cryomodule, Half Wave Resonators

(HWR). This is required to preserve surface quality of the SRF cavities and therefore, to ensure a reliable operation of the cryomodule. The MEBT design also possesses a concrete wall to shield the front-end from radiations coming from the main linac. This feature, similar to one at the SNS- MEBT, will allow maintenance of the ion sources without any interruption to the machine operation.

A design of the PIP-II MEBT that satisfies these requirements has been developed. This design is a result of several iterations accounting feedbacks from optics simulations, mechanical design and from experience gained at the PIP-II Injector Test facility (PIP2IT) [2]. The PIP2IT MEBT includes most of the features envisioned for the PIP-II MEBT. Figure 1 shows a schematic of the front-end of the PIP-II and the PIP2IT.

CONFIGURATION DRIVERS

Chopping System

The chopper system includes a pair of wide-band kickers [3,4] and a beam absorber [5]. Two kickers are separated by ~180° of betatraon phase advance and provide a vertical deflection to the beam. The absorber is positioned at ~90° phase advance from the last kicker. This arrangement provides a maximum separation of 6σ between transmitted bunches and chopped out bunches at the absorber. A high beam power density on the absorber makes it vulnerable to the vacuum failures. This in turn, results in a significant elongation of the MEBT. Apart from the chopping system of length 5m, a safe separation of the SRF section from the absorber is also required to deal with accidental vacuum failures. These accidental scenarios are considered in the MEBT design and discussed in following sections.

Vacuum Protection for SRF Linac

The MEBT interfaces directly to the SRF section of PIP-II. This close proximity to SRF requires that the downstream section of the MEBT be an ultra-high-vacuum (UHV), low particulate, and high-reliability environment.

Design for UHV The upstream portion of the MEBT is a high-vacuum environment, with characteristic pressure of 1E-7 Torr. This is driven both by the construction of the system (e.g. large O-rings in the kickers, [6]) and the very large gas load from H- beam deposited at the absorber, estimated to be up to 4E-4 Torr-l/s. However, the downstream portion of the MEBT must provide a higher-quality vacuum, in the E-10 Torr range, to limit the flux of gas condensing on the 2K surfaces of the HWR cryomodule. The separation between HV and UHV is accomplished with a Differential Pumping Insert (DPI).

A low-conductance aperture (10mm diameter × 200mm long) of the DPI is installed in the MEBT section just downstream of the absorber. The volume immediately downstream of the aperture is pumped by a 100 l/s ion
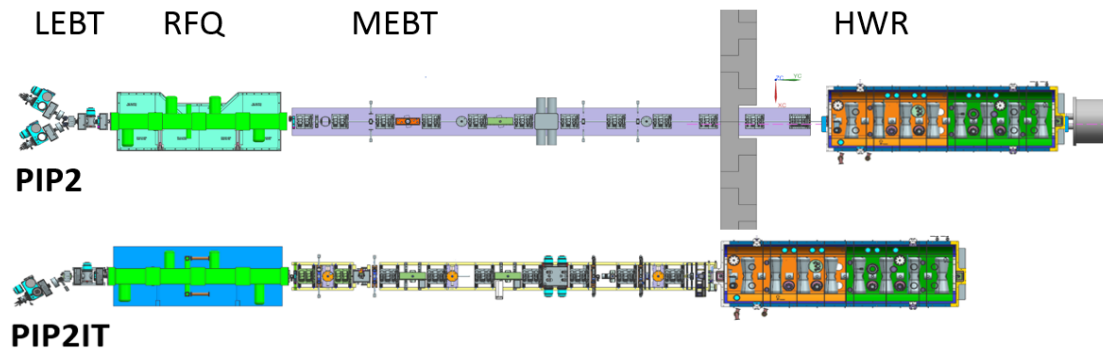
Figure 1: A schematic of the front-end of the (top) PIP-II and (bottom) PIP2IT.

pump. The DPI is electrically isolated such that any beam loss at the aperture restriction may be measured. Downstream of the DPI, all components are metal or ceramic, with no O-rings or elastomers.

Design for low particulate generation SRF cavity performance can be significantly degraded by particulate surface contamination. As such, the downstream portion of the MEBT and its associated assembly schemes must be designed in such a way that particulate material can be efficiently cleaned prior to assembly, and then minimized during assembly. A gate valve just upstream of the DPI demarcates the border between conventional and low-particulate sections of the MEBT. The low-particulate sections of the MEBT will be field assembled in a portable cleanroom. During evacuation or vent-up, the mass flow rate of gas will be limited using a Particle-Safe Vacuum Cart [7] to minimize the possibility of liberating and transporting particles with turbulent flow. Also, number of insertion devices are minimized.

Vacuum Failure Scenarios Experience has shown that vacuum failures (i.e. unintended rapid venting) can and do occur. The introduction of gas to a cold SRF cavity would be catastrophic. At best, the cryomodule would need to be warmed up to drive off condensed gasses. At worst, contamination would be transferred to the cavities and the cryomodule would need to be removed and reprocessed. Particularly in the low-β sections of PIP-II, the loss of just a few cavities, would preclude beam transport. Thus, a great care needs to be taken to protect the HWR cryomodule from vacuum failures originating upstream. As a part of these efforts, no welds directly separating water and vacuum are allowed in this section. Also, scrapers are only radiation cooled.

Several potential failure modes have been identified. A few of the most probable are human errors (e.g. incorrect opening of a manual valve), vacuum equipment failure (e.g. turbo or scroll pumps at the absorber), or beam-induced damage. Upstream of the absorber, beam power can be as high as 21kW, and in a case of a Machine Protection System failure, the beam can easily drill a hole and create a water-to-vacuum or air-to-vacuum failure.

If a failure were to occur, a shockwave will propagate from the failure location. Experiments (e.g. [8]) have demonstrated propagating velocities up to 900m/s. The

conventional mitigation is to install a fast-closing valve system. Distributed vacuum sensors can detect a pressure rise and close a downstream valve with characteristic reaction times of order 10ms. However, this system inherently relies on the long enough distance between the sensor and the fast-closing valve.

In PIP-II, the highest risk is considered to be the MEBT absorber, where all risk factors (high power, mechanical pumping, and human factors) are in play. Additionally, the MEBT is the closest high-risk component to the SRF section. In order to give the fast-closing valve system the greatest chance of success, it is desirable to maximize the distance between the MEBT absorber and the SRF section. For this reason, an additional ~3.5m (3 triplet periods) is planned, relative to the MEBT that exists at the PIP2IT testbed. This allows for >6.5m between the fast-closing valve and the absorber. Assuming fast-closing valve system response time of 13ms, and a pressure wave dominated by water vapor with characteristic velocity of 500m/s, this should be adequate to protect the HWR cryomodule from failures at the MEBT absorber and any regions further downstream. This system is shown schematically in Fig. 2.
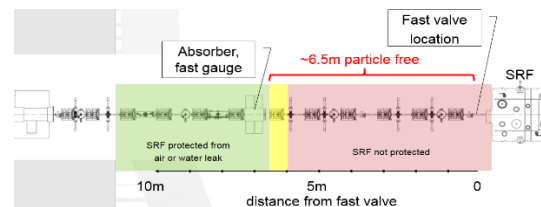

Figure 2: Plan view of PIP2 MEBT, showing fast valve protection zones.

A further attenuation of the pressure wave is possible by baffling the aperture along the propagation direction [9]. Some amount of baffling occurs naturally due to cross section changes along the MEBT beamline. The small aperture of the DPI is expected to provide an effective attenuator for shock waves originating upstream.

Due to facility limitations, it is not possible to incorporate the long (13m) MEBT at the PIP2IT. However, the short (10m) MEBT does incorporate many of the vacuum protection features envisioned for PIP-II. The PIP2IT fast-closing valve system is a VAT 752 (DN40) system. The system has been tested by introducing gas at various loca-

tions in the MEBT and observing pressure response at various locations along the MEBT. At this writing, tests are ongoing. Preliminary indications are that the system performs as expected.

Radiological and Access Considerations

The beam energy within the MEBT (2.1MeV) is chosen to be below the neutron production threshold for conventional accelerator component materials. As such, the radiation environment of the MEBT itself is dominated by gamma production at the locations where beam is scraped or absorbed. According to measurements at the PIP2IT, dose rates are such that, with modest amounts of local shielding, it should be possible for radiation-trained personnel to access to the ion source (>12m upstream of the absorber) with the beam on. This is a very desirable capability, since the dual ion sources of PIP2 are expected to require maintenance after several hundred hours of operation. If these areas are eligible for beam-on access, this periodic maintenance can be performed without accelerator downtime.

However, it is necessary to provide shielding from the SRF section of the linac, where both beam-induced radiation and cavity-produced X-rays will be present. The long MEBT recommended by vacuum protection provides an opportunity for this shielding. One MEBT section, the 650mm gap between triplets, is dedicated to a concrete shielding wall. The location of the wall is shown schematically in Fig. 1.

OPTICS DESIGN

The PIP-II MEBT consists of two quadrupole doublets and ten quadrupole triplets to provide transverse beam focusing while four quarter wave resonators are used to provide a longitudinal beam focusing. Each magnet package also includes a beam position monitor as well as, horizontal and vertical steering correctors. A focusing period of 1175mm (center to center separation between successive triplets) is chosen to facilitate installation of the kickers and absorber between triplets. Concept of the optics design is similar to the PIP2IT MEBT, except three additional quadrupole triplets and a bunching cavity installed to accommodate a 650mm wall and an elongated separation between absorber and the first SRF cryomodule. A study was performed to analyze beam optics along the MEBT using a beamdynamics code TRACEWIN [10]. A Gaussian beam distribution of macro particles truncated at 6σ with initial normalized RMS longitudinal and transverse beam emittance of 0.28μm and 0.21μm respectively was used to simulate a 5mA beam current (average over the RF bucket). Initial beam energy used in this simulation was 2.1 MeV. The beam is tracked from exit of the RFQ to the end of first focusing period in HWR cryomodule. Figure 3 shows 3σ beam envelopes in respective planes through the MEBT. In case of the passing bunches, there were zero volatge between kicker plates while for the deflected bunches, it was –1000V and 1000V at the first and second kicker respectively. It can also be observed from Fig. 3 that

vertical trajectory of the passing beam is corrected using steering magnets to minimize a beam loss at the kickers. The MEBT also houses four sets of the scrapers that provides cleaning of tail particles and a protection in case of the kicker mis-steering or any focusing errors in the MEBT. The MEBT scraping system was discussed in a detail elesewhere [11].
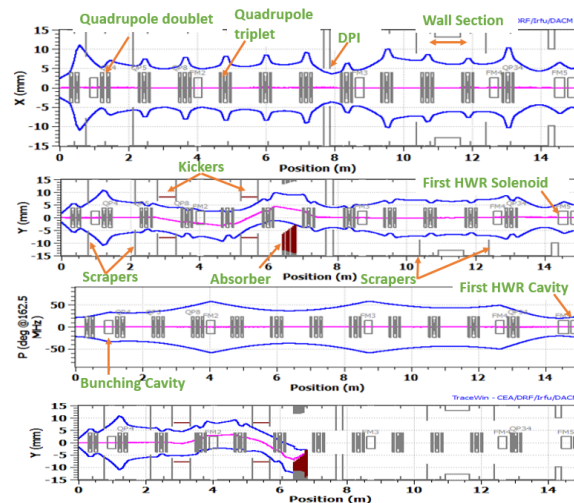

Figure 3: 3σ beam envelopes of 5mA passing bunch in horizonal (x), vertical (y), longitudinal (p) planes and for the chopped-out bunch in vertical plane along the MEBT.
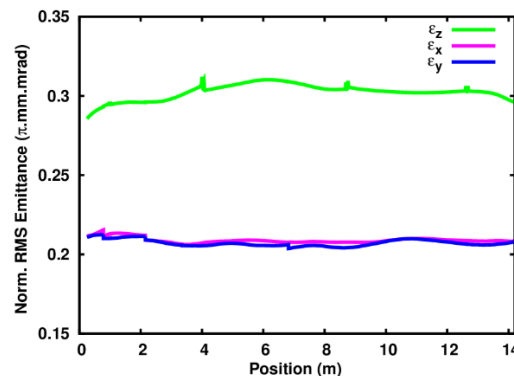

Figure 4: Normalized RMS beam emittance evolution along the MEBT.

Figure 4 shows normalized RMS beam emittance evolution for the passing beam along the MEBT. There are no significant emittance growth in the elongated MEBT.

OUTLOOK

A robust design of the MEBT is developed for the PIP-II linac. This design accommodates a bunch by bunch chopping system, a resilient vacuum protection scheme to alleviate a contamination risk of the SRF cavities and, a concrete shielding wall to allow beam-on maintenance of the ion source. A simulation study showed insignificant RMS emittance growth in all planes.

REFERENCES

[1] PIP-II Conceptual Design Report, 2017, http://pip2-docdb.fnal.gov/cgi-bin/ShowDocument?docid=113

[2] L. Prost *et al.*, "PIP-II Injector Test Warm Front End: Commissioning Update," presented at IPAC'18, Vancouver, Canada, Apr.-May 2018, paper THYGBF2, this conference.

[3] A. Shemyakin *et al.*, "Design of MEBT for the Project X Injector Experiment at Fermilab", in *Proc. LINAC'12*, Tel-Aviv, Israel, Sep. 2012, paper MOPB095, pp. 398-400.

[4] V. Lebedev *et al.*, "Progress with PXIE MEBT chopper", in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper WEPPD078, pp. 2708-2710.

[5] C. Baffes *et al.*, "Design Considerations for an MEBT Chopper Absorber of 2.1MeV H⁻ at the Project X Injector Experiment at Fermilab," in *Proc IPAC'12*, New Orleans, LA, USA, May 2012, paper WEPPD035, pp. 2585-2587.

[6] G. Saewert *et al.*, "Status of PXIE 200 Ω MEBT Kicker Development," in *Proc. NAPAC'13*, Pasadena, CA, USA, Sep.-Oct. 2013, paper THPBA17, pp. 1268-1270.

[7] L. Nobrega *et al.*, Particle Safe Vacuum Cart Technology Portfolio, http://partnerships.fnal.gov/technologies/particle-safe-vacuum/

[8] M. Ady *et al.*, "Leak Propagation Dynamics for the HIE-ISOLDE Superconducting Linac," in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, paper WEPME039, pp. 2351-2353, https://doi.org/10.18429/JACoW-IPAC2014-WEPME039

[9] T. Takiya *et al.*, "Shock Wave Attenuation by Means of Bult-in Baffles in a Tube," *Adv. Studies Theor. Phys.*, vol. 6, no. 5, p. 233, 2012, http://m-hikari.com/astp/astp2012/astp5-8-2012/takiyaASTP5-8-2012.pdf

[10] http://irfu.cea.fr/dacm/logiciels/

[11] A. Saini and A. Shemyakin, "Optical design of the PI-Test MEBT beam scraping system", in *Proc. LINAC'16*, East Lansing, MI, USA, Sept. 2016, paper THPRC026, pp. 827-829, http://dx.doi.org/10.18429/JACoW-LINAC2016-THPRC026