BEAM MEASUREMENTS AT THE PIP-II INJECTOR TEST LEBT*

J.-P. Carneiro†, B. Hanna, L. Prost, V. Scarpine, A. Shemyakin
Fermilab, Batavia, IL 60510, USA

Abstract

This paper presents the main results obtained during a series of beam measurements performed on the PIP-II Injector Test LEBT from November 2014 to June 2015. The measurements which focus on beam transmission, beam size and emittance at various locations along the beamline are compared with the beam dynamics code TRACK. These studies were aimed at preparing the beam for optimal operation of the RFQ, while evaluating simulation tools with respect to experimental data.

INTRODUCTION

The Proton Improvement Plan II (PIP-II) is a series of upgrades planned for the Fermilab complex in order to increase the proton through-cut for its experiments. At its core is the construction of an H^- CW 800-MeV superconducting RF linac. To study the feasibility of the PIP-II front-end (the first ~25-30 MeV), Fermilab has started since 2012 the construction of the PIP-II Injector Test (PI-Test) which present status is described in detail in Ref. [1]. This document presents beam measurements performed on the Low Energy Beam Transport (LEBT) and corresponding simulations.

LEBT DESIGN AND LAYOUT

The goal of the LEBT is to transport and properly inject the beam coming from the ion source into the RFQ, while avoiding beam loss and emittance growth. It includes a chopping system for commissioning purposes and Machine Protection.

LEBT Design

The originality of the PI-Test LEBT resides in its neutralization pattern. While for similar beam parameters most solenoid-based LEBTs operate in a nearly fully neutralized regime to counteract space charge effects, the PI-Test LEBT operates with a relatively long non-neutralized region upstream of the RFQ entrance. References [2] and [3] describe in detail the PI-Test LEBT design principle and report measurements validating the transport scheme chosen. In particular, a low-emittance beam with Twiss parameters close to the design ones at the end of the LEBT have been achieved. Selected beam measurements performed during the commissioning of the LEBT are also presented in Ref. [4].

LEBT Layout

Figure 1 presents a layout of the LEBT with its main elements and diagnostics as installed during the measurements

* Operated by Fermi Research Alliance, LLC under Contract No. DEAC02-07CH11359 with the United States Department of Energy

† carneiro@fnal.gov

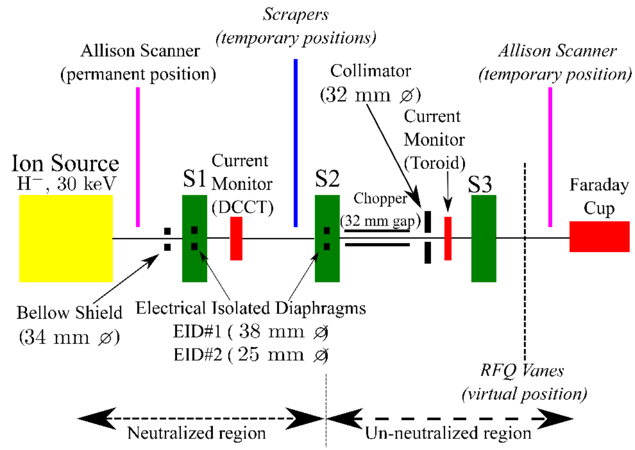

Figure 1: Layout of the PIP-II Injector Test LEBT.

presented in this document. The ion source (30 keV, 15 mA operating pulsed or DC) is followed by 3 solenoids with a Faraday Cup located at the end of the beamline. The chopper is installed downstream of the second solenoid.

Two current monitors are installed in the LEBT (downstream of the first solenoid and right after the chopper) and used for transmission studies. From November 2014 to mid-April 2015 an Allison Scanner was installed (in horizontal position) at the end of the beamline, about 20 cm downstream of the virtual position of the RFQ vanes. As indicated in Fig. 1, the Allison Scanner was eventually relocated to its final vertical position at the ion source exit. A set of 4 scrapers were installed between the two first solenoids and were used for beam size measurements. Inside the first and second solenoid, a water-cooled round Electrical Isolated Diaphragms (EID#1and EID#2) biased to +50 V are installed with the primary goal of confining the positive ions responsible for the beam neutralization between these two solenoids. An aperture restriction of 34 mm diameter (a.k.a bellow shield) protects the bellow connecting the ion source vacuum chamber to Solenoid 1.

SIMULATION TOOLS

The code TRACK [5] is the main tool for simulations. The solenoid fields were implemented in the code as 3D fields from MWS [6] and normalized to the measured field integral. A significant effort has been carried out to implement in the code a detailed aperture profile of the beamline. The space charge effects were simulated using the 3D routine in TRACK. Neutralization from the interaction of the beam with the residual gas is modeled in TRACK by a simple flag that homogeneously decreases the current. The tracking is usually performed with 100k macro-particles on the Fermi Grid. Initial beam particle distributions were generated with

PLOTWIN [7] from the phase space distributions measured at one plane at the ion source exit.

MEASUREMENTS AT THE ION SOURCE

The beam parameters exiting the ion source present a strong dependence with the extraction voltage [8], which results in significant variations in the amount of beam being lost before the beam current is being first measured with the DCCT. This beam loss (or transmission) can be estimated by comparing the current measured at the DCCT with the current inferred from phase space image integral recorded at the exit of the ion source. The latter is obtained from previous cross calibrations between the phase space image integral and an independent beam current measuring device.

The beam phase space was recorded with the Allison Scanner at the exit of the ion source for 16 different extraction voltages, ranging from 1.68 kV to 4.99 kV, corresponding to beam current ranging from 0.5 mA to 6 mA as measured by the DCCT.

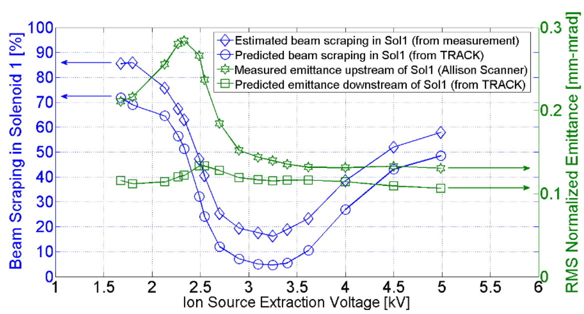

Figure 2: Measured and simulated (TRACK) beam scraping and emittance through Solenoid 1 as a function of the extraction voltage. Pulse length is 1.5 ms.

The measured beam loss is reported in Fig. 2 together with prediction from TRACK. Measurement errors, ±5%, are dominated by the uncertainty in the phase space image integral calibration. TRACK simulations were performed without space charge and with 151.4 A in Solenoid 1. Measurements from Fig. 2 show that, depending on the extraction voltage, between 20% to 80% of the beam is lost before the DCCT. TRACK reports a scraped beam current consistently ~10% lower than the measured one. TRACK also predicts in Fig. 2 that the scraping decreases the beam emittance noticeably.

MEASUREMENTS AT THE SCRAPERS

Figure 3 presents RMS beam size measurements at the Top scraper located downstream of Solenoid 1 (see Fig. 1) as a function of the Solenoid 1 current for a 0.5 mA and 5-mA beam in respectively Fig. 3(a) and Fig. 3(b). The measurements are compared with TRACK for which different neutralization levels are assumed. For 70-100% neutralization, there is a reasonable agreement between the data and simulations at 0.5 mA as shown in Fig. 3(a). Also the location of the beam waist (at ~165 A) is adequately reproduced by TRACK indicating that the solenoid is properly modeled in the code. Agreement of the location of the beam waist

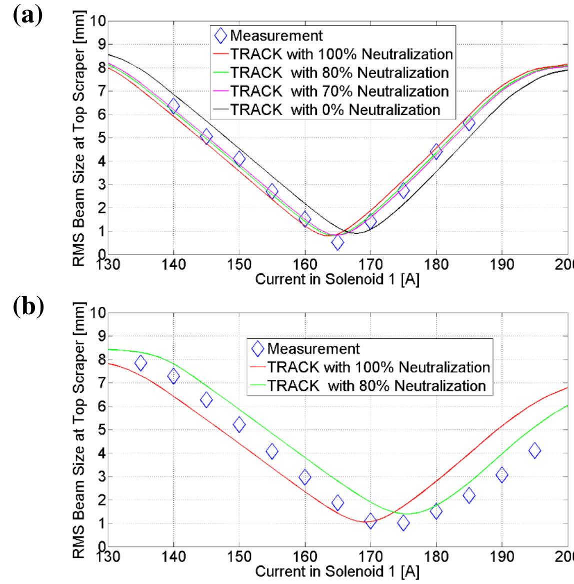

Figure 3: Measured and simulated (TRACK) beam size at the Top Scraper as a function of Solenoid 1 current for a beam current of (a) 0.5 mA and (b) 5 mA.

on Fig. 3(b) suggests a neutralization factor of 80%, consistent with the data for 0.5 mA. Nevertheless the agreement between the measurements and TRACK shown in Fig. 3(b) is not as good as in Fig. 3(a). One may conclude that the simple model for neutralization in TRACK may not be adequate enough when space charge is significant and requires a more detailed description.

MEASUREMENTS AT THE LEBT END

Measurement with a Degraded Vacuum

Figure 4 shows RMS beam size and emittance measurements derived from phase space distributions acquired with the Allison Scanner located at the end of the LEBT for a beam current of 5 mA. As in Fig. 3, the measurements are compared with TRACK taking different neutralization patterns along the LEBT. For the data in Fig. 4, the vacuum was intentionally degraded (to $\sim 5\times10^{-6}$ Torr) to enhance the neutralization. Figure 4(a) reports the beam size measured at 250 μs after the beginning and at the end (1975 μs) of a 2 ms pulse (chopper off). The corresponding emittance measurements are presented in Fig. 4(b).

Figure 4(a) shows that the measured beam size does not vary within the pulse which tends to confirm that the beam is fully neutralized. This observation is supported by TRACK simulations which show a reasonable agreement with the measurements in Fig. 4(a) taking a 100% neutralized LEBT. However the measured emittance presented in Fig. 4(b) do change with the Solenoid 3 current. It may be related either to unaccounted measurement errors or a slightly lower actual degree of neutralization.

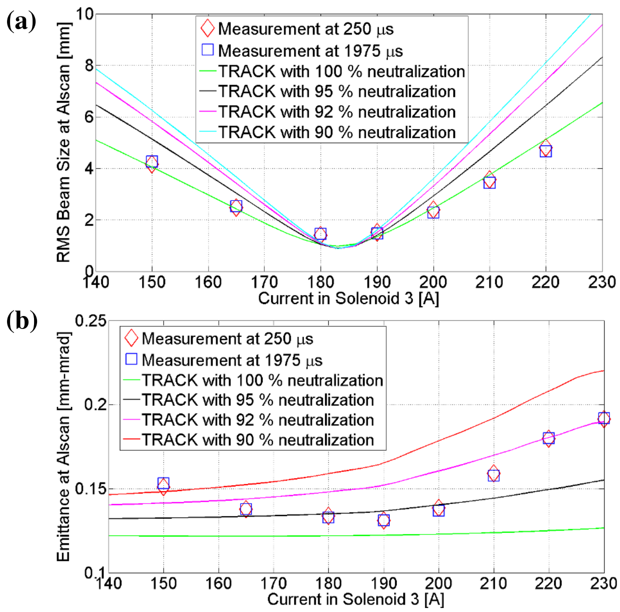

Figure 4: Measured (at 250 μs and 1975 μs) and simulated beam size and emittance at the Allison Scanner as a function of Sol3 current with a degraded vacuum downstream of Sol2 for a 5 mA/2 ms beam. Simulations from TRACK for different neutralization pattern along the LEBT.

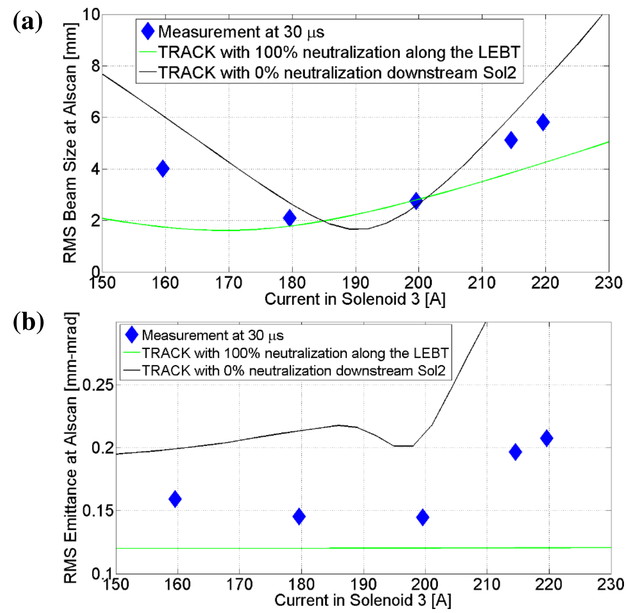

Figure 5: Measured (at 30 μs) and simulated beam size and emittance at the Allison Scanner as a function of Sol3 current with a nominal vacuum downstream of Sol2 for a 5 mA/50μs beam. Simulations from TRACK for a neutralized (100 %) and un-neutralized (0 %) section downstream of Sol2.

Measurement with a Nominal Vacuum

Figure 5 shows the measurement of the RMS beam size and emittance at the Allison Scanner at the end of the LEBT for a nominal ($\sim 1 \times 10^{-7}$ Torr) vacuum downstream of Solenoid 2. The measurements are reported at 30 μs from the beginning of a 50 μs chopped beam at 5 mA. During the measurements the chopper was kept at -300 V DC to clear the positive ions downstream of Solenoid 2 and minimize the neutralization. Corresponding TRACK simulations are also reported in Fig. 5 for two neutralization scenarios (100% neutralization along the LEBT and 100% neutralization up to the middle of Solenoid 2 then full space charge). The position of the measured minimum beam size shown in Fig. 5(a) at ~190 A is properly reproduced by TRACK taking a fully un-neutralized section downstream of Solenoid 2. The emittances reported by TRACK in Fig. 5(b) are ~25% higher than the measured ones. Simulations show that 25% of the emittance is contained in few percent of the beam halo. Taking into account as shown in Fig. 2 that the model predicts a scraped beam 10% lower than the measured one, the 25% agreement between the measured and simulated emittances in Fig. 5(b) is representative of the present accuracy of the model.

CONCLUSION

The TRACK simulations presented in this document confirm the neutralization pattern of the LEBT: a close-to-complete front-end neutralization and a long un-neutralized section downstream of Solenoid 2. A good agreement between the measured and simulated RMS beam size is reported in this document. The measured transmission is about 10% higher than expected from TRACK. In the presence of space charge, the simulated emittance at the end of the LEBT is about 25% higher than the measured one. The disagreement might be related to ambiguity of the generation of the initial particles distribution from the measured 2D one and to simplification of the neutralization profile. However, understanding of the LEBT is good enough to provide the RFQ transmission efficiency of 98% ± 3% [1].

REFERENCES

[1] P. Derwent, "PIP-II Injector Test: Challenges and Status," in *Proc. LINAC'16,* paper WE1A01.

[2] L. Prost, "Low Emittance Growth in a LEBT with Un-neutralized section," in *Proc. IPAC'16, pa*per TUPMR033.

[3] L. Prost, "The PXIE LEBT Design Choices," in *Proc. IPAC'16,* paper MOPOY049.

[4] A. Shemyakin, "PIP-II Injector Test's Low Energy Beam Transport: Commissioning and Selected Measurements," in *Proc. NIBS'16,* paper FriO7.

[5] B. Mustapha, "TRACK: the new beam dynamics code," in *Proc. PAC'05,* paper TPAT028.

[6] CST-MICROWAVE STUDIO, `http://www.cst.com`

[7] PLOTWIN (CEA-SACLAY), `http://irfu.cea.fr/en/Phocea/Page/index.php?id=263`

[8] J.-P. Carneiro, "Beam measurements at the PXIE LEBT," in *PIP-II Document #75 (2016).* `http://pip2-docdb.fnal.gov/cgi-bin/DocumentDatabase/`