BEAM OPTICS MEASUREMENTS IN MEDIUM ENERGY BEAM TRANSPORT AT PIP-II INJECTOR TEST FACILITY*

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Abstract

The Proton Improvement Plan-II Injector Test (PIP2IT) is an accelerator test facility under construction at Fermilab that provides a platform to demonstrate critical technologies and concepts of the front-end of the PIP-II linear accelerator (linac). The PIP2IT warm front-end comprises a H- ion source capable of delivering 15 mA, 30keV DC or pulsed beam, a Low Energy Beam Transport (LEBT), a 162.5 MHz, continuous wave (CW) Radio Frequency Quadrupole (RFQ) that accelerates the beam to 2.1 MeV and, a 14m medium energy beam transport (MEBT). Presently, beamline up to the MEBT has been commissioned and operates routinely at the PIP2IT facility. In this paper, we discuss transverse beam optics measurements performed at the MEBT. It includes beam based calibration of quadrupoles and correctors strengths and, transverse beam sizes measurements to prepare an optical model of the MEBT.

PIP2IT MEBT

The present MEBT configuration at the PIP2IT facility [1] is shown in Fig. 1. The MEBT transverse lattice is composed of two quadrupole doublets followed by seven triplet assemblies. These assemblies use two types of quadrupoles named F-type and D type with yoke lengths of 100 mm and 50 mm respectively. Doublets and triplets are arranged in F$^-$-F$^+$ and D$^-$-F$^+$-D$^-$, respectively. It should be noted that superscripts +/- represent horizontal/vertical focusing quadrupoles. A periodic arrangement of triplets with center to center separation of 1175 mm provides an adiabatic transverse beam focusing along the MEBT. Each doublet and triplet assembly also includes a four-buttons Beam Position Monitor (BPM) installed at the center, and horizontal and vertical steering correctors positioned at the end of each assembly. The MEBT utilizes three bunching cavities to provide a longitudinal beam focusing. In addition to optical elements, the MEBT also accommodates a variety of beam measurement devices such as a Fast Faraday Cup (FFC), Allison emittance scanner and, five sets of the beam scrapers that allow characterizing the beam properties in both transverse and longitudinal planes. In this paper we present differential trajectory measurements and transverse beam size measurements and, discuss an optical model that enables to predict the beam trajectory and beam sizes along the MEBT.

DIFFERENTIAL TRAJECTORY MEASUREMENTS

The differential trajectory method [2] is utilized to perform a beam based calibration of the quadrupoles and steering correctors. Furthermore, it is used to diagnose a potential malfunctioning of the BPMs and magnets. This method consists of, first measuring a 'reference' trajectory with all BPMs for a nominal setting. Then, the beam is deflected using one of the steering magnets and, an 'excited' trajectory is measured in downstream BPMs.

Aperture limitations in the MEBT are mainly from the Differential Pumping Insert (DPI) and kicker protection electrodes. The DPI is 200-mm long and have a round opening of 10-mm. Protection electrodes are installed at the entrance and exit of each kicker which reduce the vertical aperture to 13 mm. These aperture limitations put a stringent constraint on the maximum betatron amplitude of the 'excited' trajectories. Consequently, the proper range of corrector currents must be chosen to avoid a beam loss along the beam line, which otherwise would affect quality of the measurement. Moreover, to minimize the effect of hysteresis, corrector currents are varied only in a one direction w.r.t the initial value, which allows staying on one side of the hysteresis curve. In addition, a complete cycle of the corrector current is carried out before starting any differential trajectory measurement. All measurements reported in this paper were performed using a beam pulse of 10 μs with repetition rate of 20 Hz and a bunch current of 5mA. The RFQ was operating at 60 kV and all bunching cavities were set to operating voltages of 60, 50 and 50kV, respectively and, at RF phase of -90°.

Differential Trajectory Analysis

A Java based application was developed to automate the differential trajectory measurements at the PIP2IT.

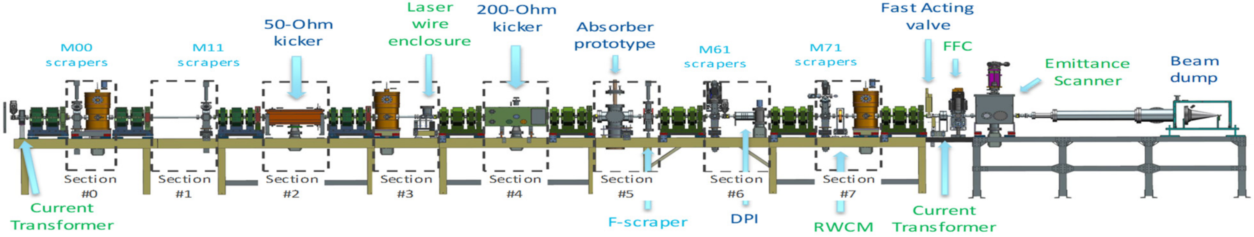

Figure 1: Present layout of the PIP2IT MEBT.

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Twelve differential trajectories (six horizontal and six vertical) are excited using the first six corrector magnets. Using OPTIM [3], an optics model of the MEBT was developed. Initially, the model utilized quadrupole strength calibration coefficients (Tesla per Ampere) obtained from the magnetic measurements performed at a current of 10A. Then, the strength of relevant quadrupoles and corrector magnets were adjusted to fit the model based trajectories with the measured trajectories.

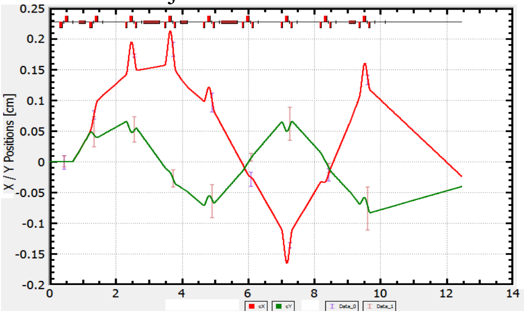

Figure 2: Model based horizontal *x* (red) and vertical *y* (green) differential trajectories obtained after excitation of the first horizontal and vertical correctors by 0.4A. Data points are shown with RMS error bars.

Since the most downstream differential trajectories include a lower number of quadrupoles to adjust, they were analysed first. After getting reasonable agreement with measurements for these, differential trajectories involving quadrupoles and correctors further upstream were analysed. Figure 2 shows horizontal (x) and vertical (y) differential trajectories obtained after excitation of the first corrector (M00C). The model based differential trajectories (solid lines) fit well with measurements. Each data point is an average over 50 beam pulses (N_p) and error bars are estimated using: $\sigma_{dif} = \sqrt{(\sigma_{ref}^2 + \sigma_{ex}^2})$; where σ_{ref} and σ_{ex} are standard deviation of the reference and excited trajectories respectively. A part of the measurement scatter comes from a low frequency beam noise of the order of a few Hz. Thus, σ is a more useful measure of errors than $\frac{\sigma}{\sqrt{N_P}}$ in this case as it represents heterogeneity of the data from its mean unlike $\frac{\sigma}{\sqrt{N_P}}$ that represents uncertainty in mean position and useful in case of a random noise.

A set of new quadrupole strength calibration coefficients was obtained after all twelve trajectories were fitted to the measurements. Figure 3 shows the calibration coefficients obtained from magnetic measurements and differential trajectory analyses. Magnetic measurements give an average quadrupole strength of 146 T/A with a RMS spread of 2.7 T/A for the F-type quads while for the D-type quadrupoles it is 85.3+/-0.3 T/A. The differential trajectory analyses lead to 139.8+/- 4.2 T/A and 80.7+/- 2.4 T/A for the F and D type quadrupoles, respectively. Noted that the first doublet and last triplets were not included in these analyses and their strength calibrations rely on the magnetic measurements. Similarly, Fig. 4 shows the strength calibration coefficients of the vertical and horizontal correctors obtained from the differential trajectory analyses. The average strength of horizontal and vertical correctors are 0.45 +/- 0.025 mT-m and 0.42 +/- 0.016 mT-m, respectively.

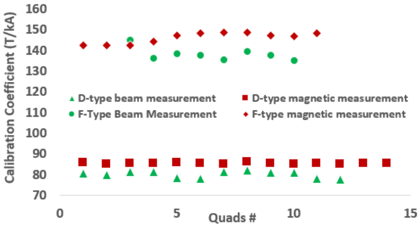

Figure 3: F-type and D type quadrupole strength obtained from magnetic measurements (brown) and from differential trajectory analyses (green).

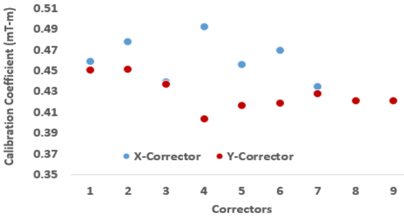

Figure 4: Calibration coefficients of the corrector magnets obtained from the differential trajectory analyses.

Error Estimation in Fitting Procedure

It could be noticed from Fig. 2 that error bars are significantly larger than the BPM resolution of several tens of microns, particularly in the vertical plane. It is because of beam centroid motion between the pulses. Figure 5 shows a typical RMS scatter of the horizontal and vertical beam centroids at respective BPMs. A comparison of pulse to pulse jitter analysis with the optical model shows that this beam motion originates upstream of the RFQ. However, attempts to locate and eliminate its source were unsuccessful so far. This relatively large beam centroid motion limits how well the model trajectories can be constrained and leads to large error bars when determining calibration coefficients. In order to understand the quality of the fitting procedure, an error analysis was performed. The strength calibration coefficients of all quadrupoles in the model were changed by a same factor and the resulting accumulated error was calculated. The accumulated error is estimated using $error = \sqrt{(x_{mea} - x_{sim})^2 + \cdots / n_{BPM}}$ where x_{sim} and x_{mea} are the model predicted and measured beam centroid positions at each BPM and n_{BPM} is total number of BPMs. The total error, accounting both horizontal and vertical planes is estimated using expression $error_{xy} = \sqrt{(error_x^2 + error_y^2})$.

Because, the differential trajectories obtained by exciting first set of correctors (M00C) provide the maximum number of measured points, they were chosen to carry out the error analysis. Figure 6 shows that accumulated errors are larger for the horizontal trajectory than for the vertical and therefore, total errors are dominated mainly by the horizontal trajectory fitting. Even after accounting for the BPMs statistical errors, the deviation of the calibration coefficient obtained with differential trajectory measurements from those obtained with the magnetic measurement lay in the range of 6% to 14%. Even including quadrupole hysteresis effect and a 1-2 % reduction in strength when quadrupoles are powered in a triplet assembly, this analysis clearly indicates inconsistencies in determining the quadrupole strengths between magnetic measurements and beam-based measurements.

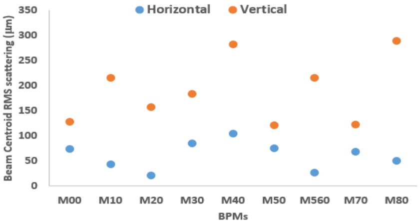

Figure 5. RMS scatter of beam positions at BPMs along the MEBT. Data were recorded for 10 minutes at 20 Hz.

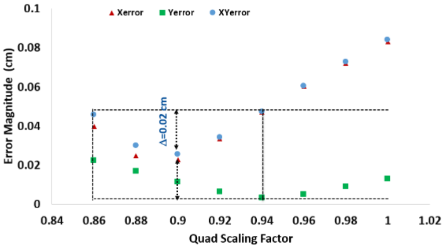

Figure 6: Deviation of the vertical (green), horizontal (red) and total (blue) accumulated error as a function of the quadrupole strength scaling factor for the differential trajectories measured using M00C. Two horizontal dashed line are separated from the minimum of the total accumulated error by total statistical measurement error in *x* and *y* positions which is 0.02cm.

Reproducibility of the optics is essential for long term operation. To quantify the optics reproducibility in the MEBT, differential trajectory measurements were performed before and after a shut-down of the machine. It can be observed from Fig. 7 that M00C differential trajectories were reproducible with a maximum difference of 150 μm and within a scatter of one RMS.

Beam Size Measurements:

Transverse beam sizes along the MEBT are measured using the scraper scans. A description of that method has been presented in [4]. In addition, an Allison scanner, installed at the end of the beamline, provides vertical phase space portrait hence, vertical beam size. Figure 8 shows a typical vertical phase portrait with a normalized RMS vertical emittance of 0.21 μm. In order to predict beam sizes along the MEBT, new quadrupole strengths obtained from the differential trajectory measurements were applied to the model. Next, using TRACEWIN [5] simulations initial transverse Twiss parameters at exit of the RFQ were adjusted such as to fit the measured RMS beam sizes at the first three scrapers. Normalized RMS transverse and longitudinal emittances of 0.2μm and 0.28μm respectively were used for the fit. Using these parameters, a 5mA beam is tracked through the entire MEBT. Figure 9 shows the predicted transverse RMS beam envelope agrees with the measurements within 10% error bars.

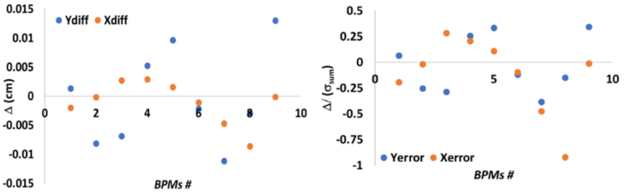

Figure 7: (Left) Difference and (right) scatter of the difference w.r.t total RMS scatter (σ_{sum} is the square root of the RMS scatter summed in quadrature in all BPMs) of the M00C differential trajectories measured on two different days for the same quadrupole settings.

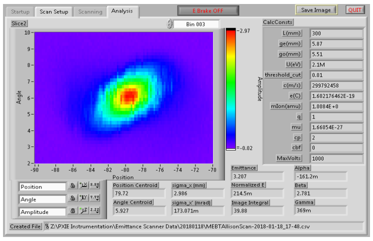

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Figure 8: Typical vertical phase portrait measured in the MEBT.

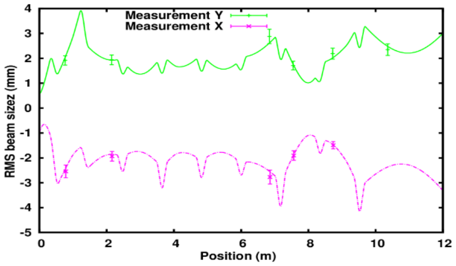

Figure 9: Beam RMS sizes along the MEBT simulated with TRACEWIN. Error bars are +/- 10% of the measured sizes.

CONCLUSION

Transverse beam optics have been characterized in the PIP2IT MEBT. Beam-based calibration of quadrupoles and steering correctors were obtained using differential trajectory measurements. It was found that even after accounting statistical measurement errors, average quadrupole strengths obtained from beam based measurements differ by more than 5% from those determined by direct magnetic measurements. An optical model developed using TRACEWIN enables to predict transverse beam sizes within 10% accuracy. The model would improve with a better understanding of longitudinal beam parameters, which are not very well known presently.

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REFERENCES

[1] L. Prost *et al.*, "PIP-II Injector Test Warn Front End: Commissioning Update," presented at IPAC'18, Vancover, Canada, April 2018, paper THYGBF2, this conference.

[2] J. Galambos, "SNS Commissioning Strategies and Tuning algorithms," HB2006, Tsukuba, Japan, 2006, paper THAZ02, pp. 283. `https://accelconf.web.cern.ch/accelconf/abdwhb06/PAPERS/THAZ02.PDF`

[3] http://home.fnal.gov/~ostiguy/OptiM/.

[4] A. Shemyakin *et al.*, "Characterization of the beam from the RFQ of the PIP-II Injector Test", in *Proc. IPAC'17*, Copenhagen, Denmark, April 2017, paper TUPVA139, pp. 2425-2428.

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