ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-TUP074

OPTICS RECONSTRUCTION IN THE SCL SECTION OF THE FNAL LINAC*

J.-P. Carneiro†, E. Chen, A. Pathak, R. Sharankova, A. Shemyakin
Fermi National Accelerator Laboratory, Batavia, IL, USA

Abstract

The Side-Coupled Linac (SCL) section of the FNAL linac accelerates the beam from 117 MeV to 401.5 MeV, operating at 22-24 mA beam current. Transverse focusing is performed by 32 quadrupoles, and the beam orbit is guided by 19 dipole correctors and measured by 29 BPMs. The bunch length is measured in a single location by a Bunch Shape Monitor (BSM). This paper presents a three-step reconstruction of the machine optics. First, the transverse and longitudinal Twiss parameters at the start of the SCL section are determined using quadrupole scans and BSM measurements at different settings of an upstream cavity. Second, the quadrupole calibrations are adjusted based on differential-trajectory measurements. Finally, the beam is propagated along the SCL linac using the code TraceWin. A comparison between TraceWin simulations and the beam envelope measured by the 12 wire scanners of the SCL linac is performed. Transverse and longitudinal beam parameters at the entrance of the transition section are reported.

INTRODUCTION

The front-end of the Fermilab linac [1] consists of an Ion Source producing 35 keV H^- beam and a Low Energy Beam Transport (LEBT) that matches the H^- beam produced by the source into a 4-rod RFQ operating at 201.25 MHz. The beam exits the RFQ with an energy of 750 keV and is matched into a Drift Tube Linac (DTL) by a Medium Energy Beam Transport (MEBT) made of two quadrupole doublets and one buncher. The DTL section operates at 201.25 MHz and consists of 207 drift tubes distributed over 5 DTL tanks. At the exit of the DTL Tank5, the H^- beam has an energy of 117 MeV. A 4-meter Transition section made of four quadrupoles and two 805 MHz cavities (the Buncher and the smaller Vernier) ensures proper matching between the DTL Tank5 and the Side Coupled Linac (SCL) section, which further accelerates the beam to 401.5 MeV. The SCL section consists of seven 805 MHz modules, with each module containing four Side-Coupled Cavities (SCC). Transverse focusing on the DTL, transition and SCL sections is made by quadrupoles.

Upon exiting the SCL section, the beam travels about 70 meters for injection into the 8 GeV Booster synchrotron. During daily operation, the linac outputs 22-24 mA beam in 35 µs long pulses at 15 Hz repetition rates.

In this paper, we present an attempt to reconstruct the Twiss parameters at the start of the Transition section, based on beam measurements and the beam dynamics code TraceWin [2]. In the second part of the paper, we describe a method based on differential trajectory method and the code Linac_Gen [3] for calibration of the Transition and SCL sections quadrupoles. Finally, we discuss the status of agreement between measured and reconstructed beam envelopes along the Transition and SCL sections.

* Work produced by FermiForward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.
† carneiro@fnal.gov

TWISS RECONSTRUCTION

Figure 1 shows a schematic of the Transition section and the start of the SCL section (Module 1, Cavities 1 and 2). We attempted to reconstruct the Twiss at the Beam Position Monitor downstream of the DTL Tank5 (as shown in Fig. 1), for normal operation at 23.7 mA. A summary of the reconstructed Twiss parameters at this location is reported in Table 1.

Table 1: Reconstructed Beam Parameters at the Start of the Transition Section (BPM Downstream Tank5, See Fig. 1)

Beam Parameters	Values
Energy	117 MeV
Beam current	23.7 mA
Alpha X	-0.49
Beta X	9.03 mm/mrad
Emittance rms norm. X	0.9 mm-mrad
Alpha Y	0.35
Beta Y	1.89 mm/mrad
Emittance rms norm. Y	0.8 mm-mrad
Alpha Z	-0.5
Beta Z	8.0 mm/mrad
Emittance rms norm. Z	1.0 mm-mrad
Emittance rms norm. Z	0.45 deg-MeV

We first started the Twiss reconstruction by performing a calibration of the Buncher and the Vernier during nominal operation. The signals of the downstream BPMs are recorded as a function of the Buncher and Vernier phases. The BPM signals (recorded at the base frequency of 402.5 MHz) are then reconstructed with TraceWin which allowed us to estimate the operating effective gap voltages and synchronous phases of the Buncher and Vernier. We estimate from these BPM studies that the Buncher and Vernier are operating daily with an effective gap voltage of respectively $E_0T = 1.68$ MV/m and $E_0T = 2.95$ MV/m and that both cavities operate with a synchronous phase of -90 deg.

ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-TUP074

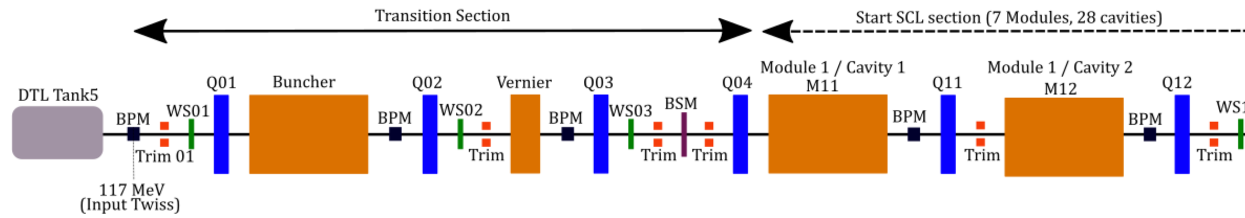
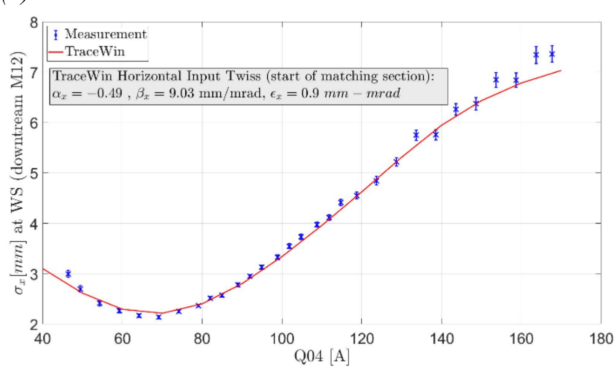


Figure 1: Schematic of the FNAL Transition section (117 MeV) and start of the SCL section.

With the Buncher and Vernier calibrated, the longitudinal emittance is estimated by measuring the rms bunch length at the Bunch Shape Monitor (BSM, located between Q03 and Q04 in Fig. 1) as a function of the Buncher phase (with the Vernier off) and comparing it with TraceWin simulations. A description of the BSM measurements is reported in Ref. [4]. The best fit corresponds to the input Twiss parameters (at the BPM downstream of the DTL Tank5) of $\alpha_z = -0.5$, $\beta_z = 8$ mm/mrad and a rms normalized longitudinal emittance of 1.0 mm-mrad.

To reconstruct the transverse Twiss, a quadrupole scan using the last quadrupole of the Transition section (Q04, Fig.1) and the first Wire Scanner of the SCL section (WS12, Fig. 1) is performed. Figure 2 shows the Horizontal (a) and Vertical (b) quadrupole scans Q04-WS12.

(a)



(b)

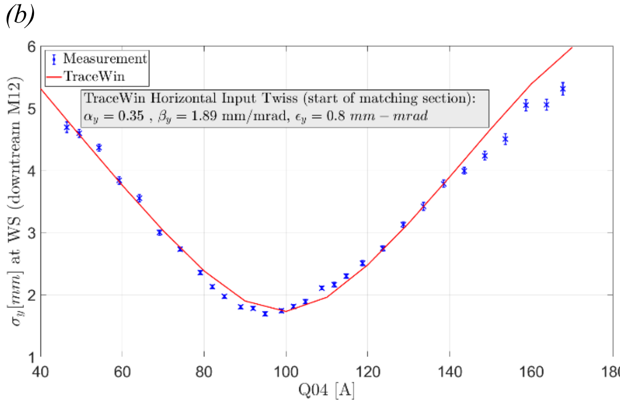


Figure 2: (a) Horizontal and (b) Vertical quadrupole scans Q04-WS12 with TraceWin reconstruction.

During the quadrupole scans, the Buncher and Vernier were operating at their nominal values (as previously described) and the quadrupoles Q01, Q02 and Q03 were optimized to enable the waist in both the horizontal and vertical planes at WS12 during the scan of Q04. All the elements between Q04 and WS12 were turned off, making the distance between Q04 and WS12 (3348 mm) a drift. The Twiss parameters at Q04 are extracted using the quadratic fits (without space charge) of the rms beam sizes at the WS12. Then the beam is backpropagated to the initial point (BPM downstream Tank 5) with TraceWin without space charge. Then, the Twiss parameters and emittance in this location are adjusted manually, and TraceWin simulations are repeated in the forward direction in the presence of space charge (corresponding to the beam current of 23.7 mA) to better match the measured rms sizes at W12 as a function of Q04. The found Twiss parameters are reported in Table 1 and Fig. 2.

ENVELOPE IN TRANSITION SECTION

Figure 3 shows the measured envelope in the Transition section at the Wire Scanners WS01, W02 and WS03 (marked in Fig. 1).

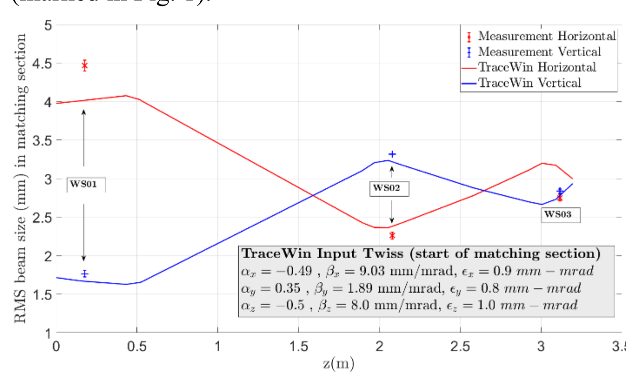


Figure 3: Measured envelope at the 3 Wire Scanners of the matching section and comparison with TraceWin.

This envelope measurement was performed the same day as the horizontal and vertical quadrupole scans mentioned above, but with the quadrupole settings in the Transition section corresponding to daily operation of the linac, which are different from those set for the quadrupole scans. One can observe in Fig. 3 that the measured and simulated envelope is in good agreement in the vertical plane, but the horizontal plane shows disagreement significantly exceeding the measurement errors, 10% in WS01 and 13% in WS03. We see two possible culprits. First, the initial beam energy (from Tank5) and phases of the Buncher and Vernier with respect to the beam are assumed to be at the design values, while measurements in Ref. [4] hint on possible significant deviations. In that case, transverse defocusing by the RF cavities could be different. Second, the described reconstruction uses the design values of quadrupole calibrations. However, the procedure described in the following section points that they can be different.

ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-TUP074

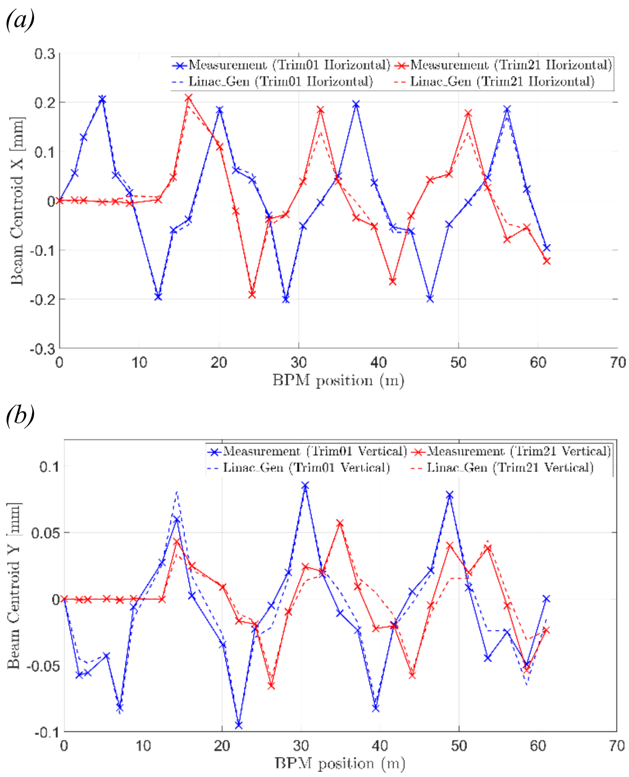


Figure 4: (a) Horizontal and (b) Vertical beam centroid motion measured and reconstructed with Linac_Gen, at all 29 BPMs of the Transition and SCL sections, for a current of 0.1 A in Trim01 (downstream DTL Tank5, see Fig1) and Trim 21 (downstream of Module 2, Cavity 1).

QUADRUPOLES CALIBRATION

To address possible deviations of quadrupole calibrations from those implemented in the present model, we attempted to use the method of differential trajectories. The differential trajectory, or orbit response, is the deviation of the trajectory from a reference resulting from a change in a dipole corrector ("trim") current. In our implementation of this method, responses in all BPMs to all correctors (Orbit Response Matrix, ORM) are measured with oscillating trajectories [5]. Then, the code Linac_Gen, developed at Fermilab, adjusts in simulations the calibrations of all 32 quadrupoles of the Transition and SCL sections to match the measured responses of 29 BPMs in both planes. Figure 4 shows the result of such fitting for 4 trajectories. In most points, fitting is good. The new quadrupole calibrations from Linac_Gen stay within 10% of their initial values. However, the result of application of the found corrections to simulation of beam envelope is discouraging.

Figure 5 shows the beam rms sizes measured with the 12 Wire Scanners in the SCL. They are compared with TraceWin predictions for the envelope in two cases, with the initial quadrupole calibrations and the ones suggested by Linac_Gen for the best fitting of data in Fig. 4. The measured beam sizes and those from TraceWin do not agree, and disagreement becomes worse for the adjusted calibrations.

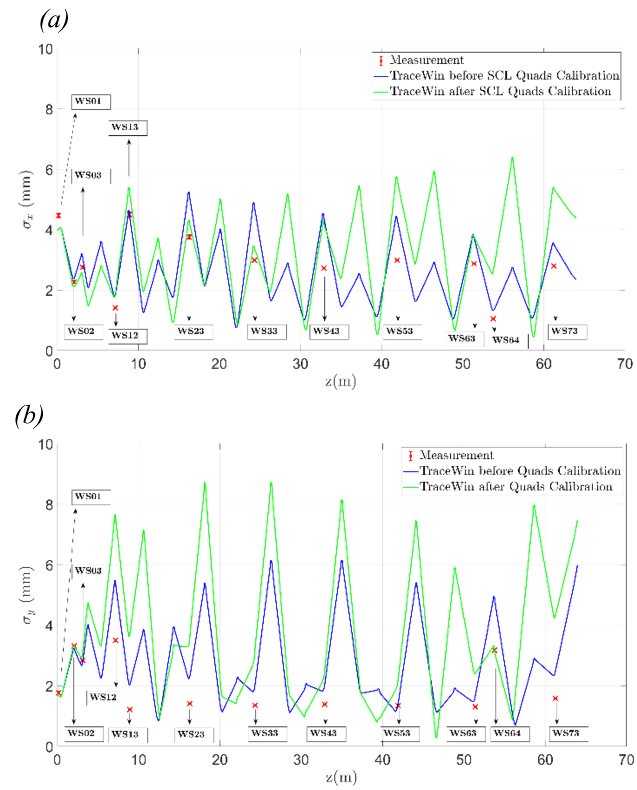


Figure 5: (a) Horizontal and (b) Vertical beam sizes measured and reconstructed with TraceWin, at all 12 Wire Scanners of the Transition and SCL sections. Simulations are performed before/after quads calibration from Linac_Gen.

The result contradicts to the previous successful experience of authors with similar procedure ([6], [7]), and presently we do not have a satisfactory explanation. One possibility is that the reconstruction of the initial beam parameters is not accurate enough, as discussed in the previous section. Another possible hypothesis is that the transverse defocusing by cavities is accounted incorrectly. It might happen because in simulations the phases and fields of the 28 SCL cavities are set to their design values, while there are indications of significant deviations. We plan further work to characterize the longitudinal dynamics in the SCL section, which should test this hypothesis.

REFERENCES

[1] E. S. McCrory, "The Commissioning and Initial Operation of the Fermilab 400 MeV Linac", in *Proc. LINAC'94*, Tsukuba, Japan, Aug. 1994, pp. 36-40. https://accelconf.web.cern.ch/l94/papers/MO2-02.pdf

[2] Tracewin code: http://irfu.cea.fr/Sacm/logiciels/

[3] A. Pathak, "Linac_Gen: integrating machine learning and particle-in-cell methods for enhanced beam dynamics at Fermilab", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 1695-1697. doi:10.18429/JACoW-IPAC2024-TUPS28

ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-TUP074

[4] R. Sharankova *et al.*, “Measurements of the beam longitudinal properties in the Fermilab Linac”, presented at NAPAC’25, Sacramento, USA, August 2025, paper TUP065, this conference.

[5] A. Shemyakin, A. Pathak, and R. Sharankova, “Measuring orbit responses with oscillating trajectories in the Fermilab Linac”, presented at NAPAC’25, Sacramento, USA, August 2025, paper THP053, this conference.

[6] A. V. Shemyakin *et al.*, “Experimental Study of Beam Dynamics in the PIP-II MEBT Prototype”, in *Proc. HB'18*, Daejeon, Korea, Jun. 2018, pp. 54-59. doi:10.18429/JACoW-HB2018-MOP1WB03

[7] J.-P. Carneiro, B. M. Hanna, E. Pozdeyev, L. R. Prost, A. Saini, and A. V. Shemyakin, “Beam Dynamics Studies at the PIP-II Injector Test Facility”, in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 601-604. doi:10.18429/JACoW-LINAC2022-TUPORI24