ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK047

COMPARISON OF PROFILE MEASUREMENTS AND TRANSPORT BEAM ENVELOPE PREDICTIONS ALONG THE 80-m LANSCE pRad BEAMLINE*

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Abstract

Here we report a comparison between the simulation of beam phase-space and profile distributions with diagnostic measurements. TRANSPORT, a particle transport code, was used for the prediction of a 800 MeV proton beam envelope from the end of the linac to the proton radiography (pRad) facility (a total length of 80 meters). The beam profile was measured at key positions along the beamline using wire scanners and gated CCD camera systems. These measurements were compared to their respective points along the simulated beamline. The predicted beam envelope and measured data correspond within expected errors.

INTRODUCTION

The Proton Radiography (pRad) [1,2] experimental facility is one of six user facilities at the Los Alamos Neutron Science Center (LANSCE) [1,3]. An H$^-$ beam is accelerated using a Drift Tube Linac (DTL) and a Couple Cavity Linac (CCL) to an energy of 800 MeV and transported to pRad. The beam transport line, starting at the end of the 800 MeV linac, is composed of many bending and focusing elements before it reaches the pRad beam optics system. The beam spot size requirement is nominally 2 mm (RMS). Small field variations of the beamline quadrupoles and/or bending magnets from the standard tune can lead to unwanted radiation spill, and potential beamline elements damage. Therefore, simulation of the beam envelope throughout the beamline is crucial in understanding the beam bunch distribution during transport. Good agreement with diagnostics measurements significantly improves our ability to predict beamline performance under various beam conditions.

In this report, we present the beam sizes obtained using the Fermilab modified version of the TRANSPORT [4] beam envelope code, as well as size measurements along the beamline. The input beam parameters for the code were extracted from emittance measurements at the end of the linac. The longitudinal input beam parameters were extrapolated from lower-energy data. New length and magnetic field measurements of the beamline elements were also incorporated.

LINE XC BEAMLINE

The Line XC, referred to as the pRad beamline, starting at the end of the Linac to pRad entry point (LCTV4), consists of 15 quadrupoles, 15 bending magnets, 9 wire scanners for beam profile measurements, 6 gated CCDs for imaging, current monitors, vacuum system, and associate mechanical and electrical systems. The effective lengths of the each quadrupoles varying from 0.17 m to 0.77 m with bore radius from 0.025 m to 0.077 m. Magnetic fields in these magnets range from 0.08 kG to 4.46 kG field. Details of the Line XC is not addressed in this report.

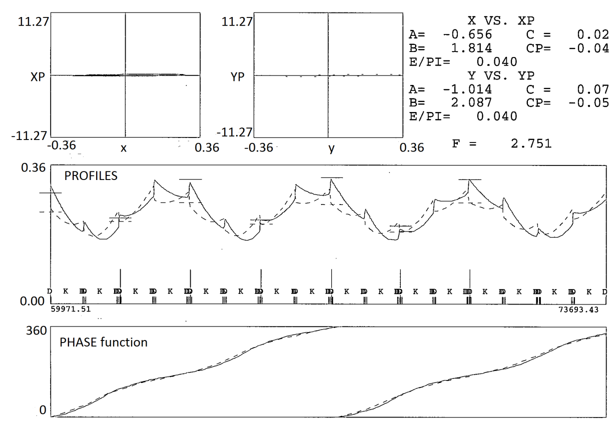

Figure 1: Measurement of phase-space parameters at the end of 800 MeV linac.

TWISS PARAMETERS AND BEAM PROFILE

The Twiss parameters are defined in terms of the phase-space ellipse of a beam. Figure 1 shows measured emittance data at the end of 800 MeV linac. The first three lines in Table 1 show measurements of the Twiss parameters α, β, and RMS emittance (ε) for 800 MeV beam. These measurements were used to extract the input beam parameters (x, x′, y, y′) for the TRANSPORT code. The longitudinal beam parameters were also necessary for the simulation. The momentum spread ($\Delta p/p_0$) was calculated from the same measured emittance used for the transverse input, but also used previously measured moment spread and beam dispersion.

A well known relation between the Twiss parameters of an ellipse is [5]

$$\gamma = \frac{1+\alpha^2}{\beta} \tag{1}$$

The maximum width of the beam envelope in the x-plane

$$x_{max} = \sqrt{\sigma_{11}} = \sqrt{\beta\varepsilon} \qquad (cm) \tag{2}$$

* LA-UR-18-22885. Work supported by the United States Department of Energy, National Nuclear Security Agency, under contract DE-AC52-06NA25396.

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where, σ_{11} is an element of the beam matrix σ [4]. The square roots of the diagonal terms of the sigma matrix provide the beam size in each coordinate of the ellipsoid. Thus, the maximum angular divergence of the beam envelope in the x-plane

$$\theta_{max} = x' = \sqrt{\sigma_{22}} = \sqrt{\gamma\varepsilon}. \qquad (mrad) \qquad (3)$$

From Eqs. (2), and (3), we find, respectively,

$$\beta = \frac{\sigma_{11}}{\varepsilon} \qquad (4)$$

$$\gamma = \frac{\sigma_{22}}{\varepsilon} \qquad (5)$$

By using Eqs. (4) and (5) in Eq. (1), the dimensionless Twiss parameter, α, can be written as,

$$\alpha = \sqrt{\frac{\sigma_{11}\sigma_{22}}{\varepsilon^2} - 1} \qquad (6)$$

Therefore, Eqs. (6), (4) and (5) provide α, β, and γ; once, σ_{11}, σ_{22} are known by execution of TRANSPORT. The emittance, ε, fixed in TRANSPORT.

Additional input parameters such as: (1) longitudinal beam extend, (2) momentum, and (3) the momentum spread are also required to execute TRANSPORT. These are calculated using the following methods.

Longitudinal Beam Extent (L)

The longitudinal beam extent is related to the velocity factor, $\beta_{(E)}$, RF wavelength of the cavity (λ), phase width ($\Delta\varphi$) and finally a factor (F) which approximate the effect of phase damping. The longitudinal beam extent is given by

$$L = \beta_{(E)}\lambda\frac{\Delta\varphi}{360^\circ} \times F, \qquad (7)$$

where $\Delta\varphi$ is the beam phase width in degrees. The wavelength, λ=c/f, is 37.267 cm, for the RF frequency (f) of 805×10^6 Hz and usual value of velocity of light (c). The factor, F, a ratio of an initial phase width ($\Delta\phi_1$) to the width at some later point ($\Delta\phi_2$) in the accelerator is [6]

$$F = \frac{\Delta\phi_2}{\Delta\phi_1} = \left(\frac{\beta_1\gamma_1}{\beta_2\gamma_2}\right)^{3/4} = \left(\frac{\beta_{(121)}\gamma_{(121)}}{\beta_{(800)}\gamma_{(800)}}\right)^{3/4} \qquad (8)$$

where, $\beta_{(121)}$ is the relativistic velocity factor, and $\gamma_{(121)}$ is the energy factor at 121 MeV; and $\beta_{(800)}$ is a relativistic velocity factor, and $\gamma_{(800)}$ is an energy factor at a higher energy (800 MeV). The velocity and energy factors are given by

$$\beta_{(E)} = \frac{\sqrt{(\gamma_{(E)})^2 - 1}}{\gamma_{(E)}} \qquad (9)$$

and

$$\gamma_{(E)} = 1 + \frac{T}{E_0} \qquad (10)$$

where, T is the beam energy (in MeV), and E_0=938.3 MeV (rest energy of a proton). Using these equations to estimate the phase-damping at 800 MeV gives F=0.441.

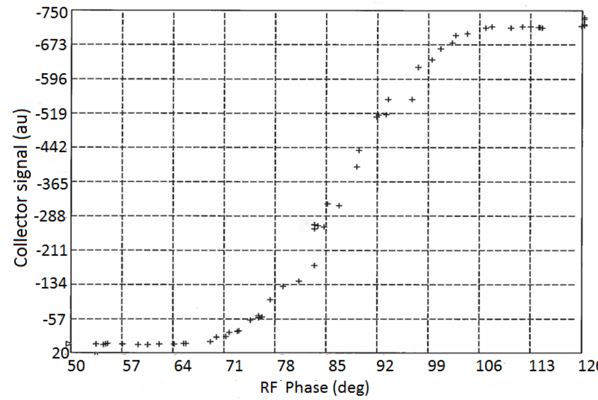

Figure 2: Measurement of RF phase at 121 MeV.

Figure 2 shows a phase scan data at 121 MeV. For a phase width, $\Delta\varphi = 25^\circ$, the estimated beam extent at 800 MeV is

$$L = \beta_{(121)}\lambda\frac{\Delta\varphi}{360^\circ} \times F \sim 0.52\ cm \qquad (11)$$

Momentum (p_0) in GeV/c

The beam momentum, (p_0), of a 800 MeV beam is given by

$$p_0 = \beta_{(800)}\gamma_{(800)}\frac{E_0}{c} = 1.463\ GeV/c \qquad (12)$$

Momentum Spread The spread in the beam momentum is defined by

$$\frac{\Delta p}{p_0} = \frac{\sqrt{(R_x)^2 - \beta_x(4\epsilon_{x-rms})}}{\eta} \qquad (13)$$

where, R_x is the 2RMS horizontal beam size (cm) at a location of wire scanner LDWS3X; β_x is the horizontal beta-function (cm/mrad) at the LDWS3X; ϵ_{x-rms} is the unnormalized horizontal rms beam emittance (π-mm-mrad), and η is the dispersion function at the LDWS3X (cm/%). If R_x=0.5793 cm, β_x=1.11236 cm/mrad, ϵ_{x-rms}=0.04 π-cm-mrad, and η=4.8798 cm/%, the beam momentum spread is

$$\frac{\Delta p}{p_0} = \frac{\sqrt{(0.58)^2 - 1.112\times4\times0.04}}{4.88} = 0.0816\% \qquad (14)$$

TRANSPORT AND MEASUREMENTS

Table 1 summarizes the necessary TRANSPORT input beam phase-space parameters obtained by emittance measurements at the end of the linac and as calculated in the previous section. Updated measurements of drift spaces, magnet fields and diagnostics locations were also used.

Figure 3 shows calculated beam envelopes using TRANSPORT. The beam size at the pRad entrance is ≃ 2mm radius (2RMS). A few examples of beam profile measurements are shown in Fig. 4. Figure 5 shows measured beam profiles at diagnostics locations (black dots in solid line) and the predicted envelope (hollow circles in dotted line) using

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Table 1: TRANSPORT Input Parameters at 800 MeV

Items	X vs XP	Y vs Yp
α	-0.656	-1.014
β	1.814 $\frac{\text{cm}}{\text{mrad}}$	2.087 $\frac{\text{cm}}{\text{mrad}}$
ε	0.040 cm(mrad)	0.04 cm(mrad)
$4{\times}\varepsilon$	0.16 cm(mrad)	0.16 cm(mrad)
γ (Eq.1)	0.788 $\frac{\text{mrad}}{\text{cm}}$	0.972 $\frac{\text{mrad}}{\text{cm}}$
x_{max} (Eq. 2)	0.538 cm	
y_{max} (Eq. 2)		0.577 cm
x'_{max} (Eq.3)	0.355 mrad	
y'_{max} (Eq.3)		0.394 mrad

TRANSPORT. The top and bottom graphs represent horizontal and vertical profiles along the pRad beamline. Variations of up to 30% were observed between simulation and measurements. We used many legacy diagnostics and accurate resolution of each of the diagnostics were unknown. In addition, there might be some analysis error due to low-level signal. Therefore, variation between measurements and predictions at the beginning or at the end of the beamline stands for uncertainty of measurements.

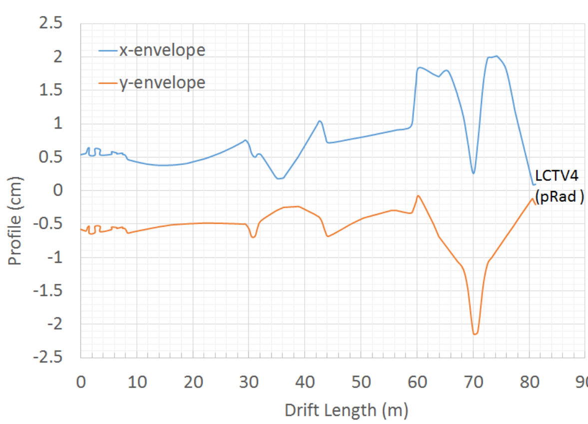

Figure 3: TRANSPORT calculated beam envelope.

CONCLUSION

The beam emittance measured at the end of the 800 MeV-linac was used as a part of the required input data for TRANSPORT. The beam profile was measured at various locations using wire scanners and gated cameras. Measured data and TRANSPORT predictions were directly compared and found in reasonable agreement. These results will be used to improve our tuning of the pRad beamline.

ACKNOWLEDGMENT

The authors wish to thank Bob Garnett for reviewing this proceeding. Thanks to Mark Gulley and Larry Rybarcyk for useful discussions regarding data collection process.

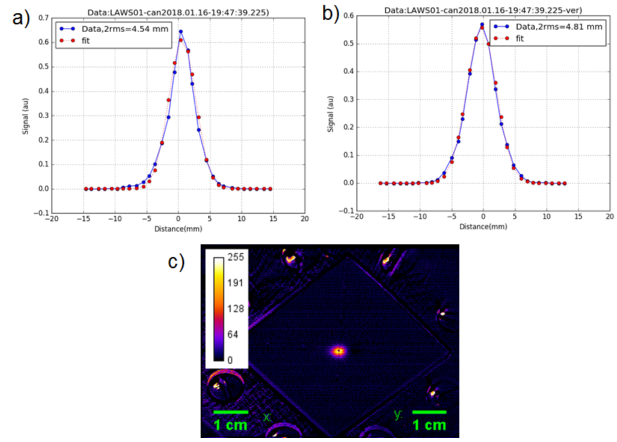

Figure 4: The beam profile at the end of linac a) horizontal and b) vertical, measured using a wire scanner; and (c) the beam profile at the end of the transport section using a gated CCD (LCTV4).

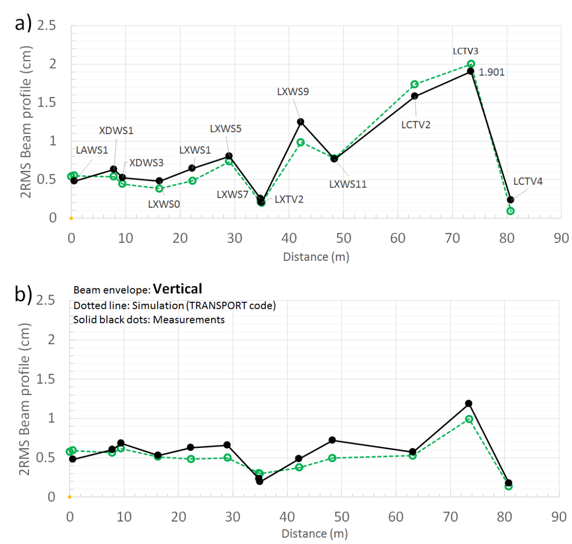

Figure 5: Measured (black dots in solid line) and calculated (hollow circles in dotted line) profiles along the beamline. (a) A horizontal profile and (b) a vertical profile.

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