FERMILAB HINS PROTON ION SOURCE BEAM MEASUREMENTS*

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Abstract

The proton ion source for the High Intensity Neutrino Source (HINS) Linac front-end at Fermilab has been successfully commissioned. It produces a 50 keV, 3 msec beam pulse with a peak current greater than 20 mA at 2.5 Hz. The beam is transported to the radio-frequency quadrupole (RFQ) by a low energy beam transport (LEBT) that consists of two focusing solenoids, four steering dipole magnets and a beam current transformer. To understand beam transmission through the RFQ, it is important to characterize the 50 keV beam before connecting the LEBT to the RFQ. A wire scanner and a Faraday cup are temporarily installed at the exit of the LEBT to study the beam parameters. Beam profile measurements are made for different LEBT settings and results are compared to those from computer simulations. In lieu of direct emittance measurements, solenoid variation method based on profile measurements is used to reconstruct the beam emittance.

INTRODUCTION

Fermilab is considering an 8 GeV superconducting H^- linac with the primary mission of enabling 2 MW beam power from the 120 GeV Fermilab Main Injector for a neutrino program [1]. New paradigms introduced into the front-end design include the adoption of short, high field superconducting solenoids as primary lattice focusing elements and a low energy transition at 10 MeV from room temperature to superconducting RF acceleration. The front-end linac in the energy range from 10 MeV to 400 MeV is foreseen as based on 325 MHz superconducting spoke resonators. The HINS R&D program is underway to demonstrate these concepts in a 30 MeV prototype linac [2].

The proton ion source and the LEBT for the HINS linac front-end has been successfully commissioned. The output beam will feed the RFQ which is currently under RF commissioning. To understand beam transmission through the RFQ, a set of beam measurement and analysis has been carried out to characterize the ion source beam parameters and to accumulate beam control experience. These studies include transverse beam profile measurement, beam emittance estimation and beam steering control under solenoidal field through solenoid magnets. The results are discussed in this article.

THE PROTON SOURCE AND LEBT

The Fermilab HINS proton source is a duoplasmatron which is capable of producing 50 keV proton beam with a pulse duration from 65 μs at 15 Hz to 3 ms at 2.5 Hz and a peak current greater than 20 mA. The beam is transported to the RFQ by a LEBT. The layout of the LEBT is shown in Fig. 1. The LEBT consists of, in sequence, an UpStream (US) Solenoid, four steering dipole magnets (one horizontal and one vertical at each location), and a DownStream (DS) Solenoid. The two solenoids are identical and each produces a magnetic field of up to 7900 G at 850 A. The dipoles generates a magnetic field of 100 G at 3 A.
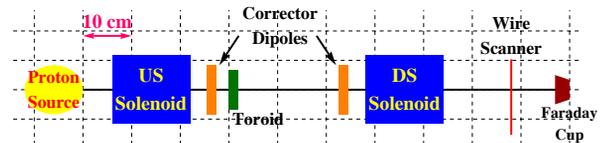

Figure 1: Layout of the HINS LEBT.

A toroid is installed in the LEBT for beam current monitoring. A wire scanner and a Faraday cup are installed at the exit of the LEBT. Beam studies and analyses in this article are based on measurements made using the wire scanner.

BEAM MEASUREMENTS AND ANALYSES

Beam Profile Measurements

Horizontal and vertical beam profiles are measured using the wire scanner. Figure 2 shows the results of a measurement for a 48 keV proton beam with a pulse length of 100 μs at 0.5 Hz and a peak current of 8 mA as recorded by the toroid. The reading at the Faraday cup is 3.5 mA. The two solenoids were optimized to locate the beam waist at the wire scanner.

In Fig. 2(a), the data points reflect the integrated electric charge as seen by the wire at every step across the beam pipe. The narrow peak is considered as the profile of the proton beam. The background signal comes from other particle species in the beam, which are believed to be mostly H_2^+. Notice that other particle species fill the whole beam pipe, whose inner radius is 16.5 mm. Two Gaussian distributions, one for the proton and one for the H_2^+, are used to fit the raw data. The fitting has a coefficient of determination, the R^2 value, larger than 0.99. The profile of the
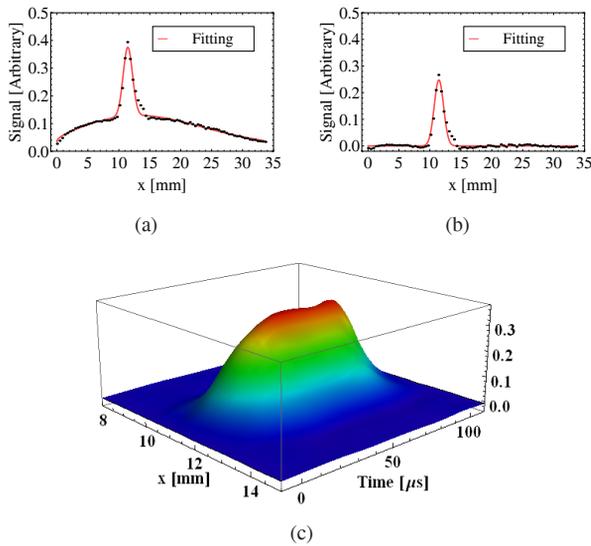
(a)

(b)

(c)

Figure 2: Beam profile measurement using wire scanner. (a) The fit has a R^2 value of larger than 0.99. (b) The fit is able to extract the profile of the proton beam from raw data. (c) The beam has a flat-top of about 50 μs. For this measurement the RMS beam size is 0.64 mm $\pm$ 2 %.

proton beam is nicely extracted for the fitting. A plot of data with the background subtracted is shown in Fig. 2(b). The RMS beam size, σ_{rms}, obtained from this measurement is 0.64 mm $\pm$ 2 %. Figure 2(c) is a plot showing the time structure of the proton beam pulse. This 100 μs pulse beam has a flat-top of about 50 μs.

Emittance Estimation

In lieu of direct emittance measurements, we attempt to reconstruct the beam emittance by solenoid variation method. This is done for a 48 keV 8 mA beam and is shown in Fig. 3. Similar to the well-known quadrupole scan method, the two focusing solenoids are optimized to locate the beam waist at the wire scanner. Beam profiles are measured for a range of DS Solenoid current.

For the quadrupole scan method, the measured beam size as a function of focusing strength can be used to fit a parabola and the RMS emittance can be obtained from the fitted parameters [3]. However, in our case, the solenoid physical length is comparable to its focal length that the solenoid cannot be considered as a thin-lens. We are not able to obtained reasonable results from parabola fitting.

The solution to the Kapchinskij-Vladimirskij (KV) envelope equation is used to fit the data. The KV equation is solved for a drift-solenoid-drift section implemented with the measured field profile for the DS Solenoid (Fig. 3(a)). The solution at the wire scanner is a function of the solenoid strength, beam current, beam emittance (ϵ_{rms}) and the twiss parameters β and α. The parameters ϵ_{rms}, β and α are independent variables of the fitting algorithm. They are varied to produce a curve that best fit the mea-

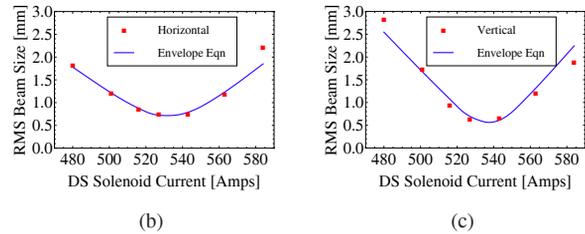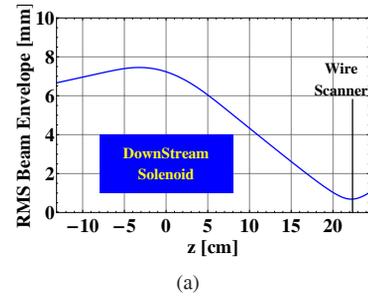**Instrumentation**

(a)

(b)

(c)

Figure 3: (a) Solution to the KV envelope equation using measured solenoid field profile. (b) and (c) Fitting to measured RMS beam sizes to obtain beam emittances.

sured beam sizes (Fig. 3(b) and 3(c)). The values of $\epsilon_{x,rms}$ and $\epsilon_{y,rms}$ obtained from the fitting routine are 23.1 and 25.1 π-mm-mrad, respectively.

Beam Rotation by Solenoid

When a beam travels through a solenoid, its horizontal and vertical dynamics are coupled due to the beam rotation by the solenoidal field. This complicates the beam orbit control system for a solenoidal transport lattice.

To understand the beam rotation through a solenoid, one can consider the trajectory of a charged particle which enters a solenoid off-axis or off-angle. The trajectory rotates about the axis of the solenoid. In the paraxial approximation, the (azimuthal) angle of rotation is given by [4]

$$\theta_{rot} = \frac{1}{2} \frac{q(B_s L_{sol})}{p}, \tag{1}$$

where q is the charge of the particle, $B_s L_{sol}$ is the longitudinal field integral along the axis of the solenoid, and $p = \gamma\beta mc$ is the mechanical momentum of the particle. θ_{rot} can also be interpreted as the angle of rotation of a beam traversing a solenoid.

Eq. 1 is tested with a set of beam rotation measurement. To measure the beam rotation, the two focusing solenoids are optimized to locate the beam waist at the wire scanner. The beam centroid is measured for different steering dipole settings. Figure 4(a) shows the results. Since the steering dipoles are located between the two solenoids, results in Fig. 4(a) reflects only the rotation by the DS solenoid. If the DS solenoid is switched off, the "square" in Fig. 4(a) should be oriented upright. Accordingly, the beam rotation in this measurement is 55 degrees.
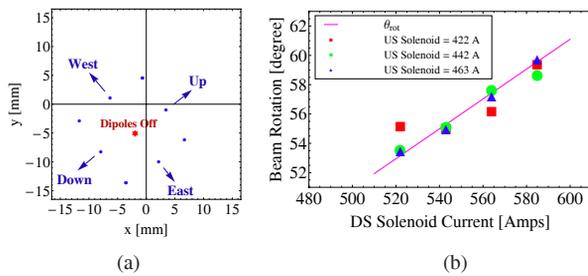
(a)   (b)

Figure 4: Beam rotation measurements. (a) Beam centroid for various dipole settings. (b) Comparison of measured beam rotation with calculations.

Figure 4(b) shows the measured beam rotation as a function of DS Solenoid current compared to results from calculation using Eq. 1. Calculation shows good agreement with measurement. This experience is important to the development of the orbit correction scheme for the higher energy section of the HINS linac, where superconducting solenoid is the primary focusing element [2].

Beam Asymmetry

Solenoid transport should deliver a round beam, i.e. $\sigma_x \approx \sigma_y$, if the input beam is axial symmetric. However, as shown in Fig. 5(a), the degree of beam asymmetry is clearly observable. We can estimate the degree of asymmetry by considering the measured beam ellipticity defined as $\text{œ}_{meas} = |\sigma_x - \sigma_y|/Max(\sigma_x, \sigma_y)$, which is calculated in Fig. 5(a). For some solenoid settings, the ellipticity of the beam can be as high as ~ 0.4. There are two possible explanations to this: (1) Asymmetric input beam from the ion source and (2) Imperfect solenoidal field, which includes solenoid misalignment errors and/or deficiency in solenoid design and manufacturing. In this section, we will examine the effect of solenoid field abberration on the shape of the beam. We will show that misalignment of solenoid alone is not sufficient to cause the observed beam asymmetry.

We perform a simple computer simulation in which an initially round beam is tracked through a solenoid which is tilted or displaced. The simulated output beam is elliptical and the ellipticity is calculated. The calculated ellipticity is defined as $\text{œ}_{calc} = 1 - (b/a)$, where b and a are the semi-minor axis and semi-major axis of the simulated beam, respectively. It is calculated near the focal point of the solenoid, where its value is largest due to the small beam size. The ellipticity as a function of solenoid tilt and offset is plotted in Fig. 5(b).

Due to mechanical limitations, the maximum offset physically allowed is 2 mm. The maximum possible tilt is 2 degree. According to Fig. 5(b), misalignment errors of this magnitude contribute less than 0.1 ellipticity, which is significantly smaller than the maximum measured ellipticity of ~ 0.4. In addition, since the beam orientation cannot be quantified by a wire scan measurement, the measured ellipticity can be zero for a very elliptical beam. Accord-
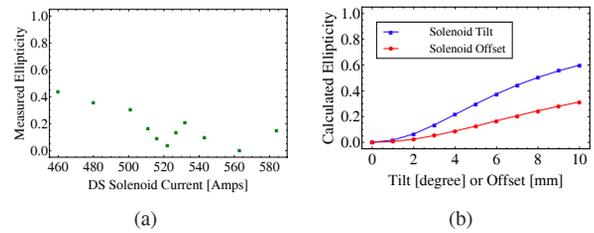

(a)   (b)

Figure 5: (a) Measured beam ellipticity from data shown in Fig. 3. (b) Calculated beam ellipticity from solenoid misalignment simulation.

ingly, the measured ellipticity is always less than or equal to the calculated ellipticity, i.e. $\text{œ}_{meas} \leq \text{œ}$. They are equal only if the measured beam, which rotates according to Eq. 1, is oriented upright.

The above analysis shows that solenoid misalignment alone is not sufficient to produce the observed high degree of beam asymmetry. These results suggest that the ion source itself is producing an asymmetric beam, or the solenoids have deficiency. Unless evidence shows that the beam asymmetry has observable adverse effect on later beam quality, at the moment we have no plan to take further action on this problem.

SUMMARY

The HINS proton ion source and the LEBT has been successfully commissioned. It is capable to produce 50 keV proton beam with a peak current higher than 20 mA at required duty factor. The horizontal and vertical beam profile are measured using a wire scanner. Solenoid variation method based on profile measurement is used to recontruct the beam emittance. The results are $\epsilon_{x,rms} = 23.1$ and $\epsilon_{y,rms} = 25.1$, both in π-mm-mrad. Beam rotation by focusing solenoid is also measured and compared to analytical calculation. The results show good agreement. This experience is important to the development of the beam orbit control algorithm for HINS solenoidal transport lattice.

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