ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THA2C1

MEASUREMENT OF TRANSVERSE BEAM EMITTANCE FOR A HIGH-INTENSITY PROTON INJECTOR*

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Abstract

We propose a simple and fast diagnostics method for the transverse beam emittance using a solenoid magnet. The solenoid scan data is analysed employing the hard edge solenoid model and thick lens approximation. The analytical method is validated by beam dynamics simulations with varying input beam parameters. To address the space charge effect in a simplified manner, the space charge force is linearized and incorporated between segments of the drift-solenoid transfer matrix. For intense hadron injectors with higher beam current accounting for space charge prove to be more effective for correction. Building upon the method validated through beam simulation, experiments are conducted on space charge compensation at the beam test stand in the Korea Multipurpose Accelerator Complex (KOMAC). In a constant ion source operating condition, beam emittance is measured from solenoid scans while varying the flow rate of krypton gas injection. Notable shifts are observed in transverse beam emittance attributable to krypton gas injection, implying some optimal gas flow rate for mitigating emittance growth.

INTRODUCTION

In the low energy beam transport section, the method of measuring the transverse beam profile with a faraday cup or microchannel plate is preferred rather than wire or grid because the ion beam has a short range in the medium. In addition, various beam diagnostic systems have been developed to obtain transverse beam emittance, such as an Allison-type scanner [1] that electrically sweeps the beamlets, a pepperpot meter that passes the beamlets through a thin mask arranged with very fine holes, or a magnet scan technique that measures the change in beam size while scanning the intensity of the focusing magnet.

The magnet scan technique has advantages in that the beam measurement system is simpler to be implemented than the Allison scanner or pepperpot meter, and it utilizes focusing magnets that are essential to control beam optics. Quadrupole magnet is commonly used in magnet scan techniques in hadron machines, because magnetic quadrupole lattices is required for hadron beams above MeV with high magnetic rigidity. On the other hand, in the low energy beam transport (LEBT) of the high-intensity linear accelerator, solenoid magnet is often used to focus beams of low magnetic rigidity. In this study, the solenoid scan technique is verified with beam dynamics simulation data, especially by linearizing the space charge effect that greatly affects the high-intensity low energy proton beam, and applying it to beam experiments.

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RFQ-BASED BEAM TEST STAND

The Radio Frequency Quadrupole-based beam test stand (RFQ-BTS) is for studying the physical characterization and industrial applications of low energy high current beams ranging from a 50 keV, 30 mA proton injector to a 1 MeV/n RFQ [2]. It is a test facility with specifications similar to those of the 100-MeV proton linear accelerator at the Korea Multipurpose Accelerator Complex (KOMAC).

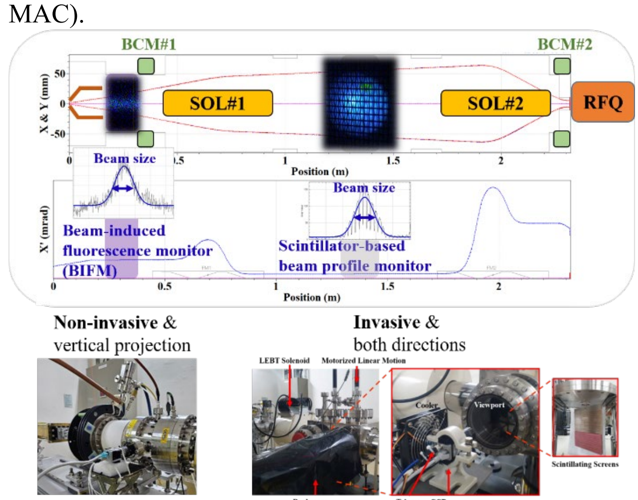

Figure 1: Layout of RFQ-based beam test stand and low energy beam diagnostics for transverse beam measurement.

The RFQ-based beam test stand has two low energy beam diagnostics for measuring the transverse beam profile as shown in Fig. 1 [3]. The beam-induced fluorescence monitor (BiFM) measures the emission light generated by interaction with the neural gas present in the beam pipe [4]. This method has the advantage of being non-invasive and enabling real-time measurement. This monitoring system is installed between the ion extraction system and the first beam optics element, the solenoid magnet, and is used to determine the initial envelope of the ion source extraction beam. The intensity of the emitted light is proportional to the product of the beam current and gas density of the ion source, assuming that the decay time of the fluorescence is much shorter than a millisecond, the normal beam pulse width of the beam test stand. Typically, the pressure of the plasma chamber corresponds to a few mTorr when generating hydrogen plasma in the microwave ion source, so the gas pressure around the beam extraction system is measured at a value close to 1 mTorr by the diffusion of hydrogen gas. Accordingly, sufficient emission light can be measured near the ion source of the high-intensity proton injector.

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The scintillator-based beam monitor (SBM) is a beam profiler that measures the scintillation light generated in the process when a screen made of a scintillating material directly blocks the ion beam. Unlike BIPM, this device is invasive to the beam, but it has the advantage of being able to obtain the beam profile of the horizontal plane and the vertical plane with only one screen and one camera pair. In the beam test stand, it is installed in the beam diagnostics chamber located between the first solenoid magnet and the second solenoid magnet and is used to measure the change in beam size during the solenoid scan process.

SOLENOID SCAN

Transverse beam distribution can be represented as the following four-dimensional matrix formalism:

$$\sigma = \begin{pmatrix} \langle x^2\rangle & \langle x'x\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle xx'\rangle & \langle x'^2\rangle & \langle x'y\rangle & \langle x'y'\rangle \\ \langle xy\rangle & \langle x'y\rangle & \langle y^2\rangle & \langle yy'\rangle \\ \langle xy'\rangle & \langle x'y'\rangle & \langle yy'\rangle & \langle y'^2\rangle \end{pmatrix} = \begin{pmatrix} \boldsymbol{\sigma}_{xx} & \boldsymbol{\sigma}_{xy} \\ \boldsymbol{\sigma}_{xy}^T & \boldsymbol{\sigma}_{yy} \end{pmatrix} \quad (1)$$

Under the paraxial approximation and thick lens hard edge approximation of a focusing magnetic field, beam transport from 0 to 1, during solenoid scan, can be calculated as:

$$\sigma_1 = M\sigma_0 M^T \quad (2)$$

where, σ_0 and σ_1 denote 4-D beam matrix before solenoid magnet and at scintillator-based beam profile monitor, and M is the transfer matrix of drift-and-solenoid.

$$M = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \quad (3)$$

In RFQ-based beam test stand at the KOMAC, ion beams extracted from microwave ion source are decoupled from each other in the horizontal and vertical planes (no x-y coupling) before entering the next optic element, the first solenoid magnet.

$$\boldsymbol{\sigma}_{0,xy} = \begin{pmatrix} \sigma_{0,xy} & \sigma_{0,xy'} \\ \sigma_{0,x'y} & \sigma_{0,x'y'} \end{pmatrix} = 0 \quad (4)$$

The initial beam is also symmetrical about the beam axis. For a round beam, the Courant-Snyder (C-S) parameters in the horizontal and vertical planes are the same as:

$$\boldsymbol{\sigma}_{0,xx} = \boldsymbol{\sigma}_{0,yy} : \begin{pmatrix} \sigma_{0,xx} & \sigma_{0,xx'} \\ \sigma_{0,x'x} & \sigma_{0,x'x'} \end{pmatrix} = \begin{pmatrix} \sigma_{0yy} & \sigma_{0,yy'} \\ \sigma_{0,y'y} & \sigma_{0,y'y'} \end{pmatrix} \quad (5)$$

Combining equations from Eq. (1) to Eq. (5) to solve beam transport equations for solenoid scan:

$$\begin{aligned} \sigma_{1,xx}^2 &= x_{rms,meas}^2 \\ &= m_{11}^2\sigma_{0,xx} + 2m_{11}m_{12}\sigma_{0,xx'} + m_{12}^2\sigma_{0,x'x'} \\ &\quad + m_{13}^2\sigma_{0,yy} + 2m_{13}m_{14}\sigma_{0,yy'} + m_{14}^2\sigma_{0,y'y'} \\ &= (m_{11}^2 + m_{13}^2)\sigma_{0,xx} + 2(m_{11}m_{12} + m_{13}m_{14})\sigma_{0,xx'} \\ &\quad + (m_{12}^2 + m_{14}^2)\sigma_{0,x'x'} \end{aligned} \quad (6)$$

Here, the transverse beam emittance before the solenoid magnet can be obtained by deducing the three free parameters with beam size datasets near the maximum focusing condition of the beam.

Solenoid Scan in Beam Dynamics Simulation without Space Charge

When space charge is not considered, transfer matrix of hard edge solenoid model is composed of thin-lens focusing at both ends and a rotation in the center of the magnet [5]. The beam transfer matrix M consisting of solenoid and drift without space charge kicks is as follows:

$$M = Drift * Solenoid \quad (7)$$

$$Drift = \begin{pmatrix} 1 & d & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (8)$$

$$\begin{aligned} &Solenoid = thin\ lens\ kicks\ IN * rotation * thin\ lens\ kicks\ OUT \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & \sin(2kl)/2k & 0 & \sin^2(kl)/k \\ 0 & \cos(2kl) & 1 & \sin(2kl) \\ 0 & \sin^2(kl)/k & 1 & \sin(2kl)/2k \\ 1 & -\sin(2kl) & 0 & \cos(2kl) \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ -k & 0 & 0 & 1 \end{pmatrix} \\ &= \begin{pmatrix} \cos^2(kl) & \sin(2kl)/2k & \sin(2kl)/2 & \sin^2(kl)/k \\ -\mathrm{k}\sin(2kl)/2 & \cos^2(kl) & -\mathrm{k}\sin^2(kl) & \sin(2kl)/2 \\ -\sin(2kl)/2 & -\sin^2(kl)/k & \cos^2(kl) & \sin(2kl)/2k \\ \mathrm{k}\sin^2(kl) & -\sin(2kl)/2 & -\mathrm{k}\sin(2kl)/2 & \cos^2(kl) \end{pmatrix} \end{aligned} \quad (9)$$

where d is a length of drift in field-free space and l is an effective length of hard edge solenoid and k is half the ratio of effective magnetic flux to magnetic rigidity of a beam:

$$k = \frac{B_{z0}}{2B\rho} = \frac{qB_{z0}}{2\beta\gamma mc} \quad (10)$$

Figure 2 shows beam dynamics data simulated by the envelope mode of TraceWin code [6], to validate solenoid scan analysis method with zero-current beam. The beam emittance and Courant-Snyder (C-S) alpha parameter are set to different values as input beam parameters, and the beam sizes at the scintillating screen are collected as a function of the solenoid magnet strength.

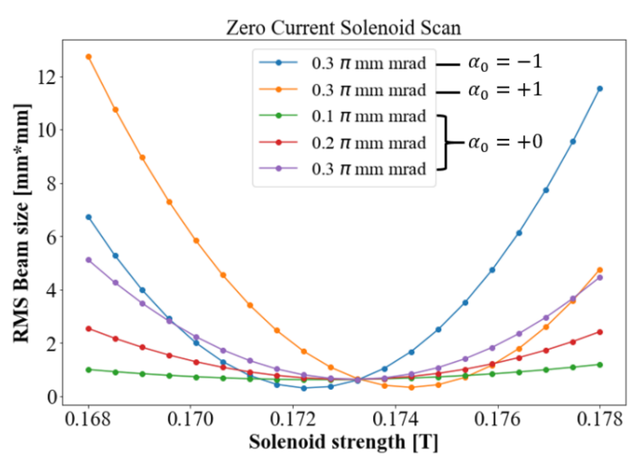

Figure 2: Solenoid scan simulation data (solenoid strength vs. RMS beam size at scintillating screen beam monitor) of zero current proton beam, varying input beam emittance and Courant-Snyder alpha parameter.

Table 1: Solenoid Scan Simulation with Zero Current Beam

Beam parameters for simulation inputs		Beam emittance evaluated from simulation outputs
C-S alpha	Norm. RMS emittance	Without space charge [π mm $mrad$]
-1	0.30	0.300
+1	0.30	0.300
0	0.10	0.100
0	0.20	0.200
0	0.30	0.300

As a result of complete orthogonal decomposition for solving least-squares problems in Eq. (6), the input beam emittance is accurately derived from the output beam data of beam envelope simulation in both tests as written in Table 1 in zero-current beam transport problems that do not consider space charge effects.

Solenoid Scan in Beam Dynamics Simulation with Linearized Space Charge

The transfer matrix M in Eq. (7) does not consider the space charge effect, causing errors in solenoid scan analysis of non-zero current beam. The modified transfer matrix M_{SC} in Eq. (11) includes transverse kicks due to space charge force in the free drift region and solenoid region for beam transport during the solenoid scan process.

$$M_{SC} = \prod_{a=1}^{n}(Drift_{d/n} \cdot SC^a_{d/n}) \prod_{b=1}^{m}(Solenoid_{l/m} \cdot SC^b_{l/m}) \quad (11)$$

$$\mathrm{SC}^a_{d/n} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ F^a_{rb} d/n & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & F^a_{rb} d/n & 1 \end{pmatrix} \quad (12)$$

where d/n denotes that drift length d is divided by n pieces and l/m means that effective solenoid length l is segmented by m pieces.

Space charge kicks are linearized and approximated for a round beam as:

$$F^a_{rb} = \frac{qI_0(1-f_{SCC})}{4\pi\epsilon_0 m(\beta\gamma)^3 r}\Big|^{z=a} \quad (13)$$

where r is a RMS radius of a round beam and f_{SCC} is a ratio of space charge compensation.

This force, which further defocus a beam, continues to change during beam transport because it depends on the beam distribution, including beam size, and the space charge compensation factor. To take this into account, the drift and solenoid are divided into several pieces in the beam transfer matrix calculation, and space charge kicks are added between them.

$$\sigma_{1,X} = M_{SC}\sigma_{0,X}M^T_{SC} \quad (14)$$

$$\sigma^2_{1,xx} = x^2_{rms,meas}$$
$$= (m^2_{SC,11} + m^2_{SC,13})\sigma_{0,xx} + (m^2_{SC,12} + m^2_{SC,14})\sigma_{0,x'x'}$$
$$+2(m_{SC,11}m_{SC,12} + m_{SC,13}m_{SC,14})\sigma_{0,xx'} \quad (15)$$

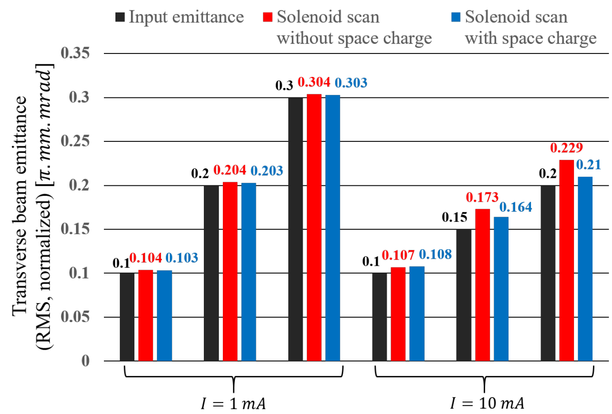

Figure 3: Solenoid scan results with non-zero current beam (1 mA, 10 mA) and comparison of space charge treatment (black: input, red: output analysis without space charge, blue: output analysis with space charge).

Figure 3 summarizes solenoid scan results by non-zero current proton beam. The beam emittance obtained by the analysis has some error with respect to the input beam emittance. Two different beam current, 1 mA and 10 mA, are simulated to compare the influence of space charge effects. When the beam current is 1 mA, the errors are less than 4%, regardless of whether the space charge effect is treated in evaluating transverse beam emittance. On the other hands, when the beam current is 10 mA and the input emittance is 0.2 mm mrad, the error occurs up to 15% with no correction of space charge. Considering the linearized space charge under these input conditions, the error is improved to 5%. These results suggest that the space charge treatment is more effective when the current is greater than a few mA with low space charge compensation.

Solenoid Scan with Beam Experiment Data With Linearized Space Charge

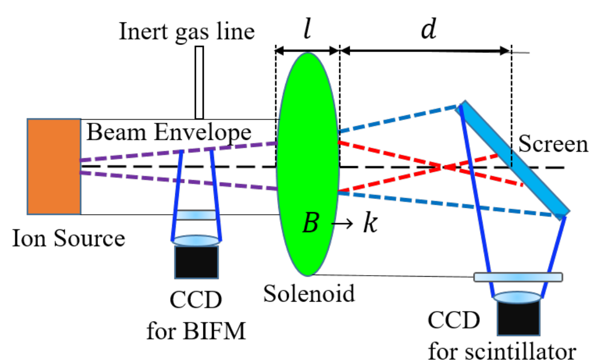

Figure 4: Schematic view of solenoid scan analysis with two beam profile monitors and a solenoid magnet.

Ion beam current I_0 and space charge compensation function f_{SCC} in Eq. (13) are determined as constants by setting the space charge compensation to 0% and the beam current value to a constant when testing solenoid scan analysis with beam simulation data. The only other variable to be determined is the beam size as a function of the longitudinal position in the solenoid-drift section. The evolution

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of the beam envelope is approximately obtained by using RMS beam size at the beam-induced fluorescence monitor (BiFM) location, as illustrated in Fig. 4, and by assuming thin-lens focusing in the solenoid.

On the other hand, in the case of solenoid scan analysis in beam experiments, the evolution of the beam envelope is approximately obtained by using the RMS beam size measurement in BiFM. Beam current I_0 is multiplication of the beam current measured from the AC current transformer located around the beam monitor and the mono-atomic fraction for the hydrogen plasma of the microwave ion source. Space charge compensation function f_{SCC} is approximately calculated by following Gabovich formula [7,8].

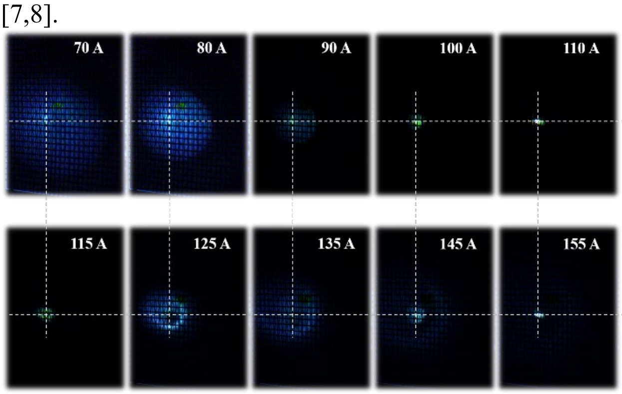

Figure 5: Transverse beam profile images taken with scintillating screen during solenoid scan.

Based on the solenoid scan method verified by beam dynamics simulation, solenoid scan experiments are performed at the RFQ-based beam test stand, and the transverse beam emittance is obtained considering the space charge effect. Figure 5 shows a beam image taken with a scintillating screen when scanning solenoid coil currents from 70 A to 155 A.

Neutral Gas Injection and Mitigation of Emittance Growth

In the low energy beam transport section, the main cause of emittance growth is non-linear space charge force. To mitigate its effect, neutral gas injection scheme is often utilized to increase the number of compensating electrons generated by ionization collisions. Krypton has high ionization cross-section to low energy proton beam, so that beam emittance is investigated by the solenoid scan analysis at various gas flow rates. Figure 6 reveals that krypton gas injection reduces the transverse beam emittance at the first solenoid position. When the krypton gas flow rate is 1.2 sccm, the beam loss is about 10% and the beam emittance is reduced up to 23%. When the flow rate is 1.5 sccm, the beam loss rate is slightly higher at about 12%, but the beam emittance is rather increased, which reduces the efficiency of space charge compensation.

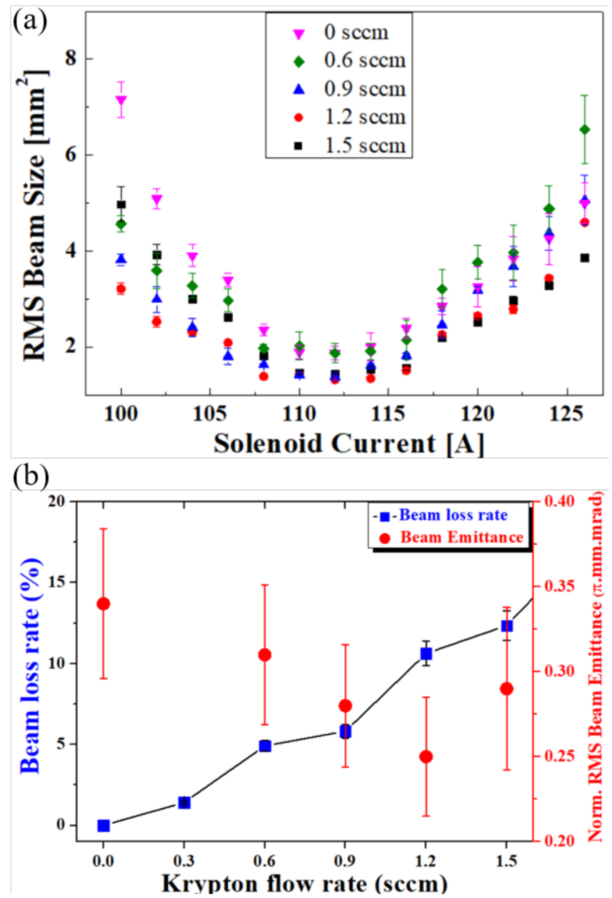

Figure 6: Experimental data of solenoid scan with various krypton gas flow rate – (a) RMS beam size data, (b) beam loss rate and estimated transverse emittance by solenoid scan analysis.

CONCLUSION

We present a methodology to estimate the transverse beam emittance for an initial round beam from a high-intensity proton injector utilizing solenoid magnet scans. In this paper, the solenoid is approximated as a hard edge model and space charge force is linearized to solve the beam envelope equation for the solenoid scan problem using beam transfer matrix. Beam experiments are performed on a neutral gas injection and the space charge compensation in the beam test stand, implying moderate gas flow rate for mitigating emittance growth near the ion source.

It is necessary to compare and analyse the method with other reliable emittance measurements under the same beam experiment conditions in the future. Particle tracking and 3D field maps can be useful to identify and correct potential error factors caused by more complex and realistic beams.

ACKNOWLEDGEMENTS

This work was supported through "KOMAC operation fund" of KAERI by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (KAERI-524320-23)

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THA2C1

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