IMPLEMENTATION OF QUADRUPOLE-SCAN EMITTANCE MEASUREMENT AT FERMILAB'S ADVANCED SUPERCONDUCTING TEST ACCELERATOR (ASTA)

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Abstract

Transverse emittance measurements based on the quadrupole scan technique have been widely used to characterize the beam phase space parameters in linear accelerators. This paper discusses the implementation of the technique at the Advanced Superconducting Test Accelerator (ASTA) at Fermilab. We plan on deploying a flexible implementation that permits an operator to select a quadrupole with associated analyzing screen to measure the beam emittance. Our implementation utilizes Python scripts combined with Fermilab's control system ACNet and ELEGANT tracking code. We also discuss the applicability of the quadrupole scan method at 20.3 MeV at an operating charge of 250 pC at ASTA. Some preliminary measurements will also be presented.

INTRODUCTION

The Advanced Superconducting Test Accelerator (ASTA) has been constructed and commissioned in Fermilab and it is currently scheduled to build a high energy beamline (150 – 300 MeV) by adding a cryomodule with construction plan of the Integrable Optics Test Accelerator (IOTA) ring by 2016. Most recently, 20 MeV of electron beam energy was successfully demonstrated in the ASTA injector beamline and it is planned to increase the beam energy up to 50 MeV with the schedule to add a capture cavity downstream of the photoinjector. Along with the timeline of the construction/commissioning schedules, it is necessary to assure a beam monitoring technique for a full scale transverse and longitudinal phase-space characterization of a commissioned beam, which enables to precisely operate the machine. Instantaneous monitoring of beam parameters is highly required for preserving the beam emittance along the beamline. We have been working on the idea of developing a real-time emittance monitoring system based on a quadruple-scan technique [1,2]. Our plan is to design a Python script programmed with a quad-scan algorithm and to implement it in the ASTA beamline control system (ACNet console). We expect that successful development of a designed system will allow a beamline operator to trace temporal profiles of transverse beam parameters and also to systematically control the dynamics using quadrupoles installed in the ASTA beamline.

BEAM DYNAMICS

Emittance is an important property of charged particle beams, allowing for a description of beam quality and the comparison of beams. Generally, emittance can be described in six-dimensional phase space $[x, y, z, p_x, p_y, p_z]$ as the spread of density of particles in the beam. In many cases, the transverse emittance is of particular interest and the six-dimensional phase space is split into subspaces comprised of (x, p_x) and (y, p_y) [1].

The area occupied by the particles of interest may be considered as being bound by an ellipse and can mathematically be described by the following beam matrix:

$$\Sigma_{beam} = \begin{bmatrix} \Sigma_{11} & \Sigma_{12} \\ \Sigma_{21} & \Sigma_{22} \end{bmatrix}. \tag{1}$$

Figure 1 shows the beam ellipse and the physical interpretation of its physical components. In the figure, x and x' are the position and angle of the particles, respectively.
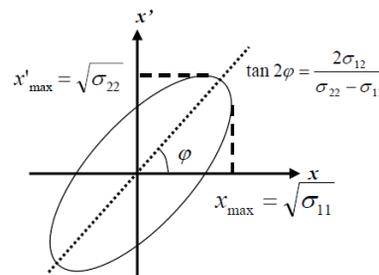

Figure 1: Beam ellipse with physical interpretation of the physical components [1].

Using the beam matrix, the geometrical emittance can then be defined as:

$$\epsilon = \pi \sqrt{\Sigma_{beam}} \tag{2}$$

The beam ellipse and matrix can also be expressed in terms of the Courant-Snyder parameters:

$$\epsilon = \gamma x^2 + 2\alpha x x' + \beta x'^2, \tag{3}$$

where $\gamma = \Sigma_{22}/\epsilon$, $\alpha = -\Sigma_{12}/\epsilon$, and $\beta = \Sigma_{11}/\epsilon$ [3].

A more complete description of the emittance may be given as the root mean square emittance (ϵ_{rms}). With this description, the moments of the particle distribution in phase space can be related to the beam matrix elements by [1]:

$$\Sigma_{11} = \langle x^2 \rangle = \iint dx dx' f_2(x, x') x^2$$

$$\Sigma_{12} = \Sigma_{21} = \langle xx' \rangle = \iint dx dx' f_2(x, x') xx'$$

$$\Sigma_{22} = \langle x'^2 \rangle = \iint dx dx' f_2(x, x') x'^2 \ . \qquad (4)$$

This new description of the beam matrix now gives a more relatable physical meaning: Σ_{11} is the square of the rms beam size, Σ_{22} is the square of the divergence, and Σ_{12}/Σ_{21} are the cross-correlational terms. With this useful new description, a normalized ϵ_{rms} is now described by:

$$\epsilon_{rms} = \beta\gamma\sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \ , \qquad (5)$$

where this time β and γ are the relativistic factors [4].

QUADRUPOLE SCAN

The quadrupole scan technique (quad scan) is a simple and widely used method for measuring transverse emittance at a particle accelerator. The goal is to measure the beam size of the particle beam as a function of the magnetic field strength of a quadrupole magnet at some imaging station (typically an OTR or YAG screen). This information allows for the determination of Σ_{beam}, the Courant-Snyder parameters, and the emittance. One way to approach the quad scan technique is to use a *thin lens* approximation [2]. This method views the quadrupole magnet as a thin focusing (or defocusing) lens and then utilizes transfer matrices. If Q represents the transfer matrix of the quadrupole and M represents the transfer matrix between the quad and the imaging screen (where D is the drift length and Kl is the quad field strength multiplied by the quad length), then the transfer matrices may be written as:

$$Q = \begin{bmatrix} 1 & 0 \\ (K \cdot l) & 1 \end{bmatrix}$$

$$M = \begin{bmatrix} D_{11} + Kl \cdot D_{12} & D_{12} \\ D_{21} + Kl \cdot D_{22} & D_{22} \end{bmatrix},$$

which is used to find the beam matrix:

$$\Sigma_{beam} = M \Sigma_0 M^T \ .$$

A quadrupole of choice is selected along with an imaging station and the field strength is varied (finding the minimum spot size is needed before evaluating the range of the scan in the field strength). Plotting the beam size (squared) as a function of K and applying a parabolic fitting function which yields three coefficients:

$$\Sigma_{11} = AK^2 + BK + C \ ,$$

which can then be equated to the beam transfer matrix:

$$\langle x^2 \rangle = \Sigma_{11} = (D_{11} + KLD_{12})^2 \Sigma_{11} + D_{12}^2 \Sigma_{22} + 2D_{12}(D_{11} + KLD_{12})\Sigma_{12} \ ,$$

which upon solving gives the beam matrix elements:

$$\Sigma_{11} = \frac{A}{l \cdot D_{12}^2}$$

$$\Sigma_{12} = \Sigma_{21} = \frac{B - 2\Sigma_{11} \cdot l \cdot D_{11} \cdot D_{12}}{2l \cdot D_{12}^2}$$

$$\Sigma_{22} = \frac{C - \Sigma_{11} \cdot D_{11}^2 - 2\Sigma_{12} \cdot D_{11} \cdot D_{12}}{D_{12}^2} \ .$$

The transverse emittance is then found via the square root of the determinant of Σ_{beam}, as stated in the section above. Courant-Snyder parameters can found using these coefficients or by simply using the three C-S equations mentioned in the previous section [2].

PRELIMINARY RESULTS

It should be noted that the following preliminary results were obtained using the *thin lens* approximation and that much work and analysis is currently taking place.

Figure 2 and Table 1 show some preliminary data taken from scanning a quadrupole magnet at ASTA.
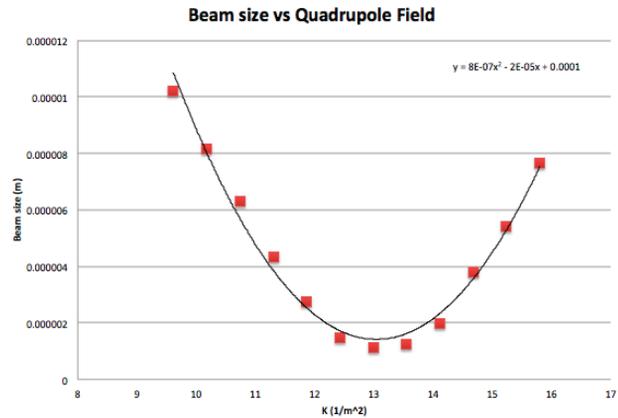

Figure 2: Beam size as a function of quadrupole field strength in the horizontal plane at ASTA using quadrupole Q112 on a YAG imaging screen at the imaging station X120.

Table 1: Beam parameters from a Quadrupole Scan with the Q112 Quad at the X120 Imaging Screen measured at the ASTA facility.

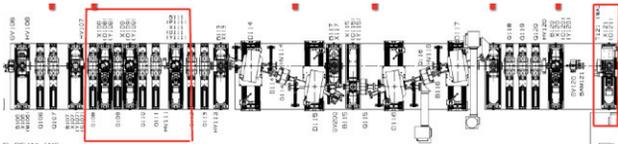| Parameter	Value
Energy	$20.3 \ MeV$
Bunch Charge	$250 \ pC$
Drift Length	$5.597 \ m$
Emittance	$0.14 \ \mu m$
α	-2.284
β	1.531
γ	4.059

PROSPECTIVE TESTS AND ACTIVITIES

Figure 3: Schematics of ASTA injector beamline [5].

Since March 2015 the Advanced Superconducting Test Accelerator (ASTA) at Fermi National Laboratory in Batavia, IL has been operating with a 20 MeV electron beam (with future plans to reach energies up to 300 MeV). Figure 3 shows some of the possible quadrupoles to be used and beam parameters expected at the ASTA facility are given in Table 2.

Table 2: ASTA Beam Parameters [5]

Parameter	Nominal Value	Range
Expected Energy	$\sim 300\ MeV$	$50 - 300\ MeV$
Bunch Charge (Q)	$3.2\ nC$	$0.02 - 20\ nC$
Bunch Frequency (f_b)	$3\ MHz$	
Macropulse Duration (τ)	$1\ ms$	$\leq 1\ ms$
Macropulse Frequency (f_{mac})	$5\ Hz$	$0.5 - 1.5\ Hz$
Num. Bunch per Macro. (N_b)	3000	$1 - 3000$
Trans. Emittance ($\epsilon_\perp$)	Few μm	$0.1 - 100\ \mu m$
Long. Emittance ($\epsilon_\parallel$)	Few μm	$5 - 500\ \mu m$
Peak Current ($\hat{I}$)		$3 - 10\ kA$

The long-term goals of this project are:
- Program a Python script of the quad-scan transport matrices based on the "*Thin Lens Approximation*" and "*Thick Lens Model.*"
- Design script with imported raw data (such as magnetic field data from an ASTA quadrupole magnet).
- Test and prove the script with ASTA beam parameters.
- Simulate a quad scan of an existing ASTA beamline component with ELEGANT simulation.

- Benchmark the ELEGANT simulation with the analytic model programmed in the Python script.
- Develop a networking platform of the Python script with the ACNet console at ASTA.
- Apply the generic Python code into the ACnet console, allowing an operator to select any quad or screen that they would like to use, allowing for automatic feedback and measurement of the beam size and transverse emittance.

CONCLUSION

Emittance from charged particle beams is integral in describing certain beam characteristics as well as being a useful tool to compare the quality of beams. The quadrupole scan technique is a simple and useful method for measuring the transverse emittance of a beam and the goal of this project is to implement this method using Python script and ELEGANT simulation with the ACnet console at the ASTA facility at Fermilab. This will allow an operator to readily choose a quadrupole magnet of interest and measure the beam size and emittance at an imaging station of choice.

ACKNOWLEDGMENT

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