DEVELOPMENT OF A PYTHON-BASED EMITTANCE CALCULATOR AT FERMILAB SCIENCE & TECHNOLOGY (FAST) FACILITY

[1, 2]A.T. Green #, [1, 2]Y.M. Shin

[1]Department of Physics, Northern Illinois University, DeKalb, IL 60115, USA
[2]Fermi National Accelerator Laboratory (FNAL), Batavia, IL 60510, USA

Abstract

Beam emittance is an important characteristic describing charged particle beams. In linear accelerators (linac), it is critical to characterize the beam phase space parameters and, in particular, to precisely measure transverse beam emittance. The quadrupole scan (quad-scan) is a well-established technique used to characterize transverse beam parameters in four-dimensional phase space, including beam emittance. A computational algorithm with Python scripts has been developed to estimate beam parameters, in particular beam emittance, from experimental results using the quad-scan technique in the photoinjector-based electron linac at the Fermilab Accelerator Science and Technology (FAST) facility. This script has been benchmarked against ELEGANT simulation and implemented in conjunction with an automated quad-scan tool (also written in Python) and has decreased the time it takes to perform a single quad-scan from an hour to a few minutes. From the experimental data, the emittance calculator quickly delivers several results including, but not limited to, geometrical and normalized transverse emittance, Courant-Snyder parameters, and plots of the beam size versus quadrupole field strength.

INTRODUCTION

Emittance is an intrinsic quality of charged particle beams in particle accelerators and needs to be fully characterized in order to assure that the beamline is operational. This beam parameter quantifies the volume of six-dimensional phase space (x, p_x) occupied by the dynamically moving particles in the beam. Beam emittance is also related to the smallest achievable spot size and divergence:

$$\sigma = \sqrt{\beta \epsilon_g} \propto \sqrt{\epsilon_g} \qquad (1)$$

$$\sigma \sigma' = \epsilon \rightarrow \frac{\epsilon}{\sqrt{\beta \epsilon_g}} \propto \sqrt{\epsilon_g}, \qquad (2)$$

where σ is the beam size, σ' is the divergence, β is a Courant-Snyder parameter, and ϵ_g is the geometrical emittance [1].

A common way of measuring the beam emittance is via the quad-scan technique. By this method, an experimenter scans the quadrupole field strength k over a desired range and records the beam size at some location downstream.

The quadrupole magnet fields strength and beam size measurements, along with the precise knowledge of the accelerator configuration, are all that are needed to calculate the beam emittance. Under conservative forces, beam emittance is a conserved quantity and as such, calculating the emittance at one location along the beamline will describe the emittance anywhere along the accelerator.

FERMILAB SCIENCE AND TECHNOLOGY (FAST)

It is at the FAST facility at Fermilab where this emittance calculator has been employed. FAST is an advanced superconducting (SRF) accelerator laboratory currently under construction at Fermilab. The goal of this facility is to provide cutting edge R&D and infrastructure critical to the research and development of both current and future accelerators. A schematic of the main components of the FAST beamline are depicted in Fig. 1 (from left-to-right):

- Low-energy beamline (red) – RF gun, bucking solenoid, main solenoid, and two superconducting booster cavities (CC-1 and CC-2) capable of accelerating electrons up to $50 \, MeV$.
- CM2 (light blue) – Cryomodule 2, an ILC-type cryomodule, for accelerating electrons up to $300 \, MeV$.
- RFQ (dark blue) – Radio frequency quad capable of accelerating protons up to $2.7 \, MeV$.
- IOTA (blue ring) – Integrable Optics Test Accelerator electron/proton storage ring for $150 \, MeV$ electron-based experiments and $2.5 \, MeV$ proton-based experiments.
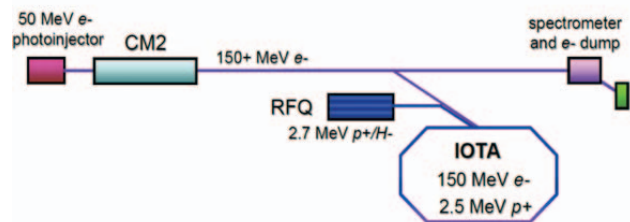

Figure 1: Sketch showing the main components of the FAST beamline [2].

Table 1 gives a brief view of the achieved beam parameters during the $50 \, MeV$ commissioning phase. It should be noted that the beam parameters marked with an asterisk were verified prior to the $50 \, MeV$ run.

Table 1: Verified beam parameters measured during the 20 MeV and 50 MeV runs at FAST.

Parameter	FAST Value
Beam Energy	20 MeV – 50 MeV
Bunch Charge	$< 10\,fC$ – $3.2\,nC$ per pulse
Bunch Train	$0 - 9 * MHz$ for up to 1 ms (3 MHz nominal)
Train Frequency	$1 - 5 * Hz$
Bunch Length	Range: 1 ps – 50 $ps *$ (Nom: 4 ps)
Bunch Emittance for 50 pC/pulse	Horz: 1.6 ± 0.2 μm Vert: 3.4 ± 0.1 μm

QUADRUPOLE SCAN

By scanning the magnetic field strength of a quadrupole magnet (by increasing/decreasing the field strength) over a desired range, the spot size of the beam is measured at a transverse profile monitor (TPM) downstream of the quadrupole. Generally, the beam is imaged either on a Ce-doped 250 μm thick crystalline YAG screen for scintillation light or a 25 μm thick Al screen for OTR production. The cameras used are 5-megapixel CCD cameras with a 1σ resolution of $\leq$ 20 μm.

Scripts have been written with Python to automate the quad-scan process and produce experimental results after some initial parameters have been set in just a window of 5-20 minutes, depending on initial conditions. From the experimental results, the Python-based emittance calculator processes the raw data and produces various results including: geometrical and normalized emittance, Courant-Snyder parameters, and plots of the beam size as a function of the quadrupole field strength, to name a few.

EMITTANCE CALCULATOR

Once the quad-scans have been performed, the raw data will be given in one of two formats. In one formation the data file contains three columns of data: quadrupole current (A), horizontal beam size ($pixels$), and vertical beam size ($pixels$). At FAST, it is the quadrupole current which is scanned and, in turn, converted to the quadrupole field strength by the Python code. From the CCD cameras and the image tool software, the beam size is measured in pixels and is then converted by Python to microns.

An alternative exists in which the user may perform a statistical analysis in order to measure coupling between the transverse plains, should it exist. Selecting this method will produce a similar data file, with the difference being that there is now a fourth column of data containing the coupling-term measurements. Additionally, the automated quad-scan script will now perform a statistical analysis when measuring the beam size as opposed to the Gaussian fitting function used by the former method.

Figure 2 shows the inputs that must be entered by the user prior to running the code as well as the steps that the algorithm takes in order to produce the results.
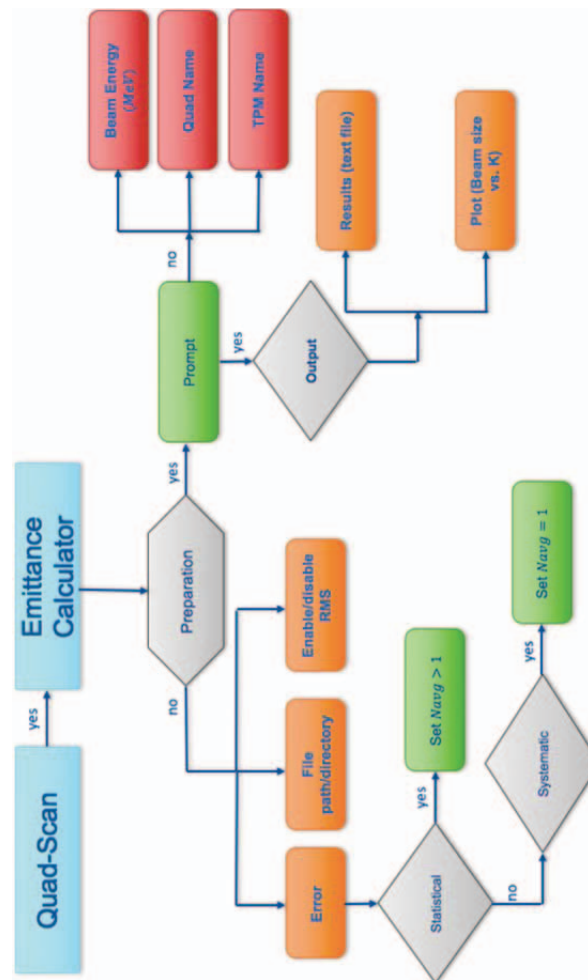

Figure 2: Flow chart giving the steps required prior to running the script as well as the subsequent steps and results taken by the algorithm.

Thick Lens Model

Quadrupole magnets in an accelerator are analogous to (thick) optical lenses. As the magnetic field is increased/decreased the magnet will focus/defocus the beam. Under conservative forces, knowledge of the emittance and Courant-Snyder parameters at one location along the beamline will yield the beam parameters anywhere along the beamline. With the quad-scan and "thick lens" model, the experimenter measures the beam size at a location z in the beamline and then using transfer matrices (R) along with the beam matrix (σ) calculates the desired beam parameters at the scanning quadrupole (z_0):

$$\sigma(z) = R(z)\sigma(z_0)R^T(z), \qquad (3)$$

An in-depth analysis of the quad-scan technique and the "thick lens" model can be found in [3].

Error Analysis

The emittance calculator has been designed to hand either statistical or systematic error. When running the automated quad-scan tool, the user can either take a single beam size measurement per scan point or multiple measurements per scan point. The former is generally chosen if there are strict time constraints as the latter can consume up to 20-30 minutes per quad-scan.

For systematic error, which is the default in the emittance calculator code, the program will apply a $20\ \mu m$ error to each beam size measurement (which is the resolution of the CCD camera). For statistical error analysis, the user will input the number of data points to analyse prior to running both quad-scan and emittance codes.

Using χ^2 and least-squares formalism, the Python script will also calculate the error on the calculated emittance and Courant-Snyder parameters. This technique is detailed in references [3], [4].

Python Output

Once the prerequisite information is entered and the code is run, the Python calculator will quickly produce various beam parameters, along with their estimated error, as well as a plot of the beam size versus quadrupole field strength in the transverse planes. Figure 3 shows one such example.
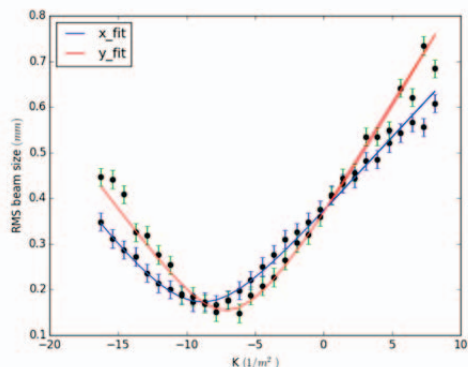

Figure 3: An example plot of the beam size vs. quadrupole field strength for the horizontal (blue) and vertical (red) planes as output by the Python script.

Experimental Results

Some of the accelerator's parameters from the $20\ MeV$ commissioning were not yet updated for the first experiments of the $50\ MeV$ run. One such way in which our Python calculator was used in an experimental setting was in calculating the emittance while optimizing the main and bucking solenoids settings at the electron gun. Figure 4 shows the results from both of these experiments.
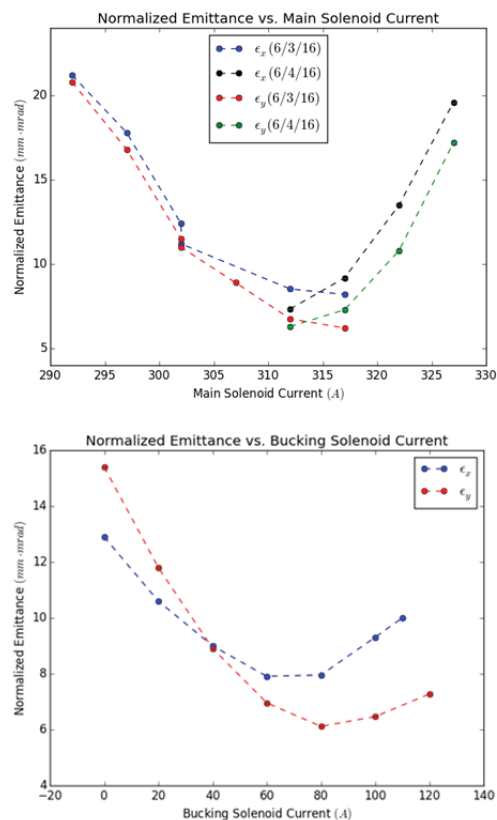

Figure 4: Plots of the normalized emittance as a function of (a) the main solenoid setting and (b) the bucking solenoid setting.

The nominal setting during the $20\ MeV$ run for the main solenoid was $290 - 295\ A$. However, as shown in Fig. 4, this was not the optimum setting for the lowest emittance. By scanning the main and bucking solenoids while measuring the emittance, early emittance values were reduced by a factor of three.

CONCLUSION

The quad-scan method has been well-established for calculating beam emittance. In conjunction with an automated quad-scan code written in Python, we have developed a Python-based emittance calculator. After benchmarking the code against ELEGANT simulation, the emittance tool was implemented during the commissioning of the $50\ MeV$ low-energy beamline at FAST.

ACKNOWLEDGMENT

REFERENCES

[1] P.M. Lapostolle, "Possible Emittance Increase Through Filamentation Due to Space Charge in Continuous Beams", *IEEE Trans. Nucl. Sci.* 18 (3) (1971) 1101.

[2] A. Valishev, "Introduction to IOTA and Injectors", Focused Workshop on Scientific Opportunities in IOTA, Fermilab, April 28-29, 2015.

[3] A.T. Green, "Development of a Python Based Emittance Calculator at Fermilab Science & Technology (FAST) Facility", Master's Thesis, Dept. of Physics, Northern Illinois University, DeKalb, IL, 2016.

[4] F. Lohl, "Measurements of the Transverse Emittance at VUV-FE", Diploma Thesis, DESY-THESIS 2005-014, TESLA-FEL 2005-03, Hamburg, July 2005.