TRANSVERSE EMITTANCE AND PHASE SPACE PROGRAM DEVELOPED FOR USE AT THE FERMILAB A0 PHOTOINJECTOR*

R. Thurman-Keup[#], A. S. Johnson, A. H. Lumpkin, J. Ruan, FNAL, Batavia, IL 60510, U.S.A.

Abstract

The Fermilab A0 Photoinjector is a 16 MeV high intensity, h igh brightness electron l inac developed for advanced accelerator R&D. One of the key parameters for the electron beam is the transverse beam emittance. Here we report on a newly developed MATLAB based GUI program used for transverse emittance measurements using the multi -slit technique [1,2]. This program combines the image acquisition and post -processing tools for determining the transverse phase space parameters with uncertainties.

INTRODUCTION

An integral part of accelerator research is a measurement of the beam phase space. Measurements of the transverse phase space can be accomplished by a variety of methods including multiple screens separated by drift spaces, or by sampling phase space via pepper pots or slits. In any case, the measurement of the p hase space parameters, in particular the emittance, can be drastically simplified and sped up by automating the measurement in an intuitive fashion utilizing a graphical interface [3].

At the A0 Photoinjector (A0PI), the control system is DOOCS, which ori ginated at DESY. In addition, there is a library for interfacing to MATLAB, a graphically capable numerical analysis package sold by The Mathworks. It is this graphical package which was chosen as the basis for a graphical phase space measurement system due to its combination of analysis and display capabilities.

EXPERIMENTAL SETUP

The A0PI at Fermilab is a 16 MeV electron linac used for advanced accelerator research. Figure 1 shows the current layout of the A0PI beginning with a 1.3 GHz rf photoinjector gun driven by a frequency quadrupled Nd:Glass laser. The photoele ctrons are accelerated to ~3 MeV by the gun and injected into a 1.3 GHz SCRF booster cavity where they are accelerated to a maximum of 16 MeV. Following the booster cavity, is a series o f quadrupole magnets and vacuum crosses containing a mix of OTR screens, Ce:YAG crystals, and T ungsten blocks with slits for emittance measurements. After this section, the beamline splits into two beamlines: a straight section, at the end of which is a s pectrometer magnet for measuring the energy spread of the beam , and a double dogleg with deflecting mode cavity for performing a longitudinal to transverse emittance exchange experiment. There are three locations which contain Tungsten slits for emittance measurements [4]: X3, X7 (not shown in Figure 1), X23.
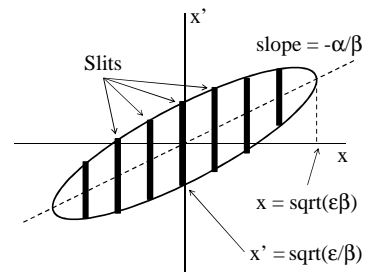

Figure 2: Diagram showing paramete rization of phase space ellipse relevant to multi slit technique.

Emittance Measuring Stations

The emittance measuring locations contain actuators in both horizontal and vertical directions, with one direction containing both the Tungsten slits and either an OTR screen oriented at 45º to the beam direction, or a Ce:YAG crystal oriented normal to the beam direct ion followed by
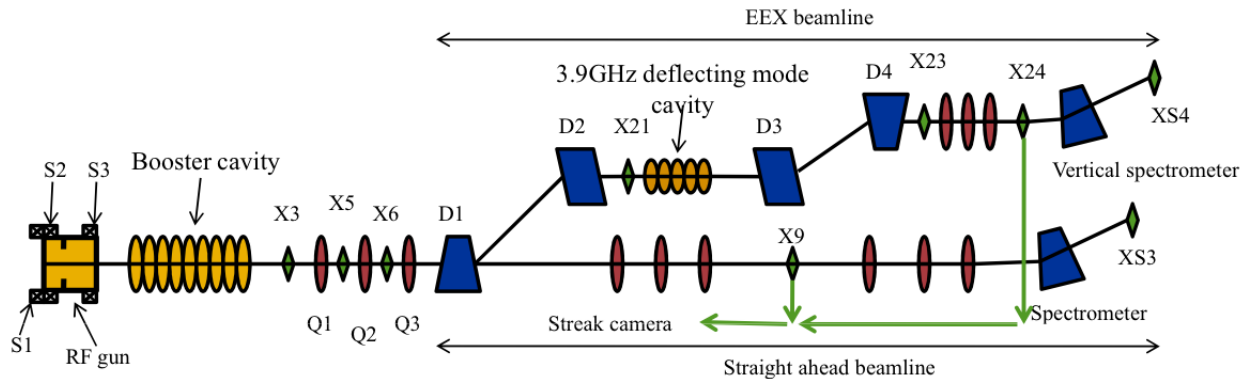

Figure 1: Schematic of the A0 Photoinjector. The green diamonds are vacuum crosses, the red ovals are quadrupole magnets, the blue trapezoids and the orange ovals are rf cavities. Not all elements are shown.

a 45º mirror for directing the light out a vacuum window to a camera system. The actuators are stepper motor based with both the linear insertion mechanism and a rotational capability which allows the slits to be aligned with the beam.

The camera system consists of a 50 mm diameter collimating field lens located approximately 150 mm from the beam to improve light collecting efficiency, followed by a flat mirror that directs the light to a camera with a 25 mm objective lens. This optical system typically exhibits a magnification scale of ~30 μm/pixel and a resolution of 30 μm.

EMITTANCE PROGRAM

The emittance program is implemented as a MATLAB GUI. The advantage of MATLAB is that it has full featured interactive display capabilities as well as the numerical analysis features. The program contains image acquisition and processing abilities, but not co ntrols for the vacuum actuators. The actuator controls were excluded since the lack of feedback as well as the complication of rotating the sl its to achieve alignment with the beam makes it difficult to automate . Thus the operator must insert the proper screen or slit, verify the alignment, and then use the program to do the acquisition.

Acquisition

The GUI (Fig. 3) has a section for acquiring the transverse beam size, and a section for acquiring the slit images which constitute the diver gence measurement. The operator selects the cross to use and the number of images and may optionally take a background image. If needed, the operator can view individual images as well as the background and summed image. The re sulting image can be rotated and have a region of interest selected. The region of interest is projected along the chosen axis and may be fit by up to 8 G aussians plus a polynomial background. Since fitting large numbers of parameters requires an accurate set of initial values, the operator chooses the peaks using the mouse. Each click specifies the position and amplitude initial values. Initial
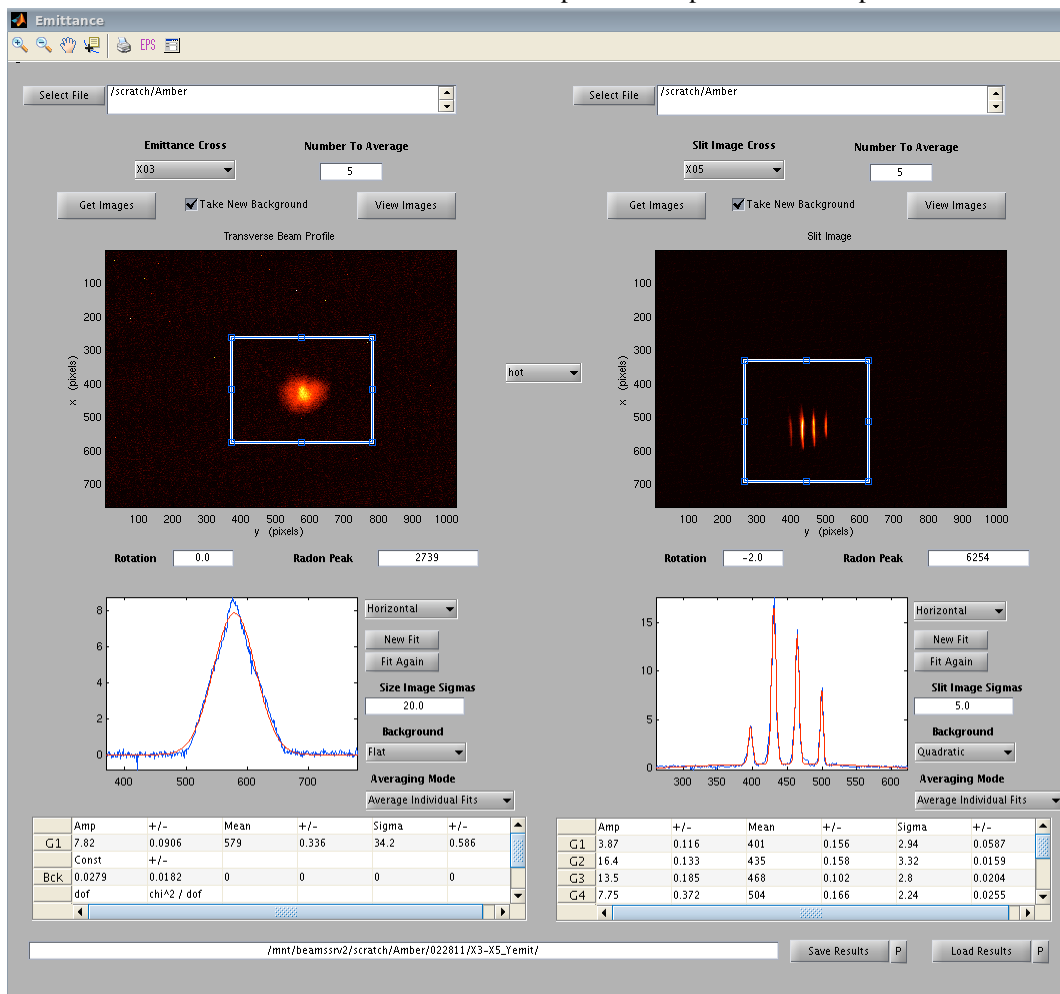

Figure 3: Left side of the emittance measurement program. The left column here contains elements related to obtaining the transverse beam size. The right column contains the elements for obtaining the divergence of the beam for the selected dimension (x or y). The operator selects the crosses for both the beam size and the slit images and then fits the resulting data. The results can be saved to a user specified folder and reread at any time. Alternatively, the operator can select a single image file to be processed as the obtained image.

values for the sigma's can be specified in a separate text box. The fit parameters and their statistical uncertainties are displayed in a spreadsheet -like box, as well as fit quality estimates, and a handful of statistical parameters such as mean, rms, skew, and kurtosis. The operator has a choice of fitting the summed image, or fitting the individual images and then averaging the fit results.

Emittance Determination

Once both the beam size and slit divergences have been measured, the phase space can be constructed. On the right side of the GUI (Fig. 4), the operator can select which of the Gaussian fits to use in the emittance measurement, and whether or not to subtract the optical resolution and the slit width in quadrature.

The uncertainties on the measured beam size and slit divergences include the statistical uncertainty from the fits, and may also include beam -pulse to beam -pulse variations if the operator chose to average the fit values for multiple images. If the operator chose to subtract resolutions, then the uncertainties also include the uncertainty on the optical magnification and the uncertainties on the resolution and slit widths. The resolution uncertainty is typically taken as part of the difference between measuring the resolution using a sharp edge (the nominal), and using line pair modulation.

The emittance is evaluated as the product of the transverse beam sigma and the weighted average of slit divergences, with the weighting being the inverse uncertainty squared.

$$\varepsilon = \sigma_x \left\langle \sigma_{slit,x'} \right\rangle_W$$

In this program the emittance reported is the normalized emittance ($\varepsilon_N = \gamma\beta\varepsilon$) calculated using the beam energy specified. The uncertainties from the beam size and divergence are carried through to the emittance using standard error propagation techniques.

The Courant -Snyder parameters are obtained from the emittance, mean slit divergence, and slit image spacing $\mu_{x'}$, which embodies the tilt of the phase space ellipse.

$$\beta = \frac{\varepsilon}{\left\langle \sigma_{slit,x'} \right\rangle_W}$$

$$\alpha = -\beta m_{\mu_{x'}}$$

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

Here m is the slope of the slit image spacing versus actual slit spacing. As with the emittance, the uncertainties are propagated through to the ellipse parameters.

SUMMARY

This automated emittance program has been in use at A0PI for over 2 years and has simplified the measurement and enabled faster and more accurate results to be obtained. The authors would like to thank all those that have used this program for useful suggestions and comments.
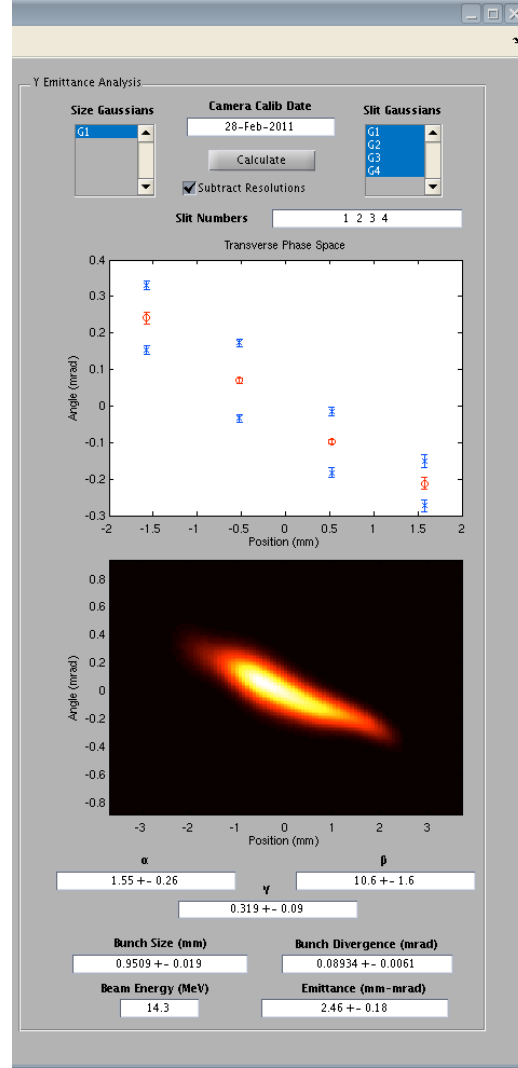

Figure 4: Right side of the Emittance program. This section involves calculation of the phase space. The top plot is the measured divergences of each slit, and the bottom plot is an interpolation of those data points, weighted by intensity and using a Gaussian shape. At the very bottom is the Courant -Snyder parameters, the bunch size, average divergence, and emittance.

REFERENCES

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[3] A. Shapovalov and L. Staykov, Proc. of Beam Instrumentation Workshop 2010, Santa Fe, NM, USA, May 2-6, 2010.

[4] See *e.g.* A. S. Johnson, *et al.* , Proc. of IPAC10, Kyoto, Japan, 2010, for A0PI emittance measurements using this program.