INVESTIGATION OF THE EFFECTS OF CHARGE SCALING ON EMITTANCE EXCHANGE AT THE FERMILAB A0 PHOTOINJECTOR*

A. Johnson[1], J. Ruan[1], A. Lumpkin[1], P. Piot[2,3], Y.-E Sun[2], J. Santucci[1],
R. Thurman-Keup[1], E. Harms[1], H. Edwards[1]
[1] Accelerator Division, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[2] Accelerator Physics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[3] Department of Physics, Northern Illinois University, DeKalb, IL 60115

Abstract

At the Fermilab A0 Photoinjector, a proof-of-principle experiment to demonstrate the exchange of the transverse and longitudinal emittances is ongoing. The emittance exchange beamline consists of a 3.9 GHz normal conducting deflecting mode cavity inserted between two doglegs. Electron bunches of varying charge levels from 100 pC to 400 pC and energy of 14.3 MeV are sent through the exchange beamline. In this paper we will present our latest results on the effects of charge on the emittance exchange process.

INTRODUCTION

Next generation accelerators, such as high-energy colliders and light sources, will benefit from phase space manipulations techniques for enhanced performance. The emittance exchange (EEX) method is one of the candidates to be used in future applications. Since its early proposal in 2003 [1] it has been further investigated both thereotically [2, 3] and experimentally [4].

The EEX experiment can be described through linear optics as a transformation matrix, M_{EEX}, that operates on the initial horizontal parameters (x, x') and longitudinal $(z, \frac{\Delta p}{p})$ phase space coordinates, leaving the vertical transverse emitance unchanged [1, 2, 3]:

$$\begin{pmatrix} x \\ x' \\ z \\ \frac{\Delta p}{p} \end{pmatrix}_{\mathrm{out}} = \begin{pmatrix} \boldsymbol{A} & \boldsymbol{B} \\ \boldsymbol{C} & \boldsymbol{D} \end{pmatrix} \begin{pmatrix} x \\ x' \\ z \\ \frac{\Delta p}{p} \end{pmatrix}_{\mathrm{in}}, \qquad (1)$$

where $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ and $\boldsymbol{D}$ are 2×2 sub-matricies. Under the thin lens approximation, the elements of the diagonal sub-blocks $\boldsymbol{A}$ and $\boldsymbol{D}$ become zero and the off diagonal sub-blocks $\boldsymbol{B}$ and $\boldsymbol{C}$ are populated, complete exchange of the horizontal transverse and longitudinal emittances will occur. The detrimental impact of higher order and collective effects such as space charge and coherent synchrotron radiation are currently being explored both experimentally and via simulations.

* This work was supported by Fermi Research Alliance, LLC under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.

EXPERIMENTAL SETUP

The EEX experiment is conducted at Fermilab's A0 Photoinjector [5]; see Figure 1. Surrounding the 1.3 GHz radio frequency (RF) gun are three solenoidal lenses used to control the beam's transverse emittance. The beam is further accelerated through a 1.3 GHz superconducting RF cavity (referred to as booster cavity) bringing the final energy to 14.3 MeV. The remainder of the beamline consists of diagnostic crosses containing either optical transition radiation (OTR) or cerium doped yttrium aluminum garnet (YAG:Ce) crystal viewers, quadrupoles, dipole correctors and beam position monitors.

The EEX beamline consists of a liquid nitrogen cooled, normal conducting 3.9 GHz $\mathrm{TM_{110}}$ deflecting mode cavity placed between two magnetic doglegs [4]. Each dogleg is composed of $\pm$ 22.5° bends and generate a horizontal dispersion of 33 cm. Inside the $\mathrm{TM_{110}}$ cavity the longitudinal electric field grows linearly off axis while the vertical magnetic field produces a time-dependent transverse kick coordinated with the synchronous particle.

EXPERIMENTAL METHODS

Transverse emittance measurements are made using the multislit technique [6]. Transverse beam profiles are measured by inserting an OTR screen at X3 and X23. Divergence measurements are made by inserting a tungsten multi-slit mask into the beam path at both X3 and X23, see Fig. 1. The masks consist of 50 μm wide slits separated by 1 mm, except at X23 where the horizontal slits are separated by 2 mm. Figure 2 (a) and (b) show a typical set of incoming horizontal beam size data and a complete set of horizontal beamlets as viewed on the X6 YAG:Ce screen. Dark current background has been subtracted from all images. Divergence is calculated as the average of the Gaussian fits of the slit images divided by the drift distance from X3 to X6. Phase space plots can be drawn based on the previous information as shown in Figure 2 (c). The whole measurement procedure and on-line analysis is performed with a MATLAB based program [7]. For each of the different charge we empirically adjusted the solenoid lens around the gun in order to achieve a reasonable emittance. However these emittance values are not necessarily optimized for our beam line at these charge settings.

Longitudinal emittance is inferred from bunch length

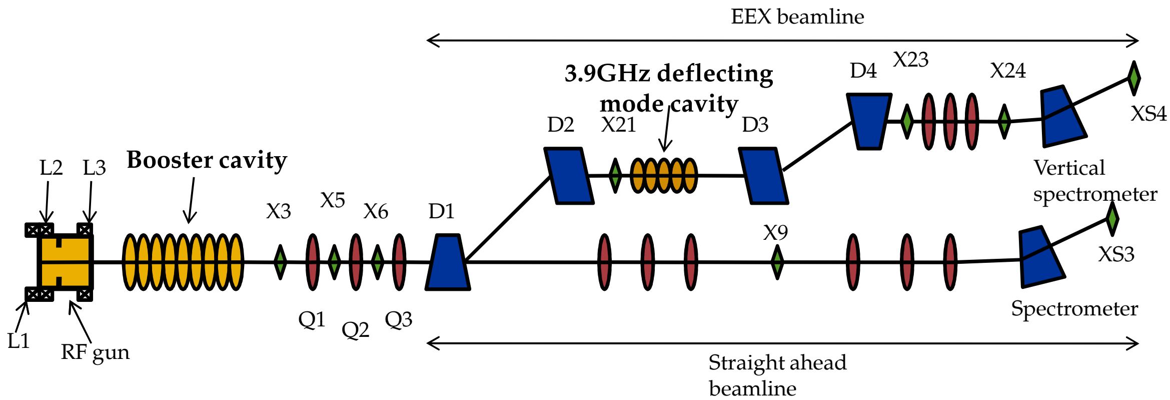

Figure 1: Top view of the A0 photoinjector showing elements pertinent to performing emittance exchange. Elements labeled “X” are diagnostics stations (beam viewers and/or multi-slit mask locations), “L” are solenoid lenses, and “Q” are quadrupole magnets. The EEX beamline with two doglegs and the 3.9 GHz cavity are also indicated.

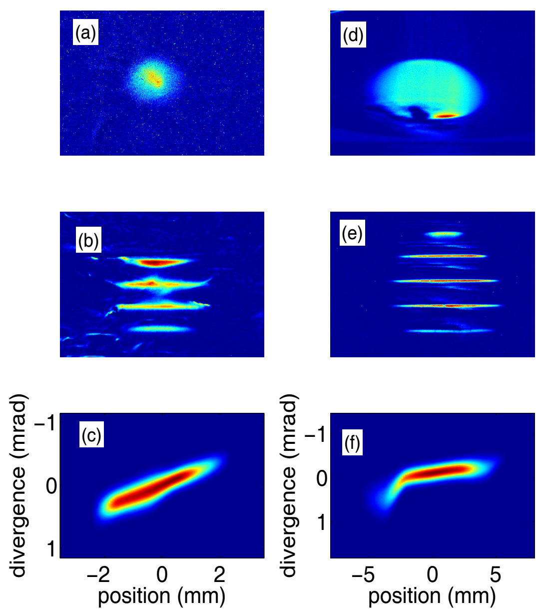

Figure 2: Horizontal emittance images for 100 pC charge before and after EEX Beamline. Beam profile image taken at X3 OTR screen (a) and vertical slit in image taken at X6 (b) before EEX beamline. Beam profile image taken at X23 OTR screen (d) and vertical slit in image taken at X24 (e) after EEX beamline. Phase space information based on the above images is plotted in (c) and (f) respectively. Top four images are rotated by 90°.

and energy spread measurements. Installed in the beam enclosure is a Hamamatsu C5680 streak camera which can be used to measure the electron bunch length both before and after the exchange at the picosecond level [8]. Sub-picosecond bunch length is measured using a Martin-Pupplett interferometer that is located at X24 of the EEX beamline [9]. A spectrometer magnet and viewing screen are located at the end of each beamline to measure the central momentum and momentum spread of the beam. The spectrometer magnet at the end of the EEX line is vertical thus decoupled from possible residual horizontal dispersion from the exchanger.

EEX RESULTS

All measurements are performed at an energy of 14.3 MeV. The booster cavity phase set for minimum energy spread for various charges. The duration of the electron beam measured at X9 varied from 1.9 ps at 100 pC to 3.5 ps at 400 pC due to the longitudinal space charge effect. This leads to the dramatic increase in incoming longitudinal emittance at different charges as shown in Table 1. At the same time, the incoming transverse emittance also increases with charge. However, the magnitude of this change is not as large as the longitudinal. For the EEX measurement incoming transverse phase space was adjusted using the three input quadrupole magnets (Q1,Q2,Q3) not only to satisfy the condition for a perfect exchange but also to yield a minimum energy spread at XS4, thereby indicating the final longitudinal phase space is upright. Thus, a relatively accurate measurement of longitudinal emittance can be done by using the measured energy spread and bunch length.

The results of our most recent EEX measurement at different charges are presented in Table 1. First of all the vertical transverse emittance (ε_y) remains unchanged as the beam propagates through the EEX beamline for all the charges. This is expected since the exchange only happens between horizontal and longitudinal planes. For the incoming horizontal to outgoing longitudinal case most of the numbers also agreed with each other. However, in the case of 400 pC, the error bar of the outgoing ε_x is much larger than the other ones. As we can see from Figure 3 (a) and (c) the horizontal beam size is very close to the screen size, that lead to a larger uncertainty during the fit. At the same time the beamlets width at X24 is also very

Table 1: Comparison of direct measurements of horizontal transverse (x) to longitudinal (z) emittance exchange at various charges. The normalized emittance measurements are quoted in mm-mrad.

	100 pC		250 pC		400 pC	
	In	Out	In	Out	In	Out
ε_x	2.92 ± 0.1	11.9 ± 0.58	3.54 ± 0.1	16.3 ± 1.6	3.51 ± 0.06	20.6 ± 5
ε_y	2.04 ± 0.06	2.5 ± 0.6	2.94 ± 0.1	3.73 ± 0.37	3.66 ± 0.07	3.68 ± 0.48
ε_z	10 ± 1	7.2 ± 0.7	16.6 ± 1.8	8.04 ± 0.8	20.7 ± 0.9	9.28 ± 1

close to the resolution limit of the camera as shown in Figure 3 (b) and (d), which also contribute to the uncertainty. The largest measured difference seemed to happen at the incoming horizontal to outgoing longitudinal case. At all three charges the measured longitudinal emittance is 2-3 times larger than the incoming transverse emittance. Previous study on 250 pC case alone suggested that space charge could play an important role in this difference [10]. However during this study the same difference exists at both 100 pC and 400 pC cases. This implies that space charge may not be the reason for this effect. As we stated before three quadrupoles in front of the EEX line are used to get the minimum energy spread in order to get an accurate measurement of emittance. According to our first order linear optics model [10] with linearized space charge, those quadrupole settings are not the optimal condition to run the EEX experiment. In fact the simulated projected longitudinal emittance value at the same quadrupole settings does agree with our measured value. Simulation also suggests that with current input condition once the quadrupole setting is optimized for EEX experiment the output phase ellipse is not upright.

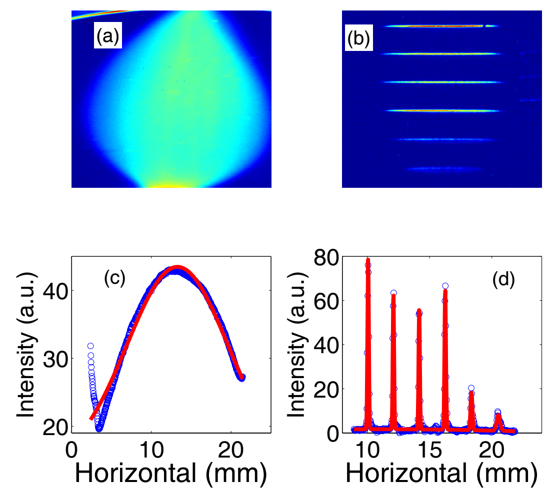

Figure 3: Outgoing transverse emittance images at 400 pC. Beam profile image taken at X23 OTR screen (a) with Gaussian fits to the x-projection (c) and the slit images taken on a YAG:Ce crystal screen located at X24 (b) with respective Gaussian fits (d). Images are rotated 90°.

CONCLUSION

Preliminary investigations into the effects of space charge on emittance exchange has begun at the Fermilab A0 Photoinjector. The measured emittance value shows very good agreement with the incoming longitudinal to outgoing horizontal transverse exchange case and also with the case of vertical transverse emittance. However relatively large difference are observed for the case on the incoming horizontal transverse to outgoing longitudinal at different charges. We attribute this to the present diagnostic system's inability to account for time-energy correlation. Further studies to optimize RF and quadrupole settings will need to be conducted in order to determine ideal operating conditions for exchange to occur with an uncorrelated outgoing longitudinal phase space.

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