Demonstration of Transverse-to-Longitudinal Emittance Exchange at the Fermilab Photoinjector

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Abstract. Phase space manipulation techniques with two degrees of freedom could be essential to the enhancement of the performance of next generation accelerators such as high energy colliders and accelerator-based light sources. At the Fermilab A0 Photoinjector, a proof-of-principle experiment to demonstrate the exchange of the transverse and longitudinal emittance is ongoing. The emittance exchange (EEX) beamline consists of a 3.9 GHz normal conducting deflecting mode cavity positioned between two doglegs as proposed by Kim and Sessler. The experiment is performed using electron bunches with charge of 250 pC and energy of 14.3 MeV. The incoming electron beam has transverse emittance of 2-4 mm mrad and longitudinal emittance of 10-14 mm mrad. After the EEX the measured horizonal emittance is blown up to 13-15 mm mrad while the measured vertical emittance (Non EEX plane) stays the same. At the same time the longitudinal emittance is reduced to 7-9 mm mrad as measued by the current longitudinal diagnostic tools. A linear optics model is established using the beam matrix calculated and measured. A first order simulation based on this model is performed to compare to our experiment results for both EEX measurement and the phase space manipulation experiment.

Keywords: Transverse to longitudinal emittance exchange, Photoinjector, Phase space manipulation
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INTRODUCTION

It is well known that state-of-the-art photoemission sources based on rf-gun photoinjectors are able to produce very low emittance in the six-dimensional phase space. Typically in some operating regime of photoinjectors the longitudinal emittance is smaller than the transverse emittance. However in some applications, such as high gain X-ray free electron lasers, there are stringent requirements on the transverse emittance while relatively relaxed requirements on the longitudinal one. Thus the emittance exchange(EEX) technique, which can repartition the emittance value in the two degrees of freedom, will be very important for those applications.

EMITTANCE EXCHANGE EXPERIMENT

Theoretical Background

Transverse-to-longitudinal phase space exchange was recently proposed as a means to mitigate the microbunching instability in high-brightness electron beams or to improve the performance of free electron lasers. [1, 2] The original proposed lattice capable of performing this phase space exchange consists of a horizontally-deflecting cavity in a dispersive region of a four dipole-magnet chicane [1]. Later a deflecting mode resonant cavity flanked by two dogleg sections was proposed by Kim and Sessler [2] to exchange the longitudinal and the bending-plane transverse emittances. Considering the four-dimentional phase space (x, x', z, δ) the 4×4 matrix takes the form:

$$M = M_{ac} M_{cav} M_{bc} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \tag{1}$$

where A, B, C, D are 2×2 blocks, M_{cav} is the cavity matrix, and M_{bc} and M_{ac} are the matricies for the before-cavity and after-cavity sections of the beamline respectively. In the thin-lens approximation model,

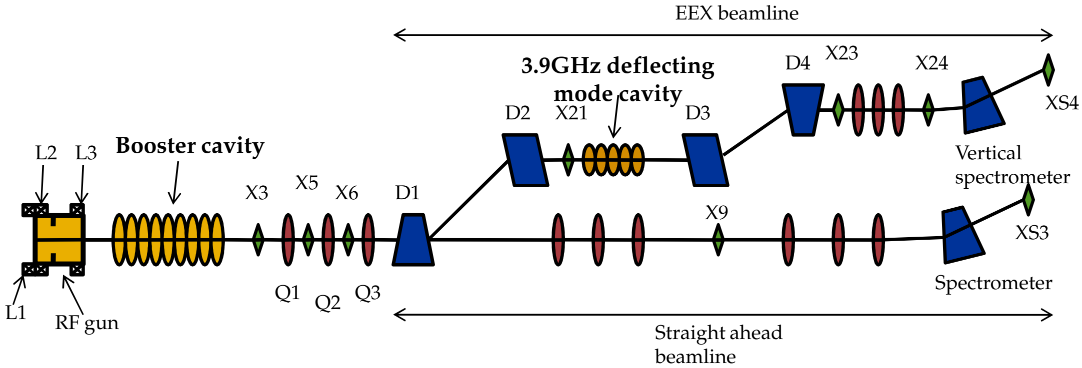

FIGURE 1. Top view of the A0 photoinjector showing elements pertinent to performing emittance exchange. Elements labeled "X" are diagnostics stations (beam viewers and/or multi-slit mask locations), "L" are solenoid lenses, "Q" are quadrupole magnets, and "D" are dipoles.

$$M_{cav} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{pmatrix}, \tag{2}$$

where k is the deflecting strength of the cavity. In the case of a dogleg, the diagonal blocks A and D will become 0 once $k = -1/\eta$ is satisfied, where η is the dispersion generated by one dogleg. This means that complete exchange can be achieved. However as pointed out by [1, 2], the diagonal block elements will not disappear due to the thickness of the cavity. A more detailed analysis in the case of thick lens is covered in Reference [3].

A0 Beamline and Diagnostics

The EEX experiment is conducted at the Fermilab's A0 photoinjector [4]; see Fig. 1. The RF photoelectron gun consists of a photocathode located inside a copper 1.5 cell 1.3GHz resonator operating in the TM_{010} π-mode. The three solenoid lenses that surround the gun control the beam's transverse size and divergence. The beam then enters a 1.3 GHz superconducting radio frequency booster cavity bringing the final energy to 14.3 MeV. Following this final acceleration stage are various beam diagnostic consisting of either optical transition radiation (OTR) or cerium-doped yttrium aluminum garnet (YAG:Ce) crystal viewers. Also found in the beamline are quadrupoles, dipole correctors and beam position monitors (BPM).

The EEX beamline at the A0 photoinjector consists of a liquid-nitrogen-cooled, normal-conducting 3.9-GHz TM_{110} deflecting mode cavity placed between two doglegs [5]. The dogleg incorporate dipole with $\pm 22.5°$ bending angles and generate a horizontal dispersion of η = 0.33 m. The longitudinal electric field of the TM_{110} cavity is zero on axis and grows linearly off axis, while the vertical magnetic field produces a time-dependent horizontal kick with respect to the synchronous particle. When the cavity strength is set to be $-1/\eta$, the EEX beamline elements generates a perfect EEX matrix from the thin lens approximation. During the experiment we will adjust the gradient of our energy boost cavity in 1% increments through a $\pm 3\%$ range. The beam will go through different positions with respect to the deflecting cavity center due to the energy difference. However, when the cavity is on, particles will also experience a kick from the cavity, which could possible accelerate or deaccelerate the particles. When the strength of the deflecting cavity is set to $-1/\eta$ the particle's energy difference will be compensated by the kick received from the cavity. Figure 2 is the screen shot of experiment data, where we plotted the BPM signal just before the XS4 dump vs time. The blue curve corresponds to the case with the deflecting cavity off. We can clearly see the difference caused by the change of the boosting cavity gradient. The red curve corresponds to the case with the deflecting cavity on with the correct gradient, which showed no sign of energy difference because of the additional compensation kick from the deflecting cavity.

The slit emittance measurement technique [6] is used to measure the transverse emittance before and after the EEX beamline. 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. The masks

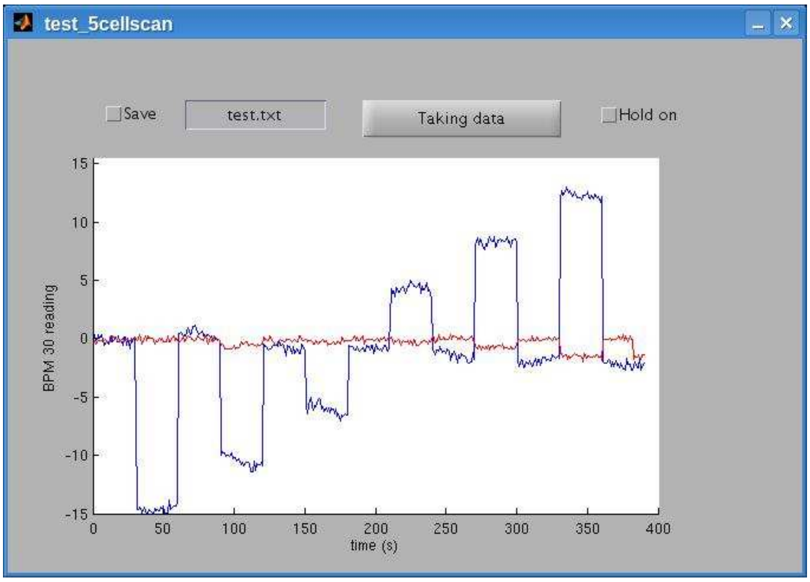

FIGURE 2. The screenshot of the program used to decide the correct gradient setting for the deflecting cavity. Blue curve is the case with the deflecting cavity off and the red curve is the case with the deflecting cavity on with the correct gradient.

consist of 50-μm-wide slits separated by 1 mm, except at X23 where the horizontal slits are separated by 4 mm. Longitudinal emittance is derived from bunch length and energy spread measurements. (The operation conditions are chosen to get an uncorrelated longitudinal phase space) The diagnostics suite also incorporates a Hamamatsu C5680 streak camera which can be used to measure the electron bunch length both before and after the EEX beamline with picosecond resolution [7]. Sub-picosecond bunch length measurements use a Martin-Pupplett interferometer that is located at X24 [8]. 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 to avoid residual dispersion from the exchange.

Simulation

A linear transfer matrix model of the EEX beamline has been assembled within MATLAB in an effort to explore the behavior of the EEX line. It includes the quadrupole and dipole magnets, and has a hybrid thin/thick lens model of the deflecting mode cavity which agrees well with the measured cavity transfer function [9, 5]. The simulation also includes linear space charge forces (both transverse and longitudinal) adapted from the TRACE3D user manual [10]. The space charge effect through the dipoles is achieved by slicing the dipoles longitudinally, and applying space charge defocusing kicks between slices. The simulation requires the phase space parameters on input to the beamline at X3, corresponding to the location where transverse emittance measurements are usually performed. The simulation is designed to be used online in the sense that the magnet settings are read from the control systems. It can nonetheless also be used offline with the settings provided by the user.

RESULTS AND DISCUSSIONS

Emittance Exchange Results

In Table 1, we present the results of our most recent EEX measurement and compare with simulation. The measurement was taken with an electron bunch charge of 250 pC at 14.3 MeV. Incoming transverse phase space was adjusted using the three input quadrupole magnets to yield a minimum output bunch length and energy spread product. The measured emittances of the incoming electron beam is around 3.5 mm-mrad for both horizontal and

TABLE 1. Comparison of direct measurements of horizontal transverse (x) and longitudinal (z) emittances with simulation. Emittance measurements are shown in mm-mrad. The "In" "out" entries respectively corresponding to values before and after the EEX beamline.

	Simulated		Measured	
	In	Out	In	Out
ε_x	3.7	18.7	3.7 ± 0.1	13.9 ± 1.2
ε_y	3.3	3.3	3.3 ± 0.1	4.7 ± 0.4
ε_z	16.2	9.2	16.2 ± 1.5	7.7 ± 2.0

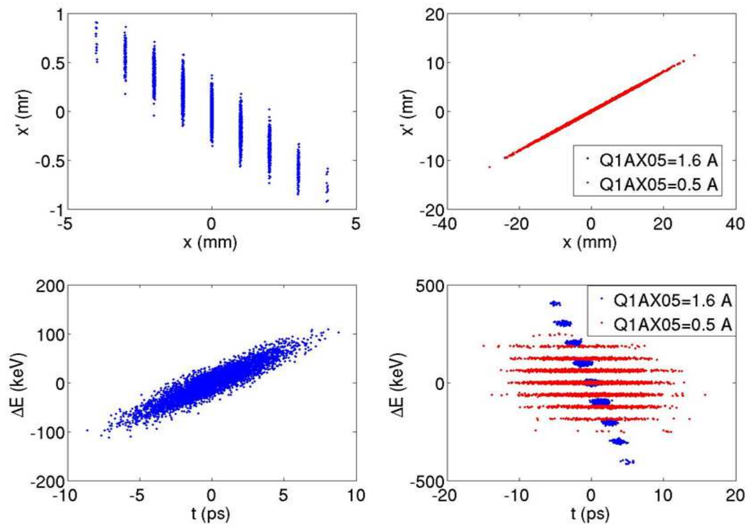

FIGURE 3. Simulation transverse (Top) and longitudinal (bottom) phase space before(left) and after(right) EEX line with vertical slit inserted at X3. Blue and red represent the particles with different quadrupole setting just before the EEX line.

vertical emittance and 16.2 mm-mrad for longitudinal emittance. After the EEX the measured horizonal emittance blows up to 13.9 mm mrad while the measured vertical emittance (Non EEX plane) stays the same. At the same time the longitudinal emittance is reduced to 7-9 mm mrad as measured with the current longitudinal diagnostic tools. According to our simulation, the optimized input quadrupole settings for minimum longitudinal emittance will lead to a beam with a time-energy correlation, which our current diagnostic system cannot measure. In addition, the EEX matrix as measured does not yield an ideal exchange matrix. In particular, the R_{43} element is non-zero simply due to the thickness of cavity.

Energy Modulation due to EEX

As pointed out by Sun et al. [11], the EEX beam line can also be used to map the transverse phase space structure into the longitudinal phase space. Here we show both with simulation and experiment such phase space manipulation. In Figure 3 we show the simulation results obtained with the Matlab-based program described previously. The particle distrbution is first created using the beam parameter measured at X3. The top left plots shows the transverse phase space after the beam passed the slits while the longitudinal phase space distribution is shown in the bottom left plots. The longitudinal phased space after EEX line (at XS4 position) is shown in the bottom right plots. The red and blue represent different settings of the quadrupole. It is very clear that the initial transverse structure is mapped into longitudinal phase space. In this particular case it appears as energy beamlets. The spacing between each energy beamlets increases with

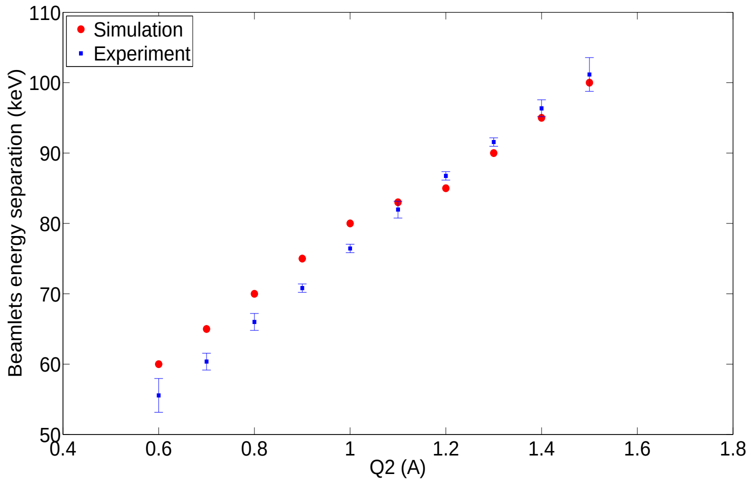

FIGURE 4. Energy spacing between slices with different quadrupole settings in the case of experiment data (blue square with error bar) and simulation data (red dot).

the quadrupole strength. In Figure 4 experimentally-measured energy beamlets spacing (blue squares with error bar) is plotted as a function of quadrupole strength. The red dots represented the corresponding simulated enregy spacing between the energy beamlets. Overall the experimental data agrees reasonably well with the simulations. It is worth noting that there is very little influence from space charge effect and other collective effect such as CSR due to the very low charge in the beamlets.

CONCLUSIONS

A proof-of-principle EEX experiment utilizing the Fermilab A0 photoinjector has been carried out for a beam charge of 250 pC. Phase space manipulation is also done using the EEX beam line. Beamlets in the transverse phase space appears as energy beamlets in the longitudinal phase space. Energy spacing between energy slices measured experimentally agrees with the simulation based on the analytical model. Further investigations of the impact of collective effects are planned.

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