EMITTANCE EXCHANGE AT THE FERMILAB A0 PHOTOINJECTOR*

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Abstract

An experiment to exchange the longitudinal emittance with the horizontal emittance has been installed at the Fermilab A0 Photoinjector. The exchange apparatus consists of a TM_{110} deflecting mode cavity positioned between two magnetic doglegs as proposed by Kim & Sessler [1]. We report on the installation of the emittance exchange beamline, measurement of the emittance exchange beamline matrix elements, and a direct emittance exchange measurement

INTRODUCTION

An emittance exhchange (EEX) experiment has been installed at the Fermilab A0 Photoinjector for a proof of principle demonstration through exchanging a larger normalized longitudinal emittance, 120 mm.mrad, with that of a smaller normalized horizontal emittance, 4 mm.mrad of a 14.3 MeV beam. The installation of the hardware is complete. In this paper we report on measurements of the emittance exchange beamline matrix elements as well as a preliminary effort to directly measure the emittance exchange.

EEX BEAMLINE OPTICS

It is the aim of our emittance exchange experiment to exchange the input longitudinal emittance with the horizontal output horizontal emittance, and vice versus, the input horizontal to the output longitudinal. The apparatus that we have developed, a variant of Kim and Sesslers proposal, can be easily described through a linear optics treatment of the exchange beamline.[1] We describe the entire exchange apparatus by a typical 4x4 matrix relating the horizontal and longitudinal parameters:

$$M_{EEX} = \begin{pmatrix} A_{11} & A_{12} & B_{11} & B_{12} \\ A_{21} & A_{22} & B_{21} & B_{22} \\ C_{11} & C_{12} & D_{11} & D_{12} \\ C_{21} & C_{22} & D_{21} & D_{22} \end{pmatrix},$$

A complete exchange matrix would be one in which the elements of the ***A*** and ***D*** sub-blocks become zero and the ***B*** and ***C*** sub-blocks become populated. However, due to the finite length of our TM_{110} deflecting mode cavity several of the on-diagonal blocks are non zero.[2] This, in addition to other higher order effects, will lead to an imperfect exchange and a coupling of the final emittances. From simulation, we expect these effects to amount to an increase in the final transverse emittance by 32% and the final longitudinal emittance by a factor of 11. [3]

EEX BEAMLINE

The emittance exchange apparatus at the A0 photoinjector consists of a 3.9 GHz TM_{110} deflecting mode cavity located between two 'dogleg' magnetic channels. The TM_{110} deflecting mode cavity is a liquid nitrogen cooled, normal conducting, variant of a superconducting version previously developed at Fermilab.[4,5] The longitudinal electric field of the TM_{110} mode is zero on axis and grows linearly off axis, the vertical magnetic field produces a time dependant transverse kick with respect to the synchronous particle. The dispersion of the first magnetic dogleg horizontally positions off-momentum electrons in the TM_{110} cavity. As a result, the TM_{110} cavity reduces the momentum spread. Additionally the cavity imparts transverse kick dependant on the electrons time of arrival. The second dogleg completes the exchange.

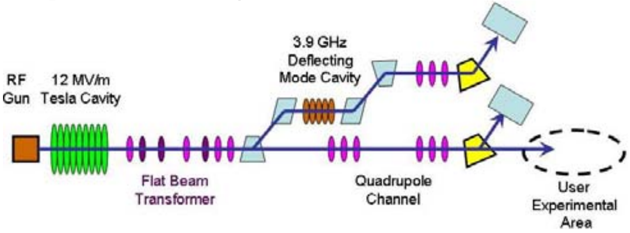

Figure 1: Layout of the A0 Photoinjector with straight ahead and EEX beamline sections.

EEX BEAMLINE DIAGNOSTICS

The EEX beam line is outfitted with ten 4-button Beam Position Monitors (BPM) for measuring transverse beam position throughout the beamline. Transverse beam profiles are measured by eight Optical Transition Radiation (OTR) viewing screens along the beamline. There are two sets of tungsten slits-YAG viewing screen pairs for measuring the transverse beam divergence before and after the exchange beamline. EEX input and output central momenta and momentum spreads are measured by two spectrometer magnets and viewing screens. Finally, a single streak camera provides a measurement of the laser pulse length, and electron bunch lengths at the input and output of the exchanger. Together, a high frequency beam phase monitor, which is installed at the exit of the EEX beamline, and an electro-optical acquisition system that is presently being developed will provide bunch time-of-arrival data with 1 picosecond resolution or better.[6] A Martin-Puplett interferometer is also being installed at

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the end of the EEX beamline to perform sub-picosecond bunch length measurements.

EEX MATRIX MEASUREMENT

Difference orbits have been used to measure the EEX beamline matrix elements. The procedure was to establish a nominal beam orbit through the EEX beamline and measure both the 6-D input and output vectors. Then one of the 6-D input vector's elements was varied and the change in the 6-D output vector was measured. This procedure was repeated with the TM_{110} deflecting mode cavity off, at the full strength for the complete EEX condition, and four strengths in-between. The BPM's gave Δx, $\Delta x'$, Δy, and $\Delta y'$ data, the streak camera provided the Δz information, and finally the vertical bending spectrometer in conjunction with the subsequent vertical BPM position reading provided the output Δp data.

A brief example of the data collection is displayed in figures 3 and 4. Both figures display the post-spectrometer BPM's vertical reading as a function of time. The data run began by recoding 60 events (seconds) of a nominal orbit. Then the input momentum was reduced by 2.2% for the next 60 events, after which the momentum was returned to the nominal orbit value. This procedure was repeated five more times, in each iteration the input Δp was incremented by +0.72%. The repeated intermediate returns to the nominal momentum value ensures that the Photoinjector parameters did not drift during the data run or, if need be, allow a subtraction of a large time constant drift. In figure 2, where the TM_{110} deflecting cavity is off, it is clear that the momentum offset is mapped to a vertical displacement in the spectrometer's dispersive channel. In Figure 3, the identical input momentum offset sequence is run, however, no deflection after the spectrometer results, thus indicating that with the TM_{110} cavity on the EEX beamline has zeroed the D_{22} element. Thus the slope of a linear fit to the outputs momentum dependence on the input momentum variation is a measure of the D_{22} matrix element. It is worth noting that by increasing the TM_{110} mode cavity above the proper EEX strength the momentum offset becomes over compensated as would be expected.

This approach has been repeated for all input parameters at five varied TM_{110} cavity strengths. There is good individual control of the Δp, $\Delta x'$ and $\Delta y'$ inputs due to automation. Because of the manual control involved, it difficult to achieve "pure" Δx and Δy input offsets without incurring an input angle as well. Utilizing the previously measured "pure" input angle's contribution to the output vector, the angle component can be subtracted from the convoluted offset-angle input runs. Finally, since the only time varying component off the EEX beamline is the TM_{110} cavity, it is sufficient to simply adjust the cavity's phase to affect a time of arrival offset from the nominal synchronous reference.

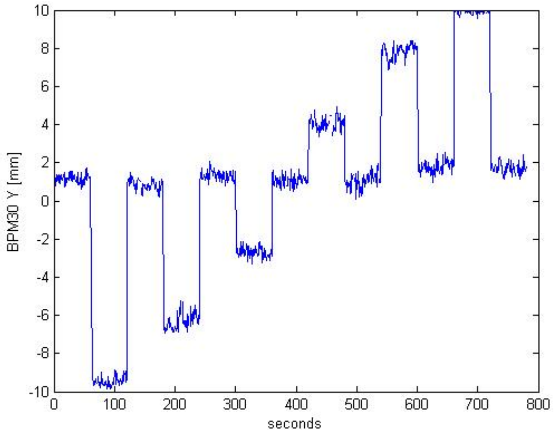

Figure 2: Post Magnetic Spectrometer BPM reading through a sequence of input momentum offsets. The TM_{110} deflecting cavity was off.

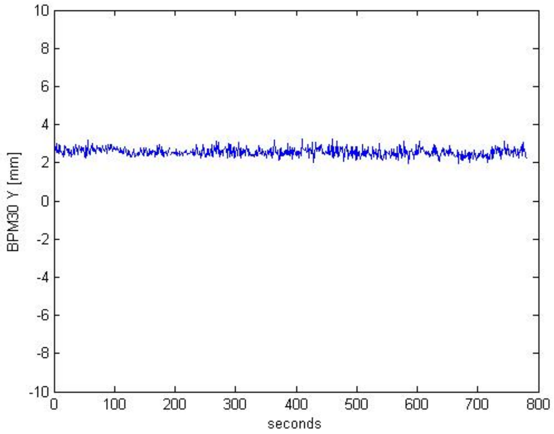

Figure 3: Post Magnetic Spectrometer BPM reading through the same sequence of input momentum offset, with. the TM_{110} deflecting cavity on – output momentum is constant.

Our efforts, to date, have yielded a partial EEX transport matrix with the deflecting mode cavity set for optimal emittance exchange. Three of the elements in the 3rd row are not yet measured; however measurements with the TM_{110} cavity at less than optimal strengths show that the EEX matrix elements do tend to the expected values.

Included below is a calculated transport matrix for comparison.

$$\begin{pmatrix} -0.018 & -0.016 & 4.833 & 0.352 \\ 0.017 & 0.013 & -0.644 & 0.160 \\ 0.162 & 0.625 & 0.036 & 0.0045 \\ -0.642 & 3.709 & 0.300 & 0.036 \end{pmatrix}$$

The measured matrix elements read:

$$\begin{pmatrix} -0.017 \pm 0.06 & -0.054 \pm 0.029 & 5.283 \pm 0.100 & 0.404 \pm 0.010 \\ 0.002 \pm 0.070 & 0.006 \pm 0.090 & 0.619 \pm 0.140 & 0.168 \pm 0.016 \\ -- & 0.607 \pm 0.060 & -- & -- \\ 0.001 \pm 0.010 & 3.315 \pm 0.010 & 0.100 \pm 0.067 & 0.08 \pm 0.010 \end{pmatrix}$$

There are discrepancies between the simulated matrix and the measured values; we are investigating the models representation of the beamline.

DIRECT EEX MEASUREMENT

After the initial matrix element measurements, an inaugurate program to directly measure the emittance exchange is underway. The input 6-D emittance is measured with the transverse with the vertical and horizontal slits and viewing screens, the longitudinal emittance with the streak camera for bunch length and the magnetic spectrometer for energy spread. The same diagnostics are available to measure the output emittances, however, the extreme values of the horizontal beam spot exceed the dimensions of our existing screens. The horizontal emittance measurement is further complicated by being in a dispersive section. Finally, the EEX output bunch length may be smaller than can be resolved by the streak camera, prompting the installation of a Martin-Puplett interferometer.

A preliminary streak camera measurement is displayed in Figure 4. For this data run, approximately 120 events were recorded with the TM_{110} mode cavity on, followed by another period of 120 events with the cavity off, and finally another 1.5 cycles of cavity on-off-on. The streak camera returns a cavity-on bunch length of 0.6±0.5 pSec (rms) and in the cavity-off case 2.2±0.3 pSec. The large error bar at the short bunch length is due to the resolution of the streak camera, which is about 1pSec.

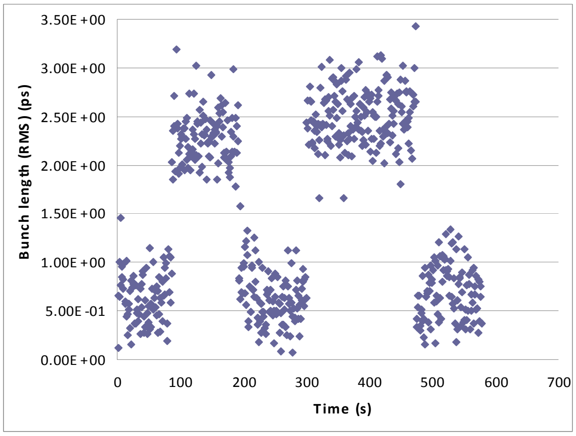

Figure 4: Streak camera measurements showing a reduction of bunch length of 0.5±0.5 ps with the TM_{110} cavity on.

The TM_{110} cavity-on measured momentum spread is 86 keV, yielding a projected longitudinal normalized emittance of 50.5±1.2 mm.mrad.

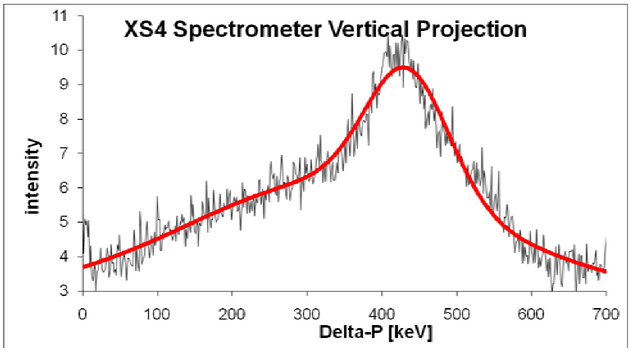

Figure 5: Projection of Spectrometer imaging screen.

CONCLUSIONS

The initial operation of the A0 Photoinjector longitudinal-transverse emittance exchange line has begun to yield exciting evidence that the EEX line optics are functioning.

Table 1: Preliminary comparison of the input and output normalized longitudinal emittances.

	ε_x [mm.mrad]	ε_z [mm.mrad]
INPUT	6	120
OUT (TM110 OFF)	--	188
OUT (TM110 ON)	--	50.5

Table 1 compares the measured input and preliminary output projected longitudinal emittances. A clear reduction in longitudinal emittance is observed when the TM_{110} mode cavity is energized.

We are refining the measurement of the EEX beamline matrix and exploring the input parameters that produce the optimal exchange. Further development of diagnostics will extend our resolution in the short bunch length measurement and handle the large transverse beam profiles.

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