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 located between two magnetic doglegs as proposed by Kim & Sessler.[1] We report on the measurement of the emittance exchange beamline matrix elements, direct emittance exchange measurements and calculations.

INTRODUCTION

An emittance exhchange (EEX) experiment has been installed at the Fermilab A0 Photoinjector for a proof of principle demonstration through the exchange of a larger normalized longitudinal emittance, 20 mm.mrad, with that of a smaller normalized horizontal emittance, 5 mm.mrad of a 14.3 MeV electron beam. 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 MATRIX MEASUREMENT

Our emittance exchange experiment exchanges 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 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.

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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, as depicted in Figure 1. The TM_{110} deflecting mode cavity is a liquid nitrogen cooled, normal conducting, variant of a superconducting version previously developed at Fermilab.[3,4] 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.

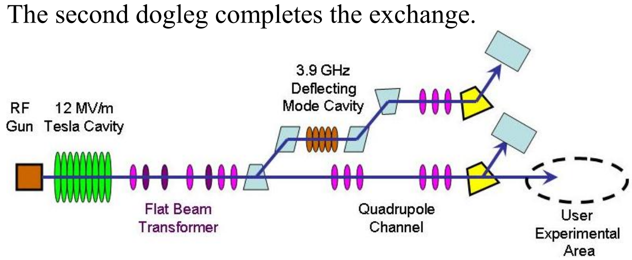

Figure 1: Layout of the A0 Photoinjector with straight ahead and EEX beamline sections.

EEX BEAMLINE DIAGNOSTICS

The EEX beamline is outfitted with ten transverse Beam Position Monitors (BPM). Transverse beam profiles are measured by Optical Transition Radiation (OTR) viewing screens. Transverse input and output emittances are measured by the interceptive method of tungsten slits-YAG viewing screen pairs.[5]

EEX input and output central momenta and momentum spreads are measured by two spectrometer magnets and viewing screens. A streak camera provides a measurement of the laser pulse length, and electron bunch lengths (greater than 1 ps) at the input and output of the exchanger. A Martin-Puplett interferometer (MPI) is installed at the end of the EEX beamline to perform sub-picosecond bunch length measurements.[6] The interferometer's pyroelectric sensors are used to make quick, but uncalibrated, bunch length measurements. The intensity of the coherent transition radiation is inversely related to the bunch length, thus the sensors signal yields a relative bunch length measurement.

We were unable to measure an energy-time correlation, thus we take the energy-spread bunch-length product,

$\sigma_p \cdot \sigma_z$, as the worst case scenario, thus potentially returning values larger than the actual longitudinal emittance.

EEX BEAMLINE MATRIX

The first priority was a measurement of the emittance exchange beamline transport matrix. The method of difference orbits was used to measure the transport matrix. Through varying individual beam input vector elements, such as x_{in}, x'_{in}, y_{in},y'_{in}, or δ_{in}, and measuring the changes in all of the beam output vector's elements, Δx_{out}, $\Delta x'_{out}$, Δy_{out}, $\Delta y'_{out}$, and $\Delta\delta_{out}$, the full 6X6 transport matrix was measured. 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 $\Delta\delta$ data. This measurement has been performed at five varied TM_{110} cavity strengths.

As expected, the elements of the 6X6 matrix which relate the vertical coordinate showed no dependence on the TM_{110} cavity status. Thus we report only the 4X4 (horizontal-longitudinal) measured matrix, which reads:

$$\begin{pmatrix} -0.02\pm0.059 & -0.23\pm0.089 & 4.75\pm0.350 & 0.40\pm0.003 \\ -0.02\pm0.167 & 0.11\pm0.041 & -.02\pm0.540 & 0.21\pm0.002 \\ 0.23\pm0.051 & 0.63\pm0.107 & -0.21\pm0.312 & 0.00\pm0.148 \\ -0.09\pm0.017 & 4.89\pm0.047 & 0.13\pm0.080 & 0.08\pm0.010 \end{pmatrix}$$

For comparison, the calculated matrix elements read:

$$\begin{pmatrix} -0.013 & -0.008 & 4.832 & 0.345 \\ 0.014 & 0.006 & -0.642 & 0.161 \\ 0.190 & 0.687 & 0.037 & 0.004 \\ -0.058 & 5.059 & 0.300 & 0.035 \end{pmatrix}$$

The measured emittance exchange transport matrix was in overall good agreement with our calculated transport matrix. However, from inspection of Figure 2, the measured R_{21}, R_{23} and R_{43} elements did not match expected values. In the case of $R_{23,}$ the cryogenic supports of TM_{110} cavity is suspected to have abruptly changed the tune and phase. The large discrepancy between the measured and calculated R_{21} element is from the approximation of the bending dipoles in our beamline simulation. Planned field measurements of the actual magnet hardware will clarify the field description.

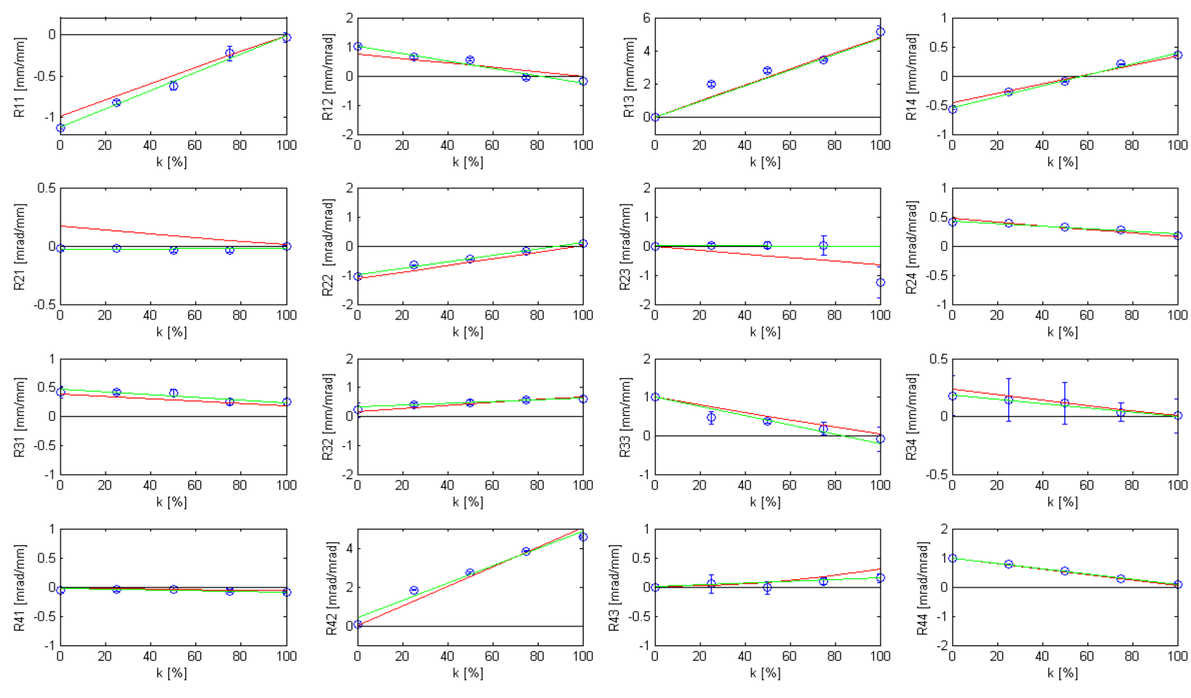

Figure 2: The 4X4 (horizontal-longitudinal) emittance exchange matrix as a function of TM_{110} cavity strength. The cavity is off at *k*=0% and is energized to the ideal emittance exchange strength at *k*=100%. The circles are measured points, the green (lighter) lines are fits to the data, and the red (darker) lines are calculated values.

DIRECT EEX MEASUREMENT

A direct measurement of the emittance exchange has been performed. The exchange was performed with a 14.3 MeV, 250 pC electron bunch train. The bunch charge of 250 pC was chosen as a compromise between diagnostic requirements and space charge effects. Transverse input parameters were tuned (by adjusting input quadrupoles) for a minimum output bunch-length energy-spread product. Input quadrupole scans were performed to identify minimums in both output σ_p and $\sigma_{z,}$ as they do not occur simultaneously. This is an indication of significant longitudinal-energy correlation, σ_{pz}, which we reiterate could not be measured. A normalized measured $1/\sigma_p \cdot \sigma_z$ product map is shown in Figure 3.

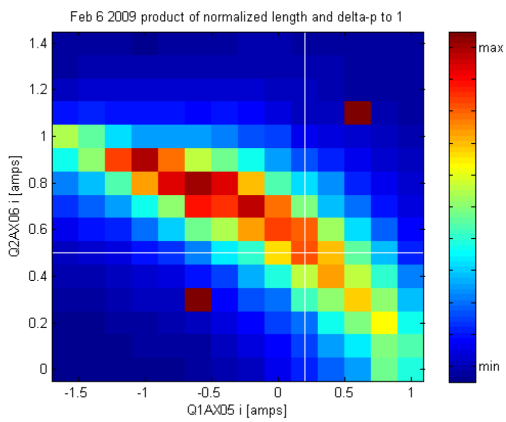

Figure 3: February 6 data; a relative output $1/\sigma_p\cdot\sigma_z$ product map against input quadrupole currents. The white cross hairs indicate a choice for EEX operation.

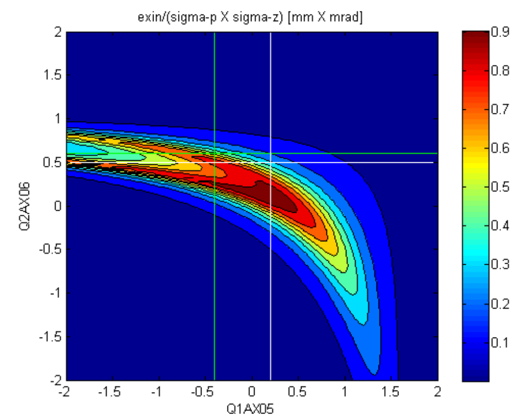

Figure 4: Calculated ratio of $\varepsilon_{x,in}/(\sigma_p\cdot\sigma_z)_{out}$ over input quad scan. The white and green cross hairs indicate the operating points for Feb 6 and Feb 11 data sets respectively.

The EEX operating points were selected at minimums along the valley of the output $\sigma_p\cdot\sigma_z$ minimum, taking $\varepsilon_{z,out} = \sigma_p\cdot\sigma_z$. There, a calibrated MPI output bunch length measurement was made, as well as measurement of all other input and output emittances. The best EEX results to date are reported in Table 1.

Table 1: February 11, 2009, Direct EEX Data Set, Reflecting Input and Output *rms* Normalized Emittances

Coordinate	$\sigma_i\,[mm]$	$\sigma'_i\,[mrad]$	$\epsilon_{i,N}\,[mm.mrad]$
x_{in}:	0.73±0.03	0.23±0.01	4.67±0.22
y_{in}:	0.78±0.03	0.23±0.01	5.11±0.21
z_{in}:	0.75±0.01	1.00±0.07	21.1±1.50
x_{out}:	2.92±0.16	0.26±0.02	20.8±2.00
y_{out}:	0.70±0.04	0.31±0.02	6.00±0.42
z_{out}:	0.26±0.04	0.97±0.05	7.06±0.43

1:1 ratio of input longitudinal to output horizontal emittance, εz,in → εx,out, exchange was observed. An input-transverse to output-longitudinal emittance, εx,in → εz,out, exchange was observed with projected emittance growth: $\varepsilon_{x,in}$ of 4.67±0.22 mm·mrad exchanged to a $\varepsilon_{z,out}$ of 7.06±0.43 mm·mrad. The apparent emittance growth is partially explained by the present longitudinal diagnostic's inability to account for longitudinal position-energy correlation.

Calculation showed that the ratio of projected emittances $\varepsilon_{z,in} \rightarrow \varepsilon_{x,out}$ is not as sensitive as is the projected $\varepsilon_{x,in} \rightarrow \varepsilon_{z,out}$ to the input beam conditions.[7] Figure 4 shows the calculated the ratio $\varepsilon_{x,in}/(\sigma_p\cdot\sigma_z)_{out}$ during an input quadrupole scan. The apparent measured $\varepsilon_{z,out}$ growth is consistent with the calculated values in which the correlation term is neglected.

In addition to the unaccounted longitudinal correlation term and the non-ideal emittance exchange matrix, i.e. effects of the thick lens cavity, emittance dilution can be a result of space charge forces and potential coherent effects, such as coherent synchrotron radiation. Finally, the resolution of our Ce doped YAG screens is presently being investigated.

CONCLUSIONS

A proof of principle transverse to longitudinal emittance exchange has been completed at the Fermilab A0 Photoinjector. The EEX transport matrix of the new beamline and unique TM_{110} deflecting mode RF cavity has been measured using the method of difference orbits. The finite length of the TM_{110} resulted in a non-zero R_{43} element, thus a non-ideal emittance exchange matrix.

An initial observation of an emittance exchange was performed. A 1:1 ratio of $\varepsilon_{z,in} \rightarrow \varepsilon_{x,out}$, exchange was observed. However an, $\varepsilon_{x,in} \rightarrow \varepsilon_{z,out}$, exchange was observed with projected emittance growth. The apparent growth could potentially be explained by the present longitudinal diagnostic's inability to account for longitudinal position-energy correlation, the non-ideal emittance exchange matrix, space charge and potential coherent effects. This will be studied.

The installation of second deflecting mode cavity prior to the magnetic spectrometer is planned for measuring the output longitudinal position-energy correlation.

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