START TO END SIMULATIONS OF TRANSVERSE TO LONGITUDINAL EMITTANCE EXCHANGE AT THE A0 PHOTOINJECTOR*

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Abstract

Various schemes to exchange the transverse and longitudinal emittance have been proposed. [1][2] One scheme involves a deflecting mode RF cavity between two doglegs to exchange the horizontal and longitudinal emittances. This will produce a complete and uncoupled emittance exchange in the thin cavity limit using first order matrix optics. Various other effects, such as a finite length cavity, can leave the emittances coupled after the exchange and dilute the final emittances. Other effects such as space charge and synchrotron radiation can be investigated through simulations.

A transverse to longitudinal exchange experiment using the double dogleg approach is underway at the A0 Photoinjector at Fermilab. In this paper we present start to end simulations of the experiment using various codes to account for space charge and Coherent Synchrotron Radiation effects. The results of these simulations are compared with analytical approximations and preliminary data. The effect on the exchange is also discussed.

INTRODUCTION

The A0 Photoinjector is doing a proof of principle transverse to longitudinal emittance exchange experiment. Such a phase space manipulation can have applications to FELs or possibly a linear collider.[2] All sources of emittance growth and coupling need to be understood, only in this way can the exchange be optimized.

In this paper we discuss start to end simulations of the transverse to longitudinal emittance exchange experiment at the A0 photoinjector. The results of these simulations are compared to linear optics predictions and existing data.

THEORY

The theory of transverse to longitudinal emittance exchange is discussed in Reference 1. The beam matrix is given by

$$\sigma = \begin{pmatrix} \sigma_x^2 & \sigma_{xx'} & 0 & 0 \\ \sigma_{xx'} & \sigma_{x'}^2 & 0 & 0 \\ 0 & 0 & \sigma_z^2 & \sigma_{z\delta} \\ 0 & 0 & \sigma_{z\delta} & \sigma_\delta^2 \end{pmatrix}. \qquad (1)$$

The determinant of the upper left block is the square of the transverse emittance, and the lower right block is the square of the longitudinal emittance.

The beam matricies at two points are related by the transport matrix R

$$\sigma_2 = R\sigma_1 R^T. \qquad (2)$$

We write the R matrix in 2x2 block form.

$$R = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \qquad (3)$$

The goal of designing a emittance exchange beamline is to produce an R matrix with the A and D block to be all zero. This will completely swap the emittances and leave them uncoupled after the exchange. If the A and D blocks of the R matrix are not identically zero, there will be residual coupling of the emittances. The input beam matrix can be manipulated to minimize this coupling.

A0 EXPERIMENT

The experiment at the A0 Photoinjector will utilize a horizontally bending double dogleg with a 3.9GHz deflecting mode RF cavity between them. Such a beamline will produce a perfect exchange in the thin cavity limit. A vertical bending spectrometer is used to measure the momentum spread after the beamline. Other diagnostics are available and are described more fully in Reference 3. The details of the cavity are discussed in Reference 4. Figure 1 shows a diagram of the beamline for the emittance exchange.

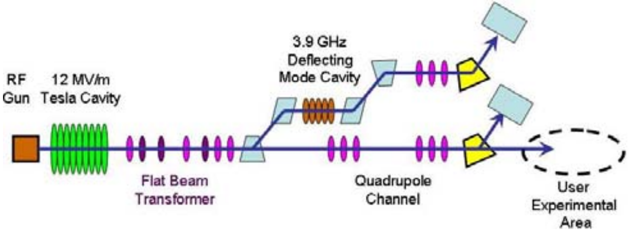

Figure 1: Cartoon of the A0 Photoinjector. The emittance exchange beamline starts at the first blue dipole magnet. The yellow spectrometer on the emittance exchange beamline is vertically bending.

The input beam has a normalized rms transverse emittance of 6mm-mrad, and a longitudinal emittance of 204 keV-ps or 120 mm-mrad. Quadrupoles upstream of the emittance exchange beamline focus the beta function at the center of the deflecting cavity. The beam is also chirped to partially compress the bunch at the cavity center. Such a scheme is used to minimize coupling that is induced in the system from the.

The beam energy is 14.3 MeV. This energy is dictated by the need to chirp the beam for compression in the first dogleg. The A0 photoinjector is capable of producing a

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bunch charge as high as 4nC. This gives us the ability to see a varied of effects associated with space charge and coherent radiation. We embarked on a simulation project to understand these effects on the emittance exchange experiment using a 1nC bunch.

SIMULATION

A variety of simulation programs were used to study the emittance exchange experiment. ASTRA was used to simulate the A0 beam from the cathode to the start of the emittance exchange experiment.[5] The output of this code was benchmarked against measurements of the A0 beam to ensure its accuracy as this serves as the input to all other simulation codes. Figure 2 shows the results of the benchmarking.

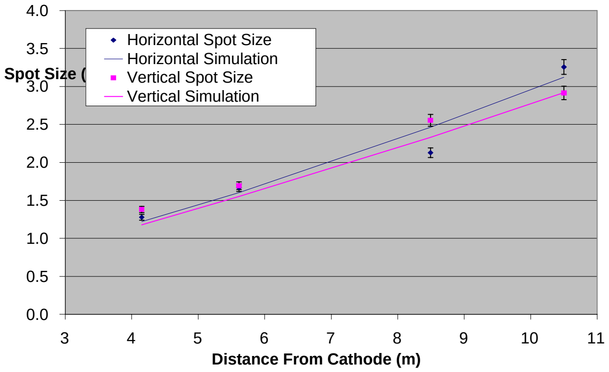

Figure 2: Comparison of beam spot size measurements through the A0 straight section compared with ASTRA simulations. The emittance exchange line starts at 5.7m from the cathode.

ELEGANT[6] and TRACE3D[7] were used for linear optics modeling of the emittance exchange beamline. These codes were checked against each other to ensure that we had the correct understanding of the emittance exchange beamline. Some discrepancies were related to errors in one or the other model. Discrepancies in the vertical plane were traced to differences in the fringe field treatment of the dipole magnets. This has not been fully resolved.

Modeling space charge and coherent radiation required a different approach. ASTRA was used to simulate a 1nC bunch of 10^5 particles from the cathode to the start of the emittance exchange line. Figure 3 shows the results of the ASTRA simulation in the horizontal and longitundinal phase spaces. The simulated transverse emittance is 4mm-mrad and the longitudinal emittance is 108mm-mrad. CSRTrack was used to simulate the first dogleg.[8] ASTRA was again used to simulate the deflecting cavity using a 3D field map. CSRTrack simulated the second dogleg. ASTRA simulated the diagnostics straight section, and CSRTrack simulated the vertical spectrometer section. A series of scripts converted the files from one program to the next.

Four separate conditions were simulated:

- Deflecting cavity off – No Coherent radiation
- Deflecting cavity off – Coherent radiation
- Deflecting cavity on – No Coherent radiation
- Deflecting cavity on – Coherent radiation

The simulations without the coherent radiation were checked against ELEGANT simulations for consistency.

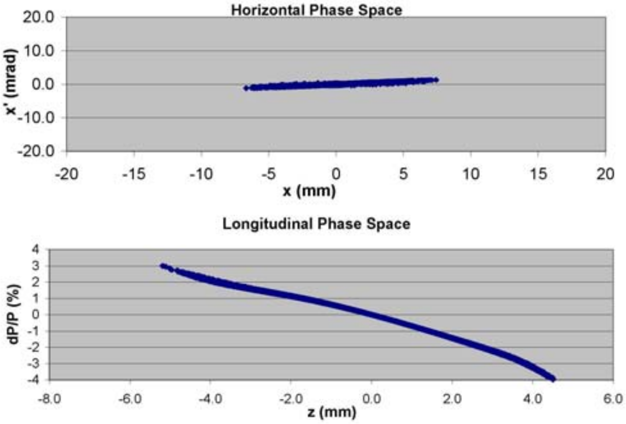

Figure 3: The input horizontal and longitudinal phase space distributions from ASTRA.

COHERENT RADIATION SIMULATION RESULTS

The first set of simulations with the deflecting cavity turned off shows the effects of coherent synchrotron radiation and space charge on the beam as it passes through the double dogleg of the emittance exchange beamline. In this scenario there is no exchange of the emittance. The emittances are coupled because of the dispersion in this scenario and the projected emittances are larger than the input emittances. The beam though compressed at the location of the deflecting cavity is uncompressed in the second dogleg and reverses the sign of its chirp.

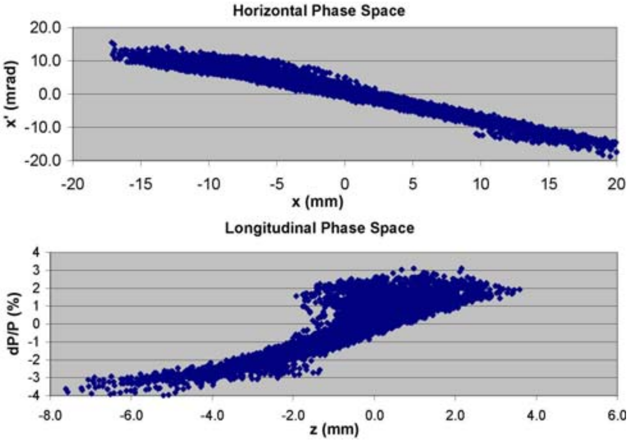

Figure 4: The output horizontal and longitudinal phase space distributions of a 1nC bunch after the double dogleg with the deflecting cavity off. Coherent radiation is included in these plots.

Figure 4 shows the output of the emittance exchange beamline with the deflecting cavity off and coherent synchrotron radiation turned on. The apparent transverse emittance is 278 mm-rad, and the longitudinal emittance isalso 278 mm-mrad. This is a growth of 10% in the horizontal plane and a reduction of 3% in the longitudinal plane as compared to the case when the coherent radiation is turned off. The vertical emittance in this simulation is unaffected.

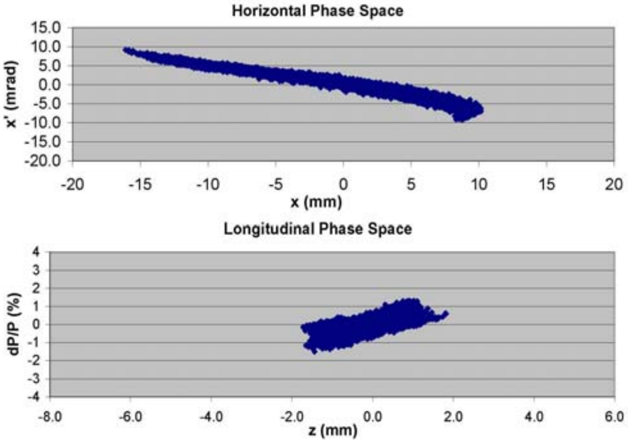

Figure 5: The output horizontal and longitudinal phase space distributions a 1nC bunch after the emittance exchange. Coherent Radiation effects are included.

The emittance exchange occurs when the deflecting cavity is turned on. Figure 5 shows the results of these simulations with coherent radiation and space charge. The transverse emittance is 143 mm-mrad and the longitudinal emittance is 50 mm-rad. This should be compared with the input emittances of 4 mm-mrad horizontally and 108 mm-mrad longitudinally. The horizontal and longitudinal emittances are exchanged.

In the thin deflecting cavity limit, the emittances should be perfectly swapped with no emittance growth. The final transverse emittance grows 1.5% and the final longitudinal emittance grows 82% from the finite length cavity. This emittance growth is from residual coupling that remains in the transport matrix. It can be shown that when the deflecting cavity length cannot be neglected some coupling will always remain in an emittance exchange of this type. [9].

The remainder of the emittance growth is from space charge and coherent synchrotron radiation. In particular, the longitudinal compression in the first dogleg combined with the reduction in momentum spread in the deflecting mode cavity causes momentum spread increase in the second dogleg from coherent synchrotron radiation. This increases the longitudinal emittance. The transverse emittance grows because each particle's momentum changes in the dipoles which causes an increase in the transverse amplitude.

The vertical emittance is not affected in this simulation.

The momentum spread is measured by using a vertically bending spectrometer. Coherent synchrotron radiation in the vertical bend will increase the measured momentum spread by 12% compared to its value after the exchange and a corresponding increase in the measured longitudinal emittance.

The available diagnostics do not allow us to measure the correlation between energy spread and bunch length. [3] The measurement of the bunch length and momentum spread allow us only to place an upper bound on the longitudinal emittance. The measured upper bound on the longitudinal emittance is 436 mm-mrad with the cavity turned off and CSR effects included. With the deflecting cavity turned on, the upper bound on the longitudinal emittance is 96 mm-mrad including CSR effects. This combined with the reduction in the transverse emittance gives a positive measurement that the emittances are indeed exchanged.

CONCLUSION

Simulations of the transverse to longitudinal emittance exchange at the A0 photoinjector have been carried out. These simulations include effects from the finite length of the deflecting cavity, space charge, and coherent synchrotron radiation. These effects increase the final transverse emittance by 32% and the final longitudinal emittance by a factor of 11 compared to a perfect emittance exchange.

Even when the emittance dilution effects are considered the measured longitudinal emittance will decrease to ½ of its original value and the transverse emittance increases factor 36 compared to its original value indicating a successful exchange.

Measurements of the matrix elements of the exchange beamline are ongoing and are presented in these proceedings. [3] Coherent radiation studies are occurring in parallel.[10]

REFERENCES

[1] M. Cornacchia and P. Emma, PRSTAB 5, 084001 (2002).

[2] K.-J. Kim and A. Sessler, AIP Conf. Proc. **821**, 115(2006).

[3] T. Koeth, et.al. "Status of the Transverse to Longitudinal Emittance Exchange Experiment at the FNAL A0 Photoinjector". These Proceedings. THPC020.

[4] T. Koeth, et.al. "A Copper 3.9GHz TM110 Cavity for Emittance Exchange". Proceedings of the Particle Accelerator Conference 2007, Albuquerque NM, TPAS079.

[5] K. Floetmann. "A Space Charge Tracking Algorithm" http://www.desy.de/~mpyflo/.

[6] M. Borland, "ELEGANT: A Flexible SDDS-Compliant Code for Accelerator Simulation." Advanced Photon Source LS-287, September 2000.

[7] K. R. Crandall and D. P. Rusthoi. "Trace3D Documentation" 3rd Edition May 1997.

[8] M. Dohlus and T. Limberg. CSRtrack Version 1.2 User's Manual. http://www.desy.de/xfel-beam/csrtrack/index.html.

[9] R. P. Flilller "General Solution to a Transverse to Longitudinal Emittance Exchange Beamline". Fermi Beams Document 2553-v2.

[10] R. P. Fliller III, et. al., "Investigation of Possible CSR Induced Energy Spread Effects with the A0 Photoinjector Bunch Compressor" These Proceedings THPC014.