# NEAR-IDEAL EMITTANCE EXCHANGE AT THE FERMILAB PHOTOINJECTOR *

A. S. Johnson, J. Ruan, H. Edwards, A. H. Lumpkin, J. Santucci, R. Thurman-Keup
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

*Abstract*

The A0 Photoinjector at Fermilab is presently home to an emittance exchange (EEX) experiment. The emittance exchange beamline consists of a 3.9 GHz normal conducting deflecting mode cavity flanked by two doglegs. Electron bunches with charges of 250 pC and energy of 14.3 MeV are routinely sent through the exchanger. Here we present results of a 1:1 transverse and longitudinal emittance exchange.

## INTRODUCTION

The advent of synchrotron radiation light sources and free electron lasers (FEL) has been a boon to a wide range of disciplines, resulting in a constantly increasing demand for brighter sources and better resolution [1]. This demand translates to requirements on the properties of the underlying electron beams which produce the light. In particular, one is driven to find ways to precisely manipulate the phase space volume of the beam to optimize it for the desired application [2, 3]. Motivated by the FEL requirement for a small transverse emittance, Cornacchia and Emma developed a transverse / longitudinal emittance exchange concept using a deflecting mode rf cavity located in the dispersive section of a magnetic chicane [4]. This method however, contained residual couplings between the two dimensions, leading Kim to propose a modified version which removed that coupling and resulted in a complete exchange [5]. In this configuration, the deflecting mode cavity is placed between two magnetic doglegs thereby removing the afore-mentioned coupling term. We have used this beamline with upgraded diagnostics to measure a near-ideal 1:1 emittance exchange.

## EXPERIMENTAL SETUP

The A0PI facility includes an 1.5-cell normal-conducting L-band rf photocathode gun using a $Cs_2Te$ photocathode irradiated by the frequency quadrupled, UV component of a Nd:Glass drive laser [6]. The drive laser can be configured to provide a train of electron beam pulses separated by 1 $\mu$s with charges up to 1 nC. The rf gun is followed by a 9-cell L-band superconducting cavity, and both a straight ahead and emittance exchange beam lines as schematically shown in Figure 1. The emittance exchange beamline at the A0PI consists of a 3.9 GHz $TM_{110}$ deflecting mode 5 cell cavity located between two horizontal dogleg magnetic channels [7].

## EXPERIMENTAL METHODS

Precise measurements of the beam parameters are critical to the evaluation of the EEX process, thus the beamline is equipped with various diagnostic instruments. Transverse beam profiles are measured by optical transition radiation (OTR) viewing screens oriented at $45\,^\circ$. Both ingoing and outgoing transverse divergences are measured with the interceptive method of tungsten slits [8]. Downstream slit images are generated by single crystal YAG:Ce scintillator screens oriented orthogonal to the incident beam direction followed by a $45\,^\circ$ mirror which directs the radiation to the camera. This configuration eliminates depth of focus issues from the field of view and improves resolution [9].

Example X3 emittance measurements consisting of beam and slit images are shown in Figure 2 for x-emittance and Figure 3 for y-emittance. The beam image is taken from the OTR screen located at X3. Horizontal and vertical slits of 50 $\mu$m width separated by 1 mm are inserted into the beamline at X3, and the beamlets are allowed to drift 0.8 m to the YAG:Ce screen located at X5. Image profiles are projected along the axis and fit with Gaussians. Sample outgoing x-emittance measurements are shown in Figure 4 with y-emittance shown in Figure 5. At X23 the horizontal slits are separated by 2 mm while the vertical slits are spaced at 1 mm. A MATLAB-based program calculates the emittances and the Courant-Snyder parameters ($\alpha$,$\beta$,$\gamma$) based on the X3-X5 and X23-X24 spot and slit image pairs [10]. Transverse beam position is monitored by 10 button beam position monitors.

Projected longitudinal emittance measurements are made by combining energy spread and bunch length measurements. EEX input and output central momenta and momentum spreads are measured by two spectrometer magnets and down-stream viewing screens. The bunch length is then determined at the X9 OTR screen using a Hamamatsu C5680 streak camera operating with a low jitter synchroscan vertical plug-in unit phase locked to 81.25 MHz as described previously [11]. The bunch length measure-

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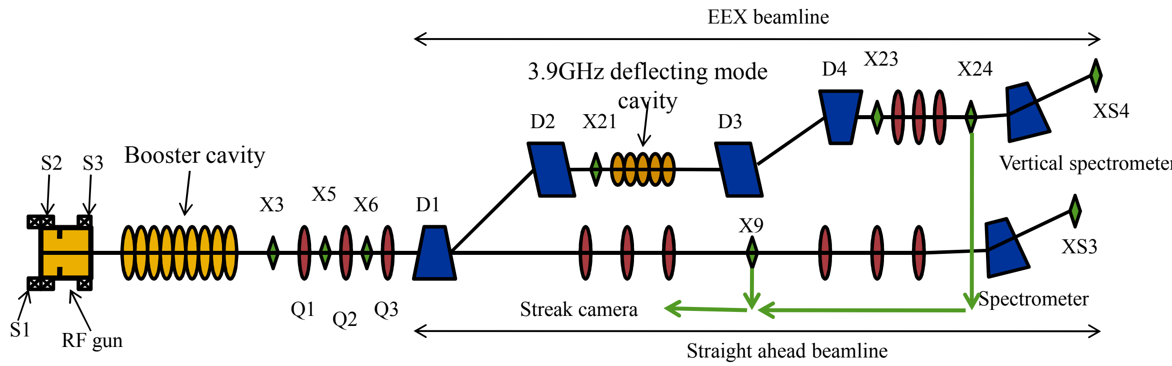


Figure 1: Top view of the A0 Photoinjector showing elements pertinent to performing emittance exchange. Elements labeled “X” are diagnostics stations (beam viewers and/or multi-slit mask locations), “S” are solenoid lenses, “Q” are quadrupole magnets and “D” are dipole magnets.

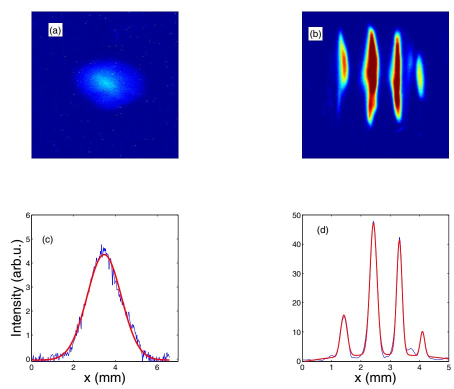


Figure 2: Example incoming x-emittance measurement data. (A) shows an OTR image of the beam spot at X3. (B) shows slit image taken at X5 YAG screen for divergence measurement. (C) and (D) are Gaussian fits to the projected profiles.

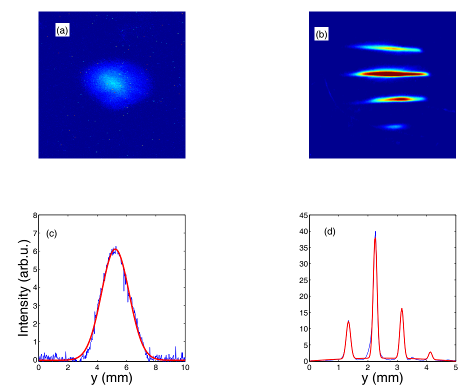


Figure 3: Example incoming y-emittance measurement data. (A) shows an OTR image of the beam spot at X3. (B) shows slit image taken at X5 YAG screen for divergence measurement. (C) and (D) are Gaussian fits to the projected profiles.

ment at X24 is made with OTR transported to the streak camera. As a graphic example of the effects on bunch length in the exchange process, Figure 6 shows the effective compression by about a factor 3 with 5-cell cavity on (blue) compared to off (red).

## EEX RESULTS

The direct measurement of the near ideal emittance exchange has been performed at $\approx$ 14.3 MeV with a bunch charge of 250 pC. To set up the incoming longitudinal phase space, the fractional momentum spread was minimized by operating the booster cavity off crest. Input transverse parameters were tuned by adjusting Q1, Q2 and Q3 for a minimum EEX beamline output bunch-length energy-spread product. Complete measurements of the initial and final emittances were collected with these conditions.

Results of the measurements are shown in Table 1 and summarized as follows. The incoming measured horizontal emittance is $\varepsilon^n_{\mathrm{x}}$=3.01 $\pm$ 0.13 mm-mrad which transfers to the output longitudinal emittance measured $\varepsilon^n_{\mathrm{z}}$=3.08 $\pm$ 0.5 mm-mrad. Similarly the input longitudinal emittance, $\varepsilon^n_{\mathrm{z,in}}$=15.9$\pm$1.5 mm-mrad and the output horizontal emittance measured $\varepsilon^n_{\mathrm{x,out}}$=18.5 $\pm$ 1.2 mm-mrad also show agreement. The vertical emittance was left unaffected, $\varepsilon^n_{\mathrm{y,in}}$=1.99$\pm$0.23 mm-mrad to $\varepsilon^n_{\mathrm{y,out}}$=2.57$\pm$0.48 mm-mrad. The combined results show the successful exchange of emittance between two planes while conserving the full 6D phase space volume.

## CONCLUSION

In summary, we have successfully exchanged the transverse and longitudinal emittances for a beam charge of

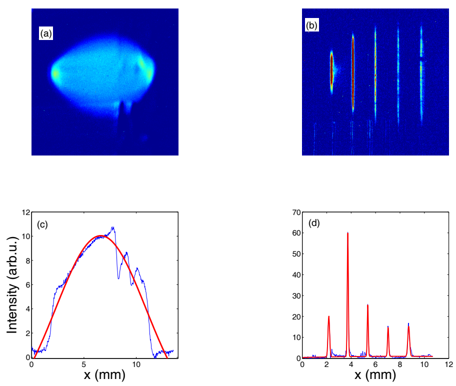


Figure 4: Example outgoing x-emittance measurement data. (A) shows an YAG:Ce screen image of the beam spot at X23 with Gaussian fits to the projected x profile in (C). (B) is slit images taken at X24 YAG screen for x-divergence measurements with Gaussian fits to the projected profiles are shown in (D).

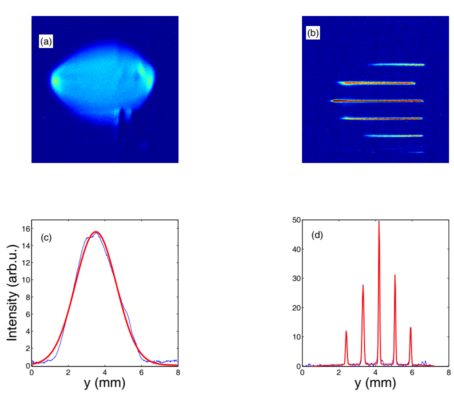


Figure 5: Example outgoing y-emittance measurement data. (A) shows an YAG:Ce screen image of the beam spot at X23 with Gaussian fits to the projected y profile in (C). (B) shows slit images taken at X24 YAG screen for y-divergence measurements with Gaussian fits to the projected profiles are shown in (D).

Table 1: Direct measurements of horizontal transverse ($x$) to longitudinal ($z$) emittance exchange. Emittance measurements are in units of mm-mrad and are normalized.

| | In | Out |
|---|---|---|
| $\varepsilon_x^n$ | $3.01 \pm 0.13$ | $18.5 \pm 1.2$ |
| $\varepsilon_y^n$ | $1.99 \pm 0.23$ | $2.57 \pm 0.48$ |
| $\varepsilon_z^n$ | $15.9 \pm 1.5$ | $3.08 \pm 0.5$ |

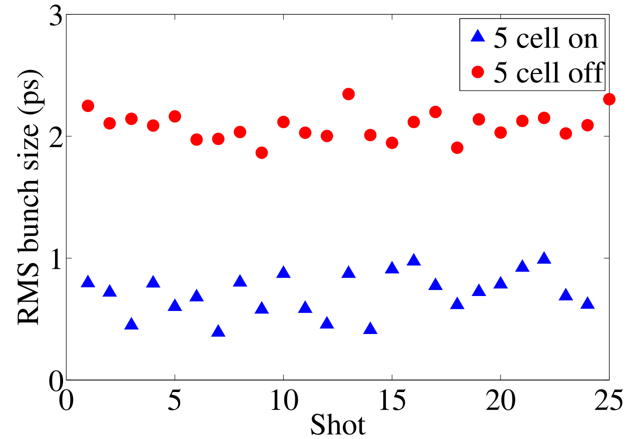


Figure 6: Effect of deflecting mode cavity on bunch length. The dots represent the bunch length as measured with the streak camera at X24 with the deflecting mode cavity off. The triangles show a reduction in bunch length when measured with the deflecting mode cavity on. Each measurement was made over 25 shots.

250 pC. Currently, we are investigationing the effects of coherent synchrotron radiation and space charge. We are limited in our measurement of longitudinal phase space by the present diagnostic system's inability to account for time-energy correlation.

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