LOW EMITTANCE IN THE CORNELL ERL INJECTOR PROTOTYPE*

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Abstract

We present a detailed study of the six-dimensional phase space of the electron beam produced by the Cornell Energy Recovery Linac Photoinjector, a high-brightness, high repetition rate (1.3 GHz) DC photoemission source designed to drive a hard x-ray energy recovery linac (ERL). A complete simulation model of the injector has been constructed, verified by measurement, and optimized. Both the horizontal and vertical 2D transverse phase spaces, as well as the time-resolved (sliced) horizontal phase space, were simulated and directly measured at the end of the injector for 19 pC and 77 pC bunches at roughly 8 MeV. The resulting 90% normalized transverse emittances for 19 (77) pC/bunch were 0.23±0.02 (0.51±0.04) μm in the horizontal plane, and 0.14±0.01 (0.29±0.02) μm in the vertical plane, respectively. These emittances were measured with a corresponding bunch length of 2.1±0.1 (3.0±0.2) ps, respectively. In each case, the rms momentum spread was determined to be on the order of 10^{-3}. Excellent overall agreement between measurement and simulation has been demonstrated.

INTRODUCTION

Cornell University has recently designed, built, and commissioned a high repetition rate DC gun based photoinjector. One major goal for this project was the demonstration of low emittance at the end of the injector merger section. The results in this work demonstrate that it is possible to produce and transport beams from a DC source which have emittances at the point of injection approaching the diffraction limit for hard x-rays, and which have a bunch length and an energy spread within the parameter space required by the specifications of a full hard x-ray ERL. Table 1 shows these parameters for the Cornell Injector.

Table 1: List of Injector Design Specifications and Target Parameters

Parameter	Specification
Beam energy	5-15 MeV
Normalized emittance	$\epsilon_n \leq 0.3\ \mu$m
RMS bunch length	$\sigma_t \leq 3$ ps
Bunch Charge	77 (19) pC
Average Current	100 (25) mA

One fundamental limit to achieving low emittance (high brightness) in a photoinjector occurs when the amount of charge extracted from the cathode nears the virtual cathode instability limit. A rough calculation shows that the lowest achievable emittance in this limit is proportional to the square root of the bunch charge q [1]:

$$\epsilon_n \propto \sqrt{q \cdot \frac{\mathrm{MTE}}{E_{\mathrm{cath}}}} \tag{1}$$

Here MTE and E_{cath} are the mean transverse energy of the cathode and the accelerating field at the cathode, respectively. Detailed simulations of well optimized DC gun photoinjectors support this square root dependence on the bunch charge and the cathode's MTE [2, 3]. In this paper, we show that the final measured emittance also scales in accordance with Eq. (1).

EXPERIMENTAL SET-UP

The injector features a high voltage DC gun operated at 350 kV, followed by emittance compensation solenoids and a buncher cavity. The beam is accelerated to 5-15 MeV using five superconducting srf cavities. The beamline section most relevant to this work is the B1 merger shown in detail in Fig. 1. The injector merger section is comprised of a conventional three-dipole achromat, a design chosen for its simplicity, and due to the limited space available for the injector experiment. The emittance measurement system (EMS) used for projected phase space measurements is the same two-slit system used in previous work [4]. For projected phase space measurements, the beamlet passed through the slits is collected using the Faraday cup at the end of the merger section. For time-resolved horizontal phase space measurements, the beamlet is passed through a horizontal deflecting cavity [5] in order to resolve the time axis of the beam on the viewscreen at the end of the merger [6]. The cathode used for this study was a GaAs wafer with a 4% quantum efficiency, and a MTE of 90 meV. The laser system used is a 50 MHz system, whose individual pulses have comparable pulse energy and duration to the our 1.3 GHz laser [7]. The final laser pulse train is chopped using a Pockells cell, and shaped using our temporal shaping system [8].

To arrive at the final optics used for these experiments, optimizations of a complete General Particle Tracer [9] model of the injector were carried out using a multi-objective genetic algorithm [2, 3]. For all optimizations, the gun voltage was fixed at 350 kV, and the beam energy was constrained to be $\leq$ 8 MeV to reduce neutron production from the tungsten slits in the EMS. The simulated temporal laser distribution was fixed to be roughly a flat-top

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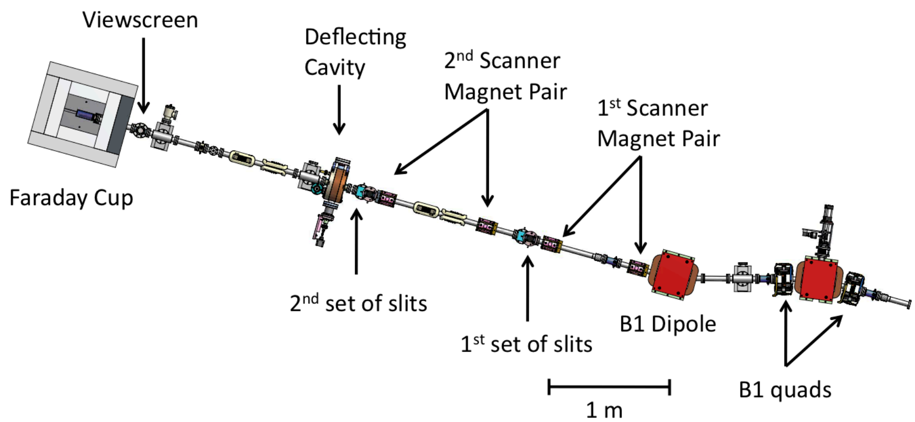

Figure 1: Top view of the B1 injector merger section showing the emittance measurement system.

with 8 ps rms length. Two settings, for 19 pC and 77 pC per bunch respectively, were derived from one optimization solution for 50 pC bunch charge, as this particular optics setting kept the beam sizes reasonably small through the entire injector. The final settings were loaded into the injector and the measured projected emittance was minimized by scanning both solenoid currents and adjusting the intensity cut off value in the measured transverse laser profile.

MEASUREMENTS

Data sets for 19 pC per bunch and 77 pC per bunch, corresponding to 25 mA and 100 mA average current when operating with the full 1.3 GHz repetition rate, were taken. Each data set consists of a measurement of the projected horizontal and vertical phase spaces, the time-resolved horizontal phase space, and the energy spread distribution. All data was taken at the end of the merger section except the energy spread data, which was measured near the entrance to the merger. From the projected phase spaces, the horizontal and vertical emittances as a function of beam fraction were computed. Similarly, from the time-resolved phase space data, the slice emittance was computed as a function of beam fraction, as well as the current profile along the bunch.

Tables 2 and 3 give the measured and simulated projected horizontal and vertical emittances for 19 (77) pC per bunch, respectively. The measured 19 (77) pC/bunch horizontal and vertical projected 100% emittances agreed with the GPT model to within 6 (5) % and 25 (8) %, respectively. Similarly, the measured horizontal and vertical 90% emittances agreed with GPT to within 21 (16) % and 27 (16) %, respectively. We point out that the measured horizontal and vertical 100%, 90%, and core emittances obey the expected scaling law $\epsilon_n \propto \sqrt{q}$. Also of note is the fact the horizontal core emittance for 77 pC meets the injector design specification for an ERL. In the vertical plane, both the 90% and core emittance meet this specification.

In order to satisfy the injector design requirements, it was important to verify that the emittance values were measured with an acceptable bunch length ($\sigma_t \leq 3$ ps). The rms bunch length was computed from the instantaneous current of each bunch measured with the time-resolved merger EMS. The rms bunch lengths for the 19 (77) pC per bunch settings were measured to be 2.1±0.1 (3.0±0.2) ps, respectively, while GPT gave bunch lengths of 2.2 (3.1) ps, respectively. The agreement between measurement and GPT was within 5% in both cases.

Table 4: Simulated and Measured RMS Energy Spread as a Function of Bunch Charge

Data Type	GPT Simulation	Measurement
19 pC/bunch, A4	0.16%	$0.14 \pm 0.01\%$
19 pC/bunch, B1	0.12%	N/A
77 pC/bunch, A4	0.27%	$0.26 \pm 0.01\%$
77 pC/bunch, B1	0.21%	N/A

The last quantity measured was the rms energy spread. To do so, the beam was sent through the A4 straight section, followed by a single dipole and viewscreen in the C2 section. Table 4 shows the simulated and measured rms energy spread in the straight section, as well as simulated values in the B1 merger. While the energy spread was not directly in the merger section, the agreement found between measurement and simulation for emittance and bunch length lead us to conclude that the values measured in the straight section at least provide an upper bound on the energy spread in the merger, following the same trend found in the simulation data.

CONCLUSION AND DISCUSSION

The projected and time-resolved phase spaces at the end of the Cornell ERL injector merger have been measured and simulated using the space charge code GPT for 19 pC and 77 pC bunch charges. In addition, the energy spread was measured in the straight section of the machine. Overall, we found excellent agreement between measurement and simulation. For both bunch charges, the agreement be-

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Table 2: Measured and Simulated Projected Horizontal Emittances

19 pC Measurement Type	$\epsilon_{n,x}(100\%)$	$\epsilon_{n,x}(90\%)$	$\epsilon_{n,x}(\text{core})$	f_{core}	$\epsilon_{n,x}(\text{core})/f_{\text{core}}$
Projected EMS	$0.33 \pm 0.02\ \mu$m	$0.23 \pm 0.02\ \mu$m	$0.14 \pm 0.01\ \mu$m	67%	$0.21 \pm 0.01\ \mu$m
Time-resolved EMS	$0.28 \pm 0.02\ \mu$m	$0.21 \pm 0.01\ \mu$m	$0.14 \pm 0.01\ \mu$m	72%	$0.19 \pm 0.01\ \mu$m
GPT Simulation	$0.31\ \mu$m	$0.19\ \mu$m	$0.07\pm\ \mu$m	59%	$0.12\ \mu$m
77 pC Measurement Type	$\epsilon_{n,x}(100\%)$	$\epsilon_{n,x}(90\%)$	$\epsilon_{n,x}(\text{core})$	f_{core}	$\epsilon_{n,x}(\text{core})/f_{\text{core}}$
Projected EMS	$0.69 \pm 0.05\ \mu$m	$0.51 \pm 0.04\ \mu$m	$0.28 \pm 0.2\ \mu$m	64%	$0.44 \pm 0.03\ \mu$m
Time-resolved EMS	$0.66 \pm 0.05\ \mu$m	$0.48 \pm 0.04\ \mu$m	$0.29 \pm 0.2\ \mu$m	67%	$0.43 \pm 0.03\ \mu$m
GPT Simulation	$0.72\ \mu$m	$0.44\ \mu$m	$0.17\ \mu$m	51%	$0.33\ \mu$m

Table 3: Measured and Simulated Projected Vertical Emittances

19 pC Measurement Type	$\epsilon_{n,y}(100\%)$	$\epsilon_{n,y}(90\%)$	$\epsilon_{n,y}(\text{core})$	f_{core}	$\epsilon_{n,y}(\text{core})/f_{\text{core}}$
Projected EMS	$0.20 \pm 0.01\ \mu$m	$0.14 \pm 0.01\ \mu$m	$0.09 \pm 0.01\ \mu$m	70%	$0.13 \pm 0.01\ \mu$m
GPT Simulation	$0.16\ \mu$m	$0.11\ \mu$m	$0.06\ \mu$m	64%	$0.09\ \mu$m
77 pC Measurement Type	$\epsilon_{n,y}(100\%)$	$\epsilon_{n,y}(90\%)$	$\epsilon_{n,y}(\text{core})$	f_{core}	$\epsilon_{n,y}(\text{core})/f_{\text{core}}$
Projected EMS	$0.40 \pm 0.03\ \mu$m	$0.29 \pm 0.02\ \mu$m	$0.19 \pm 0.01\ \mu$m	70%	$0.27 \pm 0.01\ \mu$m
GPT Simulation	$0.37\ \mu$m	$0.25\ \mu$m	$0.11\ \mu$m	59%	$0.19\ \mu$m

tween the measured projected 100 and 90% emittance values was within 30% of the simulated values in both transverse planes. We point out that for 77 pC/bunch, the measured 90% emittance in vertical plane, as well as the core emittance in both planes, meets the ERL design specification of $\epsilon_n \leq 0.3\ \mu\text{m}$. The projected emittance in both transverse planes demonstrates the correct scaling with bunch charge shown in Eq. (1). The measured rms bunch length for both bunch charges was at or below the 3 ps specification, and agreed with simulation to within 5%. Finally, an estimation of the energy spread of the beam in merger was found by measuring the energy spread in the straight section. Agreement between the measured and simulated rms energy spread was within 13% for both bunch charges. These results represent a significant advancement in high-brightness photoinjectors.

In looking to further reduce emittance, simulations indicate that lower emittances and shorter bunch lengths at the end of the merger are possible at higher beam energies (roughly 12 MeV) [10, 11]. Eq. (1) shows two more directions for further improvement. The emittance in this equation can be reduced by lowering photocathode MTE, or by increasing the accelerating field at the cathode. Currently, there is an active cathode research program at Cornell University dedicated to improving cathode performance [12]. In parallel, Cornell is developing an improved DC gun, in order to overcome the current voltage limitation. Lastly, improved laser shaping will aid in creating bunches with more linear space charge fields. According to Eq. (1), as well as more detailed calculations reported in [3, 11], these improvements are expected to reduce the emittance in the photoinjector by roughly a factor of 3, resulting in a beam brightness roughly 10 times higher than reported here.

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