PERFORMANCE OF THE CORNELL HIGH-BRIGHTNESS, HIGH-POWER ELECTRON INJECTOR

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Abstract

A high-power, high-brightness electron injector suitable for use with an energy recovery linac (ERL) x-ray light source or a free electron laser (FEL) has been built at Cornell University. The system was designed to produce a train of 77 pC bunches at a 1300 MHz repetition rate, which is equivalent to 100 mA average current, at energies between 5 and 15 MeV. The initial beam requirements are a normalized emittance below 2 μm at full bunch charge with a bunch length of <2-3 ps rms. The operation of this injector and the progress towards meeting these challenging goals will be discussed.

INTRODUCTION

Cornell University has been working towards constructing an x-ray light source using an energy recovery linac [1], and has completed a full design report. Prototype development is underway for critical components such as undulators, high-Q superconducting RF cavities, long-life cathodes, and a high-brightness, high-power electron injector.

This paper will cover recent progress with the electron injector. The goal for the Cornell ERL injector prototype is to generate 100 mA of average current, which corresponds to filling every bucket of a 1300 MHz pulse train with 77 pC per bunch. The injector consists of a DC photoemission gun, a normal conducting buncher, a superconducting RF accelerating module, a suite of diagnostics for phase space measurements, and a high power beam dump. The RF system has enough power to produce 100 mA at 5 MeV beam energy, or 33 mA at 15 MeV. A normalized emittance (100%) of less than 2 μm at full bunch charge is required initially, with a bunch length of 2-3 ps. The injector hardware has been described previously [2] and will not be covered here.

Much progress has been made towards reaching these goals. The sections below will describe the recent results for high-current and high-brightness.

HIGH BRIGHTNESS RESULTS

Extensive simulations and optimizations [3] were performed to design the Cornell injector to reach the lowest possible emittance at full bunch charge. Careful consideration of all possible parameters, including laser profile and time structure, was included.

Obtaining such small emittances has proven to be difficult. Minimization of aberrations from solenoids and RF fields was found to be critical. Emittance growth from solenoid aberrations is particularly troublesome as it scales strongly with the beam size. Since beam size at high bunch charge, especially for the lower gradients realized in DC guns, can get quite large, accurate alignment is critical for low emittance operation to avoid asymmetries.

The first emittance measurements at Cornell for full bunch charge were above the requirements, and the problem was determined to be poor alignment. Remote controlled actuators had to be retro-fitted to the solenoid magnets for beam-based alignment. The following procedure was used to accurately align the injector: (1) turn off and degauss the solenoids; (2) center the laser on the cathode by studying the aberrations of the beam after the anode; (3) center on the buncher using 2 corrector magnets between the gun and buncher; (4) center on the first 2 SRF cavities using 2 pairs of correctors after the buncher; (5) physically move the first solenoid (x, y, pitch and yaw axes) to put it on the beam axes; (6) repeat for the second solenoid. After several iterations of each step, alignment accuracies of ~20 μm were obtained.

Once the alignments were completed, the injector parameters (solenoid strengths, buncher gradient and phase, SRF cavity gradient and phase) were optimized using the fast emittance scanning system. This quickly led to emittance values of 0.8 μm (normalized, 100%) at 80 pC and 0.4 μm (normalized, 100%) at 20 pC (see Figure 1). These values are within ~40% of the model predictions, and ~80% above the cathode thermal emittance.

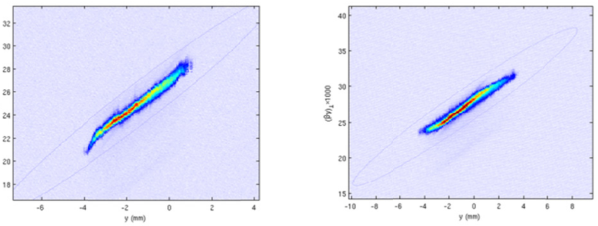

Figure 1: Phase space plot for 20 pC, 5 MeV (left) with 0.4 μm emittance, and 80 pC, 5 MeV (right) with 0.8 μm emittance. The gun voltage was 350 kV.

HIGH POWER RESULTS

There are many difficulties with running high current from photocathodes. The first attempts at high power running at Cornell could not surpass 10 mA at 5 MeV. Above this value, SRF cavity trips limited any further progress. The cause of the trips was traced to fast changes in the beam current that could not be compensated for in the RF controls. The fast fluctuations were due to laser power instability and laser pointing instability as the beam passed through an aperture. A fast-feedback loop was incorporated to keep the beam current constant (measured with a BPM) using a high-bandwidth Pockels cell after the laser. After this was implemented, currents quickly increased to over 20 mA.

Initial runs were performed using GaAs cathodes, which are very sensitive to vacuum contamination. To avoid this problem, a program was undertaken to learn how to grow alkali-type photocathodes (CsK_2Sb in particular) which are known to have better lifetime characteristics than GaAs [4]. With this type of photocathode, an extended run with 20 mA (at 5 MeV) was carried out over an 8 hour period (see Figure 2). During this time, the cathode only degraded slightly [5].

An attempt to surpass this value resulted in damage to the beam dump (see Figure 3). It was discovered that the beam diffusing/rastering system was not working properly, leading to excessive power density and burn through. The raster system was upgraded and additional interlocks were installed while the beam dump was repaired.

The major problem with operating at high currents is beam halo striking the vacuum pipes, causing excessive radiation and vacuum increase near the cathode. There are many sources of halo to consider, the worst of which must be eliminated. Possible sources of halo are: (1) stray light from the laser (spatial and temporal) reaching the cathode; (2) x-rays, UV and visible photons from cavity and gun field emission which reach the cathode; (3) space charge growth and aberrations; (4) beamline apertures; and (5) cathode response time, to name a few.

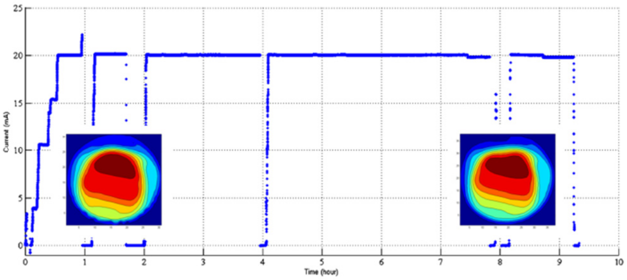

Figure 2: Beam current trace during a 20 mA run at 5 MeV. The initial map of the cathode QE is on the left and on the right shows the QE map after 8 hours. The laser is located off-center on the cathode.

It was discovered that the vacuum mirror used to deflect the laser onto the cathode was not smooth enough, resulting is too much scattered light hitting outside the desired 2.5 mm laser spot on the cathode. A new mirror (with 2 nm rms surface roughness) was purchased and installed, reducing the laser ‘halo’, and thus the electron beam halo, by a factor of 100.

Figure 3: A section of the beam dump [6] before repairs. The left shows where the beam hit, and the right shows the melted aluminium.

Halo can also be reduced by masking the photocathode so that only a small area can emit electrons when illuminated. This is easy to do with GaAs cathodes (Figure 4) which reduces much of the problem with spatial halo from scattered light. Bulk GaAs has the additional problem that for high QE (> 5%), long, low-intensity tails of electrons can be extracted from the cathode over tens of picoseconds after the laser pulse ends, which are defocused by the RF and hit the pipe. Thus, the QE must be limited to ~5% or less when using bulk GaAs, or alternatively, special thin cathodes can be grown to avoid the problem.

For DC photocathode guns, ion-backbombardment is an important issue that can limit cathode lifetime [5]. The electrons ionize background gas between the cathode and anode and even beyond the anode, which can then migrate back toward the gun where they are accelerated into the cathode, similar to ion-implantation. The simplest way to avoid this is to sacrifice the center of the cathode, and move the laser spot away from the center, far enough to avoid the damaged area. This can be accomplished by masking the cathode as described previously, or only activating a small area away from the cathode center.

With these improvements, a maximum average current of 50 mA was reached using a GaAs cathode, far surpassing the previous records for average current from a photoinjector (32 mA at Boeing [4]). Vacuum increases near the gun due to halo resulted in a short lifetime at 50 mA, but a 100 Coulomb charge lifetime was observed over several hours. Figure 5 shows the current profile over time.

FUTURE PLANS

In the near term, experiments will continue towards reaching 100 mA of average current. Alkali cathodes with a small active area are being prepared for the next round of high current experiments, which is expected to reduce halo further, along with the benefits of being a more robust cathode than GaAs.

Figure 4: GaAs can easily be masked to reduce halo. The blue area of this cathode is anodized to eliminate emission, while the grey areas have high QE.

The main upgrade planned is to build a new gun that can operate at or above 500 kV DC. This should result in lower emittance and less sensitivity to alignments of magnets and RF cavities. A 3D view of the new gun is shown in Figure 6. The monolithic cylindrical insulator used in the present gun is replaced with a segmented insulator, similar to an accelerating tube. The new device has internal rings to block any field emitted electrons ejected off the central support tube from reaching (and potentially damaging) the insulator. The diameter of the insulator is increased in order to reduce the maximum field in the gun to 10 MV/m at 750 kV. At 500 kV, this will result in a reasonable field level of 6.7 MV/m.

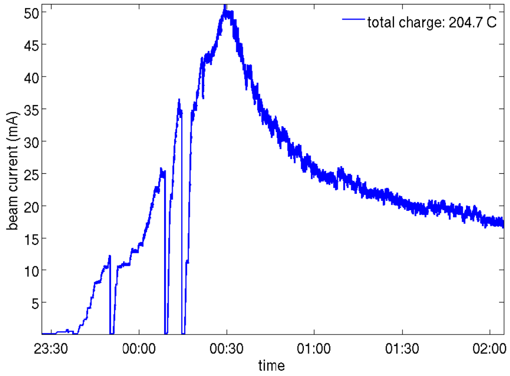

Figure 5: Beam current trace during a recent high current run at 5 MeV beam energy. Over 200 Coulombs were delivered from one spot on a GaAs cathode.

CONCLUSION

Excellent progress has been made with the high-brightness, high-power ERL injector prototype at Cornell University. The emittance at the full bunch charge of 77 pC and 5 MeV was measured to be 0.8 μm, well below the initial goal of 2 μm, and well on the way to the ultimate goal of 0.3 μm. Genetic algorithm optimizations tied to simulations were used to find the operating conditions to reach lower emittance values than previously thought possible. A fast emittance measurement system was developed to do on-line optimizations with the real hardware, and showed the simulations and measurements to be in good agreement.

The average current achieved thus far was 50 mA at 5 MeV, the highest ever for a photoemission-based injector. This exceeds the previous record by a group at Boeing. Work is continuing to reach the ultimate goal of 100 mA by reducing beam losses due to halo, improving laser operation, and finding cathodes more resistant to degradation over time.

ACKNOWLEDGMENT

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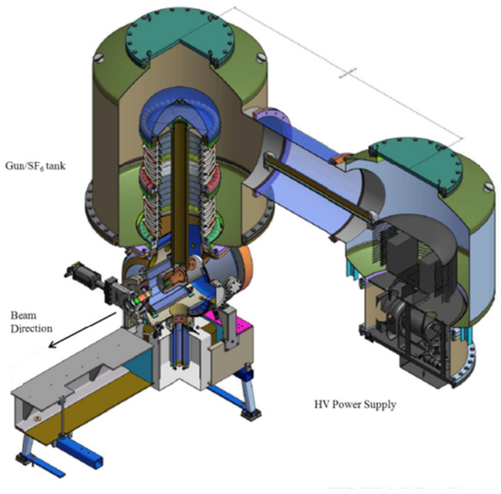

Figure 6: The new DC gun utilizing a segmented insulator is shown on the left, inside an SF$_6$ pressure vessel. The HVPS is on the right, inside a common SF$_6$ vessel.