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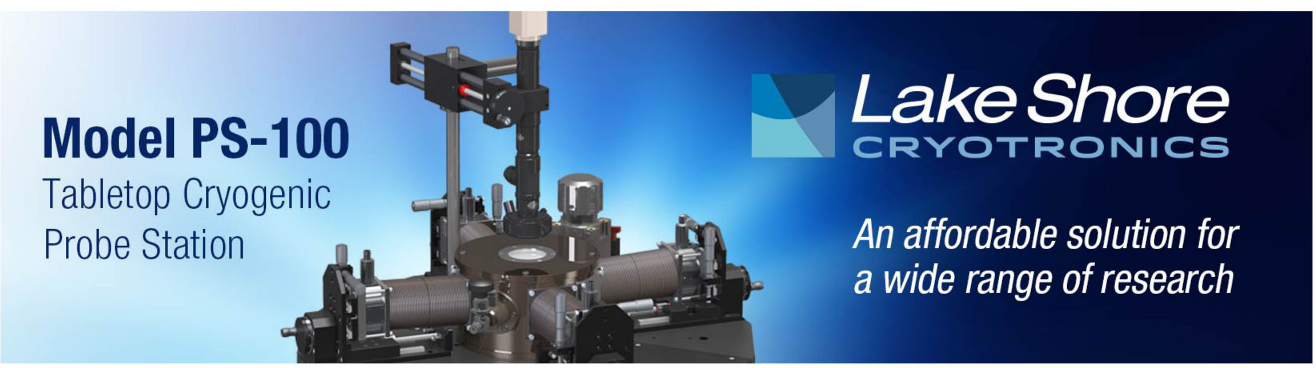

APPLIED PHYSICS LETTERS **102**, 034105 (2013)

Record high-average current from a high-brightness photoinjector

Bruce Dunham,[a)] John Barley, Adam Bartnik, Ivan Bazarov, Luca Cultrera, John Dobbins, Georg Hoffstaetter, Brent Johnson, Roger Kaplan, Siddharth Karkare, Vaclav Kostroun, Yulin Li, Matthias Liepe, Xianghong Liu, Florian Loehl,[b)] Jared Maxson, Peter Quigley, John Reilly, David Rice, Daniel Sabol, Eric Smith, Karl Smolenski, Maury Tigner, Vadim Vesherevich, Dwight Widger, and Zhi Zhao

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High-power, high-brightness electron beams are of interest for many applications, especially as drivers for free electron lasers and energy recovery linac light sources. For these particular applications, photoemission injectors are used in most cases, and the initial beam brightness from the injector sets a limit on the quality of the light generated at the end of the accelerator. At Cornell University, we have built such a high-power injector using a DC photoemission gun followed by a superconducting accelerating module. Recent results will be presented demonstrating record setting performance up to 65 mA average current with beam energies of 4–5 MeV. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4789395]

Photoemission-based electron sources began as highly specialized devices to produce polarized electrons for high energy physics,[1] atomic physics, and materials research. With the invention of the normal conducting radio-frequency (RF) gun,[2] photoinjectors moved into the mainstream for new accelerator designs. The great flexibility over bunch charge, repetition rates, bunch length, and energy makes photoinjectors the best choice for high-performance accelerators today. For many years, it was thought that RF photoemission guns provided the best beam quality and beam parameters. Continued work by a number of labs (Jefferson Lab and Cornell University, in particular) has demonstrated that DC high-voltage guns followed by superconducting accelerating cavities produce beams as good as if not better than RF guns with similar parameters. In general, the requirements of the particular application determine which type of gun is better. Until recently, the highest average current achieved using a photoinjector was from the Boeing RF gun[3] at 32 mA. The DC gun used for the Jefferson Lab free-electron laser project[4] has reliably provided 135 pC bunches at an average current of 9 mA for many years.

One of the benefits of having a DC gun is that any type of cathode can be used, from the simplest metal cathode to sophisticated, engineered semiconductor cathodes. This provides the opportunity to search for the best cathode material without having to worry about the harsh environment typically found in RF guns. For example, many types of cathodes have been tested and characterized at Cornell: GaAs,[5] GaN,[6] GaAsP,[5] CsK_2Sb,[7] and Cs_3Sb.[8] The important parameters of a photocathode for accelerator applications are fast time response, long lifetime, low thermal emittance, and high quantum efficiency (QE). To date, no cathode material meets all of these requirements simultaneously.

GaAs is often used for high-brightness applications because it has the lowest thermal emittance (or mean transverse energy (MTE)) of any cathode known. GaAs has been shown to have very long lifetimes when used at low currents[9] (~100 μA) but degrades quickly at high currents. Alkali cathodes such as CsK_2Sb have many good properties and are currently the best prospect for high power operation as they are not as sensitive to vacuum contamination as is GaAs. They have been shown to have good MTE[7,8] (about 30% larger than GaAs at 520 nm), fast response-time, high QE, and reasonable lifetime at high currents. Both GaAs and alkali-type cathodes are used in the results described here.

The photoinjector described in this paper was built for an energy recovery linac (ERL) based light-source with the requirements listed in Table I. A layout of the system is shown in Fig. 1. A DC photoemission gun (operating at 250 kV) with a cathode load-lock system is followed by a short section for focusing solenoids and a normal conducting RF buncher (labeled "A1" in the figure). A superconducting cryomodule (A2) houses five 2-cell cavities that can accelerate the beam to a maximum of 15 MeV. After the beam is accelerated, it passes through a four quadrupole matching section (A3) to a suite of diagnostics used for measuring the 6D phase space of the beam (A4, B1, and C1). Finally, a 600 kW beam dump stops the beam and dissipates the heat (A5).

All of the injector subsystems have stringent requirements in order to deliver high average power reliably. For

TABLE I. Requirements for the Cornell energy recovery linac prototype injector.

Parameter	Value
Frequency	1300 MHz
Charge per bunch	77 pC
Average current	100 mA
Normalized emittance	≤ 0.3 μm rms
Bunch duration	2–3 ps rms
Beam energy	4–15 MeV

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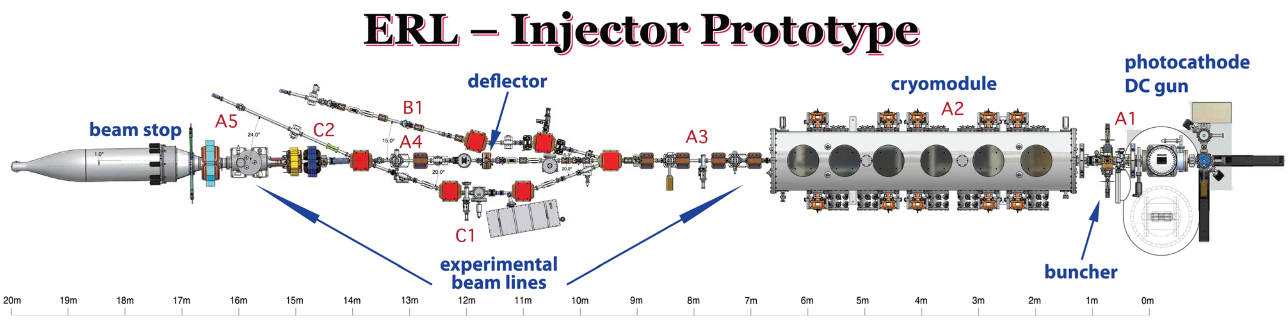

FIG. 1. A top view of the Cornell high-brightness photoinjector.

the laser system, generating 100 mA from a 1% QE photocathode (GaAs or CsK_2Sb) requires approximately 20 Watts at 520 nm, or 2 W for a 10% QE cathode. The laser repetition rate must match the RF frequency and be synchronized to the RF master clock. For the 1300 MHz laser system[10] used in these experiments, a commercial fiber oscillator generates the seed pulses for two preamplifier stages and one main amplifier stage, all using Yb gain fiber. Up to 65 W at 520 nm have been obtained, providing more than enough light to reach 100 mA with overhead for optical transport losses, laser shaping and feedback. The laser is shaped in both the transverse and longitudinal planes to produce a "flat top" profile.[11]

There are many challenges in constructing a photoinjector for an ERL, one of the most difficult being a superconducting injector cryomodule (ICM)[12] for acceleration. The system must transfer high average power to the beam, damp significant higher order modes up to tens of GHz, and preserve the low emittance generated by the electron source. For this prototype, there is 500 kW of available RF power, which limits the maximum energy at full beam current. The ICM has five 2-cell cavities which were built at Cornell, operating at gradients of 4–5 MeV/m. Each set of cavities has a pair of opposing RF input couplers which have been tested up to 60 kW average power, more than the 50 kW per coupler needed for 100 mA operation at 5 MeV.[13]

The beam dump[14] is similar to a klystron collector and is designed to absorb up to 600 kW average power for beam energies up to 15 MeV. The beam is defocused using a pair of quadrupole magnets and rastered in a circle to reduce the incident power on the dump walls. The dump is constructed of aluminum instead of copper to reduce neutron production. A closed-loop water system with a flow of 23 m^3/h and 1 MΩ-cm resistivity is used for cooling.

There are many difficulties with running high currents from photocathodes. The first attempts at higher power running at Cornell could not exceed 10 mA at 5 MeV. Above this value, RF 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 laser passed through a shaping aperture. A fast-feedback loop was incorporated to keep the beam current constant (measured with a beam position monitor) using a high-bandwidth Pockels cell after the laser.[15] This was also used as a fast shutter (1 μs response time) to block the laser as part of the machine protection system. After this was implemented, currents were increased to over 20 mA.

Initial runs were performed using GaAs cathodes, which are very sensitive to vacuum contamination and consequently can have short lifetimes. To avoid this problem during machine commissioning, a program was undertaken to grow alkali-type photocathodes (CsK_2Sb in particular), which are known to have better lifetime characteristics than GaAs cathodes. With this type of photocathode, an extended run with 20 mA (at 5 MeV) was carried out over an 8 h period.[16] During this time, the cathode only showed minimal degradation, demonstrating the ability to reliably deliver large bunch charges.

A major problem with operating at high currents is beam halo striking the vacuum pipes, causing excessive radiation and a pressure 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, ultraviolet, 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. Systems using very high-efficiency cathodes are more susceptible than those using metal cathodes, as any stray light reaching the high QE surface may generate electrons at the wrong time or outside the desired area. Temporal halo is due to "ghost" pulses that can occur between the main pulses of the laser or due to reflections that reach the cathode. The only way to eliminate this is by carefully designing the laser and optical transport system. The only way we have found to eliminate spatial halo from the cathode is to mask the cathode surface so that no electrons can be produced outside the desired area. This is straightforward for GaAs cathodes: after cleaning, the entire surface is oxidized, and then the oxide is removed from a small area (see Fig. 2). One can also use a mask during cathode activation to direct the cesium to a small area. For alkali-type cathodes, a mask is used during the deposition process.

Another major issue with using any photocathode for high average currents is damage due to ion back-bombardment. Ions are generated along the path of the electron beam from collisions with the residual gas and are accelerated back towards the cathode with energies ranging from a few eV up to the accelerating voltage of the gun. The electric fields in this gun focus most of the ions to the center of the cathode, where ion damage occurs.[9] At high currents, the damage occurs quickly (even at the typical vacuum

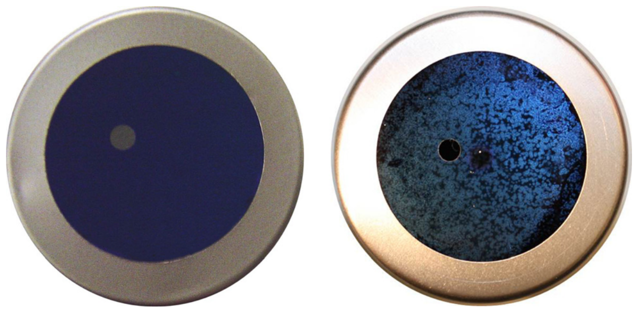

FIG. 2. A new GaAs cathode (left) with one active area (silver). The blue area is oxidized to prevent emission. The same cathode (right) after use shows the effect of ion damage at the center. The previously blue oxidized area is now speckled after heat cleaning.

levels of 1×10^{-11} mbar), rendering the center of the cathode unusable. Thus, we purposely use only a small active area offset from the cathode center. In Fig. 2 (left) the laser is directed to the active area, typically 5-6 mm off-center, with a 3–4 mm diameter. At this distance, the damage at the active area is reduced dramatically. For DC guns operating at high average currents, this is the best way to prevent damaging the high QE regions and to obtain good operational lifetime. Fig. 2 (right) shows the damaged area at the center of a GaAs cathode after prolonged use.

Any beam loss event, RF field-emission event, or other similar problem will cause a vacuum burst. If this occurs close enough to the cathode, the sudden pressure increase will cause a large burst of ions. Typically, the burst is large enough to cause visible damage to the cathode surface (near the center), and there is a 1:1 correspondence between the number of events and the visible damage spots. Since the active area of the cathode is off-center, this is not normally a problem, unless the damage is great enough to cause surface roughening that leads to enhanced field emission.

After understanding the issues with running high average currents from photocathodes and mitigating the problems as best as possible, experiments were carried out to push the current above the previous values of 20 mA. For the first attempt, a GaAs cathode with one active area was used, as at that time we were not able to grow alkali cathodes with small, offset active areas. The initial QE was 10%. As the beam current was increased, the vacuum level in an RF input coupler exceeded its limit, causing the beam to shut off. The QE dropped by a third after each event due to a pressure spike. After three such events, no further RF trips occurred, and the beam current was increased up to 52 mA for a short time. Then the laser power was held constant at 5 W as the current decayed slowly over 1.5 h. This 52 mA level exceeds the previous record of 32 mA for average current from a photoinjector (Fig. 3).

Reaching 52 mA for a short time is not enough for any real-life accelerator application, so in the next phase of the experiments a CsK_2Sb cathode was prepared. The active area was 3 mm in diameter, with its center offset by 6 mm from the cathode center. The injector was set at an energy of 4 MeV and tuned to minimize beam loss along the length of the machine. Based on radiation measurements along the beamline, the loss is estimated to be less than 1 nA total out of 50 mA or $<2 \times 10^{-8}$.

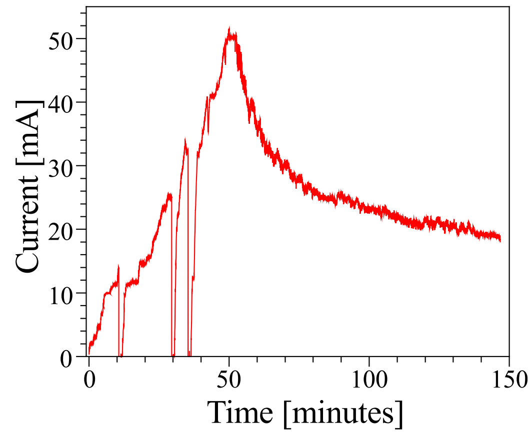

FIG. 3. Beam current versus time using a GaAs cathode. The initial QE of 10% degraded to <1% by the end. Over 200 C of charge was delivered from a single spot on the cathode.

Fig. 4 shows the beam current versus time during the longest period of uninterrupted running at 60 mA. The current was held constant using a feedback loop,[15] which varies the laser power as required. The QE can be seen to degrade slowly over time, with a 30 h 1/e lifetime. The current was later increased to as high as 65 mA for a short time. Fig. 5 shows the QE map of the cathode before and after use.

Fig. 6 shows a long-term run at 33 mA and 4 MeV, using a Cs_3Sb cathode with a single, offset active area. The purpose of the test was to get a better measurement of cathode lifetime, but for this time period the QE stayed constant and even increased slightly. Such behavior has been reported by others in the past, but the mechanism is not clear. It may be related to laser shape changes, QE uniformity changes, or local cathode heating.[17] During the 60 mA measurements, the pressure in the gun region increased from 1.5×10^{-11} to 4.0×10^{-11} mbar, indicating that the beam was starting to scrape along the beampipe, potentially degrading the QE. The pressure did not increase during the 33 mA run, which may partially explain the constant QE observed.

In summary, record high-average current operation from a photoinjector using a DC photocathode gun followed by a superconducting RF accelerating module has been demonstrated. Careful attention to eliminating and controlling sources of beam halo resulted in a beam loss of $\sim 10^{-8}$. Using a GaAs cathode, currents up to 52 mA were obtained, and up

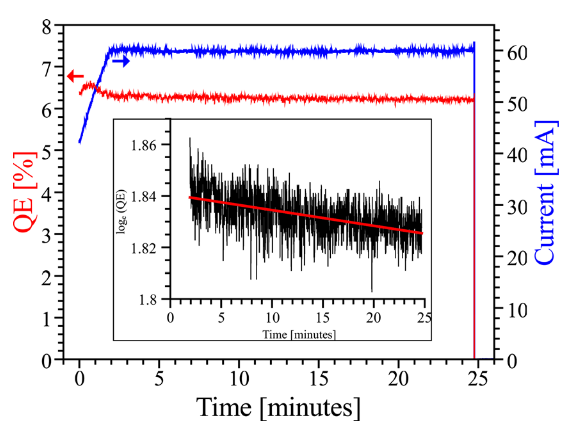

FIG. 4. The QE decay for a CsK_2Sb cathode versus time, with the current held constant at 60 mA.

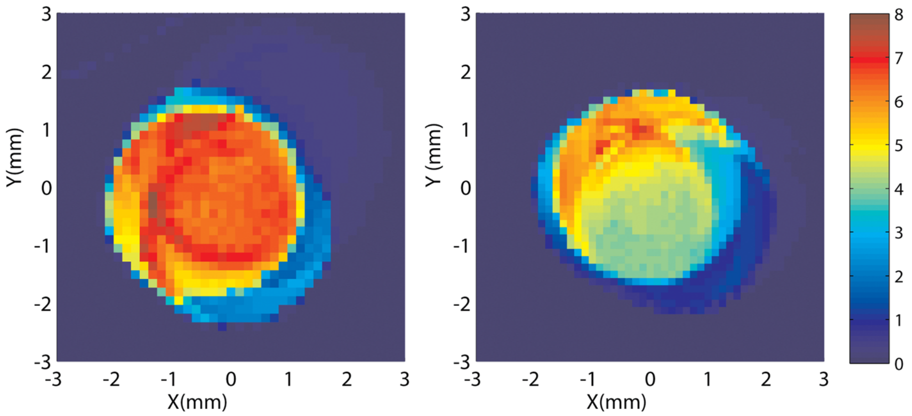

FIG. 5. The QE (%) map of the CsK_2Sb cathode before use (left), and after extended time above 50 mA (right). Over 2000 C of charge was extracted over the life of this cathode. The laser spot diameter was 2.5 mm.

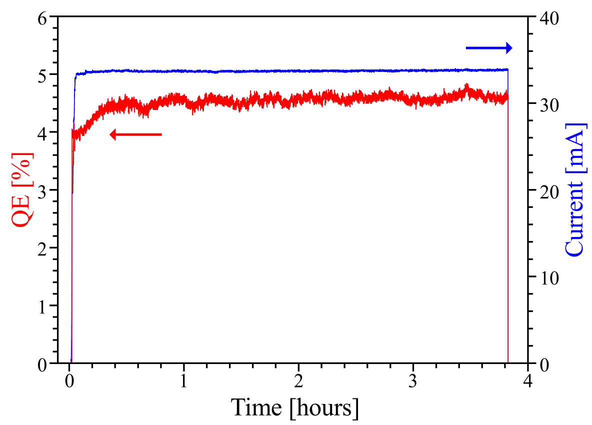

FIG. 6. The average beam current (blue) and cathode quantum efficiency (red) during the longest continuous running period using a Cs_3Sb cathode.

to 65 mA using a CsK_2Sb cathode, surpassing the previous record by a factor of two. In one case, cathode QE (for Cs_3Sb) did not decay at all over a four hour period. These results demonstrate that alkali-type cathodes can provide very high average currents and long operational lifetimes. With further experience, we expect to be able to reach the 100 mA average current desired for an energy recovery linac light source. Overall, the system of a DC photoemission gun followed by a superconducting RF accelerating module has been shown to provide the high-average current, high-power beams needed for many accelerator projects, such as energy recovery linacs and free electron lasers.

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