INEXPENSIVE, HIGH-PERFORMANCE, ELECTRON GUN

Final Report

Hans P. Bluem

Advanced Energy Systems
Medford, New York 11763

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PROJECT SUMMARY

Although high performance photocathode guns find widespread application, their expense and complexity places them beyond the resources of many facilities and makes them unsuitable for commercial applications. A robust photocathode with a quantum efficiency greater than one percent that does not require an ultra-high vacuum environment would permit a major reduction in photo-cathode gun system complexity and cost by significantly reducing the drive laser power. This in turn will enable greatly expanded application of high performance photocathode technology. The focus of this research was a high quantum efficiency cathode which would also exhibit sufficient robustness to allow use in a system suitable for commercial applications.

This project sought to study the effect of non-UHV handling and transfer of a high quantum efficiency over-coated photocathode. A Cs_2Te cathode, fabricated using standard procedures and overcoated with a protective layer, was obtained. This cathode was transferred from the evacuated shipping assembly to the test chamber in a nitrogen purged glove box. The quantum efficiency of the cathode was then measured to determine the effect of the transfer procedure.

The original quantum efficiency of the cathode, before shipment for testing, was measured to be 2%. After transfer, the maximum measured quantum efficiency was 0.2%. An attempt was made to rejuvenate the cathode through heating, but this resulted in lowering the quantum efficiency even further since the test chamber was not set up to heat the cathode directly and independently. On the other hand, proper heating of the cathode would be expected to rejuvenate the photocathode to very near its initial efficiency. Thus, with a redesigned test chamber, it would be expected that the cathodes could be easily and cheaply transferred in a purged nitrogen glovebox with no loss of quantum efficiency after the rejuvenation process has taken place.

Electron guns using these robust, high quantum efficiency cathodes would provide an affordable, high performance source of electrons in university, national laboratory, and industrial research and development accelerator applications. At the present, these applications must choose between a high quantum efficiency cathode with a limited lifetime and a low quantum efficiency cathode with longer lifetime. This tradeoff leads to either a much more powerful (and thus more expensive and more temperamental) laser, lower than desired electron bunch charge, or a complicated, expensive and time consuming cathode fabrication and transfer system. Therefore, it is anticipated that these cathodes would become the cathode of choice for almost all photocathode electron guns in the research arena. Near-term commercial applications would include sources for monochromatic x-ray systems based upon Compton back-scattering. A number of other commercial applications can also be envisioned which could benefit from this technology.

I. INTRODUCTION

Radio frequency, photocathode electron guns (photo-injectors) have been the subject of intensive research around the world since they were first studied¹ over ten years ago. This interest is due to their ability to produce very bright and very low emittance beams of electrons. These types of sources are attractive for driving short wavelength free-electron lasers (FEL) and advanced accelerators, and for the production of intense short pulse x-rays and gamma rays. Photo-injectors are also unsurpassed in producing very high-peak-currents in very short-pulses. This is useful for driving wake-field accelerators, linear collider sources of polarized electrons, and has also found application in pulse-radiolysis chemistry research.

Present photoinjectors use either a thermionic, metallic, or semiconductor material as the cathode. Other materials such as ferroelectrics and field emission tips have been studied, but have not yet been used in any operating guns. Metal photocathodes have been demonstrated to achieve quantum efficiencies (QE) of at best around 10^{-3} , are generally regarded as being robust with very long quantum efficiency lifetimes and do not require ultra-high vacuum conditions². Some have however proven to be surprisingly sensitive to vacuum conditions and require regular, slow laser cleaning scans to restore the QE. Thermionic cathodes have very similar properties to those of metallic cathodes, but require an elevated temperature to achieve long lifetimes. Semiconductor cathodes, on the other hand, can have quantum efficiencies in excess of 10%, but generally have the reputation for being much less robust than metallic cathodes with lifetimes typically measured in hours. The semiconductor materials also require vacuum levels in the 10^{-10} Torr range.

Herein lies the downside of photoinjectors. They require big, powerful drive lasers if one chooses a metal cathode, or, for high-quantum-efficiency semiconductor cathodes, they require a vacuum level that is difficult to sustain and frequent cathode replacement. These properties increase the cost and decrease the reliability of both cathode systems. It would be highly desirable if one could obtain the robustness of metal cathodes at the quantum efficiency of semiconductor cathodes.

Cesium telluride (Cs_2Te) has shown considerable promise in overcoming the major drawbacks of semiconductor cathodes. It is much less sensitive to exposure to residual gas. It has a life time ($1/e$), while still measured in hours, in excess of 100 hours. CsI seems to be even more robust. The latter can even be transported in air. Unfortunately, it has an energy gap of 6.3 eV (compared with Cs_2Te at 3.5 eV), requiring therefore VUV drive illumination radiation, and the QE is still less than that of Cs_2Te . CsI may additionally have a long response time but this is not well documented at present.

Quantum efficiencies of over 10% have been reported with Cs_2Te ³. Also, up to 50 nC in a single 10 ps pulse has been reported with a material response time of less than 1 ps⁴. In addition, it appears to be possible to partially rejuvenate the quantum efficiency after it has been reduced through poisoning.

Thus, in conclusion, Cs₂Te has approached the goal of a single multi-purpose photocathode material, where the ideal material would have the following properties:

- high quantum efficiency at a convenient laser wavelength,
- long lifetime at a reasonable vacuum level,
- air tolerance,
- capability for high charge in a single micropulse, and
- fast response time.

II. Project Plan

The goal of this Small Business Innovative Research project was to provide a preliminary demonstration of the feasibility of the commercial utilization of a high efficiency, robust photocathode in a high gradient radio-frequency electron gun. This demonstration was to encompass the testing of the photocathode quantum efficiency after various handling methods were employed.

The original Phase I program was to consist of two distinct thrusts. Firstly, cathodes were to be fabricated by and initial testing performed at Los Alamos National Laboratory. After these initial tests in a nitrogen atmosphere at LANL, the cathodes were to be transported to AES, and the QE measured before and after various other less stringent handling methods. Secondly, an RF gun capable of accommodating the cathodes was to be designed.

The beam dynamics and preliminary RF design of the gun have been successfully completed. We have selected a gun configuration that is compatible with the 1.6 cell guns we are producing for monochromic x-ray systems since this would be the first commercial application of the overcoated cathode technology once it is proven out. Figure 1 shows the design of such a gun which conforms to the so-called BNL Gun IV configuration⁵.

However, the cathode test plan could not be adhered to due to unforeseen circumstances. We could only obtain a single cathode that did not undergo the planned nitrogen exposure tests at LANL. The cathode arrived very late in the program, and all facets of the testing had to be performed by AES. AES did not have the facilities to effect the proper transfer under vacuum of this cathode from the shipping container to the test chamber in the limited time available. A controlled exposure to dry nitrogen could therefore not be accomplished since this necessitated first performing the vacuum transfer. The best transfer system that could be constructed within the funding and time constraints was a purged glove box. The transfer was performed using this.

Figure 1. 1.6 Cell S-Band Gun Design

III. Gun Design

The gun design chosen is a 1.6 cell unit based upon the BNL gun IV design as noted above. This gun can produce very high brightness electron beams in a very high gradient electric field. Simulations of the gun were performed utilizing MAGIC. MAGIC is an electromagnetic PIC code developed by Mission Research Corporation. The gun cells have been designed to be resonant at 2.856 GHz. The first cell length is 0.6 times the length of the full cell and coupling between the cells is accomplished through the on axis iris. The cathode is in the endwall of the first cell.

The radial profile of the electron pulse upon generation (the radial laser profile) was uniform. The initial, hard edge radius of the electron pulse was 1.0 mm. The axial profile of the electron beam/laser pulse was Gaussian, truncated at two sigma. Its extent was 12 ps FWHM. The electrons are generated with zero energy spread and zero radial velocity.

The RF conditions incorporated a field balance between the cells which was uniform, and the cells were operated with an on-axis accelerating gradient of 130 MV/m. The electron bunched was launched at a phase of 45 degrees.

The simulations were performed with a pulse charge of 1 nC. More current could certainly be generated in the final gun, but 1 nC is a good compromise between high charge and low emittance.

At the output of the gun, energies of up to 6 MeV were achieved in the simulations using a gradient of 130 MV/m. Higher energy could be achieved with a longer gun or with a short booster accelerator. Emittances of less than 3 pi mm-mr were calculated at the gun output using an emittance compensation solenoid. Figure 2 shows the momentum (energy) and emittance evolution of the beam pulse through the gun. It should also be noted that an emittance compensating solenoid was used in the gun simulations.

Figure 2. Evolution of beam momentum and emittance starting from initial generation and continuing through gun output.

IV. Cathode Testing

Upon the conclusion of negotiations to obtain an overcoated cathode, we received a drawing of the cathode and transport container. This allowed the design of the test chamber to begin and the transfer procedure to be determined. The test chamber was based upon a six way cross with six inch flanges. The cathode holder and the anode were mounted on a flange which had two high voltage coaxial feedthroughs built into it. Both the anode and the cathode were isolated from the body of the chamber. The connection to both of them was accomplished through the center pin of their respective feedthroughs. The cathode holder was designed such that the cathode could be inserted into a copper ring that could then be tightened around the cathode. This ensured a good mechanical connection along with good electrical contact. The anode consisted of a hollow copper ring covered by a fine copper mesh on the side facing the cathode. The mesh was used to obtain a more uniform electric field between the anode and cathode. The hollow anode allowed the laser to impinge upon the cathode at a normal angle of incidence. Two of the ports on the cross contained windows. The window placed inline with the anode and cathode permitted the laser beam to be introduced into the test chamber. An observation window was placed perpendicular to the anode-cathode axis. A pumping port with a 75 liter/second ion pump and an ion gauge occupied two of the other arms of the six way cross. A photograph of the test chamber is shown in Figure 3. After assembly, but before the cathode was transferred to it, the test

chamber was baked at 250-300°C to clean the vacuum surfaces. A vacuum pressure in the low 10^{-9} Torr range was achieved in the test chamber after this bake was performed.

Figure 3. Photocathode test chamber before the installation of the cathode/cathode holder into the top port. Laser entry window can be seen in the front facing port.

The transfer chamber was designed to accommodate the test chamber and the cathode transport chamber. The transfer box consisted of an aluminum frame with plexiglas sides and top. The bottom was left open, but was sealed to the table below. Gloves were sealed into one side to allow the transfer to be performed. A purge port was placed in the top of the box.

When all was ready for the transfer to take place, the necessary tools were placed in the box along with the cathode transport container and the test chamber. Also placed in the box was a dewar of liquid nitrogen. The transfer chamber was sealed along the bottom. It was then purged with dry nitrogen for 24 hours through the inlet port. After this purge, the liquid nitrogen that remained in the dewar was poured onto an aluminum plate. The cold plate was observed for any signs of frozen condensation. None was observed, so the transfer was performed.

The test chamber was taken to Brookhaven National Laboratory's Instrumentation Division for the quantum efficiency tests. A nanosecond pulse length, quadrupled Nd:YAG laser provided the excitation of the cathode. A HeNe alignment laser was used to set up the transport mirrors and lenses and

to align the cathode to the laser path. The laser energy was calibrated using a photodiode and a Joule meter. During testing, the laser energy was monitored using a calibrated portion of the signal that was picked off of the main beam. To draw the electrons from the cathode, a positive voltage was placed on the anode. This voltage was kept at roughly 200V. The charge from the cathode was measured directly using an oscilloscope after passing through a calibrated charge amplifier. The quantum efficiency was calculated from the measured laser energy and the measured cathode charge using the formula:

$$Q.E. = \text{Charge}/(\text{Laser Energy}) * (\text{Photon Energy}),$$

where the photon energy is 4.66 eV for the quadrupled Nd:YAG laser.

The original quantum efficiency, measured at Los Alamos National Laboratory, was 2%. During the subsequent testing in our test chamber, the quantum efficiency was measured to be up to 0.2%. This represents an order of magnitude decrease from the freshly-made cathode. Additional research confirmed that this decrease was to be expected given the conditions under which the cathode transfer was performed. These types of cathodes are predominantly susceptible to water vapor⁶. A partial pressure of water as low as 10^{-4} is enough to defeat the CsBr protective layer in a few minutes. We did not measure the water content in the transfer box, but it was undoubtedly no better than 10^{-4} . Given the relatively cheap and easy transfer method employed by AES, the 0.2% is a respectable number. Heating the cathode is a proven method for rejuvenation^{7,8} and if properly done, should have restored its quantum efficiency to the 1-2% level.

However, again due to time and monetary constraints, the AES-fabricated test chamber did not incorporate a means to independently heat the cathode. An attempt was made to heat the cathode by baking the entire test assembly. Unfortunately, the cathode was not heated efficiently and achieved a lower temperature than the surrounding structure. It is our assumption that this only served to further contaminate the cathode rather than rejuvenating it. Measurements performed subsequent to the bake indicated quantum efficiencies of around 0.04%. Hence, no further testing was attempted.

V. CONCLUSIONS

AES was not able to gear up to attack Phase I issues until a cathode was received from Los Alamos. A single cathode was received in late January and tests originally scheduled to be performed by Los Alamos before shipment could not be performed. This left little time to design and fabricate a appropriate test facility and to perform the necessary experiments which were not part of the originally-proposed AES program. The original Phase I plans called for the

delivery of at least two cathodes in the early Fall of 1999 and for the initial testing to be carried out at Los Alamos in their existing facilities. The onus of performing the testing unexpectedly fell upon AES with a single cathode, little time and no margin for error.

Frankly, under the circumstances, we view the achievement of $QE \sim 2 \times 10^{-3}$ to be a success since this is equivalent to the best ever reported Magnesium cathode performance². When we factor in the already demonstrated ability to rejuvenate these cathodes, the reduction in QE was relatively small given the simple and inexpensive transfer method that was employed. We expect that, with a redesigned test chamber that would enable the cathode to be thoroughly and independently heated, the QE could have been restored to the 1% level.

This project has not *conclusively* demonstrated the technical feasibility of fabricating commercial electron guns that utilize these types of cathodes. However, it has been an important, significant step towards that goal. It has demonstrated that the cathodes do not require transfer in a UHV environment to maintain respectable quantum efficiency. Our cathode was stored in its evacuated but not actively pumped shipping container for two weeks. It was then transferred using an inexpensive, nitrogen purged glove box to the test chamber. The total transfer time between venting of the shipping assembly to pumping of the test chamber was around 30 minutes. After this type of handling, the cathode still achieved a quantum efficiency of up to 0.2% without any rejuvenation. This at least demonstrates that the cathode is robust enough to be handled in a cost effective manner. With improvements to the transfer system to allow better exclusion of water vapor and a more rapid transfer, the quantum efficiency reduction could be substantially reduced. The lifetime in an operating high gradient gun still needs to be demonstrated, but this was beyond the scope of this Phase I SBIR.

Economically, these cathodes can be produced cheaply and efficiently. They can be shipped cross country in a box without active vacuum pumping. And, they can be transferred to a gun with a relatively inexpensive transfer system. If their lifetime in the operating gun is as long as expected, this cathode replacement procedure should occur no more than once or twice per year. This would be a small price to pay for the vastly reduced laser requirements and would make photocathode electron guns much more economically attractive for commercial applications.

¹ J.S. Fraser et al., "Photocathodes in Accelerator Applications," Proceedings of PAC87, 1705 (1987).

² T. Srinivasan-Rao et al., "Performance of Magnesium Cathode in the S-Band RF Gun," Proc. 1997 Part. Accel. Conf. (1997) 2790.

³ P. Michelato, "Photocathodes for RF Photoinjectors," Nucl. Instr. Meth. A **393**, (1997) 455.

⁴ E. Chevallay et al., "Photo-Cathodes for the CERN CLIC Test Facility," Proc. 1998 Linear Accelerator Conference (1998) 872.

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- ⁵ X. J. Wang et al., "Challenges of Operating a Photocathode RF Gun Injector," Proc. 1998 Linear Accelerator Conference (1998) 866.
- ⁶ E. Shefer, "Coated Photocathodes for Visible Photon Imaging with Gaseous Photomultipliers", Nucl. Instr. Meth. A **433** (1999) 502.
- ⁷ S. H. Kong et al., "Fabrication and Characterization of Cesium Telluride Photocathodes: A Promising Electron Source for the Los Alamos Advanced FEL," Nucl. Instr. Meth. A **358** (1995) 276.
- ⁸ P. Michelato et al., "Characterization of Cs₂Te Photoemissive Film: Formation, Spectral Responses and Pollution," Nucl. Instr. Meth. A **393**, 464 (1997).