PHOTOCATHODE ELECTRON SOURCE DEVELOPMENT AT ADVANCED ENERGY SYSTEMS[*]

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Abstract

Advanced Energy Systems is developing several novel photocathode electron sources. One of these sources, which is fully superconducting, is intended to provide a high-brightness, quasi-CW stream of electron bunches from a very compact gun system. A second source is normal conducting, but utilizes a very robust, high-quantum-efficiency photocathode. This gun is intended for use in applications such as high-gain FEL's or next generation linear colliders. We will report on the research that has been performed on the performance of the photocathode materials and describe the basic design of these photocathode RF electron guns together with projecting their expected performance. It is shown that the superconducting gun exhibits much promise while the normal conducting gun results are inconclusive at this time.

1 INTRODUCTION

Radio frequency, photocathode electron guns are the source of choice for most high-performance accelerator systems. The main reason for this popularity is their ability to produce very bright beams of electrons. However, due to inherent limitations, photocathode RF electron guns have not successfully penetrated certain key applications. One of these limitations is their inability to economically produce the high-average-current, high-brightness electron beams necessary for certain applications. Only a superconducting, photocathode RF or DC gun can be economically operated at high-average-power.

Another drawback is that one must choose between high-quantum-efficiency and durability. Durable cathodes tend to have relatively low quantum-efficiency, while high-quantum-efficiency cathode materials are invariably very sensitive to vacuum conditions.

Solutions to both of these issues are being investigated. In order to produce high-average-power, a fully superconducting RF gun is being developed which is designed to utilize niobium as the cathode material. A second approach seeks to develop a robust, high-quantum-efficiency photocathode material for use in normal conducting RF guns. For this, the robustness of a Cs_2Te cathode coated with a protective layer was tested[1]. In addition but not described below, Advanced Energy Systems is also studying high-average-current injectors utilizing DC photocathode guns coupled to superconducting RF cavities and ultra-high-brightness room-temperature guns for very intense, low repetition rate, commercial applications.

2 SUPERCONDUCTING RF GUN

We are developing an SRF photocathode injector using the niobium itself as the photoemitter. Using the niobium as such avoids the complications involved in introducing foreign materials into the interior of the superconducting cavity. The main stumbling block to this concept is the quantum efficiency of the niobium. To overcome this, the Schottky effect can be used to advantage to increase the practical quantum efficiency of the niobium. This was the main thrust of the initial portion of the research project.

2.1 Niobium Quantum Efficiency Testing

A series of measurements was successfully completed at BNL that characterized the quantum efficiency of Nb under the influence of the Schottky effect. The tests were performed at 6.5 MV/m, although it is desired to operate the photocathode at gradients approaching 100 MV/m. The results obtained from the measurements can be readily extrapolated to these higher gradient levels. Looking at the equation for quantum efficiency,

$$\eta = K(h\nu - \phi_0 + \sqrt{e/4\pi\varepsilon_0}\sqrt{E_S})^2$$

where,

η = quantum efficiency
K = a constant which depends on the material
$h\nu$ = photon energy
ϕ_0 = material work function
Es = the surface electric field (this includes the surface enhancement factor)

This can be rearranged to yield

$$\sqrt{\eta} = \sqrt{K}(h\nu - \phi_0) + \sqrt{K}\sqrt{e/4\pi\varepsilon_0}\sqrt{E_S}$$

If $\sqrt{\eta}$ is plotted against $\sqrt{E_S}$, one obtains a straight line with an intercept of $\sqrt{K}(h\nu - \phi_0)$, and a slope of $\sqrt{K}\sqrt{e/4\pi\varepsilon_o}$. If K is not a function of E_s, then we

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[*] This work was performed under US Department of Energy Small Business Innovative Research Grants DE-FG02-99ER82723 and DE-FG02-99ER82724. BNL personnel were supported under DOE grant DE-AC02-98CH10886.

should be able to apply the equation over a broad range of E_s. Hence, the slope and intercept can be determined at lower voltages and the results extrapolated linearly to higher voltages.

The quantum efficiency of Nb was measured using two test samples which had undergone different types surface preparation. The first cathode was chemically etched using a standard treatment for superconducting cavities. This heavy etch removed approximately 150 µm of material. This resulted in a surface that is visibly rough to the eye, as opposed to the mirror-polished surfaces desired for test cathodes. The QE results from this test were very disappointing and are plotted below in Figure 1. The linear fit to the data points shown is given on the plot. Extrapolation of the data to 100 MV/m gradient yields a QE of ~ $2x10^{-5}$ for this sample.

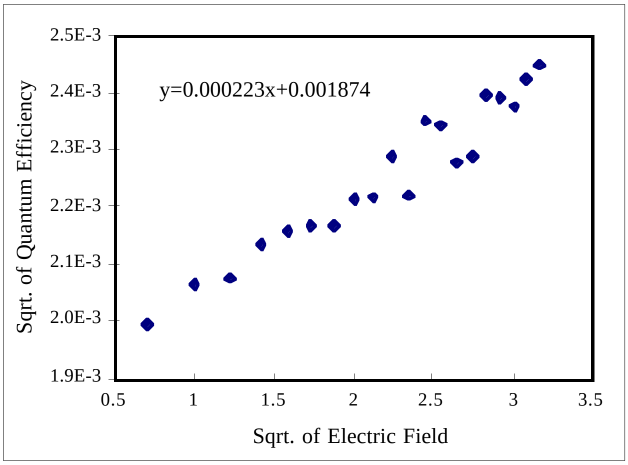

Figure 1. QE measurement results for chemically polished Nb cathode.

A second Nb cathode identical to the previous sample was mechanically polished after the chemical etching using a series of diamond polishing compounds. The sample was cleaned ultrasonically and installed in the vacuum with minimum exposure to ambient air. The system was baked for 12 hours and the quantum efficiency measured. The results are not shown in a plot, but the linear fit of the data gives an equation of $y=0.00469x+0.0143$. Extrapolation of the data to 100 MV/m gradient yields a QE of $3.745x10^{-3}$ for this mechanically polished sample. This resulting QE is a factor of 34 higher than our original QE goal of $1.1x10^{-4}$.

The next step in the quantum efficiency testing will be to utilize a high voltage pulser. This will enable verification of the QE at the higher gun gradients.

2.2 Cavity Design

An initial RF design of a cavity for use in the superconducting RF photocathode electron gun has also been completed. The design is based on the traditional elliptically shaped cavity in wide use today. The cavity is terminated with a flat endwall on which is located a small knob that will serve as the photocathode. The intent is to enhance the cathode surface fields using the knob while keeping the peak electric and magnetic fields within an achievable range. The limiting factor chosen for the design is the peak magnetic field that would quench the cavity. The design was not limited based on maximum electric field. Since the cavity will be designed, fabricated, and treated expressly to allow high fields to be maintained on a limited surface area, we believe we will be able to operate at peak fields higher than normally achieved.

A SUPERFISH plot of the fields in the 1300 MHz SC Gun cavity is shown in Figure 2.

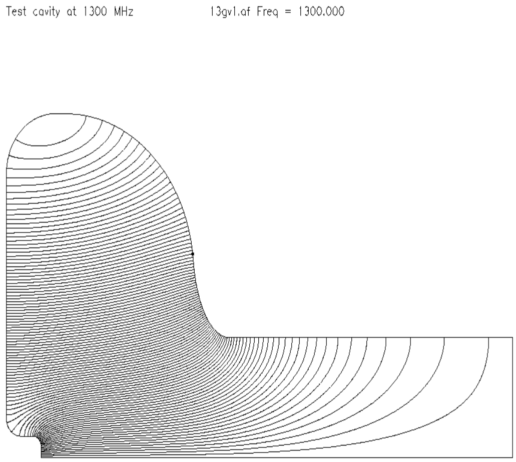

Figure 2. SUPERFISH plot of the SC gun cavity.

The knob shown on the left of the figure is the cathode. At a maximum H field (at the cathode base) of 1000 gauss, the E field at the center of the cathode is 131 MV/m, with a peak electric field at the cathode edge of 201 MV/m. The peak field on the aperture is a more reasonable 37 MV/m and the EoT is 16 MV/m.

Tables 1 and 2 summarize the system operating parameters and the resulting performance predictions using the QE measurements for the mechanically-polished sample, the present cavity design and assuming 1W of average laser power. Table 1 shows the expected QE along with the calculated field levels within the cavity for increasing electric field levels on the cathode.

Table 1. Expected quantum efficiency and cavity surface fields as a function of cathode field level.

Ecathode (MV/m)	Quantum Efficiency	E_{peak} (MV/m)	$E_{aperture}$ (MV/m)	E_o (MV/m)	H_{peak} (A/m)
10	0.000849	15.34	2.80	1.53	6095
20	0.001244	30.68	5.60	3.05	12190
30	0.001599	46.03	8.39	4.58	18284
40	0.001933	61.37	11.19	6.10	24379
50	0.002253	76.71	13.99	7.63	30474
60	0.002563	92.05	16.79	9.15	36569
70	0.002866	107.39	19.59	10.68	42663
80	0.003164	122.74	22.39	12.20	48758
90	0.003457	138.08	25.18	13.73	54853
100	0.003745	153.42	27.98	15.25	60948
110	0.004031	168.76	30.78	16.78	67043
120	0.004313	184.10	33.58	18.30	73137
130	0.004593	199.45	36.38	19.83	79232

Meanwhile, Table 2 presents the RF power requirements for two operating temperature regimes along with the expected output beam and power.

Table 2. Output beam voltage, current, and power along with RF power requirements for two helium temperature ranges as a function of cathode field level.

Ecathode (MV/m)	Beam Voltage (MV)	2K RF Power (W)	4.2K RF Power (W)	4.2K LHe Boiloff (L/Hr)	current for 1 W Laser (mA)	beam power (W)
10	0.3	0.37	0.70	0.97	0. 182	55
20	0.6	0.74	2.79	3.86	0. 267	160
30	0.9	1.10	6.28	8.70	0. 343	309
40	1.2	1.47	11.16	15.46	0. 415	498
50	1.5	1.84	17.44	24.15	0. 483	725
60	1.8	2.21	25.12	34.78	0. 550	990
70	2.1	2.58	34.19	47.34	0. 615	1292
80	2.4	2.94	44.66	61.83	0. 679	1629
90	2.7	3.31	56.52	78.26	0. 742	2003
100	3.0	3.68	69.78	96.61	0. 804	2411
110	3.3	4.05	84.43	116.90	0. 865	2854
120	3.6	4.42	100.48	139.12	0. 926	3332
130	3.9	4.78	117.92	163.28	0. 986	3844

3 OVERCOATED CATHODE

As mentioned previously, one of the drawbacks of high-quantum-efficiency photocathode materials is their sensitivity to residual gas that makes them difficult to use and even more difficult to transport. Overcoating these cathodes with a protective layer has been shown to be effective in increasing their durability[1]. The feasibility of utilizing this type of cathode in a commercial RF gun was examined. The goal was to determine whether they could be produced in one location and then transferred to a photocathode gun at a remote site without the complication and expense of a UHV load lock system.

To perform these tests, an overcoated Cs_2Te cathode was obtained from Los Alamos National Laboratory. The cathode was shipped in an evacuated container and transferred to the test chamber. This transfer took place within a nitrogen purged glove box. Other than the nitrogen purge, no attempt was made to control the atmosphere within the box. The cathode was quickly transferred to the test chamber and re-evacuated. The total time outside of vacuum was about 20 minutes.

Cathode QE testing was performed at BNL. A nanosecond pulse length, quadrupled Nd:YAG laser provided the excitation of the cathode. During testing, the laser energy was monitored using a calibrated portion of the signal that was picked off from 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 after passing through a calibrated charge amplifier by using an oscilloscope. The quantum efficiency was calculated from the measured laser energy and the measured cathode charge using the formula:

Q.E. = Charge/(Laser Energy)*(Photon Energy),

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

The original quantum efficiency, measured at LANL, had been 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. Since these types of overcoated cathodes are predominantly susceptible to water vapor[1], this type of decrease was to be expected. A partial pressure of water as low as 10^{-4} is enough to defeat the 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 simple transfer method employed, which was enforced by schedule and other external pressures, the 0.2% is a respectable number. Heating the cathode is a proven method for rejuvenation[2,3] and if properly performed, should have restored its quantum efficiency to the 1-2% level. Unfortunately, a proper rejuvenation test could not be performed at the time. Hence, unfortunately, the overcoated cathode results remain inconclusive at this time and further testing is required.

4 SUMMARY

The development of novel photocathode RF guns is being pursued. These sources are intended to overcome some of the present limitations of RF guns and open up new application areas. The feasibility of operating a superconducting RF gun with niobium as the photo-emitter has been demonstrated. This type of gun will enable the generation high-average-power, high-brightness beams in a relatively simple structure. The use of robust, high-quantum-efficiency photocathodes in a commercial setting has also been studied. Although the results were inconclusive, it appears but remains to be confirmed, that it should be possible to transfer these cathodes in a simple purged atmosphere followed by a rejuvenation heat to restore the quantum efficiency.

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