

# DEVELOPMENT OF A NOVEL SUPERCONDUCTING RF PHOTOCATHODE ELECTRON GUN\*

M. Cole, H. Bluem, J. Rathke, T. Schultheiss

Advanced Energy Systems Inc. 27 Industrial Blvd, Medford NY 11763, USA

I. Ben-Zvi, T. Srinivasan-Rao

Brookhaven National Laboratory Upton NY, USA

## Abstract

Over the past year Advanced Energy Systems Inc. and Brookhaven National Laboratory have undertaken a program to develop a Superconducting Photocathode Electron Gun utilizing a unique cathode concept<sup>1</sup>. The cathode concept is much simpler than many other approaches and should avoid many complications which might otherwise be encountered. This cathode concept does not utilize an insert of any kind and is fully integrated with the Nb cavity. The results of experiments which demonstrate the feasibility of the cathode concept will be presented. We will review the important gun design parameters, discuss how they play against each other, and present results of an optimization of the design. Anticipated beam output parameters will be given, based on the optimized design and experimental results. Finally we will review our plans to continue the development program. This program will include the design and fabrication of the cavity and associated cryostat at Advanced Energy Systems Inc, integration of the entire system, and testing of the full system at BNL.

## 1 INTRODUCTION

It is widely acknowledged that the electron injector is the principal development issue for high-brightness superconducting CW accelerators presently using separated electron sources. Significant gains in compactness, beam brightness, efficiency and reliability could be realized by developing a superconducting gun where the photocathode is an integral part of the initial accelerating cavity. The improved system we are developing, eliminates the need for a separate electron gun, and will utilize the cavity endwall itself as the integral photocathode. We have fabricated representative Nb test specimens and measured the quantum efficiency of candidate photocathodes under the influence of the Schottky effect and demonstrated that a significant electron beam power can be emitted. We determined, through beam dynamics simulations, that a high quality electron beam can be generated and

accelerated through a superconducting structure. We are currently refining the initial cavity and cathode designs.

## 2 NIOBIUM QUANTUM EFFICIENCY (QE) MEASUREMENTS

A series of measurements were successfully completed at BNL that characterized the quantum efficiency of Nb under the influence of the Schottky Effect. For these measurements a niobium cathode and a plane anode are held parallel inside an evacuated chamber with a base pressure of  $\sim 1 \times 10^{-8}$  Torr. The interelectrode spacing was set to be 0.8 mm before inserting in the vacuum chamber. The anode has a circular opening for the laser to pass through, the circular opening is covered with a copper mesh to maintain the field lines normal to the electrodes. The anode could be biased to 10kV, limited by the electrical feed through of the vacuum system. Photoelectrons leaving the cathode as a result of laser irradiation were measured using a calibrated charge sensitive preamplifier, shaping amplifier and oscilloscope. Initially it is not obvious that QE measurements at 12.5MV/m would have much meaning when we are interested in operating in the range of 100MV/m. If we look at the equation for the quantum efficiency vs the applied field:

$$h = K(h\nu - f_o + \sqrt{\frac{1}{4\pi\epsilon_0}} \sqrt{E_s})^2$$

Where:

$$\begin{aligned} h &= \text{QuantumEfficiency} \\ h\nu &= \text{PhotonEnergy} \\ f_o &= \text{ElectronWorkFunction} \\ K &= \text{Const.} \\ E_s &= \text{AppliedElectricField} \end{aligned}$$

Then:

$$\sqrt{h} = \sqrt{K}(h\nu - f_o + \sqrt{\frac{1}{4\pi\epsilon_0}} \sqrt{E_s})$$

And Finally:

$$\sqrt{h} = \sqrt{K}(h\nu - f_o) + \sqrt{K} \sqrt{\frac{1}{4\pi\epsilon_0}} \sqrt{E_s}$$

If  $\sqrt{h}$  is plotted against  $\sqrt{E_s}$ , one obtains a straight line with an intercept of  $\sqrt{K}(h\nu - f_o)$ , and a slope of

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$\sqrt{K} \sqrt{\frac{e}{4\pi\epsilon_0}}$ . If  $K$  is not a function of  $E_s$  then we should be able to apply the equation over a fairly broad range of  $E_s$ .

The cathode was irradiating with a mode-locked YAG laser with frequency doubler and quadrupler. UV radiation at 266 nm was separated using a fused silica prism, passed through a half wave plate and a polarizing cube to adjust the energy, then a lens to irradiate the cathode. The laser energy entering the vacuum cell was measured using a calibrated photodiode.

After initial poor results with an unpolished etched cathode, a Nb cathode was mechanically polished after a BCP chemical etch using a series of diamond polishing compounds of 9, 6 and 1 micron grain size. The sample was cleaned ultrasonically in a hexane bath 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 shown in figure 1.

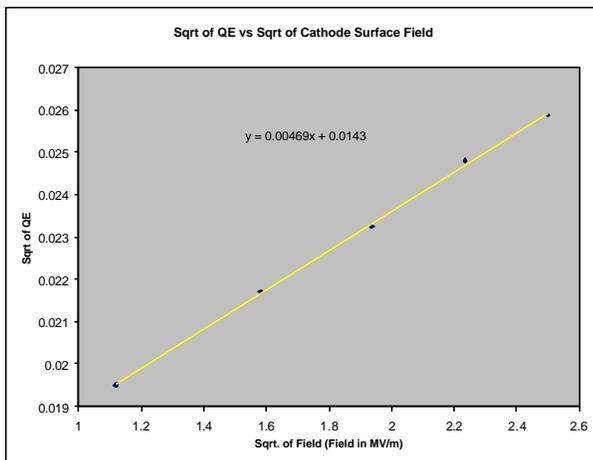


Figure 1: QE Results for Nb cathode After Mechanical Polishing

Linear fit lines through the data and the fit parameters are shown on the plot. Extrapolation of the data to 100 MV/m gradient yields a QE of  $3.745 \times 10^{-3}$  for the polished sample.

### 3 INITIAL CATHODE CONCEPT AND BEAM DYNAMICS

In the initial concept the cavity design was based an elliptically shape terminated with a flat endwall on which is located a small knob which will enhance the cathode surface fields and serve as the photocathode. A SUPERFISH plot of the initial cavity geometry and electric fields are shown in figure 2.

The knob shown on the left of the plot is the 1.2cm diameter cathode used for the initial study. At a maximum H field (at the cathode base) of 1000 gauss the E field at the center of the cathode would be 131 MV/m, with an  $E_p$  at the cathode edge of 201 MV/m. The peak field on the aperture was 37 MV/m and the  $E_oT$  is 16 MV/m.

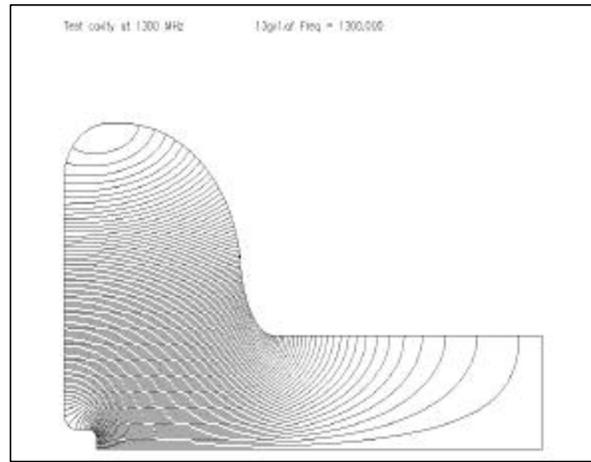


Figure 2 SUPERFISH Plot of initial cavity with protruding cathode

The two-dimensional particle-in-cell code MAGIC was used to study the beam dynamics. Although the system will be quasi-CW, the bunches will still be separated by at least 6 RF buckets, assuming a laser mode locking frequency of 200 MHz or less. As such, a single pulse of charge is sufficient to model the beam dynamics in this initial study. A charge of 0.01 nC per pulse was used. This corresponds to an average current of 2 mA for a laser repetition rate of 200 MHz. The peak gradient on the cathode surface was set at 120 MV/m, while the launch phase of the electrons was varied between 45 and 70 degrees. The beam size and pulse lengths were also varied and the effect of a solenoid focusing field examined. The initial beam profile was always modeled as a gaussian truncated at 1-sigma. Thus, all of the initial radii quoted here correspond to the full beam radius at the cathode. Any final radius however, will be quoted as the rms value.

First, the beam was allowed to nearly fill the full cathode flat. The initial beam radius was 2.5 mm. However, the large radial electric field due to the cathode corners gives rise to a large RF induced beam divergence. The large divergence leads to a significant increase in the beam size, reaching a radius of 9 mm rms, and causes a fairly large beam emittance. As the beam size was reduced, an emittance of 1.0 mm-mr was achieved with an initial beam radius of 1 mm. Coarse adjustment of the phase reduced this number to 0.5 mm-mr. Reducing the initial beam size to 0.4 mm resulted in an unoptimized emittance of less than 0.3 mm-mrad but there is still considerable growth in the size of the 0.4 mm beam. It is expected that this growth can be reduced substantially by redesigning the cathode region to either eliminate the protrusion or by making it larger in radius.

The major disadvantage with the initial design lies in the size of the cathode protrusion. The final design will be a compromise between the required beam quality, beam current, and desired cathode gradient. The beam dynamics simulations have shown that it is possible to

achieve a high quality, high average current beam from this electron gun.

### 4 IMPROVED CAVITY DESIGN

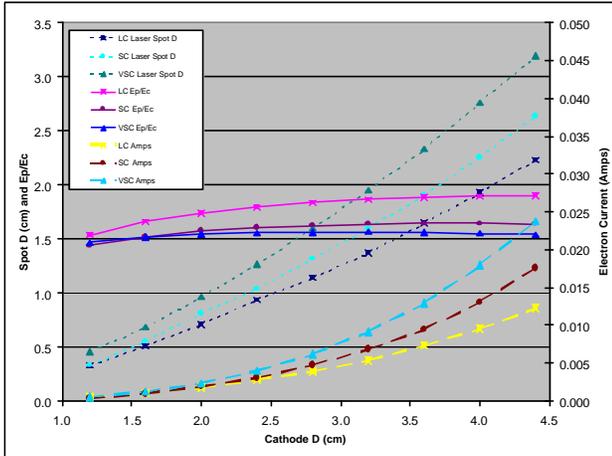


Figure 3: Spot D, electron current, and Epeak/Ecathode plotted as a function of cathode diameter for three cathode lengths

We examined a series of cavities with cathode varying in diameter and length. The cavity we used in the initial study was defined as the long cathode and had a 1.23cm long cathode. A cavity with short cathode of 0.61 cm was examined along with one having a very short cathode of 0.31 cm. Each of these was run with the cathode diameter varying from the original 1.2 cm up to 4.4 cm. The cavities were tuned by adjusting the cavity outer diameter.

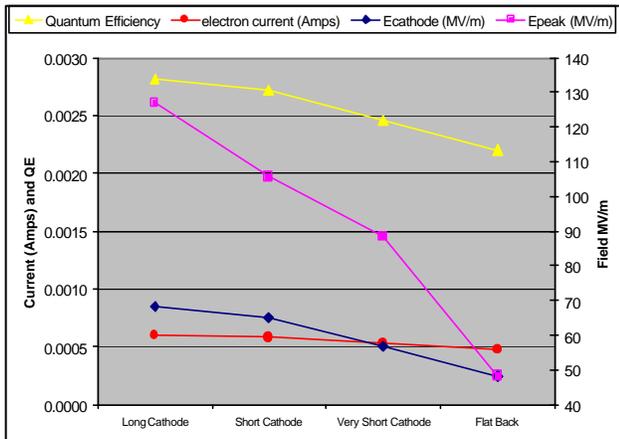


Figure 4: QE, current, Ecathode, and Epeak for cathode configuration.

We initially chose a laser spot sized so that the field would not vary by more than 5% from the cathode center. The larger diameter cathodes had less radial field variation on the surface so larger cathodes allowed larger laser spot sizes. The laser spot was not held to any maximum. We assumed a constant  $6W/cm^2$  [2] laser power so larger cathodes always had more laser power.

It turned out that in all cases larger cathode diameters ultimately yield more electron current since QE falls more slowly than the laser power increases. The results for the QE, current, cathode fields, and Epeak/Ecathode are plotted in figure 3.

We also ran a case with a flat back plate, at a laser spot of 3.91cm in diameter we can get a current of 34 mA with a cathode field of 48.36 MV/m.

We limited the laser power to 1 Watt and can support a laser power density of  $6W/cm^2$ , fixing the laser spot size to 4.607 mm in diameter. Limiting the variation in cathode field over that spot to 2% yields one cathode diameter for each cathode length which satisfies the requirement. In the flat back cavity the field is uniform to 2% over an area larger than the laser spot size. The results are plotted in figure 4 and clearly indicate that there is little to be gained from a protruding cathode.

### 5 CONCLUSION

We have performed initial conceptual design work and experimentation to show the viability of our SCRF photocathode gun concept. We have moved onto preliminary design and concept optimisation. Based on our examination of the effect of various cathode configurations we have chosen to eliminate the initial protruding cathode and use a flat back plate. We may add a slight dome to the back plate later for improved structural performance. Our next steps will be to perform detailed beam dynamics and thermostructural analysis on the improved cavity. Detail design of the cavity and cryostat system will follow. Fabrication and system procurement/integration will take place next leading up to installation and testing on-site at BNL.

### REFERENCES

[1] H. Bluem et. al., 'PHOTOCATHODE ELECTRON SOURCE DEVELOPMENT AT ADVANCED ENERGY SYSTEMS', EPAC'00, June 2000.

### ACKNOWLEDGMENTS

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