OPTIMIZATION OF DC PHOTOGUN ELECTRODE GEOMETRY *

J. M. Maxson†, I. V. Bazarov, K. W. Smolenski, B. Dunham
CLASSE, Cornell University, Ithaca NY 14853, U.S.A.

Abstract

DC photoguns that employ electrostatic focusing to obtain lower beam emittance must inherently trade off between focusing strength and the field at the photocathode, and are traditionally pushed to the limits of breakdown voltage. In this paper, we numerically investigate a highly parametrized electrostatic geometry exploring the trade-off between the voltage breakdown condition and electrostatic focusing. We then compare the results to DC gun designs where the focusing is introduced via embedded solenoidal fields. Finally, we present investigations for a multi-anode gun design that seeks to simultaneously achieve both high electric field at the photocathode and high gun voltage without violating the empirical voltage breakdown condition. In the most feasible cases, the electrode geometry is optimized via genetic algorithms. Designs on the optimal front are compared with the current performance of the Cornell ERL prototype DC photogun.

INTRODUCTION

The design and use of DC photoemission guns for use in high brightness beam production has already had considerable success in several laboratories. For such photoinjectors to approach the theoretical maximum brightness limits, the main gun design parameters– accelerating voltage, transverse focusing fields, and electric field strength at the surface of the photocathode–must be optimized beyond the current state of the art. Fundamental trade-offs exist between all three quantities in the conventional one-gap design, which includes a Pierce-type electrode and solenoid optics just downstream. The goal of this work is to numerically analyze various gun geometries to determine the interplay and importance of each of these design parameters.

The electric field at the surface of the cathode is a direct figure of merit for beam brightness. A larger axial field at the photocathode surface provides more surface charge for extraction, which causes the theoretical maximum brightness of the gun, set by the initial momenta of the photoemitted electrons (thermal emittance), to scale with the E_{cath}, the cathode field [1]. However, the electric field at the surface of the cathode must directly trade off with the electrostatic focusing fields, associated with the angle of the Pierce electrode. Electrostatic gun focusing serves at least two roles in providing high brightness, in that it both combats the strong effect of space charge inside the gun, and offsets the defocusing effects of the anode electrode. The trade-off between focusing fields and cathode axial field can be seen directly in the off-axis expansion of the transverse field component. If z denotes the beam direction, then the radial component can be written: $E_r(z) = -r\partial_z E(0,z)/2 + \mathcal{O}(r^3)$, where the leading term suggests that for strong focusing near the photocathode (negative E_r), one requires a steep decrease in the axial field.

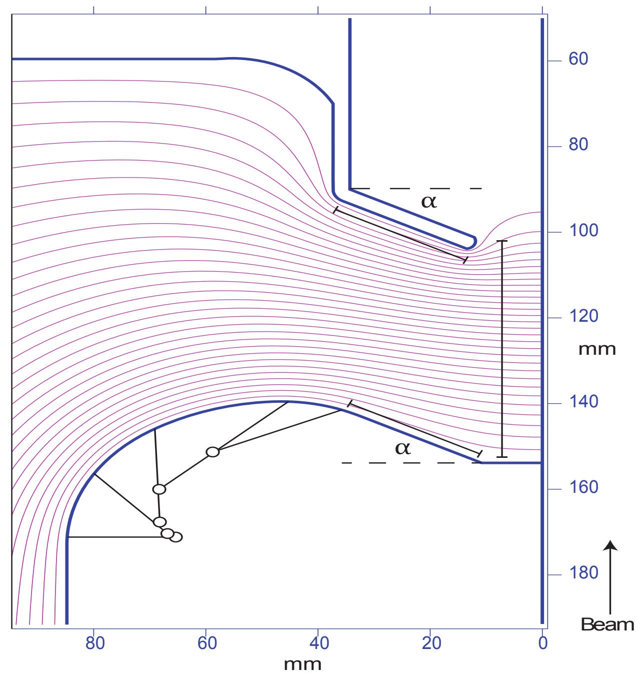

Figure 1: Gun geometry parameters for optimization. Each line represents a parameter varied by the optimizer. The geometry shown is that on the optimal front which has simultaneously minimum focal length and maximum field on the non-active region of the cathode electrode.

To simultaneously achieve both high field at the photocathode and strong focusing, one must increase the voltage or decrease the cathode-anode gap. For photoguns in operation today, the achievable voltage is limited by the onset of field emission which can lead to punctures in the ceramic HV insulator. However, this is a technological issue which may be alleviated by new ceramic designs, such as the use of a segmented ceramic, in which guard rings are attached between segments. Such a design is planned for use in the new DC gun under construction at Cornell. If ceramic puncture is mitigated, DC photoguns are fundamentally limited by field emission from the cathode electrode itself. Though the scaling of field emission current with voltage is well described by the Fowler-Nordheim re-

* This work supported by the NSF under Grant No. DMR-0807731
† jmm586@cornell.edu

lations [2], the stochastic nature of inclusion/impurity density and their location makes absolute breakdown voltages difficult to predict for a given material. As we seek to use a realistic constraint on our simulated gun geometries, we use empirical data compiled by Slade [2] of vacuum breakdowns as a function of cathode-anode gap for large area electrodes. Data suggest that the highest electric fields can be obtained for smaller gaps (< 1 cm) and modest voltages ($\sim$100kV), however there are notable benefits to a higher energy electron beam. Higher energy affords more relativistic suppression of the space charge emittance growth, which can provide a smaller transverse beam size. Small beamsize reduces the effect of aberrations in the optics, particularly the defocusing due to the anode electrode, as well as geometric aberrations in the solenoids.

FIELD AND EMITTANCE OPTIMIZATION

The current photogun in operation in the Cornell ERL injector prototype features a Pierce-type electrode pair containing essentially three geometrical parameters: the cathode-anode gap (d=50 mm), the cathode focusing angle ($\alpha = 25°$), and the radius of the arc which terminates the electrode. We seek first to understand the effect of a higher degree of geometry parameterization on the trade-offs between: 1) the reduction in maximum electric field on the cathode electrode (which would contribute to field emission), 2) the increase in the photocathode field, and 3) the decrease in focal length. Here, we define the focal length of the gun as a the axial distance from the photocathode that an electron emitted slightly off axis ($r \sim$1 mm) takes to cross the z axis.

An optimizer was developed that first parameterizes the electrode geometry as shown in Fig. 1. The geometry parameters that are varied are the cathode-anode gap, the angle and length of the cathode cone, as well as the introduction of an arbitrary number of terminating arc radii, enforced to be tangential, with a fixed voltage of 500kV. The optimizer first generates an input file for the field solver POISSON [4], then extracts the field map and figures of merit, including the focal length (calculated via particle tracking), the cathode field, as well as the maximum field at the surface of the cathode. The geometry was allowed to vary from $\alpha \approx 0$ to greater than $40°$, and the gap allowed to vary between 30-70 mm. The optimizer itself was genetic in nature, which is beneficial for such multivariate optimizations, in that the optimizer regularly "mutates" solutions to sample regions sufficiently beyond local (false) minima.

Multiple runs were performed with different constraints and objectives. In the first of these runs, the objectives were minimum focal length and minimization of the largest field on the non-photoemitting portion of the cathode. The current Cornell gun has a maximum field of 13 MV/m, and a photocathode field of 5 MV/m. The solution with maxiumum field closest to 13 MV/m is presented in Fig. 1. This

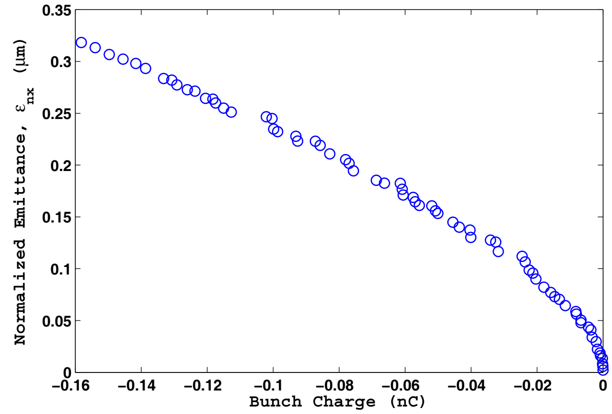

Figure 2: Full-beamline emittance optimization for varied bunch charges.

solution also has a photocathode field of 5 MV/m, but an increase in focusing of approximately 5%, with $\alpha = 26.5°$. This was achieved via the flattening of the arc closest to the anode, but in other respects highly resembles the existing Cornell geometry.

A second optimization was performed to maximize the field on the cathode, while simultaneously minimizing the focal length. The optimal solutions reveal a strong decrease in focusing for field strengths beyond 6MV/m, with the optimizer pushing for flatter cathodes with decreasing gap. Specifically, an increase of the photocathode field to 7 MV/m requires an increase in focal length by a factor of 10, which is essentially the zero focusing regime. Thus, both optimization runs demonstrate insensitivity of the trade offs to higher degrees of parameterization. Therefore, further optimization must center on the relative importance of voltage, gap, and focusing on final emittance, with smaller number of gun geometry parameters.

Next, an optimization was performed with a simplified gun geometry (only angle, gap and voltage varied) on an ASTRA [5] simulation of the Cornell ERL injector. Each of the downstream beam parameters, (optics, cavity phases and fields) as well as the laser pulse and bunch charge were optimized. The optimizer structure, function, and all parameters can be found in Ref. [3]. The results of final emittance vs. bunch charge are plotted in Fig. 2. These were for an initial electron distribution with a mean transverse energy of 120 meV, which is the value that has been measured previously [6] in photoemission from GaAs photocathodes with $\lambda = 520$ nm light. It must be noted that the optimal emittances are dominated by thermal emittance (70-85%), suggesting that the optics may be chosen to cancel both space charge emittance growth and optics aberration effects. Thus, the optimizer pushed for higher gradients ($\sim$ 6 MV/m) and correspondingly smaller angles (9-11°), with a nearly constant gap and voltage of d=55mm and V=470 kV. Furthermore, it is also clear that this residual focusing remains due to a constraint on a laser pulse length of $\Delta t < 10$ ps, which introduces extra space charge

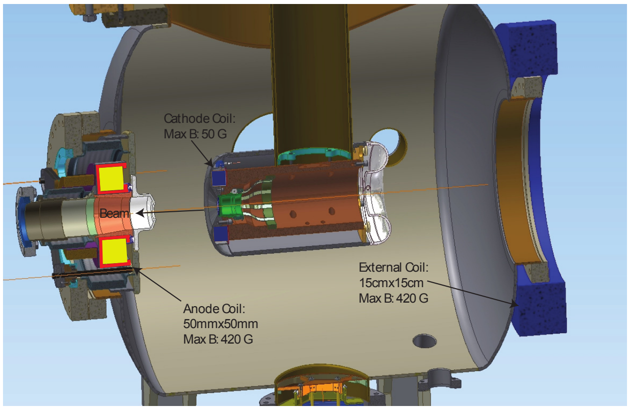

Figure 3: CAD drawing of gun assembly, showing anode coil, and two bucking coil options: embedded solenoid (within cathode) and external solenoid (both shown in blue).

repulsion near the cathode as compared to that of a longer bunch.

A separate method to alleviate the tradeoff between electrostatic focusing and photocathode field would be to introduce magnetostatic focusing via solenoid coils within the gun assembly. A possible configuration would be to place a solenoid coil within the anode assembly itself. Such is the configuration shown in Fig. 3. However, for the low emittance limits of high brightness machines such as the Cornell ERL injector, the presence of nonzero magnetic field at the surface causes an increase in the emission emittance due to the presence of the vector potential in the Hamiltonian. To mitigate this growth, a bucking coil of opposite polarity is placed behind the cathode to cancel the field at the photocathode surface. This could be most completely accomplished via the inclusion of an embedded solenoid coil within the cathode electrode itself.

However, floating a solenoid coil at high voltage introduces a number of additional complexities. There must be an isolated means of generating the solenoid power, perhaps by inclusion of an external motor surrounded by insulating material, or by the alteration of the existing HV power supply. Furthermore, perhaps up to 50W (for the layout shown) of additional power must be dissipated within the cathode structure. Another option would be to place a bucking coil outside of the gun chamber (shown in blue), where the increased distance to the photocathode requires that the solenoid bore increase significantly. This however causes greater cancellation of the anode coil field beyond just the photocathode surface, and reduces overall focusing ($\sim 10\%$).

We must also note that the addition of solenoid focusing in actual application can cause emittance growth via solenoid abberations, due to terms cubic in the magnetic field, analogous to the second term in Eq. 1. We calculate in Ref. [3] that for a rigid, collimated beam, the normalized emittance growth due to aberrations scales with the beam size as $\epsilon_{nx} \propto \sigma_x^4$, as well as with the derivative of the magnetic field as: $\epsilon_{nx} \propto \int (\partial_z B_z)^2 \, dz$, which are both problematic for anode solenoid fields, considering the short extent of the coil package, and the large beam size at the anode.

THE DUAL GAP GUN

It is possible to envision a photogun which features two anodes–one at intermediate voltage ($\sim$100kV) and small gap ($<$10mm), for the purpose of creating strong field at the photocathode, and a ground anode much farther away to provide maximal energy gain (500kV or greater). Successful implementation could yield a solution to the breakdown trade-off between cathode field and voltage present in one-gap designs, but initial investigations into possible geometries has presented difficulty in supplying adequate focusing. With the close proximity of the first anode, the effect of the $\partial_z E_z$ focusing term is suppressed for the Pierce electrode form, and the effect of anode defocusing is increased. A possible solution to increase focusing may be to round the photocathode itself, as is done in high power thermionic guns, combined with the Pierce cone. Modest radii of curvature (greater than twice the photocathode radius) of the photocathode can provide focal lengths commensurate with a corresponding flat photocathode with $\alpha = 25°$. This curvature naturally also experiences trade-off between photocathode field and focusing, but considering the proximity of the first anode, significant field enhancements at the cathode compared to the one-gap case may be achieved.

CONCLUSIONS

In this report, we have first demonstrated the insensitivity of the one-gap Pierce electrode geometry trade-off between focusing fields and fields at the photocathode to high degrees of geometry parameterization. Next, using a simplified model of the electrodes and a full beamline optimization, we determine the (emittance) optimal parameters to be $\alpha = 10°$, V=470kV, and d=55mm. Next generation additions to photogun designs, such as embedded solenoid focusing and the use of an intermediate anode are argued to be viable partial solutions to many one-gap trade-offs.

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