Shaping Electrostatic Conditions in the Stalk of the ERL -750 kV Electron Gun

David Stone
Department of Physics, Carnegie Mellon Univeristy, Pittsburgh, PA, 15289
(Dated: August 7, 2008)

High voltage (750 kV) is difficult to maintain in the DC electron gun for Cornell's ERL while simultaneously keeping ultra high vacuum conditions. To deter high voltage breakdown, electron emission, secondary electron emission, and associated negatives phenomena, new stalk/ceramic configurations are explored and compared on a set of objective values to determine optimal parameters. Field-curving stacked potential ring ceramic designs are found to best suit high voltage, ultra high vacuum constraints. Additionally, some ground work is laid for reducing surface area of high voltage cathodes to reduce field emission, as well as exploration into using magnetic fields to deflect electron emissions from the ceramic.

I. INTRODUCTION

The DC electron gun for Cornell's Energy Recovery Linac (ERL) Phase Ia injector is designed to sustain -750 kV for 2 picosecond laser pulses centered on a GaAs photocathode. A low emittance 100 mA CW electron beam is produced and sent to 100 MeV superconducting accelerator cavities [1].

Due to the high electrostatic fields and large surfaces areas associated with the electron gun structure, it is difficult to maintain a -750 kV potential difference between the cathode and anode structures without experiencing undesirable effects in the gun, such as ceramic surface charging, local field enhancements, and field emission currents [2]. These effects can cause high voltage flashover (breakdown) and break ultra high vacuum (UHV) by inducing electron emission from local geometry enhancements, triple junctions (where ceramic, vacuum, and conductor meet), or from residual desorbed gas in the vacuum [3, 4]. However, the ERL requires a high energy electron beam in UHV for the injector to work at optimal parameters; high voltage hold-off is therefore of crucial importance to the function of the ERL.

The problem of high voltage hold-off of insulators in vacuum has been deeply studied and usually is approached by reducing field emission and creating designs that minimize damage precipitated by emission (rather than attempting to eliminate emission altogether, which is nearly impossible). These approaches include ceramic shaping [3], stacking metal rings or shields on ceramic pieces to prevent electron impact on insulators [5–7], spraying various types of coatings on the ceramic [8], and various field shaping geometries [6, 8, 9].

This paper outlines the development of stalk-ceramic configurations for a new Cornell ERL gun that exhibits better high voltage hold-off. The above mentioned approaches are considered and tested in depth, focusing on field emission reduction and damage prevention for the maintenance of UHV within the electron gun. The configurations are created in the Opera-2d electrostatics modeling software package. They are tested through 4 considerations:

- The value of $|E_\perp|$ or $|E_r|$, the magnitude of the perpendicular electric field component at the surface of the stalk. A greater perpendicular field component reduces the work function of a metal and increases field emission.
- The value of ρ_e, the electric field energy density in the stalk-ceramic configuration. A constant or symmetric distribution of energy density throughout the area of concern is desirable to reduce field enhancements.
- The value of $|E_{max}|$, the magnitude of the maximum electric field strength at key locations in the configuration. High voltage breakdown, depending on the conditions, occurs around 20 MV/m in Cornell's gun case. It is attempted to keep maximum fields strengths below 12 MV/m in the models.
- The engineering and machining feasibility of the geometry of the configuration. Limitations such as brazing effectiveness and metal machinability will constrain the models.

II. CURRENT GUN SCHEMATIC

The layout of the full gun operating apparatus with equipotential lines is shown in figure 1, with a cross section of the actual electron gun shown in figure 2.

The full apparatus has the -750 kV power supply and the electron gun stored in a large 1.5 m tall metal tank, held at ground, which is filled with SF_6 ($\epsilon_r \approx 3$). The actual gun is essentially composed of a 3.75" diameter, 38" long stalk that transmits power to the cathode; a cathode with a position for the photocathode (GaAs) puck; the electrode chamber, which is held at ground and has the anode protrusion shaped into it; and the ceramic insulator that

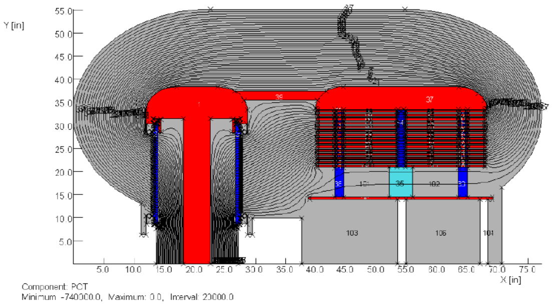

FIG. 1: Equipotentials in current entire gun apparatus

separates the top dome(-750 kV) from the electrode chamber (0 kV). The pulsed laser (not shown) is fired through the anode hole onto the photocathode, and the beam is directed between the anode protrusions out of the gun.

The area of concern is between the bottom of the dome and the top of the chamber. The initial stalk, shown in figure 2, was segmented into 3 parts. The joining of each segment provided electron emission sites that led to high voltage breakdown and secondary emission in the ceramic. This resulted in the loss of an entire ceramic as it cracked under the intense current induced in it via electron emission and allowed SF_6 to breach the ultra high vacuum inside [11]. The gun also exhibits asymmetric geometries on either side of the stalk due to the presence of the power supply, leading to an asymmetric equipotential distribution. Corona rings have been added (not shown) at the flanges where the ceramic is brazed with the -750 kV dome and ground chamber to protect the triple junction from strong fields. the strongest field strengths in the apparatus are sustained around 6 MV/m near the corona rings (at ground) with maximum values approaching 16 MV/m near the tips of these rings. The values of $|E_r|$, ρ_e, and $|E_{max}|$ for the current model are shown in comparison with other configurations further on.

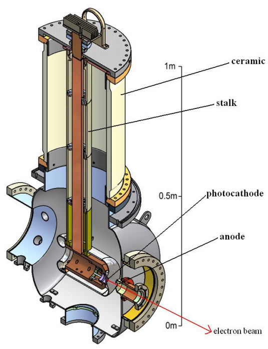

FIG. 2: Cut-away diagram of current gun schematic.

III. PRELIMINARY CERAMIC/CONDUCTOR DESIGNS

Several papers were reviewed for a new ceramic design. The stacked ceramic design with graded metal potential rings separated by resistors from each other has been around for decades, first used as ion accelerating tubes [5]. The National Electrostatics Corporation (NEC), which makes such accelerators, was contacted to discuss metal ring designs. More recently the stacked design has been suggested for very high voltage vacuum insulation [2] and investigated for pulsed power guns [6].

Preliminary designs were done in the design environment in the Opera software package, modeled after Leopold's work, but for DC power. Leopold's design can be seen in figure 3. The potential rings were evenly spaced and the potential steps between each were linear. The design of the ceramic (alumina, $\epsilon_r \approx 10$) between each ring was also considered in light of work done by Leopold and Miller [3, 6]. A ceramic that has a 45° angle from the horizontal, such as the ceramic pieces (blue) in figure 4 have, have significantly higher voltage hold-off capabilities than plainly rectangular pieces (Miller actually found that most complex ceramic designs have higher voltage hold-off than simple

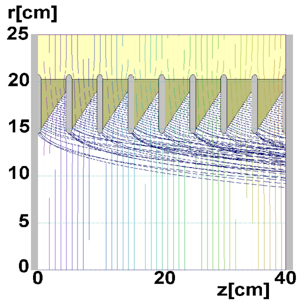

FIG. 3: Stacked ceramic design for pulsed power gun. Credit: Leopold, et al.

rectangular ones) [3]. While the fields between each conductor ring in the model shown in figure 4, and almost all models afterward, are far below critical field strengths (> 20 MV/m), the angled ceramic design is important to prevent currents induced from secondary emission from building up on the surface of the ceramic, as well as damping negative triple junction and 'crowded corner' effects [6]. The effects of various ceramic angles in the model were investigated; there was negligible field shaping and most problems associated with harmful electron trajectories into the ceramic were dealt with by the metal rings ending the electron paths (see diagram). Although not possible with Opera, secondary emission from the metal rings can be modeled as in Leopold's work (figure 3). It should be noted that although models further in the paper have rectangular ceramic sections, this is only done for design simplicity; when possible, the 45° angled ceramic should be used.

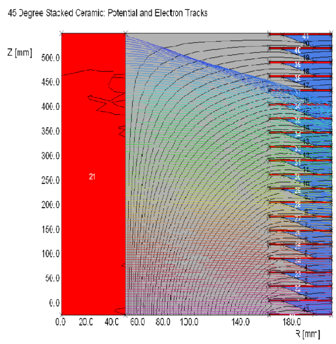

FIG. 4: Preliminary stacked ceramic design with equipotential lines in black and simulated electron trajectories in multicolor for the setup.

IV. MAGNETIC FIELD AND CATHODE SHAPING

Due to technical problems with the Opera software and a delay before a visit to MIT's Plasma Science and Fusion Center (PSFC), a small side project investigated deterring electron impact on the ceramic with magnetic fields. With a z-directed **B** field, easily created by a solenoid with wires wrapped around the outer ceramic, electrons are deflected into a quasi-spiraling trajectory. A simple calculation of the required **B** field strength to deflect electron with a minimum radius of curvature of the inner radius of the ceramic yields a 10 gauss field. Depending on the desired current, this translates to 4,000 to 50,000 wire turns around the ceramic. The calculation is identical for a circumferential, ϕ-directed field created by shaped permanent magnets or some other current configuration (none seemed feasible), which directs electrons toward the chamber flange held at ground.

Additionally, reduction of cathode surface area was investigated. Reduction in surface area decreases electron emission sites, but was also found to alter photoemitted beam. At the head of the cathode, a Pierce electrode design is used with the field shaping slopes at 15° from the vertical [10]. Surface area and curvature of the supporting metal segments around the Pierce electrode were also reduced, resulting in a noticeably more uniform, smaller beam emittance through the anode. Figure 5 shows these results. It should be noted, however, that the space charge package in the Opera software was not available, and this analysis is based on reiterated electron tracking, which may

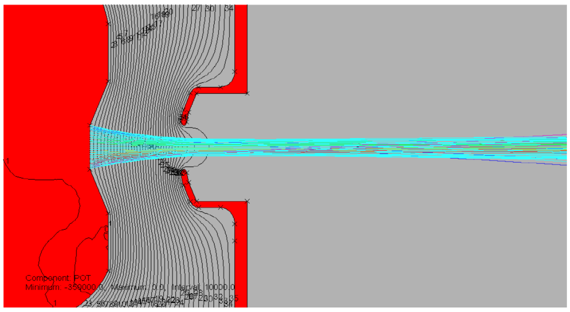

FIG. 5: Electron trajectories from the photocathode puck. Solid blue lines are trajectories from the reduced surface area cathode, while multicolor lines from the current cathode. The reduced surface area beam has less anomaly trajectories and a more uniform emittance.

not be entirely accurate. However, the electrons are already highly relativistic when accelerated through 750 kV past the anode, and thus space charge concerns are effectively canceled by relativistic magnetic field effects [12].

V. FINAL STACKED CERAMIC/CONDUCTOR DESIGNS

After a visit to MIT's Plasma Science and Fusion Center (PSFC) and discussions with Jacob Haimson of Haimson Research Corporation, it was decided that the stacked ceramic with graded potential rings design should be reassessed in more depth. Further research into these stacked designs involved uneven ring spacing and non-linear potential differences. Two new designs were approached in the design of the new stalk-ceramic configuration: a design with a

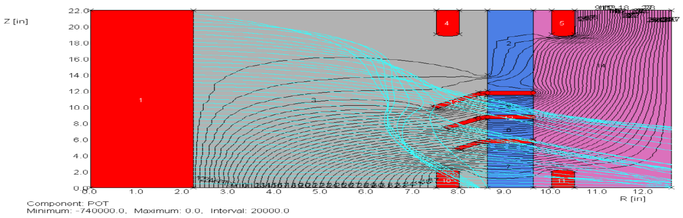

FIG. 6: 'Curved' stacked ceramic design with radically altered **E** field and electron trajectories.

significantly curved **E** field that would direct electrons directly toward the chamber flange at ground; and a design which attempted to present a uniform **E** field that would evenly distribute any electron emitted from the stalk. Figures 6 and 7 show equipotential lines and electron trajectories from various points along the stalk for a 'curved' design (fig. 6) and a 'uniform' design (fig. 7). Of the 'best' designs from each approach, each was compared with the current gun

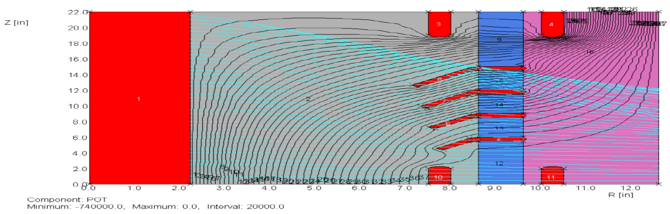

FIG. 7: 'Uniform' stacked ceramic design with approximately uniform **E** field and electron trajectories.

design in the categories mentioned in the introduction. A comparison of $|E_\perp|$ on the surface and just off the surface of the stalk for two curved designs, two uniform designs, and the original design is given in figure 8.

Figure 9 shows the energy density distribution ($\rho_e = \frac{1}{2}\epsilon_0 E^2$) for the same designs at sample heights of $z = 4$, 10, and 16 inches in the model. Finally, table 1 indicates the maximum magnitude of the electric fields at problematic locations (the corona rings) throughout each model (the number labels indicate models shown in previous figures).

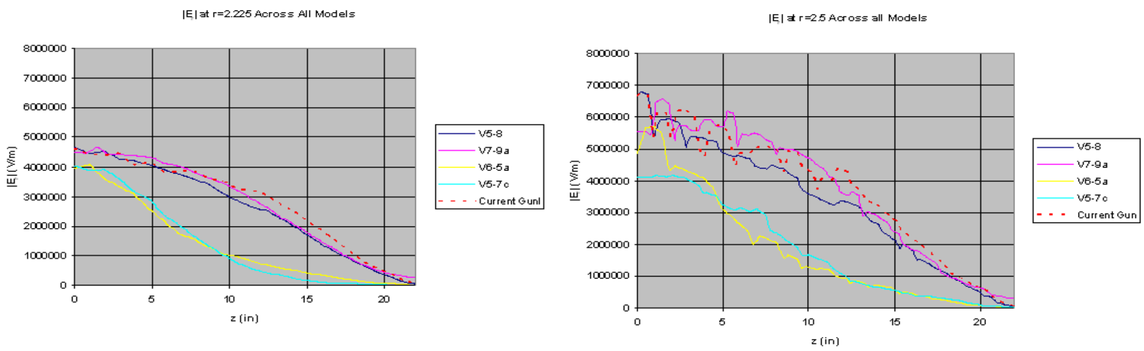

FIG. 8: $|E_{\perp}|$ on and a small distance away from the stalk across uniform and curved models.

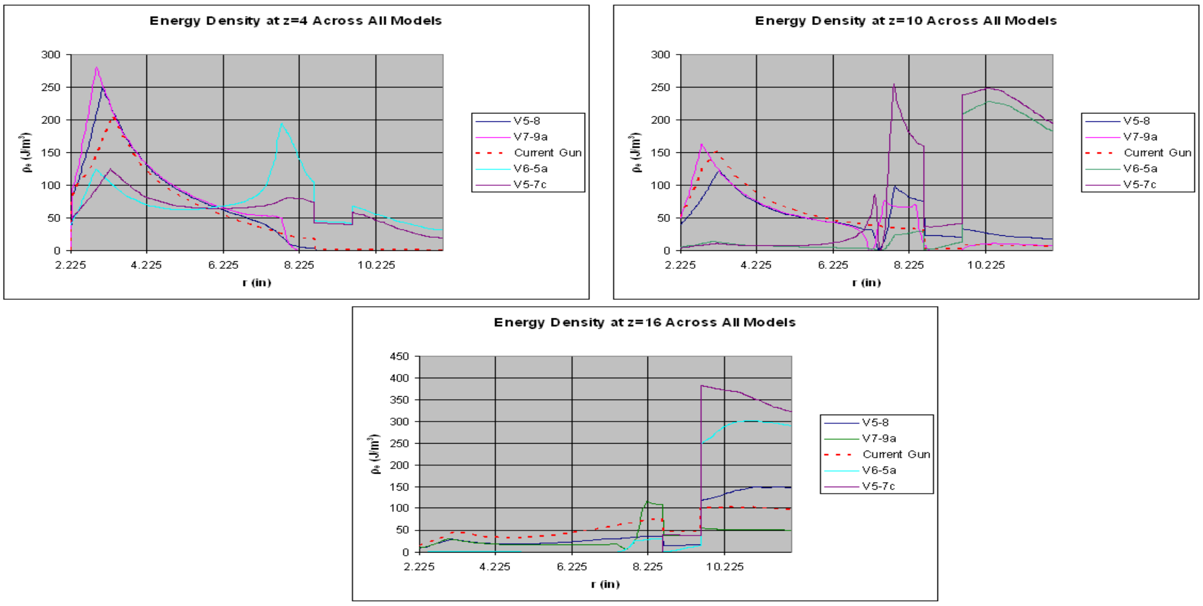

FIG. 9: Horizontal energy density distribution across all models at selected heights.

Location	**r (in)**	**z (in)**	**6-5a**	**5-7c**	**7-9a**	**5-8**	**Original**
Inner bottom ring	7.75	2.25	6.08	5.56	1.44	1.74	2.37
Outer top ring	10.25	18.75	11.6	10.8	21.3	17.0	17.3

TABLE I: $|E_{max}|$ (MV/m) at problematic corona rings

A bit of analysis and consideration will show that the uniform models proposed are not that attractive an option for the future ERL gun- it's only strength, a uniform **E** field and electric energy density distribution, do not help much in the case of electron emission, which is bound to happen during gun processing or injector operation. The field curving designs greatly reduce the perpendicular electric field component, $|E_{\perp}|$, on the stalk, and in the case of electron emission actively deflect electrons away from the ceramic.

In this case, both field curving configurations are sufficient for investigation for engineering design. The V5-7c model (fig. 6) provides a unique case that might also be studied because it assumes a type of metal coating or thin shield held at -750 kV to deflect electrons, which has certainly not been tried (though coatings have been tried with mostly failure). The V5-7c model is additionally advantageous for the lower amount of metal rings it uses, decreasing brazing vacuum troubles. It is important to note, however, that any potential metal rings brazed in the design must be shortened with decreasing distance to chamber flange at ground (as seen in fig. 6 and 7)- to prevent electron avalanche currents from forming [6].

It is also pertinent to mention that the entire current gun apparatus can be modified so that the gun and the power supply are compartmentalized into 2 separate metal cylinders (at ground) connected by a space for a new cable at -750 kV from the power supply to the gun (figure 10). The resulting field energy density distribution was perfectly symmetric for the electron gun about the stalk, erasing asymmetric distributions in the current gun design that gave a preferred electric field direction. It is expected that any new ERL gun will follow this design.

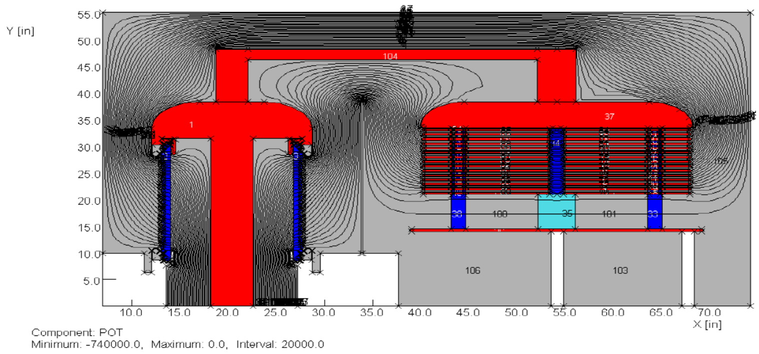

FIG. 10: New gun apparatus compartmentalized with metal cylinders as the tank gives symmetric energy density distribution.

VI. CONCLUSIONS

The ERL is just getting started with beamline tests being run in the phase Ia injector. Should the ERL recieve full funding, a new, more robust gun will undoubtedly need to be built. The work done in this REU project lays the foundations for engineeering considerations that *must* go into designing the stalk/ceramic area and cathode electrode area of the new gun. Manufacture of new reduced surface area cathodes and magnetic field aided ceramic protection is also left open to be explored by others at LEPP. Additionally, the research and modeling completed may be useful in redeveloping electron guns at other accelerator facilities such as SLAC and CEBAF, and hopefully, the International Linear Collider (ILC).

VII. ACKNOWLEDGMENTS

Work done on this project was not possible without the guidance and aid of Bruce Dunham and Karl Smolenski of Wilson Synchrotron Laboratory at Cornell University, both my advisers. They dictated the project and ideas that began my work and gave helpful input and suggestions as it developed.

This work was supported by the National Science Foundation REU grant PHY-0552386 (Cornell LEPP) and research co-operative agreement PHY-0202078.

---

[1] Hoffstaetter, G.H.; Barstow, B.; Bazarov, I.V.; Belomestnykh, S.; Bilderback, D.; Gruner, S.; Liepe, M.; Padamsee, H.; Sagan, D.; Shemelin, V.; Sinclair, C.; Talman, R.; Tigner, M.; Veshcherevich, V.; Krafft, G.A.; Merminga, L., "The Cornell ERL prototype project," Particle Accelerator Conference, 2003. PAC 2003. Proceedings of the , vol.1, no., pp. 192-194 Vol.1, 12-16 May 2003

[2] Sinclair, C.K., "Very high voltage photoemission electron guns,"Particle Accelerator Conference, 2003. PAC 2003. Proceedings of the , vol.1, no., pp.76-80 Vol.1, 12-16 May 2003

[3] Miller, H.C. "Surface flashover of insulators." Electrical Insulation, IEEE Transactions on. Volume 24, Issue 5, Oct 1989 Page(s):765 -786

[4] Latham, Rod. High Voltage Vacuum Insulation. Padstow, Cornwall: Academic P, 1995

[5] Haimson, J., "Recent Advances in High Voltage Electron Beam Injectors," Nuclear Science, IEEE Transactions on , vol.22, no.3, pp.1354-1357, June 1975

[6] Leopold, John G., ChaimLeibovitz, ItamarNavon, and Meir Markovits. "Different Approach to Pulsed High-Voltage Vacuum-Insulation Design." Phys. Rev. ST Accel. Beams 10. June 2007. 14pp

[7] Sinclair, C K. "A 500 KV Photoemission Electron Gun for the CEBAF FEL." Nuclear Instruments and Methods in Physics Research Section A 318 (1992): 410-414

[8] Haimson, J.; Mecklenburg, B.; Stowell, G.; Wright, E.L., "A fully demountable 550 kV electron gun for low emittance beam experiments with a 17 GHz linac," Particle Accelerator Conference, 1997. Proceedings of the 1997 , vol.3, no., pp.2808-2810 vol.3, 12-16 May 1997

[9] M. Breidenbach, M. Foss, J. Hodgson, A. Kulikov, A. Odian, G. Putallaz, H. Rogers, R. Schindler, K. Skarpaas, M. Zolotorev(SLAC). "An Inverted geometry, high voltage polarizedelectron gun with UHV load lock." SLAC-PUB-6501, May 1994. 27pp

[10] Pierce, J.R. "Rectilinear Electron Flow in Beams." J. Appl. Phys. 11, 548 (1940); DOI:10.1063/1.1712815

[11] Bazarov, Ivan. "April 10, 2006 Electron Gun Minutes." LEPP Wiki: ERL. 10 Apr. 2006. 5 Aug. 2008 ¡https://wiki.lepp.cornell.edu/lepp/bin/view/erl/private/minutesgun10apr2006¿

[12] Talman, Richard. "Novel Relativistic Effect Important in Accelerators." Phys. Rev. Lett. 56.14 (1986): 1429-432