Electrode Design Adjustments to a High Voltage Electron Gun

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Abstract

In order to emit and accelerate electron bunches for the new ERL demanding small longitudinal emittance, a very high voltage electron gun needs to be designed.[1] To these ends, several geometric parameters were analyzed computationally in order to isolate a feasible design. Attempting to provide a practical lifetime to the cathode with a quantum efficiency that is vulnerable to ion back-bombardment, several theoretical tests were performed on off-axis electron acceleration.

Introduction

The design of the electrode gun has to abide by many constraints, the most important of which are imposed by the extreme operating conditions of the electrode chamber. One of the main constraints is the prevalence of field emission by electrode surfaces. At significant electric fields, electrons in the metal may be easily removed and accelerated, colliding with potentially sensitive structures. Some of the undesirable effects of this phenomenon include localized melting, accumulation of charge in vital insulation components (as the colliding electrons nest themselves in the material without a way to be conducted away[2]) and vacuum degradation.[3] The intended electrode voltage will be from 500kV-750kV with distances possibly less than 5cm to the anode around the acceleration gap. This exposes the necessary convex areas of the electrode (described below) to fields on the order of 10MV/m. This is much in excess of the acceptable fields for most practical materials and nears the threshold for even advanced materials and coatings applied in such environments.[4] Thus the imposed limit on the electrode design was 15MV/m.

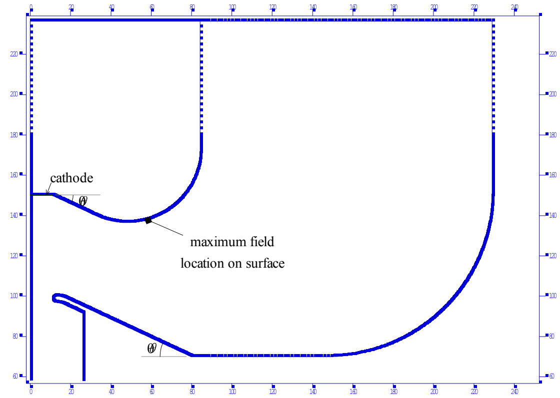


Figure 1: Basic electrode chamber geometry.

Another important operational constraint is the quality of the vacuum and the effect of back-bombardment of electron beam-ionized particles that remain in the chamber. At these voltages, the cathode quantum efficiency will degrade quickly as these back-bombarded deposits accumulate.[5] Since the damaged area of the cathode is confined to the projection of the electron bunch path onto the plane of the cathode, the cathode disk can be rotated to use fresh emission spots. However, using multiple emission spots over the course of the cathode's lifetime (without the translational freedom to change emission spots) requires emitting the electrons off axis. One of the main focuses of this project was to simulate the path of a charge through the effective fields and find a configuration that returns the charge to the beam axis within a reasonable distance from the emission site.

A major concern in the design of this electron gun is the field at the cathode. Space-charge calculations show that the field must be greater than 3MV/m on the cathode to compensate for the most extreme repulsive effects of the bunch (which is on the trailing electrons) and ideally 7-10MV/m, for the bunch to emerge the gap in the best shape. Another motivation for high fields in this gap is to get the electron bunch to relativistic velocities, where the repulsive effect becomes much less significant.[6]

For the purposes of this paper, it will suffice to provide the basic dependencies between different dimensions of this apparatus, without going into exact specifications. The source of the optically emitted electrons – the cathode, is centered on the beam axis with a fixed standard radius. The cone-like concave region around the cathode (the function of which is described below) has also been fixed with space-charge effects in mind.[7] The cathode size anode aperture is designed with walls that match the slope of the electrode concavity and then curve near the aperture edge to be parallel to the cathode. Since the electrode is cylindrical, a toroidal section is fitted between the concave region and the outside surface so as to minimize curvature (and consequently the resulting fields on the surface). The chamber's radius is adjusted proportionally to that of the electrode. All the other features outside the emission site including the overall electrode radius and its fitting toroidal radius are adjusted to ameliorate the discussed concerns and, where possible, minimize the overall surface area of the apparatus. This is motivated by the prevalence of gaseous emissions from metallic surfaces that spoil the vacuum (and increase the probability of back-bombardment). However, contracting the electron gun radially while keeping the axial structures fixed requires a smaller toroidal radius, increasing its curvature and the resulting field drastically. This is the most prohibitive effect in surface area minimization.

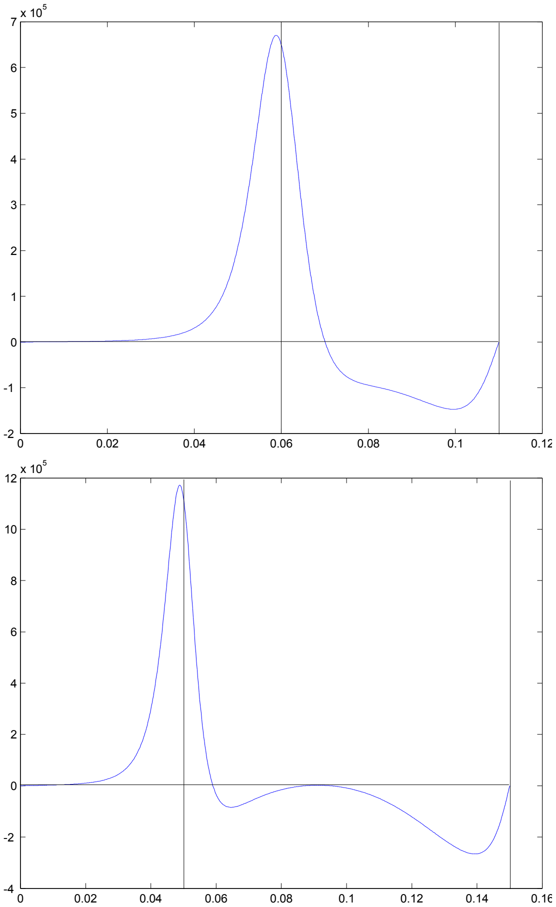


Figure 2: Radial components of electric field on axis vs z. (50mm and 100mm gaps respectively) The anode plane is shown with a dashed line, while the cathode is on the far right.

In order for the bunch to reach the beam axis at some point along the beam-pipe, it must receive enough of a contribution to momentum in the radial direction while in the gap between the cathode and the anode. This is accomplished by the focusing effect of the mentioned concave section of the electrode. This concave region is adjusted via the angle theta of the surrounding cone (see Figure 1). There are several restrictions on adjusting this parameter, however. Increasing this cone angle necessitates a smaller radius on the toroidal edge of the electrode (in order to conform to the fixed overall electrode radius), exposing this section to strong fields and approaching our threshold of 15MV/m. A very small cone angle may not give the bunch a sufficient radial momentum before entering the “convex lens field” of the anode: it may then be deflected away from beam axis or sent at too low an angle for the design of the injector (preferred angle being on the order of 10mrad). A very high theta or a large cathode-anode gap (that can allow the bunch to get too close to the axis) will cause the charges to pass through the center region of the anode-lens fields without any trajectory correction.

Methods and Results

First, the basic electrode chamber geometry was mapped and submitted to Poisson Superfish software for electrostatic field calculations. One of the difficulties with Poisson was the need for a level of precision around the beam axis that makes calculation times impractical (even unstable) when applied to the entire chamber. This was resolved by starting with a fine mesh for field calculations around the gap region and doubling the mesh cell size at subsequent steps away from the axis, avoiding abrupt resolution changes. Thus the uninteresting majority of the chamber space received little processing time. Also, (as shown in Figure 1) to expedite calculations, only the

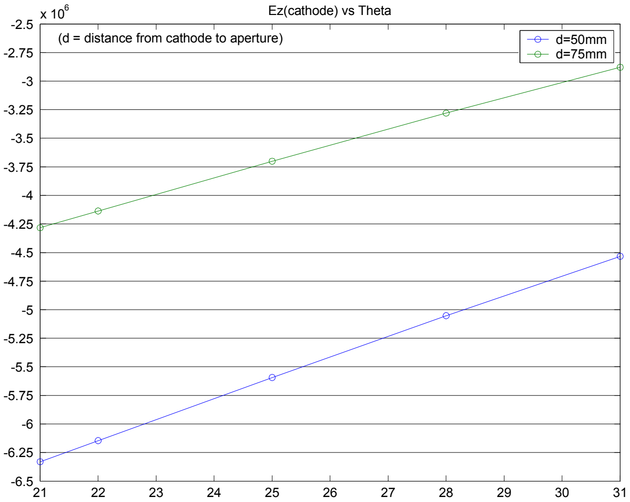
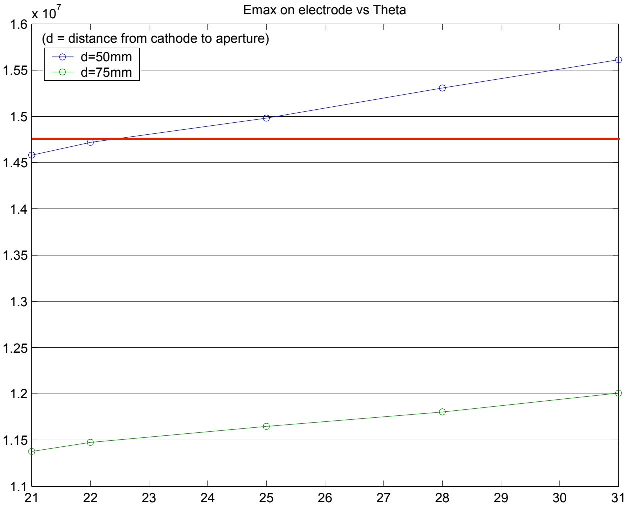


Figure 3: A linear dependence of the cathode field (measured at beam axis) on θ. Below: maximum electric fields on the electrode as a function of θ.



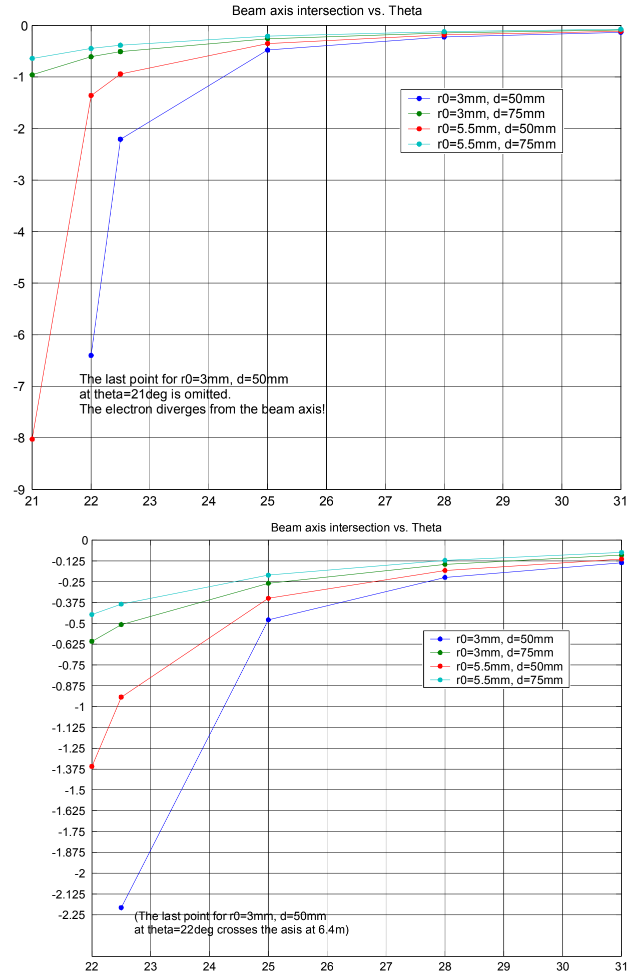
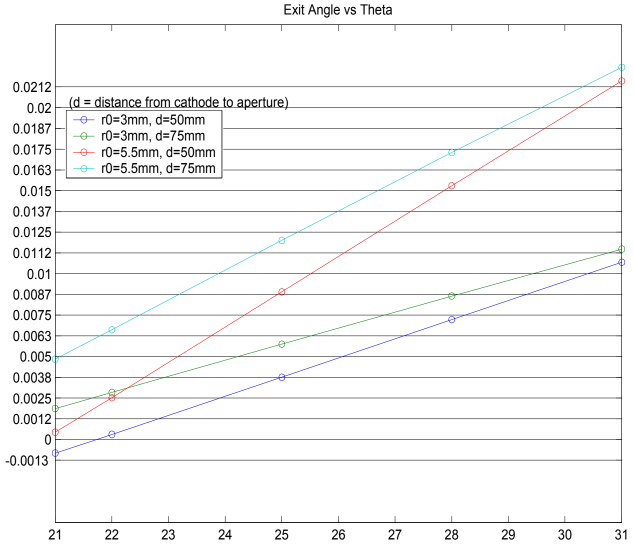


Figure 4: Beam axis intersection distance (from the anode plane). Top: overall distribution of results. Bottom: a detail of the (more feasible) range of [22°, 31°]. Below: angle of beam axis intersection as a function of θ



emission side of the electrode was used, imposing a Neumann boundary condition in the space between the electrode and ground. The rest of the chamber would have had a negligible effect on fields around the emission site.

The fields generated by Poisson within the radius of the cathode were exported to Matlab to calculate the expected path of a point charge. A Runga-Kutta stepping program was written to calculate relativistically the momentum, velocity, and position of the particle as a function of time. Based on the results of these tracks, two electrode design parameters were adjusted: distance from cathode-anode gap size and "theta" (see Figure 1).

Figure 2 shows two extremes of the range on the gap. Apparently, the radial field between these terminals drops significantly in large gaps. Also, the test charge showed a fairly linear path in this middle region. Its trajectory correction was then configured by selecting the location of the anode plane (i.e. adjusting how far off axis it enters the convex fields of the anode).

Figure 3 shows electric fields in trials with 50mm and 75mm gaps at various angles and two initial emission sites. When considering the cathode fields based on this data, it seems appropriate to use a small gap. Using a 50mm gap, however, restricts the choice of theta to the lower range (of tried angles) to remain below the field emission threshold. Additionally, the data on beam axis intersection distances and angles (Figure 4) mandates a mid-range choice of theta to bring the bunch to beam axis within a reasonable distance. Therefore, we chose a cone angle of 25°.

Finally, overall surface area was minimized by attempting to decrease the electrode radius (and the chamber radius proportionately) without jeopardizing the more important factors mentioned above. Minimization was done carefully so as to preserve the high field on the cathode and maintain the maximum fields at about 13.5MV/m. Because the highest fields on the electrode are localized just outside the concave region, simply extending the sloping walls around the aperture seemed impractical (Figure 1). Alternatively, bringing the downstream wall (around the aperture) back and recovering the triangular cross-sectional area that is just across from the vulnerable spot, as shown in Figure 5 showed significant decrease in the maximum electric field experienced on the electrode. Though this adjustment decreased the cathode field by more than 5%, minimizing the radius compensated (by decreasing the toroidal radius) and returned the cathode field to normal (less than 2% loss from the "unoptimized" design).

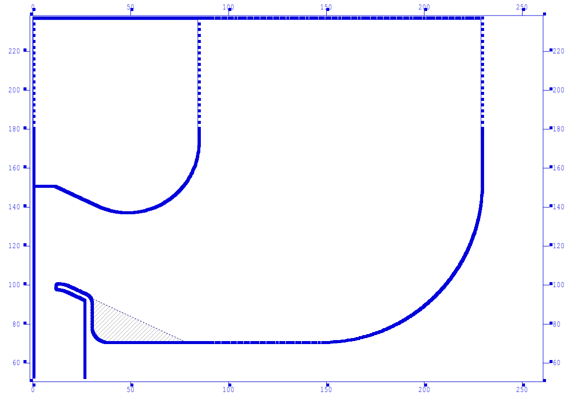


Figure 5: Optimized design to relieve high fields on the toroidal section.

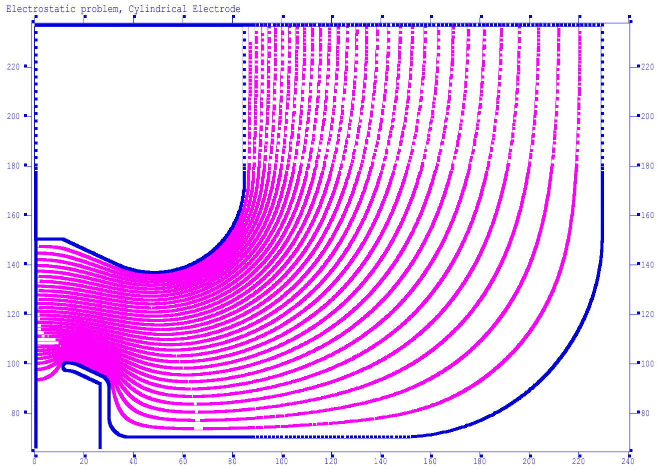


Figure 6: Final configuration with potential contours.

Conclusion

From this theoretical analysis of high voltage electrode chamber geometry and off-axis charge emission, a workable configuration was found. Though the cathode field is below the ideal range, it is more than sufficient for accelerating a bunch of relatively small longitudinal emittance and condensing its longitudinal profile in later optics of the injector. Further analysis will be done on full electron bunch acceleration via ASTRA software to determine the ideal shape and electron density distribution upon emission.

Acknowledgment

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References

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