Designing and Modeling a 750KV Electron Gun for an Energy Recovery Linac

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Abstract

The Energy Recovery Linac proposed by Cornell University requires an electron source of high energy and low emittance. We hope to use a high energy (750 KV), DC photoemission gun for this purpose. Basing our gun design on an earlier, lower-energy design explored by Engwall [2], we use numerical simulation with the electrostatics modeler *Poisson* to determine the modifications necessary to operate this style of gun at 750 KV. We also demonstrate in simulation that by electrode shaping the gun emittance may be significantly improved.

Introduction

The Energy Recovery Linac (ERL) is a high-energy x-ray source proposed by Cornell University [1]. This source will be used for studies in biology and crystallography, as the CHESS facility (which harnesses the synchrotron radiation from Cornell's accelerator) is used today. To improve the eventual quality of the x-ray beam, we desire the electron source for the linac to supply a beam of the highest energy and the lowest emittance feasible. Emittance, in an approximate sense, is proportional to the product of the size of the beam and its divergence. More precisely, emittance is $1/\pi$ the area occupied by the particle distribution in phase space. Phase space traditionally includes position coordinates and momenta; in this application, we use the derivatives of the transverse coordinates with respect to z (the beam direction), which are proportional to the momenta. For example, the x-emittance, describing the distribution in x–x' space, would be:

$$\epsilon\pi = \iint_{area} \mathrm{d}x\mathrm{d}x' \tag{1}$$

Provided the beam is acted on only by conservative forces, this area, the emittance, is conserved—thus one can use the quantity to model the beam size and shape at arbitrary locations downstream. A small emittance, qualitatively, means a narrow and minimally diverging beam. We decided that a photoemission DC electron gun was most appropriate for our purposes.

As a starting point for our design we considered the DC photoemission gun designed by David Engwall and discussed in his doctoral thesis [2]. In this paper we discuss how one must modify this gun geometry to operate it at voltages exceeding its design limit of 500 KV. We also demonstrate our progress in improving emittance by implementing focusing, accomplished by shaping the DC gun electrodes. Each of these issues will be considered in turn.

Triple-point shielding and basic gun geometry

To model different DC gun designs we used an electrostatics modeling program called

Poisson [3]. The Poisson program, developed by the Los Alamos Code group, solves the Laplace equation at intervals (in a mesh) throughout the modeled volume. Poisson depends on symmetry to model 3-D volumes, and for electrostatics calculations, is limited to cylindrically symmetric geometries. As the gun designed by Engwall is radially symmetric, this was not a serious limitation, although this flaw may force us to pursue other modeling programs if we consider alternate, non-symmetric gun geometries.

Prior to producing revisions of Engwall's design we familiarized ourselves with the simulation and double-checked its results by comparing our simulation of Engwall's unmodified design with the contents of his thesis [2].

Engwall's gun was designed to operate with 500 KV of accelerating voltage [2]. We desired a significantly higher-voltage gun, with 750 KV as our preliminary goal. The increased field intensities that result from such a change would potentially lead to problems with excessive field-emission from the cathode support structure and with insulator flashover originating in the triple-point regions.

The latter phenomenon, which is described in more detail in Ref. [4], is the result of field-emitted electrons originating near the "triple-point" regions of the gun. The *triple-points* are the unions between metal, ceramic, and vacuum that reside around the flanges attatched to the ceramic shell of the gun. An electron that is field emitted by the metallic electrode in this region may strike the ceramic wall, where due to the material properties of the insulator, it has a high probability of generating secondary emissions of multiple electrons which can cause a chain reaction "cascade" down the length of the ceramic. To prevent the cascade, one needs to prevent field emission in the vicinity of the triple points; to do that, one must keep the field intensities as low as possible in those regions. Engwall accomplished this with metallic shielding rings—pairs of concentric rings, one inside the gun and one outside—which by being held at the same potential significantly lower the field intensity between their radii. Figure 1 shows a "zoomed-in" view of a shield ring pair. The equipotential lines shown were calculated and plotted by the Poisson simulation program mentioned at the beginning of this section.

As suggested earlier, moving the design requirements from 500 KV to 750 KV required that we reconsider the gun geometry, particularly in the region of the triple points, because what was adequate shielding for the lower potential was not so for the higher.

a	ceramic insulators
b	shield rings
c	vacuum inside gun
d	atmosphere external to gun

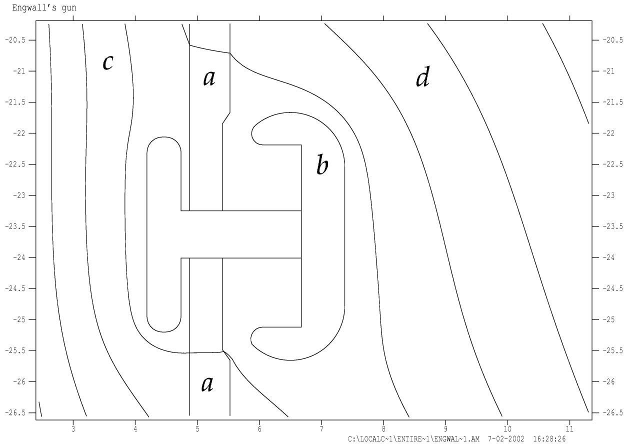

FIGURE 1. Shield ring pair. Left side is interior of gun. The vertical shapes running to the edge of the frame are pieces of the ceramic wall. The lines are equipotentials.

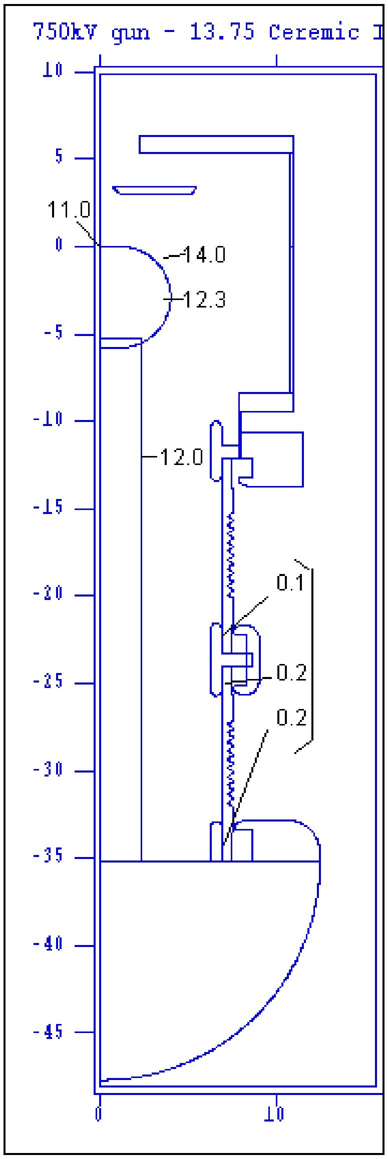

FIGURE 2. 750 KV Electron Gun. Field densities in MV/m.

The reader may wish to refer to figure 2, which represents our modified design, throughout the following discussion. We set as our preliminary requirements the following:

- Field density at photoemitting cathode should be 10–11 MV/m
- Field densities elsewhere should not exceed 14 MV/m (to prevent excessive field emission)
- Field densities at triple points should not exceed 1 MV/m, and be below $\frac{1}{4}$ MV/m if possible (to prevent insulator flashover)

First we increased the distance between the cathode and the anode to 7.5 cm (from 5.0 cm), moving the field at the cathode to 11 MV/m. The inside diameter of the gun (by

Dimension	Change	End value
Cathode-anode gap	+2.5 cm	7.5 cm
Gun I.D. (Ceramic I.D.)	+4.0 in.	13.75 in.
Cathode ball radius	+0.225 in.	2.9 in.
Cathode stalk O.D.		$1/e \times$ Shield ring I.D.
Cathode internal ring length	+0.725 in.	
Internal mid ring length	+0.37 in. each dir.	
Ring-to-ceramic gap (all rings)	−0.08 in.	0.02 in.

TABLE 1. Summary of changes to Engwall's design to enable 750 KV operation

which I mean the I.D. of the ceramic structure) we increased by a full 4 in., to 13.75 in. total inside diameter. The radius of the cathode ball and cathode stalk were also increased, to prevent excessive field emission by keeping the field intensities in these regions below 14 MV/m (see table 1 and figure 2). This additionally made shielding the triple points more achievable.

To shield the triple points we both lengthened the shielding rings and moved them closer to the ceramic (table 1). Particularly the latter change, the reduction of the clearance between the rings and ceramic to 2/100 in., dramatically improved the fields in the cathode and middle triple point areas (bracketed series of lines on fig. 2). The final triple point at the anode was grounded and therefore cannot emit field.

The results of the simulation (a simplified view of which are shown in figure 2) demonstrate that a DC gun of Engwall's design *can* be modified to solve the shielding and emissions issues associated with a 750 KV potential.

Focusing by electrode shaping

To produce a narrow x-radiation beam, the beam traveling through the linac must have the best (lowest) emittance than can be achieved[1]. As the quality downstream can be much influenced by the emittance at the source, improving the emittance performance of the DC gun would provide substantial benefit.

Focusing could also increase the time between required servicing of the photocathode. During gun operation, accelerating electrons strike stray gas molecules or atoms remaining in the vacuum. Positive ions formed as a result of the collisions are accelerated back toward the cathode, where they embed in the surface. The process, over a period of time, renders the impacted region of the cathode unable to photo-emit. These ions tend to track toward the center of the cathode, even when the point of laser illumination is off axis (being much heavier than the electrons, the gas ions do not respond as strongly to the weaker transverse component of the field). This allows one to move the illumination point around the cathode, from the inside spiraling outward. The gas ions only impact spots near the center which have already been degraded in earlier runs, and the "good," larger radius, portion of the cathode remains undamaged for later use. However, illuminating these off-axis portions of the cathode is only feasible if the focusing of the gun is adequate to direct the electrons so

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[1] For a brief explanation of emittance, see the discussion around equation 1 on page 1. Emittance is approximately proportional to the product of spot size and divergence.

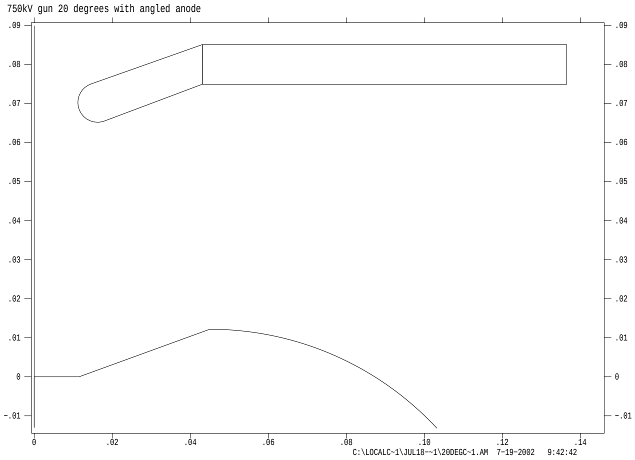

FIGURE 3. Angled cathode and anode. Volume described by rotating on y-axis.

Dimension	**Measurement**
Flat region radius	1.15 cm
Angle	20°
Slope “hypotenuse”	3.57 cm
Anode aperture	2.30 cm

TABLE 2. Relevant dimensions of electrodes depicted in fig 3 and described in this paper

emitted back onto the gun axis.

We pursued the focusing by shaping the electrodes around the actual photoemitting element, the wafer of GaAs. Figure 3 demonstrates the nature of the shaping we explored: beyond the radius of the GaAs wafer, we created a truncated cone, and duplicated the pattern in the anode. Consult table 2 for a more detailed explanation of the dimensions. The intent was that these modifications would introduce enough transverse component to the accelerating field that the desired focusing would occur.

To model different electrode configurations, we used a computer code called ASTRA[2] [5]. ASTRA applies the solved E-field maps from Poisson and space charge calculations to model the path taken by a specified input distribution of particles. For our input distribution we specified quantities anticipated for the actual ERL: A radially uniform distribution 1.5 mm in diameter and gaussian in time ($\sigma = 20$ ps).

We have not yet found what we can confidently claim is the optimum configuration of electrodes, but we can demonstrate that applying this sort of focusing (*via* the electrode shaping shown in fig. 3) provides improvement over the unfocused, flat-electrode case. The following plots model the gun together with a solenoid immediately downstream.

Figure 4 is a plot of the transverse emittance for the flat-cathode, unmodified design. The cathode is at $z = 0$, and the solenoid is at $z = 16$ cm. Note that the emittance does not achieve a minimum within this range, which is in fact somewhat overextended—the next beam element downstream will not even start as far downstream as $z = 1$ m. In this range,

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[2] A Space Charge Tracking Algorithm

the emittance never drops below 1, and in most positions the emittance at the start of the next beam element would be greater.

In contrast, consider figure 5. This plot shows the simulation results for the electrode set shown in figure 3 and described in table 1. Not only is there a clear minimum in the vicinity of $x = 80$ cm, but that minimum is 0.5 mmrad mm, at *least* a 50% improvement. In both cases the solenoid was optimized for position and strength to achieve the lowest possible emittance, so the plots displayed here demonstrate a comparison between the best behavior achieved with each of the electrode configurations.

It is clear from these simulations that for the reason of improving emittance alone it is worth including some manner of focussing in the final gun designs for the ERL. The 50% simulated improvement is quite dramatic, and even if that number cannot be matched in a physical gun, substantial benefit would still be expected. Concerning off-axis illumination of the cathode, and the ability of the focussing to bring such beams on-axis, we are unable to comment, due to a limitation in our simulation code which prevents us from testing this behavior.

Acknowledgments

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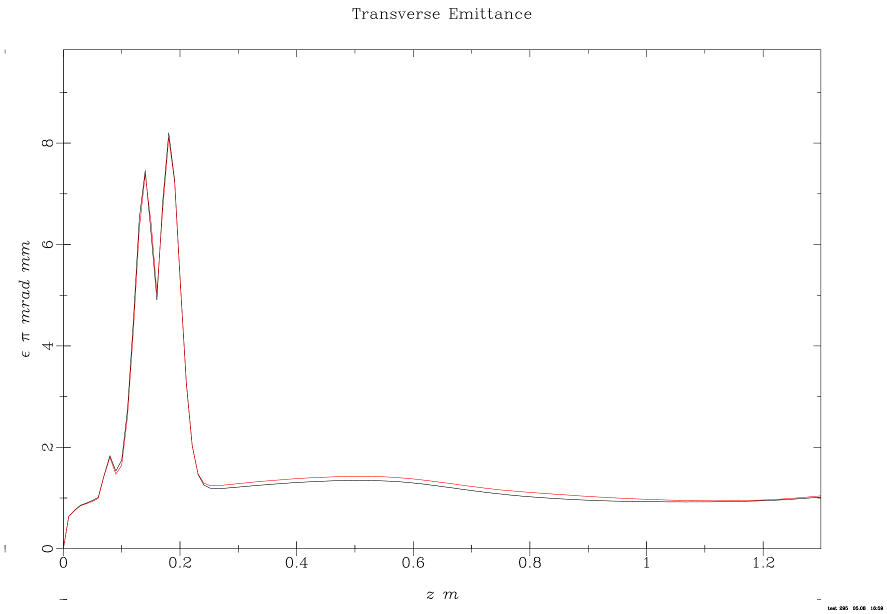

FIGURE 4. Transverse emittance, unshaped electrodes. Solenoid at 16 cm and .095 Tesla.

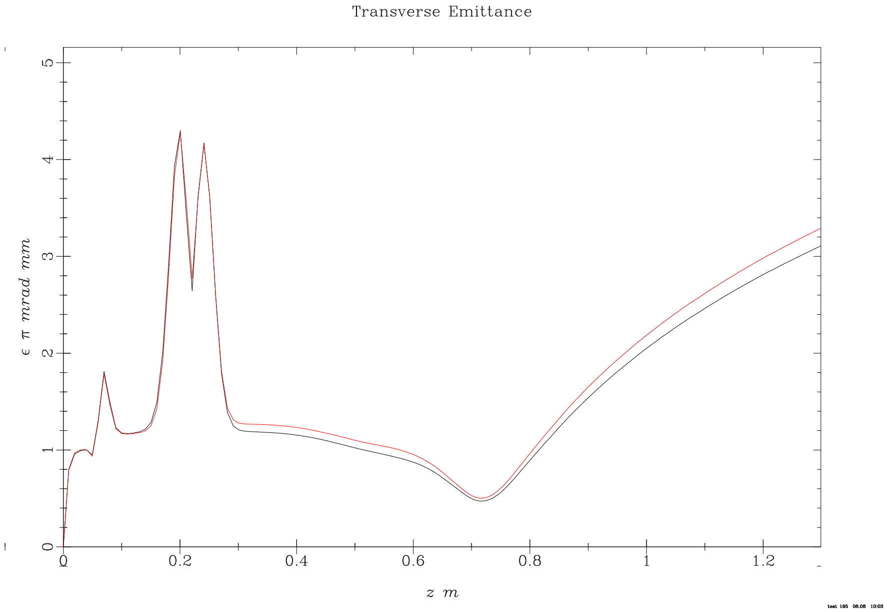

FIGURE 5. Transverse emittance, cathode & anode angled at 20° (see table 2). Solenoid at 22 cm and .095 Tesla.