NUMERICAL MODELLING OF THE CEBAF ELECTRON GUN WITH EGUN*

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Abstract

The electron source used in the injector for the CEBAF accelerator is a Hermosa electron gun with a 2 mm diameter cathode and a control electrode. It produces a 100 keV electron beam to be focussed on the first of two apertures which comprise an emittance filter. A normalized emittance of less than 1π mm mrad at 1.2 mA is set by the requirements of the final beam from the CEBAF linac, since downstream of the filter, a system of two choppers and a third aperture removes 5/6 of the current. In addition, for RF test purposes a higher current of about 5 mA is needed, possibly at higher emittance.

This paper presents a way of calculating the characteristics of the CEBAF electron gun with the gun design code EGUN, and the accuracy of the results is discussed. The transverse shape of the beam delivered by the gun has been observed, and its current measured. A halo around the beam has been seen, and our calculations can reproduce this effect.

Introduction

The nominal voltage of the gun is −100 kV. The electrons are emitted by a 2 mm diameter dispenser cathode; the gun current depends on the voltage of the control electrode, which has a 2 mm aperture. The control voltage (V_{ce}) is set between −70 and +400 V with respect to the cathode. The distances are 1.75 mm between the cathode and the control electrode, and 159 mm between the cathode and the exit through the anode hole.

Because the length of the gun is large compared with the size of the cathode, it is impossible to compute the gun properties in a single EGUN run. A complete calculation involves five EGUN runs; only the final three runs include beam space charge. The calculation procedure is outlined in the first part of this paper. Next, sensitivity of the results to changes in EGUN parameters is discussed. Finally, the calculated results, the beam profile and the delivered current versus V_{ce}, will be compared with measurements.

EGUN Calculation

The program is operated using cylindrical coordinates, the axis being through the centers of the cathode, the control electrode aperture, and the anode aperture. Since the cathode is so small relative to its distance from the anode and since the number of mesh points in the code is limited, a grid fine enough to resolve the cathode cannot be generated in a single EGUN run. EGUN allows one to define several regions of different mesh size and provides a way to connect results between adjacent regions. One can focus on cathode details in one set of runs, the region between the control electrode and a point 8 mm downstream in a second set of runs, and from there to the anode in a third set of runs. For our problem, we found that at least three regions were needed to eliminate unacceptable dependence of the results on the input parameters of the run.

Region 1 runs use 7,238 mesh points to model the region between the cathode and the control electrode. The left-hand boundary represents the cathode, where emission occurs along 32 mesh units of 0.03125 mm size. The control electrode occupies most of the right-hand boundary. A Neumann boundary condition is placed on the large radius open boundary, and a Dirichlet boundary condition is placed on the control electrode aperture. The boundary values are chosen as discussed below. Region 2 runs use 10,879 mesh points of 0.2 mm size to describe the cathode and the control electrode to the left, to 8 mm downstream from the control electrode on the right, and to the radius of a focussing electrode at large radius. The upper and right-hand limits are both Dirichlet boundaries; the potential along the upper boundary is set point by point, and the downstream boundary is an equipotential surface drawn nearly point by point as discussed below. Region 3 runs use 3853 mesh points of 2.0 mm size to describe the main body of the gun. The field is dominated by that given by the 100 kV.

Figure 1 shows EGUN generated boundary plot for Region 3. The figure also shows the equipotential surfaces when there is no beam.

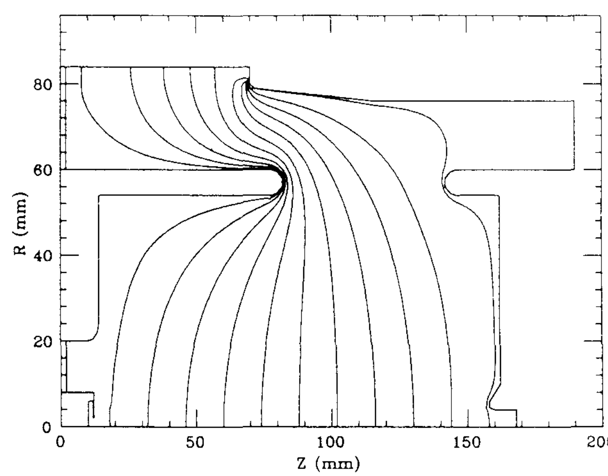

Figure 1. EGUN plotted calculation of Region 3 boundaries and equipotential lines.

As an example consider using EGUN with the following voltages: 0.0 V at the cathode, 322.0 V at the control electrode, and 100 kV at the anode. The Region 2 downstream equipotential values are found by solving the Laplace equation in Region 3, and by interpolating the coordinates of the solution's 1650.0 V points to fit the contracted coordinate scale of Region 2. This 1650.0 V equipotential surface is far enough from the control electrode to prevent the ray dynamics nearby the control electrode from any serious error due

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to the interpolation. It is close enough to the control electrode, however, to let Region 2 hold less than 11,000 mesh points, the maximum in our version of EGUN. The Region 2 upper boundary values are fixed to the potential computed from the Region 3 calculation. Once the Region 2 boundaries are specified, the Laplace equation is solved to find the potential on the Region 1 boundary. Now a Region 1 calculation is done with beam. The rays are stopped upstream of the boundary of Region 1 to avoid error introduced by the Dirichlet boundary condition imposed in the space charge calculation. These rays provide initial conditions for a Region 2 calculation with space charge. The cycle is repeated to go from Region 2 to Region 3, where the beam dynamics are again computed with space charge.

Thermal Effects

To model thermal effects at emission, EGUN splits each generated ray into 3 or 5 subrays which are given different perpendicular velocities. The initial radial velocities are

$$v_{\perp_1} = 0, \qquad v_{\perp_2} = \sqrt{\frac{2kT_c}{m}}, \qquad v_{\perp_3} = -\sqrt{\frac{2kT_c}{m}},$$

in case of 3 subrays, and in addition

$$v_{\perp_4} = 2\sqrt{\frac{2kT_c}{m}}, \qquad v_{\perp_5} = -2\sqrt{\frac{2kT_c}{m}},$$

in the case of 5 subrays, where T_c is the cathode temperature. The splitting process conserves the current of each original ray. In the case of the 3 subray split, the non-deflected ray transports half of the current, and each deflected ray transports a quarter of the current (1-2-1 ratio). In the case of the 5 subray split, the non-deflected ray transports no current, the two less deflected rays transport 9/20 of the current, and the two more deflected rays transport 1/20 of the current (1-9-0-9-1 ratio).

Splitting the current in other distributions has given similar results except when the subrays which are not deflected (0 transverse velocity) carry more than 10% of the total current. Results of using different current distributions are presented in Table 1. The emittance figures include only the beam core, not the secondary halo discussed below. For 5 subray calculations, one observes that the emittance varies by a factor 2 depending on the model of current distribution used, but the total current delivered by the gun stays constant. The difference between 1, 3, and 5 subray calculations seems to provide the largest EGUN parametric dependence we observe in our problem, and the 5 subray calculations are probably most accurate. The 5 subray calculation of the gun current agrees with the measurement.

Beam Profile

The beam has been observed 63 cm downstream of the anode on a fluorescent viewscreen. Figure 2 is a picture of the beam produced by the gun with 125 V control voltage. One clearly distinguishes a halo of electrons surrounding the central beam.

One way to produce the beam halo is to assume that the control electrode emits secondaries on the edge parallel to the beam current, since at 120 V, secondary emission is the most probable result of electron bombardment of the surface[3]. An example of the EGUN rays calculated in Region 1 appears in Fig. 3. It was assumed that the secondaries are emitted with energies up to 15 eV and angles from normal to the surface to within 1° of the surface[4]. Figure 4 shows the rays when they are near the viewscreen. The halo rays occupy radii at about 6.6 mm, very close to that measured, and the beam core has a radius of 3.5 mm, again precisely as measured. The only conditions that we have found when the secondaries would actually stay in the core is if the secondaries are emitted along the emitting surface at angles less than 0.5°, a highly unlikely event.

TABLE 1
EGUN results for various emission models

Number of Subrays	Current Ratio	Current (mA)	Normalized Emittance (π mm mrad)
1	1	3.366	0.19
3	1-2-1	3.224	0.51
3	2-1-2	3.231	0.63
5	1-1-1-1-1	3.104	0.93
5	5-5-0-5-5	3.107	1.04
5	4-6-0-6-4	3.108	0.98
5	3-7-0-7-3	3.108	0.91
5	2-8-0-8-2	3.109	0.84
5	1-9-0-9-1	3.110	0.77
5	1-9-1-9-1	3.109	0.75
5	1-9-2-9-1	3.108	0.73
5	1-9-3-9-1	3.107	0.72
5	1-9-6-9-1	3.106	0.68
5	1-9-9-9-1	3.104	0.65

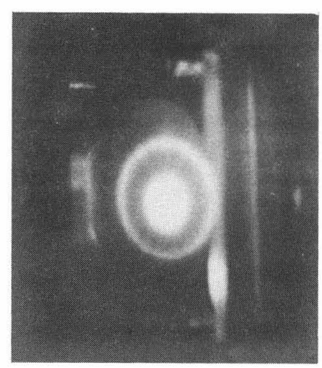

Figure 2. View of the beam delivered by the gun. The halo is 13 mm in diameter.

Current Versus Control Voltage

The control electrode intercepts a significant fraction of the current emitted by the cathode. There is complete transmission through the anode, even in the extreme case of 322 V on the control electrode, where the transmitted current and the beam dimensions are maximum. For 26 values of V_{ce}, between 70 V and 322 V, the procedure to calculate potentials on the downstream limit of Region 2 was repeated, by solving the Laplace equation in Region 3.

Next, two sets of calculations were done. Firstly, an EGUN run with Region 2 was used to compute the current emitted by the cathode. Secondly, EGUN was used to solve the Laplace equation in Region 2 to obtain boundary values for a Region 1 calculation. The code was then used to compute the current emitted by the cathode and the current transmitted through the control electrode. Figure 5 shows the results of these calculations of current versus the voltage of the control electrode, along with the measurements of the current from the CEBAF gun. In descending order, the curves are the current emitted by the cathode according to the Region 1 calculations, the current emitted by the cathode according to the Region 2 calculations, the current passing the control electrode from the Region 1 calculations, and the measurement. The current emitted by the cathode is about the same in the two calculations, giving an indication of the error expected from our procedure. Due to the agreement with the measurements, it is concluded that by subtracting the current carried by rays which are stopped at the control electrode from the total emitted current, one obtains the delivered current.

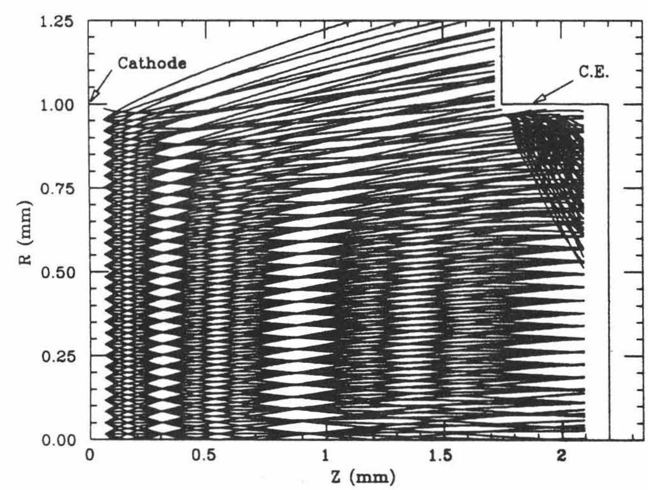

Figure 3. EGUN rays in Region 1, $V_{ce} = 120$ V.

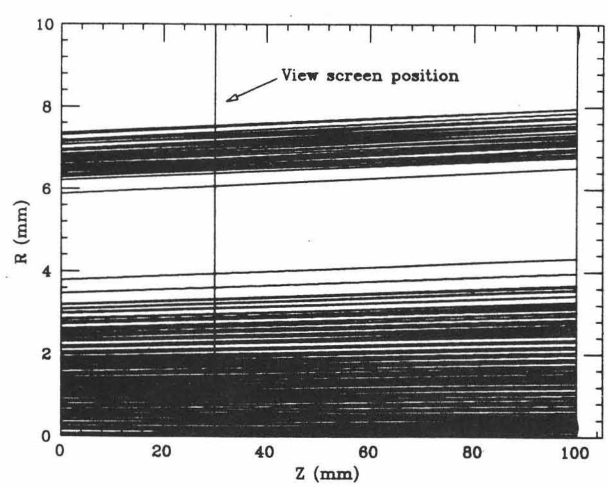

Figure 4. EGUN rays near viewer, $V_{ce} = 120$ V.

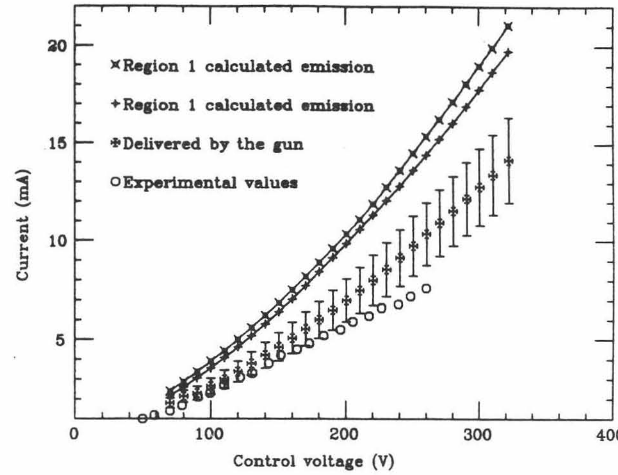

Figure 5. Current versus control voltage.

As expected, the emitted current varies as the 3/2 power of the control voltage. The control electrode stops 32% of the emitted current for V_{ce} from 90 to 320 V. The uncertainty of 10% indicated in Fig. 5 corresponds to the current carried by the outer ray passing through the control electrode. The calculations agree with measurements in the range of V_{ce} from 90 to 170 V. The difference at higher voltages arises from the neglect of thermal effects in the calculations. For example, when V_{ce} is 120 V the current transmitted through the control electrode decreases from 3.4 mA to 3.2 mA using 3 subrays with $T_c = 1250$ K, and to 3.1 mA using 5 subrays with $T_c = 1250$ K, while measurements give 3.1 mA when V_{ce} is 121.7 V.

Summary

Some properties of the CEBAF gun have been computed, despite a design which makes an EGUN calculation difficult. The results are consistent with measured beam properties. A beam halo is formed from secondary electrons emitted from the control electrode. Since the computed value of the normalized emittance of the core depends sensitively on the run parameters, we can only estimate its value to within a factor of two, 0.75 π mm mrad at the anode.

Acknowledgements

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