

# Optimization of a triode-type cusp electron gun for a W-band gyro-TWA

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A triode-type cusp electron gun was optimized through numerical simulations for a W-band gyrotron traveling wave amplifier. An additional electrode in front of the cathode could switch the electron beam on and off instantly when its electric potential is properly biased. An optimal electron beam of current 1.7 A and velocity ratio ( $\alpha$ ) of 1.12 with an  $\alpha$  spread of  $\sim 10.7\%$  was achieved when the triode gun was operated at 40 kV.

Keywords: gyrotron traveling wave amplifier, triode-type gun, cusp electron gun, large orbit electron beam, cusp magnetic field

## I. INTRODUCTION

Usually the electron beam of the microwave vacuum electronic devices (MVEDs) is required to be turned on and off when it is in operation, especially for those applications that require high repetition rate operation. Various ways to switch on and off the beam have been developed for the MVEDs<sup>1</sup>. The simplest method is through applying a pulsed voltage between cathode and anode. However, such a way normally requires a complicated and expensive high power pulsed modulation circuit, which is difficult to achieve a short rise-time for the high voltage pulse. Meanwhile, the noise generated from the fast switching of the high voltage, which is proportional to  $dV/dt$ , could affect the proper operation of not only the MVED itself but also those electronic devices nearby. For the operation of high power microwave amplifiers, one might control their output by switching the input seed signal on and off whilst the electron beam is continuously on. However, the electronic efficiency of the microwave amplifier would be zero when the seed signal is in the 'off' state, which is not desirable as this may overload the cooling system and even damage the high-power microwave amplifier.

Another method to control the output state of the electron beam is to introduce an additional voltage-biased electrode, to form a triode gun. The electrode could be in the form of a grid, a modulation anode or a focusing electrode. The gridded electron gun has been used in MVEDs such as travelling wave tubes and klystrons<sup>2-4</sup>, where a thin gridded electrode made from molybdenum or graphite is placed immediately in front of the emitter to switch on and off or modulate the velocity of electron beam whilst allowing the beam to pass. When it is charged at a small negative voltage (usually around 50-500 V) with respect to the cathode, the electron current emitted from the cathode would be switched off if the overall electric field at the emitter is negative (the direction of the field is into the cathode).

The gridded electron guns are mostly Pierce type which generate a solid cylindrical beam. In the cusp electron gun, an annular beam is generated. In order to reduce the electron beam velocity spread, the value of  $\Delta R/R_c$  is set to be small, where  $\Delta R$  and  $R_c$  are the thickness and the mean radius of the emitter, respectively. For a mm-wave cusp gun, the emitter thickness was  $\sim 0.5$  mm, which was chosen to be small to achieve good quality electron beam. A simple structure of modulation electrodes can therefore be used in this case. Such a modulation electrode has been used in the gyro-devices, both in the Pierce gun and the magnetic injection gun (MIG), as an extra way to improve the quality of the electron beam<sup>5-8</sup>. To turn on and off the electron beam more effectively, the modulation electrodes are preferably placed close to the emitter so that a low biasing potential can be used.

In this paper a structure of two co-centric electrodes is proposed to control an annular, large-orbit electron beam. More specifically, a triode configuration was applied to a cusp electron gun for a W-band gyrotron traveling wave amplifier (gyro-TWA). The optimization of the electron gun geometry and the simulation results are presented.

## II. DESIGN OF THE TRIODE-TYPE CUSP ELECTRON GUN

The triode-type cusp electron gun was based on a previously developed cusp electron gun used in two W-band gyro-devices, as reported in references<sup>9,10</sup>. The motivation of this work is to enable the W-band gyro-TWA<sup>11</sup> to operate at high repetition rate. The required beam parameters were an applied voltage of 40 kV and current of up to 1.7 A. The beam velocity  $\alpha$  (transverse-to-axial velocity ratio) was 1.1 for an efficient beam-wave interaction in the gyro-TWA. The magnetic field in the interaction region was 1.84 T.

From the theoretical analysis of a cusp electron gun<sup>12-14</sup>, the mean radius of the emitter and the required magnetic field strength at the cathode region could be determined. Further improvement of the beam  $\alpha$

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spread was investigated using a multiple objective numerical optimization routine. A general geometry of the previous diode-type cusp electron gun is shown in Fig. 1. The geometry was parameterized using the free parameters labeled in Fig. 1. Among those parameters the average radius of the emitter  $R_c$  and the emitter thickness  $\Delta R$  could be obtained from the theoretic equations.  $R_n$  and  $\varphi$  had less effect on the alpha spread, therefore less sample values could be used in the optimization to reduce the overall simulation time.

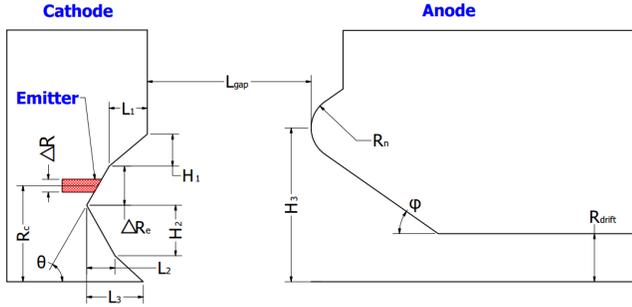


FIG. 1. (Color online) The general structure of a cusp electron gun used for optimization.

The geometry of the triode-type cusp electron gun was based on Fig. 1. To allow the fast beam switching, a small biasing voltage of 1 kV between the cathode and the modulation electrode was used. The gap distance from the cathode to the modulation electrode could be approximated from the electric field strength at the cathode region, which was in the order of  $1 \times 10^6$  V/m from the previous simulations, to be  $\sim 1$  mm. The geometry of the triode-type cusp electron gun developed from Fig. 1 is shown in Fig. 2. Two concentric modulation electrodes, with an annular gap in between for the electron beam to pass, were formed surrounding the cathode. They have the same biasing voltages and can be electrically regarded as one single electrode. The modulation electrodes have a similar outside profile as the cathode in Fig. 1. Therefore the previous experience on optimizing the cusp electron gun in Fig. 1 is still valid for such triode-type gun.

As the modulation electrodes have the same potential, the electric field in the gap (the region labeled as  $L$ ) becomes much smaller. The thickness of the modulation electrodes  $d$  and the gap distance  $s$  have great effect on the performance of the triode-type cusp gun. The thinner the electrodes are, the less the electric shielding effect would be. However, a reasonable thickness is required to maintain sufficient mechanical strength. As a tradeoff, the thickness was chosen to be 0.2 mm. The beam quality will become better when reducing the gap distance  $L$ , as the electric field becomes more uniform in this region. However it has to be wider than  $\Delta R / \sin \theta$  to allow the electron beam passing through freely, i.e., to reduce the leak current of the electrodes.

Compared with the case without modulation elec-

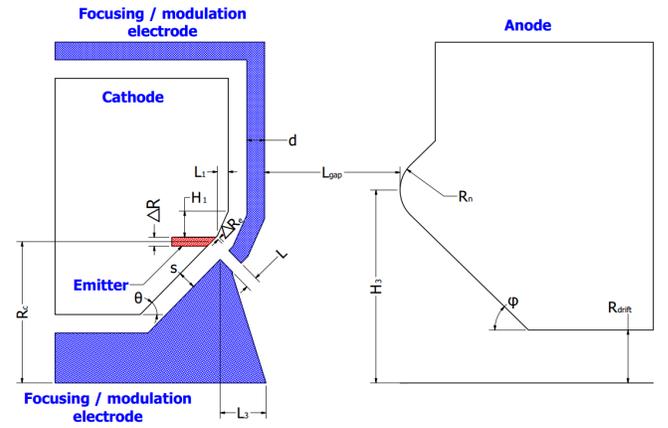


FIG. 2. (Color online) The geometric model of the triode-type cusp electron gun.

trodes, the triode-type cusp electron gun had two more free geometry parameters, which are marked as  $s$  and  $L$  in Fig. 2. The electric field should match with the magnetic field to achieve the optimal results. As it has been demonstrated through numerical simulations that there exists an optimal electron gun geometry if the magnetic field profile is within a suitable range<sup>15</sup>. Thus the same coil setup from the previous cusp gun could still be used for this triode-type design. In the optimization, there were two free parameters applied to the magnetic field profile. One was to shift the whole coil system along the axial axis, the other one was to adjust the driving current of the reverse coil so that the magnetic field at the emitter can be finely tuned.

In the previous study, the cusp electron gun was simulated and optimized by using the particle-in-cell (PIC) code MAGIC<sup>16</sup>. It can model the space charge effect very accurately by simulating millions of electrons. However because a conformal meshing method is inherently used by MAGIC, it is not ideal to simulate the proposed geometry. That is because a very fine mesh is required to well represent the geometrical details of the thin modulation electrodes. It would result in very long computing time. The finite element simulator Vector Fields OPERA<sup>17</sup> was used to simulate the beam trajectories of the triode-type cusp electron gun.

Among the various solvers in OPERA simulation package, SCALA is capable to simulate the electron beam dynamic in the static electric and magnetic fields. It solves the finite-element discretization form of the electrostatic Poissons equation with tetrahedral mesh, therefore it is able to accurately present the thin modulation electrodes and curved shapes. Similar to the other particle tracking solvers, such as CST particle studio and EGUN, SCALA calculates the space charge effect by iterating the deposited charge along the beamlet trajectories. The thermal velocity and angular distributions also affects the alpha spread in a cusp electron gun. Fortunately various emission models for a thermionic emitter, which allows

the inclusion of those effects, are available in OPERA.

In the simulations, the alpha spread and the central alpha value were the two major parameters to be optimized. The electron gun was designed to operate in the temperature limited emission mode. In this case, it was hard to fix the emitted current at the desired value because the electric fields at the emitter surface varied for different geometries. A threshold value of the emitted beam current was used in the optimization. If the emitted current of an electron gun was smaller than 1.5 A, then a penalty factor would be applied to the evaluation functions to denote a poor geometry.

### III. SIMULATION RESULTS OF THE TRIODE-TYPE CUSP GUN

The beam parameters of the optimized triode-type cusp electron gun are listed in Table 1. The geometry of the optimized electron gun was exported from OPERA and then imported into CST particle studio for verification. A contour plot of the potential distribution of the designed electron gun simulated by CST EM studio is shown in Fig. 3. The inset shows a detailed view of the area around the modulation electrodes. With this configuration, a uniform field at the emitter surface was achieved. This helped to reduce the alpha spread.

Symbol	Quantity	Value
$V_0$	Cathode voltage	-40 kV
$V_m$	Modulation voltage	-39 kV
$I_0$	Emitted beam current	1.74 A
$v_{\perp}/v_{\parallel}$	Center alpha value	1.12
$B_c$	Magnetic field at the cathode	-3.6 mT
$R$	Emitter radius	6.0 mm
$\Delta R$	Emitter thickness	0.5 mm
$B_0$	Magnetic field at the flat region	1.84 T
$R_0$	Average beam radius	0.28 mm

TABLE I. OPERATING PARAMETERS OF THE TRIODE-TYPE CUSP GUN

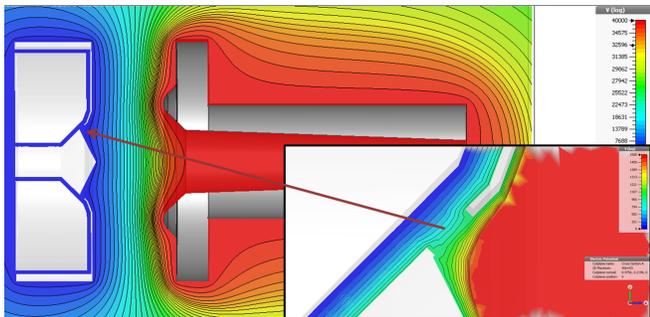


FIG. 3. (Color online) The electric field distribution at the cathode region.

Fig. 4 shows the evolution of the axial and transverse velocities along the axial positions. The acceleration

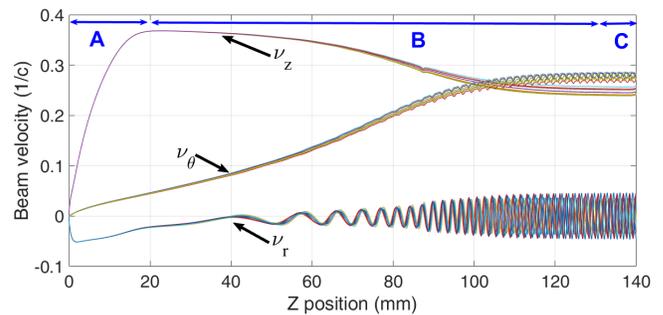


FIG. 4. (Color online) The axial and transverse velocities as the function of the axial position.

region (A) was about 20 mm length, and  $v_z$  of electrons continuously increases until the axial electric field strength becomes zero. A large electric field in the radial direction close to the cusp position is preferred as it helps the electrons to gain sufficient velocity in radial direction,  $v_r$ .  $v_r < 0$  at the small axial region means the compressing of the beam radius and its value then gradually reduces as the variation of the beam radius becomes smaller. Ideally,  $v_r$  value should reduce and keep to be zero. However the electron beam always had small radial movement against its guiding center and hence a small  $v_r$  value. The average value was 0 at  $z > 40$  mm. After the acceleration region, the electron beam entered into the compression region (B). The axial momentum was then gradually transferred to transverse momentum due to the conservation of the angular momentum and the increasing magnetic field strength. The electron beam finally moved into the flat magnetic region (C), which would also be the region that the beam-wave interaction occurs. The axial momentum becomes stable at this point.

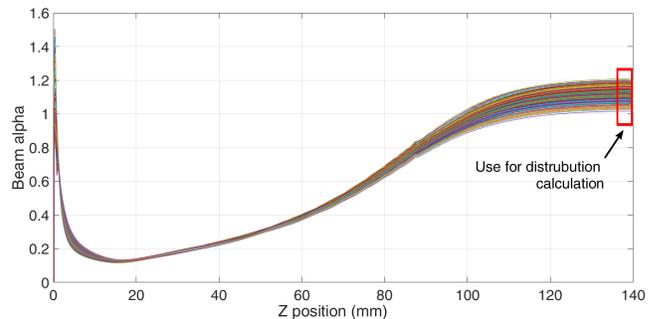


FIG. 5. (Color online) The simulation beam alpha as a function of the axial position.

Fig. 5 shows the beam alpha as a function of axial position. To calculate a beam current weighted alpha distribution, the alpha values at the last 5 mm of the simulation region were exported and post-processed. The alpha spread as the function of electron current (normalized to the peak value) is shown in Fig. 6. The full width at half maximum (FWHM) is 0.12 and the central value

of alpha is 1.12. The alpha spread is about 10.7%.

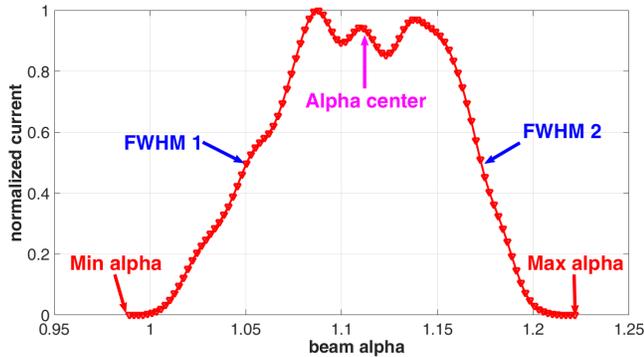


FIG. 6. (Color online) The alpha spread of the designed triode-type cusp electron gun.

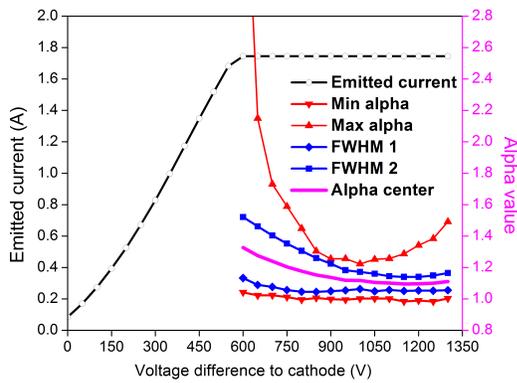


FIG. 7. (Color online) Switching property of the designed triode-type cusp electron gun.

The beam switching property of the triode-type cusp electron gun was also simulated. Fig. 7 shows the emitted current as a function of the biasing voltage of the modulation electrodes. The electron beam current could be completely switched off if the voltage difference is zero. The electron beam could be completely switched on at 600 V, however the beam quality was bad as the alpha spread was huge. At this voltage, the electric field near the emitter was small and the electrons located at lower part of the emitter were unable to gain sufficient  $v_z$  and they were reflected back to the cathode in the compression region. A leak current of 4% was also predicted at a biasing voltage of 600 V. Further increasing the biasing voltage helps to improve the electron beam quality and avoid the leak current. The FWHMs of the alpha values were nearly constant when the biasing voltage were greater than 1 kV. The optimal beam quality was achieved if the biasing voltage of 950-1050 V was chosen. The difference in the alpha values of the electrons were a few percent.

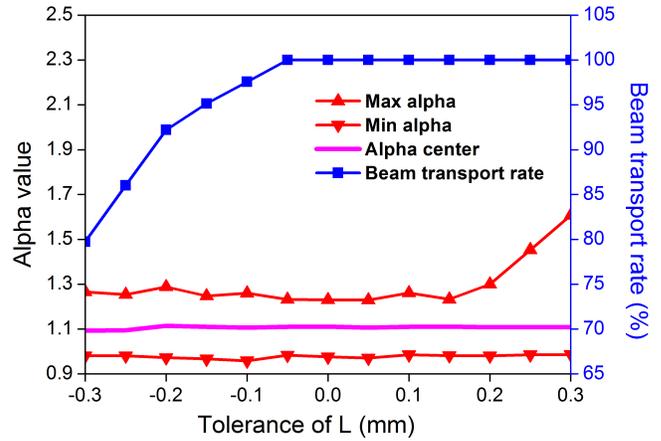


FIG. 8. (Color online) The effect of tolerance of dimension  $L$ .

#### IV. TOLERANCE STUDY OF THE DESIGNED GUN

The effects of the machining tolerance on the key parameters  $L$ ,  $s$  and  $d$  were also investigated and the results are shown in Fig. 8 - 10, respectively. It was found that within the simulated tolerance ranges, the minimum alpha, alpha centers, FWHM 1, FWHM 2 of the alpha distribution curves have small changes. The tolerances had bigger impacts on the electrons generated from both ends of the emitter. These electrons had larger alpha values which show a larger maximum alpha in the figure. Some of the electrons were reflected due to too high alpha values which resulted in lower beam transport rate.

The acceptable tolerance range of dimension  $L$  for the designed triode-type cusp electron gun was approximately from -0.1 mm to 0.2 mm. A further smaller  $L$  would result in a lower beam pass rate or a larger leak current. On the other hand a larger  $L$  would result in a larger electric field variation on the emitter surface and hence an increased maximum alpha (Fig. 8).

The acceptable tolerance range of dimension  $s$  and  $d$  were both approximately  $\pm 0.1$  mm as shown in Fig. 9 and Fig. 10 respectively. A larger value of  $s$  and  $d$  would reduce the electric field strength and increase the electric field variation at the surface of the emitter and hence result in lower beam transport rate and larger maximum alpha.

#### V. CONCLUSION

In this paper, a triode-type cusp electron gun was optimized for a W-band gyro-TWA to enable fast switching, on and off, of the emitted electron beam. With a control voltage of  $\sim 1$  kV, the alpha spread was about 10.7% when operated at voltage of 40 kV, current of 1.74 A and with an alpha center of 1.12. The optimal beam quality was achieved if the biasing voltage was chosen in the range of 950-1050 V.

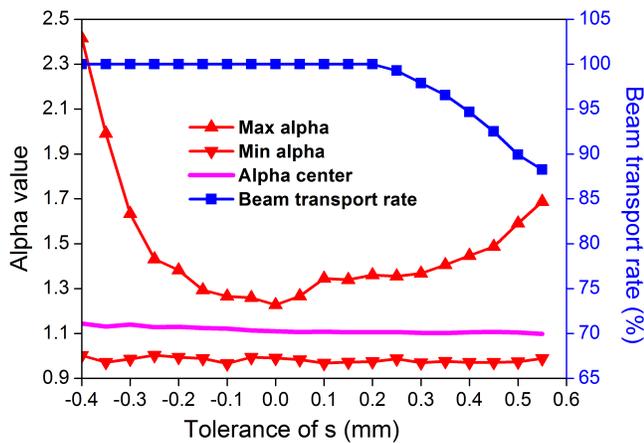


FIG. 9. (Color online) The effect of tolerance of dimension  $s$ .

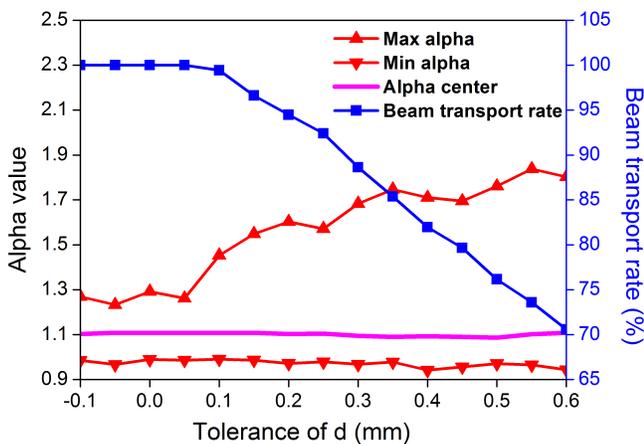


FIG. 10. (Color online) The effect of tolerance of dimension  $d$ .

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