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Abstract

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Full Text

Emittance Optimization of Gridded Thermionic-Cathode Electron Gun for High-Quality Beam Injectors

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Abstract

Electron beam injectors are pivotal components of large-scale scientific instruments such as synchrotron radiation sources, free-electron lasers, and electron-positron colliders. The quality of the electron beam produced by the injector critically influences the performance of the entire accelerator-based scientific research apparatus. The injectors of such facilities typically employ either photocathode or thermionic-cathode electron guns. Although photocathode injectors can produce electron beams of excellent quality, their associated laser systems are massive and intricate. The thermionic-cathode electron gun, particularly the gridded electron gun injector, features a simple structure capable of generating high-current electron beams, though its emittance is typically high. In this study, methods to reduce beam emittance are explored through comprehensive analysis of various grid structures and preliminary design results, examining the evolution of beam phase space at different grid positions. An optimization method for reducing the emittance of a gridded thermionic-cathode electron gun is proposed through theoretical derivation, electromagnetic field simulation, and beam dynamics simulation. A 50% reduction in emittance was achieved for a 50 keV, 1.7 A electron gun, laying the foundation for subsequent design of a high-current, low-emittance injector.

Keywords: Electron gun, Gridded, Beam injector, Beam dynamics, Emittance optimization

INTRODUCTION

Electron beam injectors in accelerator facilities, such as synchrotron radiation sources [?], free electron lasers (FEL), and electron-positron colliders [?, ?], play a crucial role in generating, accelerating, and focusing high-performance electron beams. The overall performance of the device depends largely on the quality of the driving electron beam provided by the injector, and the initial electron beam generated by the electron gun largely determines the performance limit of the injector and even the entire apparatus [?]. Therefore, large scientific research facilities based on accelerators have strict requirements regarding the quality of injectors, especially electron guns [?, ?, ?].

Common methods of electron emission from electron gun cathodes include photoelectric, field, and thermal emissions [?, ?, ?]. Electron extraction and acceleration typically involve the use of either direct-current (DC) high voltage or radio-frequency (RF) high voltage [?, ?, ?]. Electron guns commonly used for FEL and synchrotron radiation include photocathode RF electron guns [?] and thermionic-cathode high-voltage electron guns. The former requires a costly laser system with complex operation and maintenance, whereas the thermionic-cathode injector has a simple structure, affordability, high power and current output capabilities, and long-term stable operation [?, ?]. The gridded thermionic-cathode electron gun offers flexible beam quality control through the grid. By regulating beam emission via the grid, wear on the gun components is minimized and thermal expansion is reduced, thereby extending the operational lifetime of the electron gun [?].

Gridded thermionic cathode electron guns have been employed in various global projects. For instance, Asaka et al. developed a low-emittance RF electron gun system using a gridded thermionic cathode for a 1 GeV storage ring NewSUBARU injector, demonstrating stable operation. The system comprises an electron gun operating at 50 kV, a 238 MHz RF accelerating cavity, and solenoids. It offers notable advantages including compact size, low emittance, and high stability [?]. The injector for Beijing's fourth-generation synchrotron radiation source, the High Energy Photon Source [?], incorporates a gridded thermionic-cathode electron gun. The linear accelerator achieves an output beam energy of 500 MeV and a macro pulse repetition rate of 50 Hz. The electron gun is capable of delivering a bunch charge of up to 10 nC [?].

However, the beam energy generated by conventional gridded thermionic-cathode electron guns is limited by significant space charge effects [?, ?, ?], resulting in excessive emittance. This limitation significantly affects the design and optimization of subsequent facilities. Therefore, it is important to use the RF field to rapidly accelerate the output electron beam of the gun to offset these space charge forces. The electron gun primarily comprises a cathode, focusing structure, and anode [?]. A gridded electron gun involves adding a grid near the cathode surface of a conventional gun, which is set to the same potential as the focusing structure. This configuration controls the emission timing of the electron beam and optimizes its initial quality [?]. Structural modifications in the electron gun alter the electric field, thereby influencing the quality of the emitted beam. Simulation and iterative optimization of the design are necessary to ensure that the emitted beam current meets the requirements of subsequent accelerator facilities.

This study focuses on optimizing a gridded electron gun. Using the CST Studio Suite, we simulated electron beam drift under electric field effects and optimized key parameters to achieve high-quality electron beam currents. The optimization of key parameters such as grid type, wire spacing, grid bias voltage, and other structural aspects is conducted by analyzing the transverse phase space [?] information of the beam near the grid. To verify the applicability of the electron gun to subsequent facilities, a subharmonic bunching (SHB) cavity was added to accelerate the electron beam [?], and solenoids were added to compensate for emittance. This scheme aims to achieve low-emittance, high-quality electron beam output. Based on the injector structure in Japan, an electron gun model was developed using the Tracking solver within CST. A negative high voltage is applied to the cathode while the anode is grounded, causing electrons to be emitted across the cathode surface barrier and accelerated toward the anode port by the electric field between them [?]. This setup resulted in extremely low emittance at the exit of the electron gun system. The final section discusses the scheme of using an SHB to accelerate and solenoids to constrain the electron beam at the exit of the electron gun system [?], along with the electron beam current parameters at the final beam waist position.

II. BRIEF REVIEW OF PREVIOUS DESIGN FOR ELECTRON GUN

The development of an electron gun system that generates high-quality, low-emittance beams is of paramount importance for achieving breakthroughs in the key technology of free-electron laser (FEL) injectors. This section provides a detailed discussion of the electron gun system design, which includes the cathode, grid, focusing structure, and anodes.

The cathode operates at a high voltage of -50 kV, with a specific voltage difference set between the grid and cathode known as the grid bias voltage. The focusing structure and grid were maintained at equipotential, whereas the anode was grounded.

In simulation studies from a previous publication, we designed an electron gun with a cathode emission surface radius (rcathode) of 3.5 mm, achieving a normalized emittance of 2 mm mrad at the electron beam exit [?]. The electron gun of this structure produced a beam current of 1.5 A, but a higher current of 1.7 A was desired. According to the emission capacity of the cathode, larger cathode size yields higher current intensity, so we expanded rcathode to 4 mm. However, this resulted in an emittance increase to 2.5 mm mrad. Therefore, further structural optimization was necessary to reduce emittance. Drawing from previous electron gun design experience, the tilt angle of the focusing electrode was adjusted to 57°, the height to 7.5 mm, and the anode-cathode distance was set to 16 mm to achieve a beam characterized by higher laminar flow and lower emittance. The optimized structure of the electron gun and beam trajectory obtained from CST simulations are shown in Fig. 1 Figure 1: see original paper. From this figure, it can be seen that the beam waist is very long and the beam spot size at 40 mm after the anode outlet does not change much compared with the beam spot size at the anode outlet, indicating that the beam has good laminar flow.

Fig. 1. (Color online) (a) Electron gun structure and electron beam energy distribution characteristics. (b) The structure diagram of different grids (including honeycomb, rectangular, spoke).

In previous electron gun models simulated using CST, various mesh shapes including honeycomb, spoke, and orthogonal configurations [?] were investigated, as shown in Fig. 1(b). According to preliminary results, the spoke-wheel grid exhibited the lowest emission efficiency. The orthogonal and honeycomb grids resulted in comparable beam qualities, with the orthogonal grid being easier to fabricate than the honeycomb grid [**?**]. Therefore, from an engineering implementation perspective, this study adopts an orthogonal grid structure. The Tracking solver within the particle tracking module of CST software is utilized to achieve an emission current of 1.7 A at the electron gun exit using the Fix emission mode. The width ratio between the analysis mesh and wires was set to 1:2 to meet the accuracy requirements of the simulation.

To achieve higher beam quality, selecting an appropriate cathode material is essential to provide larger emission currents from a smaller emitting area. Rare earth hexaborides (RB6), such as cerium hexaboride (CeB6), possess unique characteristics including high hardness, high melting point, low work function, good chemical stability, and resistance to ion bombardment [**?**, **?**]. Among various RB6 materials, CeB6 exhibits lower evaporation rates, higher electrical resistivity, and longer lifetimes [**?**]. In this study, a CeB6 planar cathode with an emission surface radius of 4 mm was chosen, which theoretically meets the requirements for emission current density. The application of CeB6 cathodes in facilities such as Spring-8 FEL has confirmed their reliability [**?**, **?**].

A model of the cathode was established in CST, and subsequently a grid structure was integrated behind it, with the configuration of the cathode and grid structure being optimized and analyzed. Based on the aforementioned simulation model, it is crucial to investigate the influence of the voltage difference between the grid and cathode on beam emittance. The variation in emittance with bias voltage is illustrated in Fig. 2 Figure 2: see original paper. The beam emittance initially decreased and then gradually increased as the bias voltage increased, reaching a minimum at a grid bias voltage of approximately 320 V. At lower bias voltages, the insufficient electric field between the cathode and grid leads to larger beam emittance. As the absolute value of the bias voltage increased, the laminarity of the beam improved, resulting in enhanced emittance performance. However, beyond a certain threshold, further increasing the bias voltage caused emittance to increase again.

Fig. 2. (a) The emittance varies with voltage difference. (b) The emittance varies with the spacing between wires.

The spacing between the wires and the wire width significantly affect beam quality. Simulations were conducted to compare grids with wire widths of 0.02 mm, 0.03 mm, and 0.04 mm. Table 1 shows that finer wires result in higher electron transmission rates, but thinner wires are prone to deformation and increase manufacturing difficulty. Therefore, it is recommended to choose a wire width of 0.02 mm.

The simulation and calculation of the effect of spacing between wires on emittance were performed using two methodologies: one by setting the cathode output current to 2 A, and the other by maintaining the current at the anode outlet position at 1.7 A. Figure 2(b) illustrates that within a specific range of wire spacing, emittance tends to increase with larger wire spacing. The emittance stabilizes around 2.1 mm mrad when wire spacing exceeds 0.26 mm. In addition, when wire spacing is less than 0.15 mm, emittance is stable at about 1.9 mm mrad. Therefore, within the range of wire spacing from 0.15 mm to 0.26 mm, smaller wire spacing yields lower emittance levels. Notably, under the two setting conditions, a consistent inflection point appeared at a wire spacing of 0.17 mm. The smaller the wire spacing, the more electrons bombard the grid, and the more obvious the thermal deformation effect. A wire spacing of 0.17 mm not only reduces emittance but also enhances beam transmission rate, improves cathode efficiency, and extends the lifetime of both the cathode material and the grid. Finally, the simulated electron gun achieved an acceleration gradient of less than 4 MV/m, resulting in a beam emittance of 1.3 mm mrad and a current intensity of 1.7 A (charge of 1 nC, pulse length of 600 ps).

Table 1. The beam transmission rate varies with the width of the wire.

Wire size (mm)	Particle transmission rate (%)
0.02	92.5
0.03	89.3
0.04	85.7

III. EMITTANCE OPTIMIZATION VIA GRID RECONFIGURATION

The preceding section demonstrated that beam emittance is significantly affected by the grid structure. Hence, further optimization of the grid structure is essential. During electron gun simulations using the CST Studio Suite, 2D particle monitors were placed at positions where electrons passed through the grid and at the gun exit. Observations from these monitors revealed that grid-induced field effects caused the electron beam spot to exhibit a consistent pattern aligned with the grid structure, as shown in Fig. 3 [Figure 3: see original paper]. Yellow and blue dots represent electrons, and the circular pattern depicts the beam-spot image. Local amplification revealed the electron distribution, which demonstrated that the magnified beam spot displayed a distinct grid pattern. For convenience in further study, particles on the stripes within y of 0 mm 0.17 mm need to be marked in blue.

A. Basic Idea and Theoretical Analysis

In the realm of beam physics, analysis of phase space (x–x′ plane) provides a more intuitive understanding. Analysis of the position and momentum within each phase space cell enables exploration of their relationship with the overall emittance.

The emittance of a beam is quantified by the area of the phase-space ellipse. In addition to geometrical explanations, emittance can be described statistically by assessing the dispersion of all particles in the x-x′ phase space. The RMS emittance can be defined by the following Eq. (1) [**?**]:

$$\varepsilon = \sqrt{\sum_i (x_i - \bar{x})^2 \cdot \sum_i (x'_i - \bar{x}')^2 - \left\langle \sum_i (x_i - \bar{x}) \cdot (x'_i - \bar{x}') \right\rangle^2}$$

Because the beam spot cross-section can be considered as composed of individual grid cells, the transverse phase space of the beam can also be decomposed into transverse phase spaces of multiple grid cells. Normalizing each cell's transverse phase space, represented as (x_i, x'_i), involves methods such as finding their centroids to yield a single point $(\bar{x}, \bar{x}')$.

As shown in Figs. 4(a) and 4(b), the phase space information of each grid cell can be discretized using its emittance and normalized slope away from the centroid point. Here, Fig. 4 Figure 4: see original paper illustrates the representation of the grid phase space using the coordinates of n electrons, denoted by the four coordinate points $(a, 0)$, (a, k_{1a}), $(-a, 0)$, $(-a, -k_{1a})$, where k_1 represents the normalized slope.

Thus, for the analysis of each grid's phase space, the emittance in Eq. (1) can be transformed into the following Eq. (2):

$$\varepsilon = \sqrt{\frac{1}{n}\left(\frac{n}{4}a^2\right) \cdot \left(\frac{n}{4}k_1^2 a^2\right) - \left(\frac{n}{4}k_1 a^2\right)^2} = \frac{1}{2}\sqrt{\frac{n^2}{n^2}}k_1 a^2 = \frac{1}{2}k_1 a^2$$

To achieve a more approximate and uniformly discretized distribution of electrons within each grid cell, for electrons of each grid, the center point in Fig. 4(b) is denoted as $(\bar{x}, \bar{x}')$, with scattered electron coordinates labeled as (a, b), $(2a, b)$, $(2a, 2b)$, ..., (pa, pb), $(-a, -b)$, $(-2a, -b)$, $(-2a, -2b)$, ..., $(-pa, -pb)$, where $b/a = k_1$.

Thus, the emittance Eq. (1) for each grid cell can be transformed into the following Eq. (3):

$$\varepsilon = \sqrt{\frac{1}{n}\sum_i (ia)^2 \cdot \sum_i [p - (i-1)](ib)^2 - \left(\sum_i \sum_j (ja \cdot ib)\right)^2} = \frac{1}{3p^4 + 6p^3 - p^2 - 4p - 4} \cdot a^2 b^2$$

Figures 4(c) and (d) demonstrate the fitting of this method to phase space. Evidently, the two fitting methods are well aligned and can be utilized for subsequent simplified calculations.

The normalized slope of the overall transverse phase space of the beam spot is primarily determined by the electric field distribution between the cathode grids. The grid structure influences the electric field within each grid aperture, thereby altering the phase space of the beam, specifically the transverse phase space of the grid. To simplify the phase space information, as shown in Fig. 5 [Figure 5: see original paper], the blue line connecting the blue dots represents the overall transverse phase space of the beam spot, with each blue dot denoting a normalized point corresponding to each grid. The yellow dots represent discrete points obtained from the emittance and normalized slope of the grid. Thus, the area of the ellipse containing all the yellow dots represents the overall beam-spot emittance.

As shown in Figs. 5(a) and 5(b), it is evident that as the slope of each grid approaches the overall slope, the beam spot emittance decreases significantly.

Fig. 5. The yellow line denotes the normalized slope of the beam across each small grid. The blue line represents the normalized slope of the entire beam spot. The absolute difference of slopes between the blue and yellow lines in (a) is greater than that in (b).

Utilizing the emittance formula derivation shown in Fig. 6 [Figure 6: see original paper], consider a total of $8n_1$ electrons composing the entire beam spot, divided into four grid cells with $2n_1$ electrons in each cell. Assume the normalized position coordinates of electrons within each grid cell, as depicted by the blue dots in Fig. 6, are $(a, 0)$, (a, b), $(-a, 0)$, $(-a, -b)$. For this beam spot consisting of $8n$ electrons, the relationship for its emittance, derived using the method of least squares, yields a normalized slope of $b/2a$. The emittance relationship is given by:

$$\varepsilon = \frac{1}{(8n_1)^2}(8n_1a^2 \cdot 4n_1b^2) - \frac{1}{(8n_1)^2}(2n_1 \cdot 2ab)^2 = a^2b^2$$

Therefore, it is essential to examine the relationship between the normalized slope of the four grid units and the overall normalized slope of the spot. As depicted in Fig. 4(a), the blue coordinate points in Fig. 6 are discretized into yellow coordinate points. For simplification of the calculation, the electron emittance within each grid was disregarded, focusing solely on the normalized slope. Each blue coordinate point was eventually discretized into two yellow points. Assuming a consistent normalized slope of k_2 for each small cell, the dispersed electron coordinates are: $(2a, b+k_{2a})$, $(0, -k_{2a}+b)$, $(0, k_{2a})$, $(-2a, -k_{2a})$, $(0, -k_{2a})$, $(2a, k_{2a})$, $(-2a, -k_{2a}-b)$, $(0, k_{2a}-b)$, with n_1 particles at each coordinate point.

Thus, the emittance formula for each cell, Eq. (1), can be transformed as follows:

$$\varepsilon = \frac{1}{8^2}\cdot[4(2a)^2 + 2(k_{2a}+b)^2 + 2(-k_{2a}+b)^2 + 4k_2^2a^2] - \frac{1}{8^2}\cdot[2a\cdot(k_{2a}+b) + 4k_2a^2 + 2a\cdot(k_{2a}+b)]^2 = a^4\cdot\Big(2k_2^2$$

The overall emittance decreased when the slope of each grid cell closely approximated the overall normalized slope $b/2a$ of the beam spot. This provides a theoretical foundation for optimizing the emittance of gridded electron guns.

Fig. 6. Dispersing four blue coordinate points into eight yellow coordinate points.

Fig. 4. (Color online) (a) The electrons are evenly separated from the normalized coordinate points to four coordinate points. (b) Electrons are uniformly dispersed from the normalized coordinate points to multiple regular coordinate points, and each coordinate point contains only one electron. The blue dots represent the fitted electron position, and the yellow dots represent the actual electron position. (c) Comparison between the fitting obtained by the discrete method of (a) and the actual electronic phase space. (d) Comparison between the fitting obtained by the discrete method of (b) and the actual electronic phase space.

B. Beam Emittance Optimization

Based on the theoretical derivation and diagram in the previous section, the structure of the electron gun grid was optimized to enhance beam emittance. It is necessary to analyze the particles labeled in blue within the grid near the x-axis of the beam spot, as shown in Fig. 3. The normalized emittance slopes were calculated individually for 48 cells containing electrons, and their trajectories were tracked to assess their respective beam spots and phase spaces upon reaching the anode exit. The electron beam spot and transverse phase space are shown in Fig. 7 [Figure 7: see original paper]; the color gradient from blue to purple indicates the distribution of the beam spot and transverse phase space of electrons. The electrons from the selected stripe of the beam spot are highlighted in orange, along with their transverse phase space distribution. Figures 7(a) and (c) represent the electron information at 0.8 mm from the grid, whereas Figs. 7(b) and (d) show the electron information at the electron gun exit, with purple and orange indicating the positions of electron beam concentration. According to the transverse phase space diagram, the normalized emittance slope of the overall beam spot was negative. The normalized beam emittance at the electron gun exit is 1.3 mm mrad (99.7% core part).

Fig. 7. (Color online) (a) Transverse phase space diagram at a distance of 0.8 mm from the grid. (b) Transverse phase space diagram at the anode exit position. (c) Beam spot diagram at a distance of 0.8 mm from the grid. (d) Beam spot diagram at the anode exit position.

The normalized slopes of each grid cell within the yellow stripe shown in Fig. 7(a) are calculated, yielding the blue line around x in Fig. 8 [Figure 8: see original paper]. It can be observed that all grid cell slopes are positive. The absolute differences between these data points and the overall normalized slope of the large beam spot are depicted by the red curve. The red curve illustrates a notable disparity between the phase space slope of an individual grid cell and the slope of the entire spot, particularly noticeable within the annular region of radius 2 mm 4 mm. Hence, to effectively decrease the slope of the edge grid unit and minimize overall emittance, the external structure of the grid must be adjusted to alter the distribution of electric field lines. Increasing the height of the grid edge relative to the center position and reducing the distance from the cathode to the perimeter of the grid can enhance field strength, ultimately decreasing the slope of each grid.

Fig. 8. The blue points represent the slope of particles within each grid near the grid. The red points represent the absolute difference in slope between the grid of small patches and the macro-bunch slope.

For the conventional grid structure, the yoz cross-section shown in Fig. 9 Figure 9: see original paper appears rectangular. To achieve the desired optimization goals, the edges of the grid structure were elevated, as shown in Fig. 9(b), resulting in reduced beam emittance. Further optimization of the slopes was pursued, leading to the design shown in Fig. 9(c), and a subsequent improvement in emittance reduction. Figure 9(d) illustrates a three-dimensional view of the structural optimization results for grid thickness, as shown in Fig. 9(c). These modifications enable the electric field structure to enhance the laminarity of the beam flow. The results near the grid and at the anode exit regarding the beam spot and transverse phase space are shown in Fig. 10 [Figure 10: see original paper].

Fig. 9. (Color online) The schematic diagram illustrates the yoz cross-section of the grid. (a) Conventional rectangular cross-section. (b) Elevated edge structure. (c) Further optimized structure. (d) Three-dimensional view of the optimized grid thickness.

The normalized slopes of the particles within the yellow-marked grid cells shown in Fig. 10(c) are calculated, resulting in the blue curve depicted in Fig. 11 [Figure 11: see original paper]. The absolute differences between these data points and the overall normalized slope of the large beam spot were computed to generate the red curve. The electron beam spot was symmetrical about the center of the circle. The number of each square-shaped spot increased along the radial direction and was proportional to the perimeter. Consequently, the slope differences at varying radii, as depicted in Figs. 8 and 11, are weighted by the radius. The pre-optimization value is 2.47, while the post-optimization value is 1.44. The overall beam emittance can be reduced, and the beam emittance at the exit position of the electron gun can be reduced to 1.1 mm mrad (99.7% core part) as shown in Fig. 12 [Figure 12: see original paper].

Fig. 10. (Color online) (a) Transverse phase space diagram at a distance of 0.8 mm from the grid. (b) Transverse phase space diagram at the anode exit position. (c) Beam spot diagram at a distance of 0.8 mm from the grid. (d) Beam spot diagram at the anode exit position.

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Fig. 12. Variations in beam current and emittance after optimization of section 2 and section 3.

IV. FURTHER CONSIDERATION WITH SUBSEQUENT COMPONENTS

To verify the application of the optimized electron gun beam in subsequent components, simulation analyses were conducted using the CST Studio Suite. We designed a gridded thermionic RF accelerator system capable of emitting high-quality beam currents, which comprised a gridded electron gun, SHB, and solenoids. Beam dynamics simulations [**?**] and optimizations have been performed to achieve high-quality beam emission [**?**, **?**].

The initial RF component in the injector system following the electron gun is an SHB. It is used for beam pre-bunching and acceleration and plays a crucial role in the injector setup. The SHB compresses the longitudinally uniform electron beam emitted by the electron gun and enhances longitudinal electron density, which is essential for subsequent acceleration and focusing in the following accelerator section [**?**, **?**]. The microwave field within the RF cavity is a time-varying standing wave field, necessitating optimization of the cavity structure and phase tuning to achieve high-gradient acceleration and adequate focusing for subsequent stages of beam acceleration and focusing.

Introducing a solenoid in the beam transport process is similar to introducing a lens. It utilizes lensing to focus the electron beam, compensating for space charge effects that affect the normalized transverse root-mean-square emittance on the x–x′ plane. This lensing effect mitigates the growth in projected emittance on the x–x′ plane observed prior to focusing [**?**].

Fig. 13. (Color online) The trajectory and energy variation of the beam passing through the focusing solenoids and RF cavities. The red curve represents the axial electric field distribution generated by the RF cavity, and the blue curve represents the longitudinal distribution of the magnetic field generated by the solenoids.

In the context of electron guns, the transverse emittance of the particle beam varies with longitudinal changes. The beam energy at the exit of the electron gun is only 50 keV, which is much lower than relativistic velocities. Consequently, substantial space charge forces among electrons cause rapid emittance growth during drift. Thus, minimizing the distance between the RF cavity and electron gun outlet is crucial. Here, the distance from the electron gun exit to the center of the RF cavity is set to 200 mm. Structural optimization of the RF cavity allows for integration of a solenoid between the electron gun and RF cavity. Additionally, considering future requirements for feeding other harmonic cavities and traveling wave tubes, another solenoid was added at the exit of the 238 MHz RF cavity. Optimization across these three components ensures that the normalized emittance of the beam reaches 1.5 mm mrad after a certain drift distance beyond the second solenoid, surpassing typical emission levels of conventional thermionic electron gun injectors.

In CST simulations, when the electron beam reaches the RF cavity, its energy is 50 keV with a normalized root-mean-square emittance of 1.1 mm mrad. By adjusting the phase of the RF cavity to accelerate electrons and considering longitudinal focusing, the changes in beam energy and transverse size after passing through the RF cavity are shown in Fig. 13. The figure also indicates the phase space at the exit of the RF cavity and the transverse phase space of the beam waist obtained from the overall structure of the RF cavity. Under the influence of the RF field, the beam energy increases by nearly a factor of ten, reaching 500 keV. The normalized root-mean-square emittance remained at 1.5 mm mrad.

Table 2. Beam parameters at the exit of the RF cavity before and after optimization of the grid structure.

Parameters	Original value	Optimized value
Current (A)	1.7	1.7
Energy (keV)	500	500
RMS emittance (mm mrad)	2.0	1.5

V. CONCLUSION

We designed, derived, and simulated a low-emittance, high-quality RF gridded thermionic electron gun system. Using the electron gun system model established in CST, information such as the emittance and current of the electron beam was analyzed. Considering that the grid structure has a significant influence on the output of the electron gun, we analyzed and optimized this component in detail. First, we selected the appropriate grid shape and preliminarily optimized key parameters such as grid wire width, spacing, and grid bias voltage. Subsequently, the longitudinal structure of the grid was optimized. Specifically, we further analyzed the electron beam phase space of different grids through the grid and studied the influence on overall emittance through data and theoretical analysis, formula derivation, and so on. Based on this, we propose adjusting the longitudinal length of the grid at different radius positions to reduce electron beam emittance.

Ultimately, the designed electron gun is capable of emitting a beam current of 1.7 A, with the normalized emittance reduced by approximately 50% to 1.1 mm mrad, and a beam spot radius of 3 mm at the anode position. Furthermore, the exit of the electron gun is positioned at the shortest mechanical distance from the solenoid and RF cavity to facilitate beam focusing and acceleration. Beam dynamics simulation involves adjusting the structure, phase, and magnetic field intensities of these components. The beam can be accelerated to 500 keV over a short distance, achieving a normalized emittance of 1.5 mm mrad. In future work, we plan to fabricate this grid structure and conduct emission experiments to evaluate its practical application.

APPENDIX

Eq. (3) can be derived from the following equation, where $n = p(p+1)$:

$$\begin{aligned}
\varepsilon^2 &= \frac{1}{n^2}\sum_i (x_i - \bar{x})^2 \cdot \sum_i (x_i' - \bar{x}')^2 - \left[\frac{1}{n}\sum_i (x_i - \bar{x}) \cdot (x_i' - \bar{x}')\right]^2 \\
&= \frac{1}{n^2}[a^2 + 2(2a)^2 + 3(3a)^2 + ... + p(pa)^2] \cdot [pb^2 + (p-1)(2b)^2 + (p-2)(3b)^2 + ... + (pb)^2] \\
&\quad - \frac{1}{n^2}(ab + 2a \cdot b + 2a \cdot 2b + 3a \cdot b + 3a \cdot 2b + 3a \cdot 3b + ... + pa \cdot pb)^2 \\
&= \frac{1}{n^2}(1^3a^2 + 2^3a^2 + ... + p^3a^2) \cdot \{(p+1)(b^2) + (p+1)(2b)^2 + ... + (p+1)(pb)^2 - [(b^2) + 2(2b)^2 + ... + p(pb) \\
&\quad - \frac{4a^2b^2}{n^2}\left[\sum_{i=1}^{p} i^2(i+1)\right]^2 \\
&= \frac{4a^2b^2}{p^2(p+1)^2} \cdot \frac{p(p+1)^2(p+2)}{6} \cdot \frac{p(p+1)(2p+1)}{6} - \frac{4a^2b^2}{p^2(p+1)^2}\left[\frac{p(p+1)(2p+1)}{6}\right]^2 \\
&= a^2b^2 \cdot \frac{2p(p+1)^2(2p+1) - 3p^2(p+1)^2}{9p^2(p+1)^2} \\
&= a^2b^2 \cdot \frac{3p^4 + 6p^3 - p^2 - 4p - 4}{9p^2(p+1)^2}
\end{aligned}$$

Eq. (4) can be derived from the following equation, where $n = 8n_1$:

$$\begin{aligned}
\varepsilon^2 &= \frac{1}{n^2}\sum_i (x_i - \bar{x})^2 \cdot \sum_i (x_i' - \bar{x}')^2 - \left[\frac{1}{n}\sum_i (x_i - \bar{x}) \cdot (x_i' - \bar{x}')\right]^2 \\
&= \frac{1}{(8n_1)^2}(2n_1 \cdot 4a^2 \cdot 2n_1 \cdot 2b^2) - \frac{1}{(8n_1)^2}(2n_1 \cdot 2ab)^2 = a^2b^2
\end{aligned}$$

Eq. (5) can be derived from the following equation, where $n = 8n_1$:

$$\begin{aligned}
\varepsilon^2 &= \frac{1}{n^2}\sum_i (x_i-\bar{x})^2 \cdot \sum_i (x'_i-\bar{x}')^2 - \left[\frac{1}{n}\sum_i (x_i-\bar{x})\cdot(x'_i-\bar{x}')\right]^2 \\
&= \frac{1}{(8n_1)^2}\cdot 4n_1(2a)^2\cdot\left[2n_1(k_{2a}+b)^2+2n_1(-k_{2a}+b)^2+4n_1(k_{2a})^2\right] \\
&\quad - \frac{1}{(8n_1)^2}\cdot\left[2n_1a\cdot(k_{2a}+b)+4k_2n_1(a)^2+2n_1a\cdot(k_{2a}+b)\right]^2 \\
&= \frac{1}{16}\cdot 16a^2\cdot\left[2\cdot 2((k_{2a})^2+b^2)+4(k_{2a})^2\right] - \frac{1}{64}\cdot\left[8k_2a^2+4ab\right]^2 \\
&= a^2\cdot\left[2(k_{2a})^2+b^2\right] - \left(k_{2a}^2+\frac{ab}{2}\right)^2 \\
&= 2k_2^2a^4+a^2b^2-k_2^2a^4-k_2a^3b+\frac{a^2b^2}{4} \\
&= a^4\cdot\left(k_2^2+\frac{b^2}{a^2}-k_2\frac{b}{a}\right) = a^4\cdot\left(2k_2^2+\frac{b^2}{a^2}-k_2^2\right) = a^4\cdot\left(k_2^2+\frac{b^2}{a^2}\right)
\end{aligned}$$

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Note: Figure translations are in progress. See original paper for figures.