Numerical simulation and design of a thermionic electron gun

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Abstract: This paper reports the simulation of an electron gun. The effects on the beam quality of some parameters on the beam quality were studied and optimal choices were identified. It gives numerical beam qualities for a common electrostatic triode gun, and the dependencies on design parameters such as electrode geometries and bias voltages to these electrodes are shown. An electron beam of diameter 5 mm with energy of 5 keV was assumed for the simulation process. Some design parameters were identified as variable parameters in the presence of space charge. These parameters are the inclination angle of emission electrode, the applied voltage to the focusing electrode, the gap width between the emission electrode and the focusing electrode and the diameter of the focusing electrode. The triode extraction system is designed and optimized by using CST software (for Particle Beam Simulations). The physical design of the extraction system is given in this paper. From the simulation results, it is concluded that the inclination angle of the emission electrode is optimized at 22.5°, the applied voltage to the focusing electrode was optimized and found to be $V_{\text{foc}} = -600$ V, the optimal separation distance (gap between emission electrode and focusing electrode) is 4 mm, and the optimal diameter of the emission electrode is 14 mm. Initial results for these efforts aimed at emittance improvement are also given.

Keywords: electron gun, electron beam trajectories, beam emittance and beam diameter, focusing voltage

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1 Introduction

Electron guns are routinely used for various metallurgical applications [1−5] such as melting, welding, coating, annealing, heat treatment, surface hardening, alloy formation and in atomic, molecular, and surface physics. Electron guns are also one of the essential parts of electron accelerators. They are used in various types of devices such as vacuum tubes and particle accelerators. The role of the electron gun is producing and shaping a current of electrons in a proper form for injection into accelerating fields. Electron guns can work in continuous or pulsed mode. There are different methods for production of bursts of electrons in electron guns. Major methods are thermionic, photoelectric and electric field emissions [6]. Two important characteristics of electron gun cathodes are their emission continuity and uniformity [7, 8]. The DC thermionic electron guns are basically configured by cathode, anode, emission and focusing electrodes. They are constructed in different configurations, with most of them being triode and diode [9]. Computer simulation plays an increasingly important role in the analysis and optimization of such electron guns. It provides both detailed insight into the source physics as well as the basis for improved design of high performance electron guns. Due to the importance of the triode extraction system for a high current density electron gun, the operation principle of the electron gun is carefully examined, and the triode extraction system is designed and optimized by using CST software (for Particle Beam Simulations) [10]. A detailed simulation process and the key parameters of the system are presented in this paper.

2 Theoretical considerations

For simulation of electron beam guns laws and equations describing the generation and emission of electrons from the cathode, the electric and magnetic fields and the trajectories of the electron beams are given in the following equations. The basic emission laws are used to describe the generation and emission of electrons. For the case when the electric field extracts all the thermally generated electrons, the emission current density is given by the Richardson-Dushman law,

$$J_{\text{eT}} = AT^2 \exp\left(\frac{-e\varphi}{KT}\right), \tag{1}$$

where A is Richardson's constant with the theoretical value 120 A/cm^{2}k, while φ is the cathode work function and T is the temperature of the cathode.

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For space charge limited emission, the emission current density of electrons is given by the Child-Langmuir law as [11],

$$J = C\left(\frac{V^{3/2}}{d^2}\right), \tag{2}$$

where C is Child's constant, and V is the potential difference between the cathode and the anode lying at a distance d.

The electric field in the gun is first calculated using Poisson's equations derived from Maxwell's equations in the absence of the magnetic field. The electron trajectories are then calculated using the Lorentz force equations. The governing equations of the fields are the time-independent Maxwell's equations given by:

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0}, \tag{3}$$

where E is the electric field, ρ is the charge density and ε_0 is the permittivity of vacuum. The electron trajectories are determined by the Lorentz force given by:

$$F = \frac{\mathrm{d}P}{\mathrm{d}t} = q(E + V \times B), \tag{4}$$

which simplifies to

$$F = \frac{\mathrm{d}P}{\mathrm{d}t} = qE, \tag{5}$$

when there is no magnetic field. Commonly, the Child-Langmuir model is used for DC electron guns [12]:

$$j_{\mathrm{e}} = \frac{4\pi\varepsilon_0}{9}\sqrt{\frac{2e}{m_{\mathrm{e}}}}\frac{V_0^{3/2}}{d^2}, \tag{6}$$

with d in meters and V_0 is the applied voltage in volts. Substituting values for physical constants gives the practical expression:

$$j_{\mathrm{e}} = 2.33 \times 10^{-6}\frac{V_0^{3/2}}{d^2}, \tag{7}$$

the units are $\mathrm{A/m^2}$ for d in meters.

In the case where the radius of $< d/2$, then the extraction area $A = \pi d^2/4$ and using Eq. (6), the maximum total current from an electron gun is:

$$j_{\mathrm{e}} = 2.33 \times 10^{-6}\frac{\pi}{2}V_0^{3/2}, \tag{8}$$

the perveance of an electron gun is defined as:

$$P = \frac{\mathrm{I}}{V_0^{3/2}}. \tag{9}$$

3 Thermionic electron emitter characteristics

When a current is passed through a wire, electrons and photons are emitted under the laws of thermionic and photoelectric emission. Electrons are introduced into the system by thermionic emission from the insert surface. The Richardson-Dushman equation [7] illustrates the thermionic emission of the filament.

Temperature can be alternatively determined with Stefan-Boltzmann's law, which says that the power radiated from the surface of a hot body is:

$$P = e\sigma A(T^4 - T_0^4), \tag{10}$$

where P is the radiated power in watts, e is the emissivity of the material, σ is the Stefan-Boltzmann constant (5.6×10^{-8} $\mathrm{W/m^2K^4}$), A is the surface area of the filament, T is the temperature of the filament (K) and T_0 is the temperature of the environment surrounding the filament.

A tungsten cathode was used for the design in this study.
At high temperatures, for tungsten, the emissivity is approximately 0.35. If the filament temperature is much greater than the surrounding environment, we can neglect the T_0 term.

Solving for the temperature we get the expression below (good only at high temperatures)

$$T = (P/e\sigma A)^{1/4}. \tag{11}$$

If we assume that the total radiated power is equal to the electrical power into the filament ($P = IV$), then we can calculate the temperature of the filament.

Here we use the power supply with the voltage and current of 30 V and 30 A respectively, so the power should be about 900 W. The surface area of the filament shown in Fig. 1 is roughly 2×10^{-3} $\mathrm{m^2}$. So with this power supply the temperature of the filament would be about 2200° K.

By substituting this current into Eq.(10), the current density emitted from this filament would be 37 $\mathrm{mA/cm^2}$.

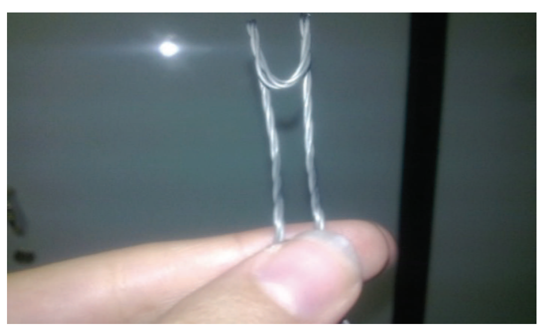

Fig. 1. (color online) Tungsten filament of electron gun.

4 Model and description of electron gun

The electron gun is, mechanically and functionally, composed of two main parts: the electron generator and the electron beam accelerator. The electron generator is a 400 mm copper cylinder and 200 mm in diameter which is supposed to generate 25 mA current with energy of 16 kV operating in continuous mode.

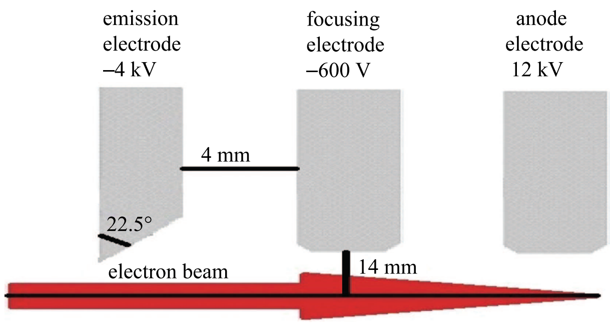

Fig. 2. (color online) Electron gun geometry elements assumed for the CST calculations.

In this study, the CST particle tracking was used for simulation and precise dimensioning of the electron gun. The rough schematic of electron gun is shown in Fig. 2 and its 3D view in CST is illustrated in Fig. 3. Fig. 4 shows the equipotential lines of the extraction system.

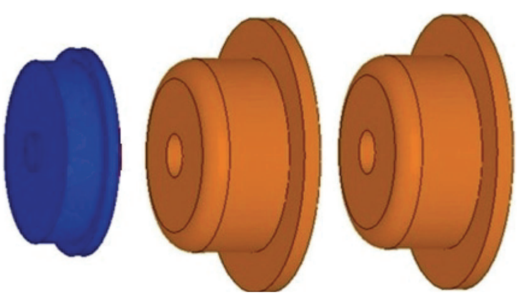

Fig. 3. (color online) Schematic of thermionic electron gun.

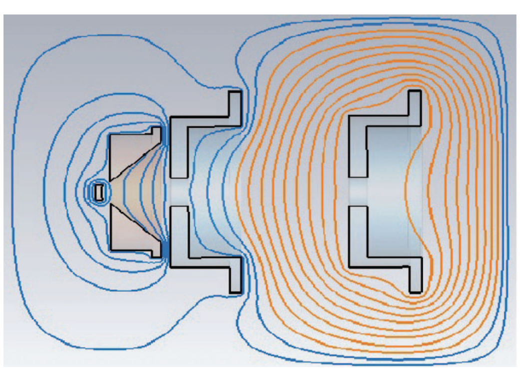

Fig. 4. (color online) The equipotential lines of electron gun extraction system.

5 Simulation of thermionic electron gun by particle tracking software

Beam simulation codes have been valuable tools in understanding and designing electron gun extraction and beam transport systems. There are quite a number of different codes developed and used within this community.

The CST code [10], a program developed for simulating ion beam optics in a certain accelerator configuration, has been widely used in designing ion sources and electron gun accelerators.

Simulation of extraction systems using this simulation code is presented. The ideas applied to the accelerator design are as follows: shaping the emission electrode angle, the applied voltage to the focusing electrode, gap between emission electrode and focusing electrode, and the diameter of the focusing electrode.

5.1 Shape of the emission electrode

There have been long discussions over many years about what angle should be applied to the emission electrode at the corner where the electrode meets the electron beam boundary. For solid emitters such as electron guns and negative sputter ion guns the answer is the famous Pierce angle of 67.5°, which provides the coexistence of a Poisson solution inside the beam and a Laplace solution outside of it. With this condition, there are no aberrations at the beam boundary, and there is a laminar flow of charged particles. It has been accepted that shaping the emission electrode, in general, is helpful to extract a beam at a low divergence angle.

In these simulations using CST Particle Studio, the emission electrode was inclined with respect to the outer edge of the cathode at the Pierce angle of 22.5° while keeping all of the other dimensions fixed. In the configuration shown in Fig. 5, various angles including 22.5°, 30°, and 45° have been used.

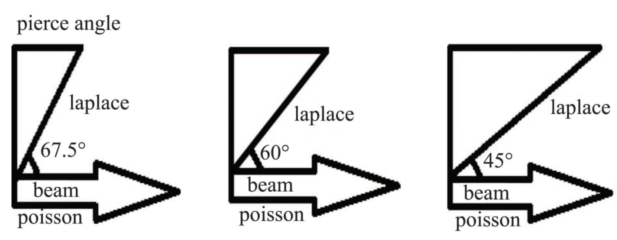

Fig. 5. Different inclination angles of emission electrode.

Table 1 summarizes the simulation results. The wider the electrode angle, the more electron beam can be extracted. A wide electrode angle allows a higher field penetration into the chamber of electron gun than a small angle; therefore, more current is extracted. In addition, high field penetration into the electron gun causes distortions of the beam boundary, which leads to aberrations in the extraction system and divergence increase in the ion beam. The smallest beam diameter and emittance is achieved at small angle of 22.5°.

Table 1. Extraction system simulation results with varying plasma electrode inclinations.

angle of inclination/(°)	beam diameter/mm	emittance /(cm mrad)
30	3.2	4.51
22.5	2	4.23
45	4.3	5.35

5.2 Effect of focusing electrode voltage on beam parameters

Figure 6(a) and (b) show the influence of the voltage applied to the focusing electrode on both the beam emittance and beam diameter of the electron gun. It is concluded from this figure that minimum beam emittance and beam diameter are obtained at focusing voltages V_{Focusing} of −600 and −700 V, respectively.

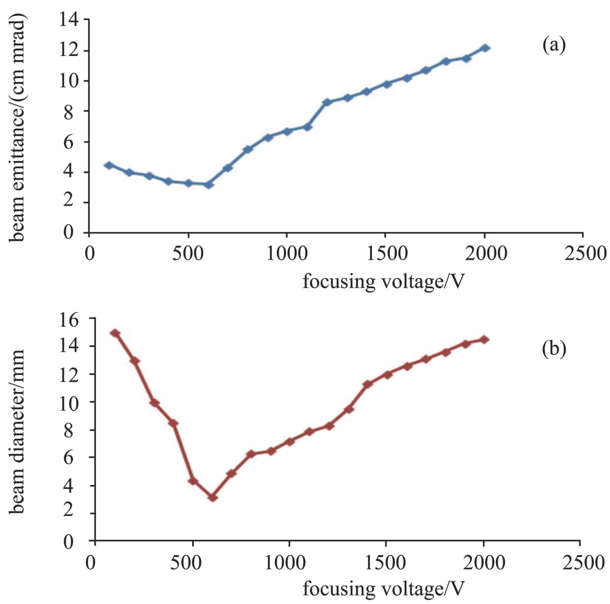

Fig. 6. Influence of the voltage applied to the focusing electrode on both beam emittance (a) and beam diameter (b) of the electron gun.

5.3 Effect of gap width of emission and focusing electrodes on beam parameters

The variation of the distance between the emission electrode and the focusing electrode (gap width) was investigated with space charge at emission voltage of −4 kV, focusing voltage of −600 V and voltage applied to the anode voltage of 12 kV (Fig. 2). Fig. 7 (a, b) show the relation between the distance (gap width) between the emission and focusing electrode from one side and the anode electrode from other side on both the beam emittance and beam diameter of the electron gun. It was found that minimum beam emittance is for a gap width of 4 mm, whereas minimum beam diameter was obtained for a gap width of 6 mm.

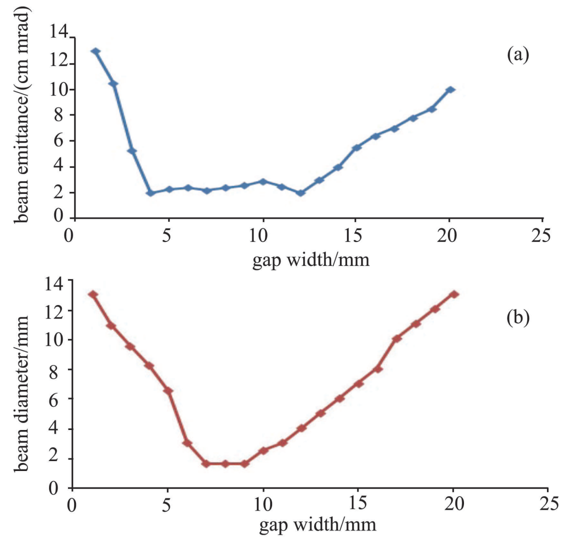

Fig. 7. Beam emittance (a) and beam diameter (b) as a function of the gap width of the emission and focusing electrode.

5.4 Effect of emission electrode diameter on beam parameters

Figure 8 (a, b) show the influence of gun size (inner

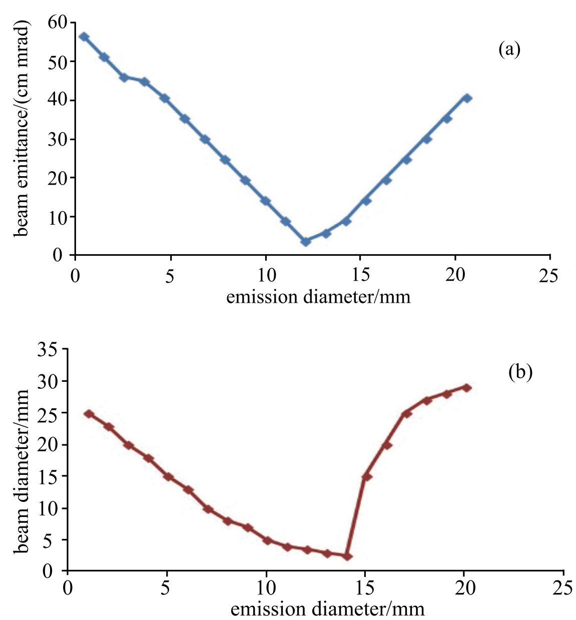

Fig. 8. Beam emittance (a) and beam diameter (b) as a function of the emission electrode diameter for the electron gun system.

tube diameter of the focusing electrode) on the output beam emittance and diameter. This can be attributed to the variation of the electric field inside the accelerating tube. The appropriate diameter was found to be 12 mm and 14 mm for both beam emittance and diameter, respectively of the electron gun.

6 Discussion

We can make a desirable accelerator design that satisfies our goals: low emittance and minimum beam diameter. From the above simulations, an idea has been given in regard to reforming the accelerator configuration. It was concluded that the inclination angle of the emission electrode for good beam optics should be 22.5°. Moreover, minimum beam emittance and beam diameter were found at focusing voltages of −600 and −700 V, respectively. Also, minimum beam emittance and beam diameter were obtained for gap widths of 4 mm and 6 mm respectively. The influence of gun size (inner tube diameter of the focusing electrode) on the output beam emittance and diameter was investigated. This can be attributed to the variation of the electric field inside the accelerating tube. So the appropriate diameter of emission electrode was found to be 12 mm and 14 mm for both minimum beam emittance and diameter of the electron gun respectively. Figure 9 is the calculated profile of the extracted ion beam in the electron gun accelerator structure, which shows its acceptable beam optics properties.

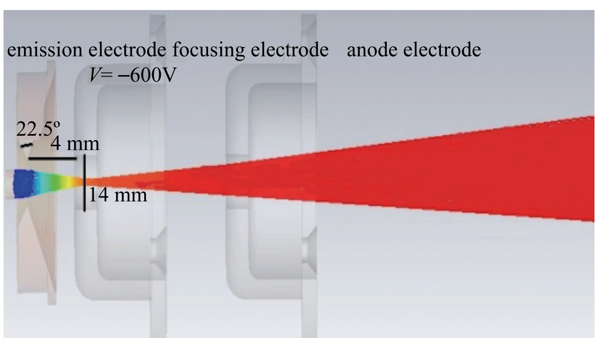

Fig. 9. (color online) Simulation run for the electron gun accelerator structure.

7 Construction of electrodes

Three electrodes were constructed for the emission electrode with different angles (22.5°, 30° and 45°). They were made of st-37, and the focusing and anode electrodes were made from OFHC copper as shown in Fig. 10. Here the electrodes are illustrated before polishing.

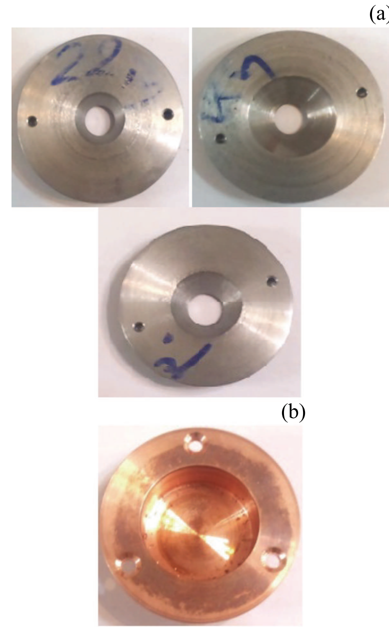

Fig. 10. (color online) (a) the emission electrodes for the three angles (22.5°, 30° and 45°) and (b) focusing and anode electrode.

8 Beam diagnostic results

The beam emittance was measured using a homemade emittance scanner composed of a cube with 15 cm length and width and a 35 cm height aluminum scanner box (Fig. 11) installed on the end of the electron gun to measure the electron beam profiles. This profile monitor system is based on placing 2 separate isolated 0.6 mm thick and 80 mm long tungsten wires for scanning beam profile in both x- and y-directions.

Fig. 11. (color online) A homemade emittance scanner composed of a cube with 15 cm length and width and a 35 cm height aluminum scanner box.

Emittance measurements were performed for three conditions: first for electrodes with different inclination angles as shown in Fig. 10, second by changing the distance between the emission and focusing electrode and thirdly by changing the focusing electrode diameter. Figure 12 shows the change of the emittance as a function of emission electrode inclination angle at fixed parameters corresponding to those used in the simulation process. These parameters are gap width between emission electrode and focusing electrode of 4 mm, focusing electrode voltage of −600 V and diameter of the emission electrode of 14 mm.

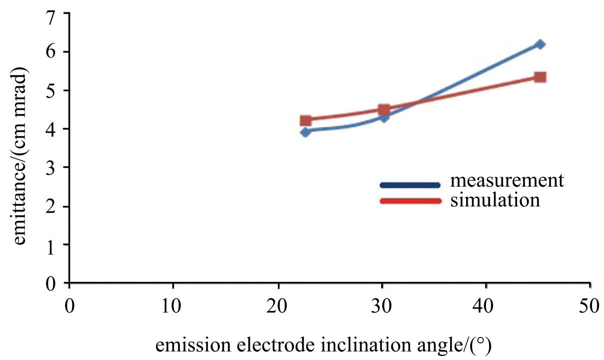

Fig. 12. (color online) Measured and simulated emittance as a function of emission electrode inclination angle.

Figure 13 shows the change of the emittance as a focusing electrode voltage on beam parameters at inclination angle of emission electrode of 22.5°, gap width of 4 mm and diameter of the emission electrode of 14 mm.

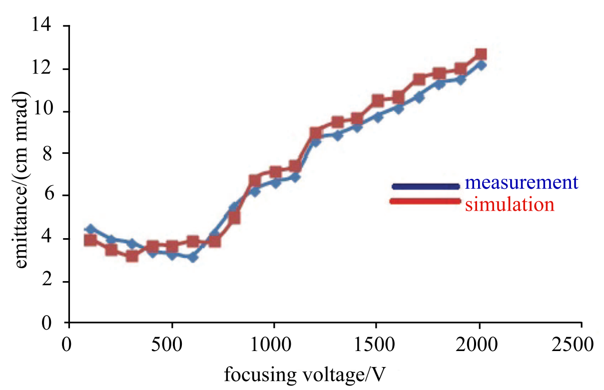

Fig. 13. (color online) Measured and simulated emittance as a function of focusing electrode voltage.

Figure 14 shows the change in emittance as a function of gap width of the emission and focusing electrode at emission electrode inclination angle of 22.5°, focusing voltage of −600 V and diameter of the emission electrode of 14 mm.

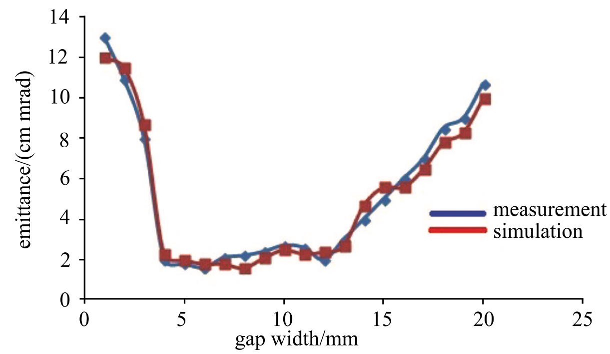

Fig. 14. (color online) Measured and simulated emittance as a function of gap width.

For the experimental part of the work we focused on the emittance measurement, ensuring that its diagnostic was constructed and tested successfully. In all of the experiment process the key parameters were set as constant and just one of them was changed to see its effect on emittance. These parameters are the inclination angle of the emission electrode, the gap width of the emission and focusing electrodes and the voltage applied to the focusing electrode. Moreover, throughout the experimental process, the diameter of the emission electrode was kept at 14 mm. As is clear from the figures above, the measurements and simulation results for these three parameters are consistent.

9 Conclusion

This paper presents the parametric optimization and design of an electron gun system. The influence of the voltage applied to the focusing electrode, inclination angle of emission electrode, the gap between emission and focusing electrode and the diameter of focusing electrode on both the beam emittance and beam diameter of the electron gun have been studied.

In this paper, the ion beam trajectories for different parameters of the accelerator structure were simulated and optimized. The CST simulation provided some conclusions. The inclination angle of the emission electrode is optimized at 22.5°, the applied voltage to the focusing electrode was optimized and found to be roughly $V_{\rm foc} = -600$ V, the separation distance (gap between emission electrode and focusing electrode) is 4 mm, and the diameter of the emission electrode should be about 14 mm.

Also, tungsten filament was chosen as the electron emitter and its temperature and current density were calculated.

The simulation results helped to direct the experimental setup and the emittance measurement was done by wire scanner. Relatively good overlap was found between the experimental and simulation results.

References

1 S. Schiller, U. Heisig, S. Panzer, *Electron beam technology,* New York: Wiley; 1982

2 N. Rykalin, A. Uglov, I. Zuev, A. Kokora, *Laser and electron beam material processing handbook,* Moscow: MIR Publishers; (1988)

3 *Proceedings of the 7-th International Conference on Electron Beam Technologies* (EBT'2003) Varna, Bulgaria; 1e6 June (2003)

4 P. H. Ron, Bulletin of Indian Vacuum Society, **1**(2):3 (1998)

5 R. J. Bakish, Metals, **38**: 53 (1986)

6 A. S. Gilmour, Jr., *Principles of Traveling Wave Tubes,* (Artech House, Inc., Norwood, 1941)

7 Alexander Wu Chao, Herbert Moser, *Principle of Physics Charge Particle Acceleration,* Part IX, (1996)

8 M. Sedlacek, *Electron Physics of Vacuum and Gaseous Devices,* (Wiley, New York, 1996)

9 C. J. Karzmark, *Medical Electron Accelerators, Department of Radiation Oncology Stanford University School of Medicine* (McGraw-Hill, New York, 1993)

10 CST PS manual, (2011)

11 A. Spetier, *Focusing of charged particles,* New York and London: Academic press, (1967)

12 P. Spadtke, *The physics and technology of ion sources,* New York: John Wiley, (2004)