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SIMULATION STUDY FOR ELECTRON GUN USING SIMION COMPUTER PROGRAM

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ABSTRACT

The manuscript reports the simulation of an electron gun with a view to optimizing the design of radio-frequency sources. The effects of eight parameters on the beam quality were studied and optimal choices were identified. It gives numerical beam qualities in common electrostatic triode gun, and the dependences on design parameters such as electrode geometries and bias voltages to these electrodes are shown. The electron gun is used in a number of various applications as in atomic, molecular, and surface physics. The electron optics of the electron gun was simulated and optimized using electron-beam ray-tracing simulation program SIMION 3D 7.0. An electron beam of diameter 5 mm with energy of 5 keV was assumed for simulation process. Eight design parameters were identified as variable parameters in the presence of space charge. These parameters are the gap width between the emission electrode and the anode electrode, the gap width between the emission electrode and the focusing electrode. The diameter of the anode of the electron gun, and also, diameter of the focusing electrode are studied. The applied voltage to both the emission electrode and the focusing electrode are investigated. Furthermore, the influence of space charge on the electron beam envelope through the extraction region of electron source was investigated. The space charge started to have a clear influence on the electron beam envelope at currents of 10^{-4} A. Beam quality was significantly improved when the applied voltage to the anode electrode was optimized and found at V_{anode} = + 29 k V, also, voltage applied to the emission electrode was optimized and found $V_{emission}$ = - 3.6 kV, and finally voltage applied to the focusing electrode, $_{Vfoc}$= - 500 V. separation distance (gap between emission electrode and) = 12 mm, the diameter of the focusing electrode = 14 mm and finally the best focused point was found at a distance of 550 mm from the end of the lens system.

Keywords: Electron beam trajectories, Beam emittance and beam diameter, Focusing voltage and space charge.

INTRODUCTION

Design, fabrication and utilization of electron guns have gained unique importance in the areas of fundamental research as well as for industrial and space applications (Spadtke, 2004; Ulu *et al.*, 2007) .

Electron and ion beam equipment play a vital role in the semiconductor manufacturing and nanotechnology industries. The computer simulations (Spadtke, 2004; Ulu *et al.*, 2007) come as a complementary approach, which involves elements from both theory and experiment. As a numerical model of the experiment based on observations, it allows to study the behavior of a real system by following the response to changes in the input parameters. The simulations prove to be a very powerful tool in acquiring quantitative characteristics and identifying the significant phenomena in each particular case. Moreover, there are situations, where realistic experiments cannot be performed.

Electron guns (Molokovsky and Sushkov, 2005; Ignatova *et al.*, 2006; Oks, 2006) are used in many vacuum electron devices to convert electrical power into an electron beam. Electron beam devices include RF sources for numerous applications such as communications, radar, industrial heating, and high energy accelerators. Electron beams are also used in medical and industrial x-ray devices, for electron beam lithography and electron beam welding, and in cathode ray guns for televisions and oscilloscopes. Many of these devices (Peter and Brady, 2004; Tomi, 2008) are critical for national defense and science and industrial applications.

The most common use of electron guns is in cathode ray tubes, which were widely used in computer and television monitors. An electron gun can also be used to ionize particles by adding or removing electrons from an atom. This technology is sometimes used in mass spectrometry in a process called electron ionization to ionize vaporized or gaseous particles. In this work, the electron optics of the electron gun was simulated and optimized using electron-beam ray-tracing simulation program SIMION 3D 7.0. An electron beam of diameter 5 mm with energy of 5 keV was assumed for simulation process. Eight design parameters were identified as variable parameters in the presence of space charge. Beam quality was significantly improved when the applied voltage to the anode electrode was optimized and found at V_{anode} = + 29 k V, in addition to, voltage applied to the emission electrode was optimized and found $V_{emission}$ = - 3.6 kV, and also finally voltage applied to the focusing electrode, $_{Vfoc}$= - 500 V. separation distance (gap between emission electrode and) = 12 mm, the diameter of the focusing electrode = 14 mm and finally the best focused point was found at a distance of 550 mm from the end of the lens system.

THEORETICAL TREATMENT

In plasma sources, the shape of the plasma meniscus defines the output beam shape (concave, convex and flat), but in thermionic electron gun, a shaping electrode (focusing electrode) is used.

This electrode has many shapes according to the gun type to avoid beam dispersion. An electron gun is an electrical component that produces an electron beam that has a precise kinetic energy and is most often used in television sets and computer displays which use cathode ray tube (CRT) technology, as well as in other instruments, such as electron microscopes and particle accelerators. Electron guns may be classified in several ways:

- by the type of electric field generation (DC or RF),
- by emission mechanism (thermionic, photocathode, cold emission, plasmas source),
- by focusing (pure electrostatic or with magnetic fields), or
- by the number of electrodes.

The electric field in the gun is first calculated using Poisson's equations (Vittuone *et al.*, 1992), 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:

$$\nabla . E = \frac{\rho}{\epsilon_0} \qquad (1)$$

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 Lorentz force given by:

$$F = \frac{dP}{dt} = q(E + VxB) \qquad (2)$$

which simplify to (there is no magnetic field)

$$F = \frac{dP}{dt} = qE \qquad (3)$$

The maximum electron current density that can be accelerated across a planar gap is given by the Child law [9]:

$$j_e = \frac{4\pi \epsilon_0}{9} \sqrt{\frac{2e}{m_e}} \frac{V_0^{3/2}}{d^2} \qquad (4)$$

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

$$j_e = 2.33x10^{-6} \frac{V_0^{3/2}}{d^2} \qquad (5)$$

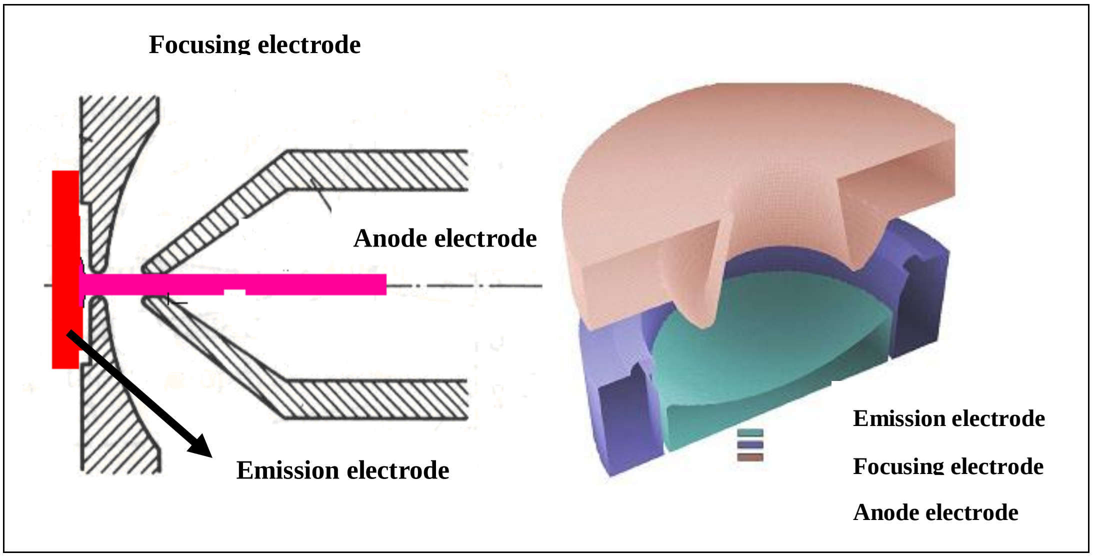
The units are A/m^2 for d in meter.
In case of radius of < d/2, then the extraction area A = лd^2/4 and using eq.5, the maximum total current from an electron gun is:

$$j_e = 2.33x10^{-6} \frac{\pi}{4} V_0^{3/2} \qquad (6)$$

The perveance of an electron gun is defined as:

$$P = \frac{I}{V_0^{3/2}} \quad (7)$$

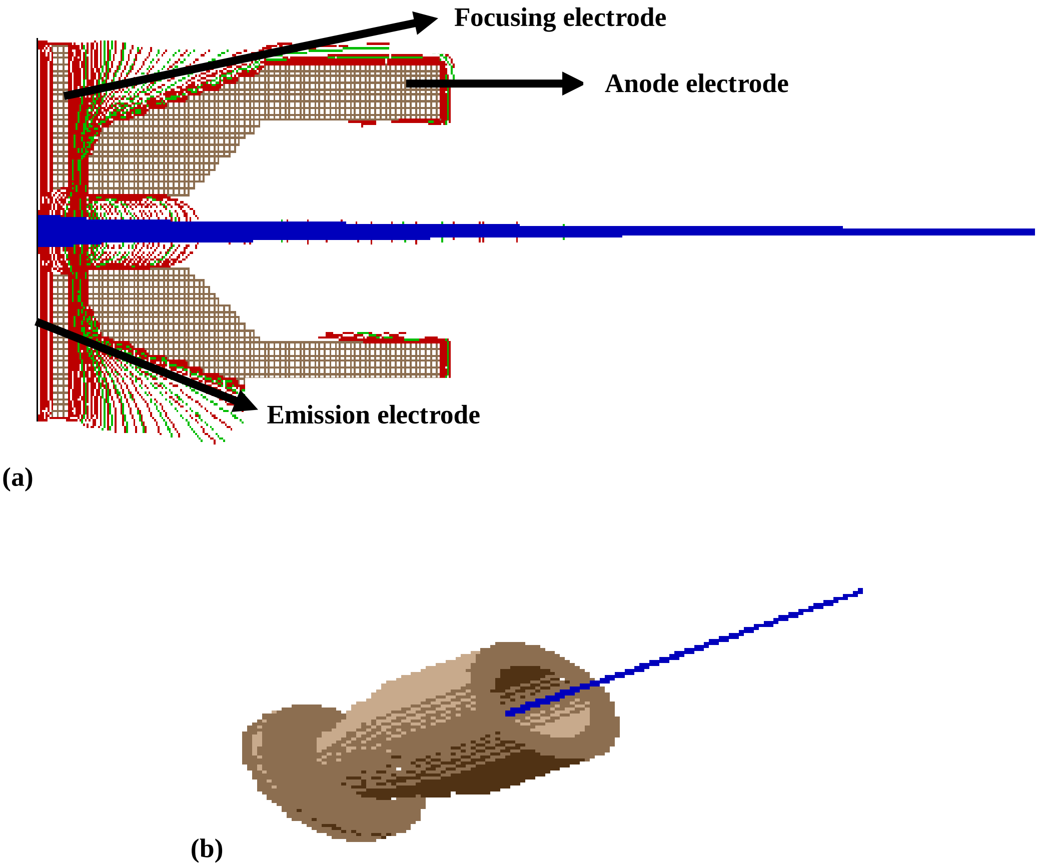
Fig-1. Electron gun elements



Simulation Process

Simulations were run using SIMION 3D v7.0 (lUrtmarrasfeldt, 1988; Dahl, 2000; Kojima *et al.*, 2007) to study electron gun parameters. Ssimulation of the charged electron trajectories for flat plasma was studied with and without space charge effect using a model of constant plasma density. In this work, beam simulation is carried out to reveal the influence of the space charge effect on the beam emittance and beam diameter. Indeed, the influence of the tube diameter on beam emittance for the charged electron trajectories was investigated. The emission electrode was considered as the plasma emission surface, where the electrons are starting to fly away. The voltage applied to the emission electrode was varied and optimized. The voltage applied to the extraction electrode (anode electrode) was varied and optimized to accomplish the suitable electron trajectories without hitting the extraction electrode. The simulations were also helpful in determining the proper biasing of the electron gun. To operate SIMION, the locations and sizes of the electrodes were input with their proper potentials. SIMION then used these potentials as boundary values to solve Laplace's equation to determine the potential everywhere. The program approximates solutions to Laplace's equation with a finite difference technique called over-relaxation, which is based on successive approximations. In each iteration, the potential of a point is estimated based on the fields of the four nearest points. For a 3D simulation the 6 nearest neighbors are used. As the iterations proceed, the potentials change less and less with each iteration. SIMION takes the values of the potential as an approximate solution to Laplace's equation when this change is less than a certain value. SIMION estimates the potential of four points that are 0.5 grid units away from the ion. These points are then used to determine the voltage gradient and hence electric field at the ions position.

Fig-2. Electron gun geometry assumed for the SIMION calculations with the contours.



Simulation Results

Fig.3 a and b show the influence of the voltage applied to the anode electrode on both the beam emittance and beam diameter of the electron gun. It was seen that from this figure, minimum of beam emittance and beam diameter is got, at anode voltage V_{anode} of 29, 35 kV, respectively.

Fig-3a,b. Influence of the anode voltage applied to the anode electrode on both beam emittance and beam diameter of the electron gun..

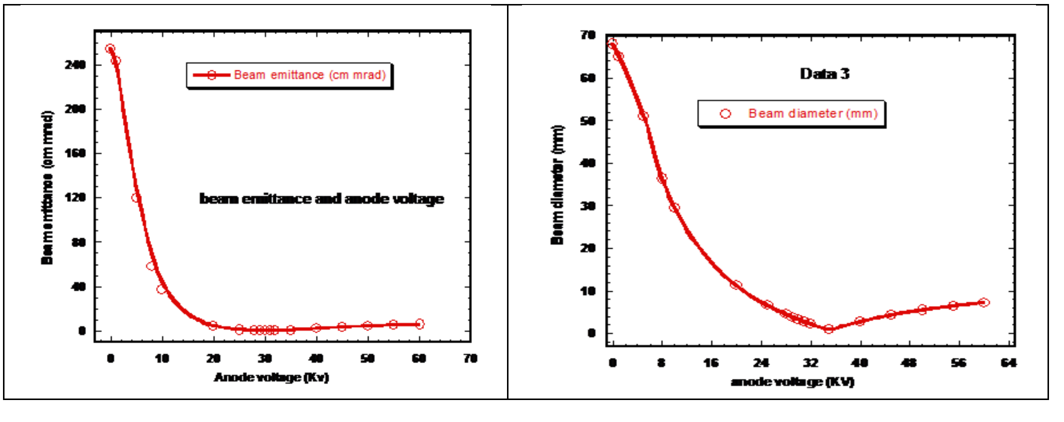


Fig.4 a and b show the influence of the voltage applied to the emission electrode on beoth the beam emittance and beam diameter of the electron gun. It was found that from this figure, minimum of beam emittance and beam diameter is got, at an emission voltage $V_{emission}$ of – 3.6, 3.1 kV, respectively.

Fig-4a. Influence of the emission voltage applied to the emission electrode on both beam emittance and beam diameter of the electron gun.

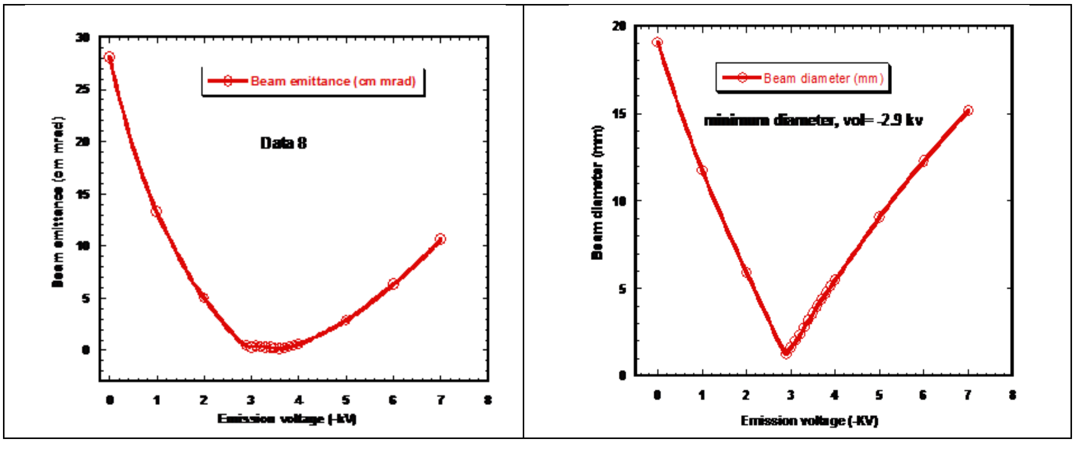
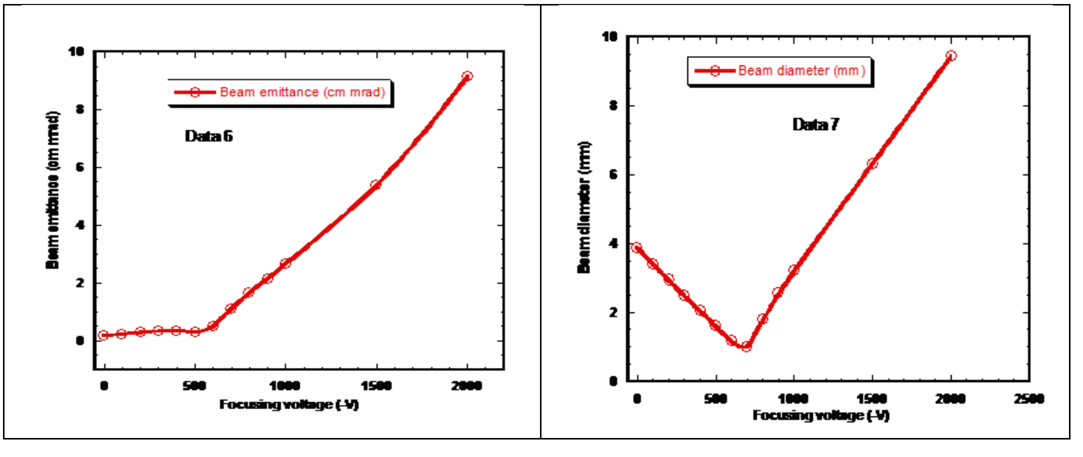


Fig.5 a and b show the influence of the voltage applied to the focusing electrode on both the beam emittance and beam diameter of the electron gun. It was concluded that from this figure, minimum beam emittance and beam diameter is obtained, at focusing voltage $V_{Focusing}$ of – 500, - 700 V, respectively.

Fig-5a. Influence of the voltage applied to the focusing electrode on both beam emittance and beam diameter of the electron gun.



In the presence of space charge, the electric field acting on electron beam is (Ishikawa, 1982; Abdelrahman and Zakhary, 2009):

$$E_r = \frac{q}{2\pi\varepsilon_0 r} = \frac{I_0}{2\pi\varepsilon_0 v_0 r}, \qquad (8)$$

where q is the charge of the beam per unit length within radius r and $q = \frac{I_0}{v_0}$ where I_0 is the total electron beam current, v_0 is the axial ion velocity and ε_0 is the permittivity of free space.

Equation (8) becomes

$$E_r = \frac{I_o}{2\pi\varepsilon_o r(2e/m)^{1/2}V^{1/2}} = \frac{I_o}{ArV^{1/2}} \qquad (9)$$

where A= $2\pi\varepsilon_o(2e/m)^{1/2}$

The variation of the distance between the emission electrode and the focusing and anode electrodes (gap width) was investigated with space charge at emission voltage of – 3.6 kV, focusing voltage of – 500 V and voltage applied to the anode voltage of 29 kV (Fig.6). Fig.6 a and b shows the relation between the distance (gap width) between the anode and focusing electrode from one side and the emission electrode from other side on both the beam emittance and beam diameter of the electron gun. It was found that, minimum beam emittance of 4 mm for a gap width of the electron gun, whereas minimum beam diameter of 6 mm was obtained.

For ion beam extraction, the current, $I_i = \frac{J_i}{A}$ the perveance is given by (Spetier, 1967):

$$P = \frac{I_i}{V^{3/2}} \times \left(\frac{A}{z}\right)^{1/2} = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m}}\frac{A}{d^2} \qquad (10)$$

where A is the emitting area, z is the charge, I_i total ion beam current ε_0 is the free space permittivity, d is the extraction gap width and V is the acceleration voltage.

Fig-6a,b. Beam emittance and beam diameter as a function of the the gap width of the anode and focusing electrode from one side and the emission electrode from other side of the electron gun.

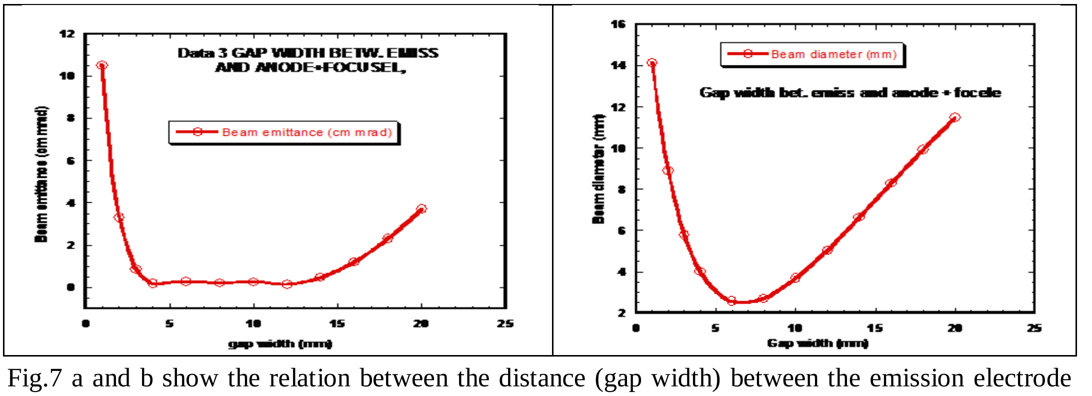


Fig.7 a and b show the relation between the distance (gap width) between the emission electrode and focusing electrode from one side and the anode electrode from other side on both the beam emittance and beam diameter of the electron gun. It was found that, minimum beam emittance of 3 mm for a gap width of the electron gun, whereas minimum beam diameter of 4 mm was obtained downstream of distance 190 mm.

Fig-7a, b. Beam emittance and beam diameter as a function of the the gap width of the emission electrode and focusing electrode from one side and the anode electrode from other side of the electron gun.

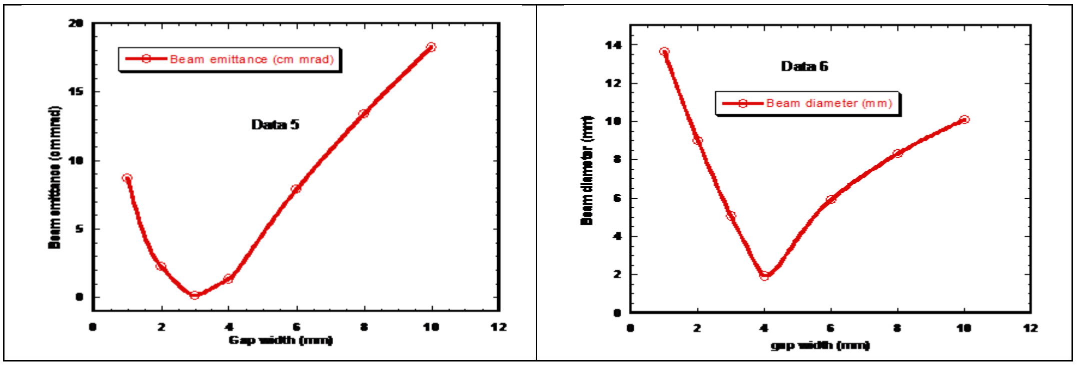


Fig.8 a and b show the influence of gun size (inner tube diameter of the focusing electrode) and the output beam emittance and diameter. This can be attributed to the variation of the electric field inside the accelerating tube. The appropriate diameter was found to be 14 mm and 12 mm for both beam emittance and diameter, respectively of the electron gun, whereas minimum beam emittance and diameter were obtained downstream of distance 190 mm.

Fig-8a, b. Beam emittance and beam diameter as a function of the focusing diameter for the electron gun system.

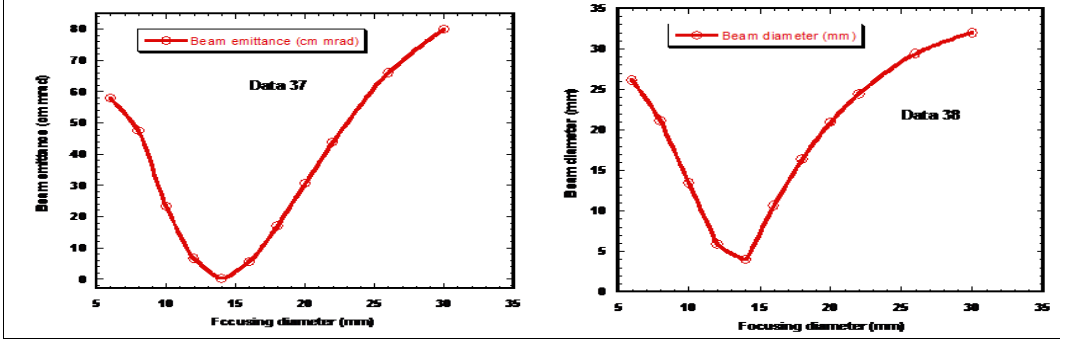
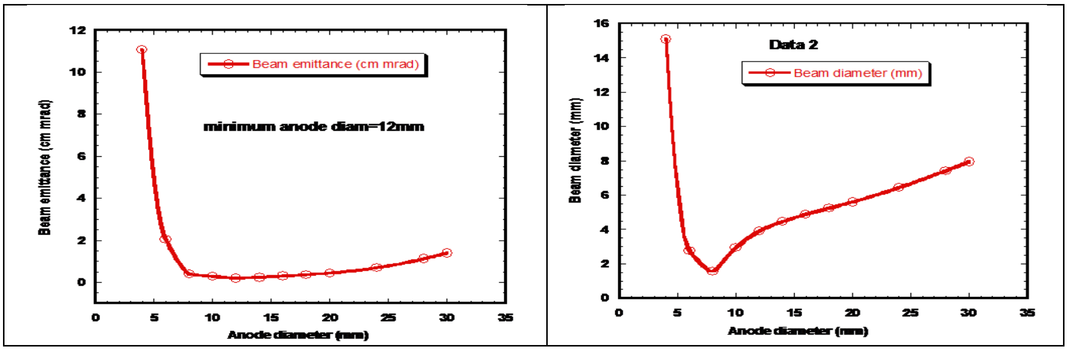


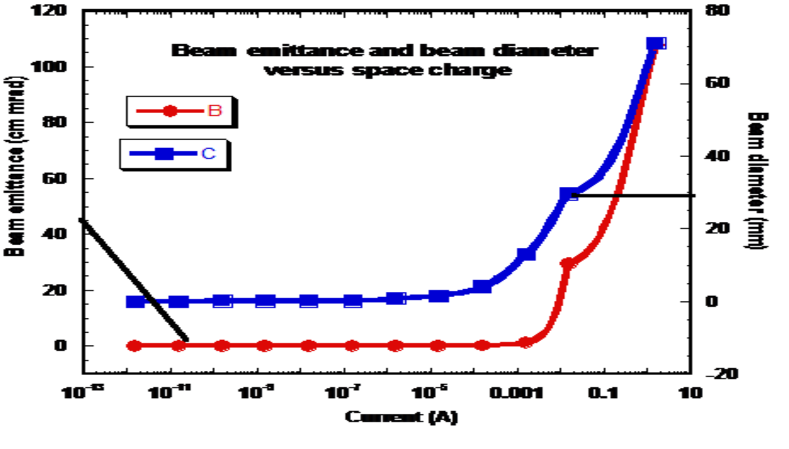
Fig.9 a and b show the influence of gun size (inner tube diameter of the anode electrode) and the output beam emittance and diameter. This can be attributed to the variation of the electric field inside the accelerating tube. The appropriate diameter was found to be 12 mm and 8 mm for both beam emittance and diameter, respectively of the electron gun, whereas minimum beam emittance and diameter were obtained downstream of distance 190 mm.

Fig-9a, b. Beam emittance and beam diameter as a function of the anode diameter for the electron gun system.



The space charge is only considered in the gap between the plasma boundary and the extraction electrode, where the axial potential changes rapidly. In this region, the electrons formed by ion impact on residual gas atoms will always be pulled out of the ion beam. Therefore, in this region space charge repulsion between the ions is important as soon as the ion current density becomes sufficiently large. On the other hand, in a freely drifting electron beam (no acceleration potential applied) space charge compensation will automatically work and therefore space charge repulsion is not considered there. The influence of space charge on the electron beam envelope through the extraction region of electron source was investigated. Space charge was compensated in the extraction region for electron currents between micro amps and milliamps. It was found that space charge has no influence on the electron beam envelope at currents of micro amps. The space charge started to have a clear influence on the electron beam envelope at currents of 10^{-4} A (Fig. 10). Space charge depends on the geometry of the electrodes, applied potentials and electron current. Therefore, the change of the electron current has a clear influence where other parameters were fixed. The space charge force acts as a diverging force because particles of the same charge repel each other.

Fig-10. Influence of the current on both beam emittance and beam diameter for the electron gun system.



CONCLUSION

This paper presents parametric optimization of optimizing and designing an electron gun **system.** Influence of the voltage applied to the anode electrode on both the beam emittance and beam diameter of the electron gun **has been investigated.** It was seen that minimum beam emittance and beam diameter **was** obtained, at anode voltage V_{anode} of 29, 35 kV, respectively. **Further,** the influence of the voltage applied to the emission electrode on both the beam emittance and beam diameter of the electron gun has been studied. It was found that , minimum beam emittance and beam diameter was obtained, at an emission voltage $V_{emission}$ of – 3.6, 3.1 kV, respectively. In further consequence, the influence of the voltage applied to the focusing electrode on both the beam emittance and beam diameter of the electron gun. It was concluded that, minimum beam emittance and beam diameter was found at focusing voltage $V_{Focusing}$ of – 500, - 700 V, respectively. The relation between the distance (gap width) between the anode and focusing electrode from one side and the emission electrode from other side on both the beam emittance and beam diameter of the electron gun. It was found that, minimum beam emittance of 4 mm for a gap width of the electron gun, whereas minimum beam diameter of 6 mm was obtained. Also, the relation between the distance (gap width) and the emission electrode 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 of 3 mm for a gap width of the electron gun, whereas minimum beam diameter of 4 mm was obtained downstream of distance 190 mm. The influence of gun size (inner tube diameter of the focusing electrode) and 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 14 mm and 12 mm for both beam emittance and diameter, respectively of the electron gun, whereas minimum beam emittance and diameter were obtained downstream of distance 190 mm. It was found that space charge has no influence on the electron beam envelope at currents of micro amps. The space charge started to have a clear influence on the electron beam envelope at currents of 10^{-4} A. Space charge depends on the geometry of the electrodes, applied potentials and electron current. Therefore, the change of the electron current has a clear influence where other parameters were fixed.

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