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Simulation Study of Electron Beam Spot Size From Thermionic Electron Gun Using SIMION 8.1 Software

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Abstract. This paper is deal with the result of simulation study of electrons beam spot size from thermionic electron gun using SIMION 8.1 software. The thermionic electron gun is an important part of electron beam machine (EBM) currently developed at CAST BATAN Yogyakarta. It produces electrons beam which is dedicated for latex pre-vulcanization process. The aim of simulation is to analyse the influence of electron gun parameters, such as electron beam intensity, extraction voltage and acceleration voltage, on electron beam spot size and to predict the optimum size of electron beam spot at titanium window of EBM. The simulation was carried out by varying beam intensity from 2 mA up to 20 mA, extraction voltage from 2 kV up to 12 kV and accelerating voltage from 150 kV up to 300 kV. From the result of simulation it is concluded that thermionic electron gun can produce linear divergent electrons beam trajectory. This trajectory is depend on the equipotential lines which are defined by electron gun parameters comprises electron beam intensity, extraction voltage and accelerating voltage. Based on the simulation result, the influence of electron gun parameters on electron beam spot diameter can be summarized as follows: the variation of electron beam intensity from 2 mA up to 20 mA at extraction voltage of 12 kV and accelerating voltage of 300 kV yields the variation of electron beam spot diameter from 5.35 cm up to 5.49 cm. The variation of extraction voltage from 2 kV up to 12 kV at accelerating voltage of 300 kV and electron beam intensity of 20 mA yields the decrease of electron beam spot diameter exponentially. The smallest diameters of electron beam spot are $d_1 = 5.41$ cm and $d_2 = 5.44$ cm at extraction voltage of 10 kV and 12 kV respectively. The variation of accelerating voltage from 150 kV up to 300 kV at extraction voltage of 12 kV and electron beam intensity of 20 mA yields the decrease of electron beam spot diameter significantly. The smallest diameters of electron beam spot are $d_1 = 5.41$ cm and $d_2 = 5.42$ cm at accelerating voltage of 300 kV and 275 kV respectively. d_1 and d_2 are diameter of electron beam spot along y axis and x axis respectively.

INTRODUCTION

Currently an electron beam machine (EBM) is fabricated at The Center for Accelerator Science and Technology (CAST) BATAN for latex irradiation process. One of the components of EBM is electron gun which provides electron beams. This electron beam is guided, focused and transported into an accelerator tube for achieving desired energy and finally exit through thin window made of titanium foil. A thermionic electron gun has been designed and fabricated based on Pierce electrode configuration. Before being installed with other components of EBM, this

electron gun has been tested and the result shows that it has capability to produce electron beam up to 55 mA. However, based on the test result after the electron gun was installed it is shown that the electron beam is not parallel to the axis of EBM so that most of them will hit the wall of scanning horn and the flange of window [1].

The problem of electron gun construction in EBM is the isolation between electrodes of electron gun. It is very difficult to joint metal and ceramic. To solve this problem the three electrodes electron gun has been designed and constructed by utilizing accelerator tube of National Electric Corporation (NEC) as electrode and chamber of electron gun. The electron gun is a Pierce type thermionic electron gun which consists of filament, Pierce cathode and focusing anode installed at a flange loaded to accelerator tube [2].

The characterization of above Pierce type electron gun has been carried out to measure the shape of the electron beam profile using a fluorescence detector material and to measure the electron beam current output using faraday cup. The result of characterization is that the Pierce type electron gun is functioning well, the beam profile is influenced by the focusing anode voltage, and the electron beam current output is determined by the extraction voltage [3]. This result is relevant to the statement of M.M. Abdelrahman that the shape of electron beam extracted from electron gun is defined by the shape of plasma meniscus in electron gun chamber. Thermionic electron gun uses focusing electrode as shaping electrode which has many shapes according to the gun type to avoid electron beam dispersion [4].

The size of electron beam spot in EBM has to be suited with the dimension of EBM window. The research done by A.V. Deore, et.al. shows that the electron beam diameter depends on the bias voltage of the control electrode. The beam diameter decreases with increasing the bias voltage of the control electrode [5]. This paper reports the results of simulation study of electron beam spot size from thermionic electron gun using SIMION 8.1 software. The simulation was carried out at CAST BATAN Yogyakarta in collaboration with The Physics Department of Graduate Program Sebelas Maret University Surakarta. The aim of this work is to analyze the influence of thermionic electron gun parameters on electron beam spot size and to predict the optimum electron beam spot size.

THEORETICAL BASICS

An electron gun is an electrical component that produces an electron beam that has a precise kinetic energy. It 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 accelerator. A thermionic electron gun uses a shaping electrode (focusing electrode) to avoid beam dispersion where the output beam shape is defined by the shape of the plasma meniscus (concave, convex and flat) in plasma source of electron gun [4].

The shaping electrode used to form a parallel electron beam is a Pierce electrodes configuration which consists of cathode and anode. The electron current density J_e flowing from Pierce cathode toward focusing anode is given by Child equation [6]:

$$J_e = \chi \frac{V_a^{3/2}}{a^2} \tag{1}$$

 V_a is anode potential in volts, a is the distance between Pierce cathode and anode in meters, $\chi = \left(\frac{4\varepsilon_0}{9}\right)\sqrt{\left(\frac{2e}{m}\right)}$ is a constant. For electron, χ has a value of 2.334 x 10^{-6} A/V^{3/2}.

The potential distribution between Pierce cathode and anode for rectangular electron beam can be found with analytical approximation and the result is given by the equation:

$$V(x,y) = \left(\frac{J_e}{\gamma}\right)^{\frac{2}{3}} (x^2 + y^2)^{2/3} \cos\left(\frac{4}{3}tan^{-1}\frac{y}{x}\right)$$
 (2)

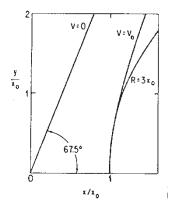
The equation (2) describes the equipotential planes between Pierce cathode and anode for rectangular electron beam with the assumption that the cathode is equipotential plane V(x,y) = 0. It is shown from equation (2) that the equipotential V(x,y) = 0 requires $\left(\frac{4}{3}\right) tan^{-1} \left(\frac{y}{x}\right) = \frac{\pi}{2}$. It means that the angle between cathode plane and x axis (electron beam direction) $3\pi/8$ radians or 67.5 degrees. If V(x,y) normalized to V_0 which is given by equation:

$$V_0 = V(x_0, 0) = \left(\frac{J}{\chi}\right)^{2/3} x_0^{4/3}$$
 we get normalized potential given by equation: (3)

$$\frac{V}{V_0} = \left[\left(\frac{x}{x_0} \right)^2 + \left(\frac{y}{x_0} \right)^2 \right]^{2/3} + \cos \left(\frac{4}{3} \tan^{-1} \left(\frac{\frac{y}{x_0}}{\frac{x}{x_0}} \right) \right) \tag{4}$$

Equipotential planes for normalized potential given by equation (4) can be illustrated as shown in Fig.1 [6]. We can set the cathode potential V = 0 and anode potential $V_0 = \left(\frac{I}{\chi}\right)^{2/3} x_0^{4/3}$ to get a rectangular electron beam with Pierce electrode configuration.

For cylindrical electron beam, the potential distribution between Pierce cathode and anode can be found with electrolytic tank approximation. The equipotential planes are as illustrated in Fig.2 [6].



Edge Axis O 2 4 6 8 10 2/r₀

FIGURE 1. Equipotential planes in Pierce electrode configuration for rectangular electron beam [6].

FIGURE 2. Equipotential planes in Pierce electrode configuration for cylindrical electron beam [6].

METHODOLOGY

Simulation was done using SIMION 8.1 to study the effects of electron gun parameters on electron beam spot size and to predict the optimum electron beam spot size. SIMION 8.1 is a software package used to calculate electric fields and the trajectories of charged particles in those fields when given a configuration of electrodes with voltages and particles initial conditions. This program provides extensive supporting functionality in geometry definition, user programming, data recording and visualization [7].

SIMION 8.1 is Windows based software for simulation of ion/electron beam optic/trajectory. It makes use of potential arrays that define the geometry of electrodes or magnetic poles as well as the potentials both on the electrodes and in the empty space between the electrodes. The potentials on the electrodes are defined by user, and then SIMION solves the potentials in the space between the electrodes by solving the Laplace equation by finite difference methods. This process is called refining the potential array [8].

The steps of simulation using SIMION 8.1 to study the effects of electron gun parameters on electron beam spot size are as follows[9]:

Designing the Geometry of Electron Gun Electrodes

The simulation was started by defining the geometry of electron gun electrodes. The geometry of electrodes was adopted from the geometry of electrodes which has been simulated earlier using Opera 3D software. It consists of emitting cathode (filament), Pierce cathode and focusing anode which are mounted at a flange loaded to NEC (National Electric Corporation) accelerator tube. The geometry of electrodes was designed using Notepad⁺⁺, saved as GEM.file and then inputted to SIMION 8.1 using the menu *New > Use Geometry File* (GEM). Then using the menu *Modify* of SIMION 8.1 the electrodes geometry design is as shown in Fig.3.

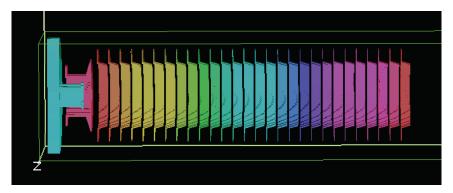


FIGURE 3. Electrodes geometry design as displayed by the menu Modify of SIMION 8.1.

Refining Process

The next step was refining process which is the process for calculating equipotential of the given electrodes geometry. Refining means using the potentials of electrode array points to estimate the potentials of non-electrode array points. The refining process makes use of finite difference technique to solve the Laplace equation numerically. Using the *Refine* button of SIMION 8.1 the refining process as shown in Fig.4.

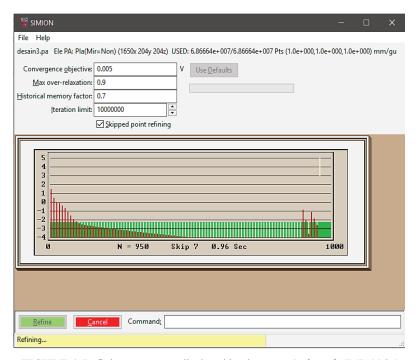


FIGURE 4. Refining process as displayed by the menu Refine of SIMION 8.1

Defining the Initial Particle Parameters

The next step was defining initial particle parameters including particle number, particle species (electron, proton or default), particle mass and charge, particle source position, particle initial energy, etc. using the menu *View/Load Workbench > Particle > Define Particle* as shown in Fig.5. In this simulation the number of particle is 1000.

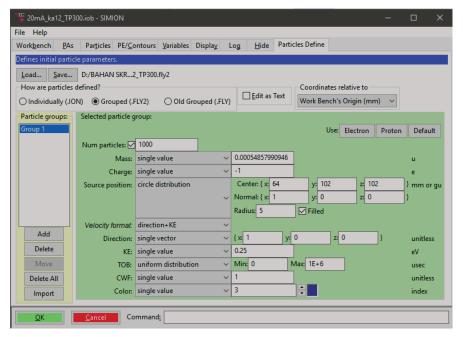


FIGURE 5. Initial Particle Parameters as displayed by the menu Define Particles of SIMION 8.1

The beam current I_b is varied from 2 mA up to 20 mA with interval of 2 mA. For inputting I_b activate the *Particles* menu and check the *Grouped* to activate *Repulsion* and choice *Coul*. For inputting extraction voltage V_e and accelerating voltage V_a use the menu $PAs > Fast \ Adjust \ Voltages$. The extraction voltage V_e is a voltage between cathode and anode. V_e is varied from 2 kV up to 12 kV with interval of 2 kV. V_a is varied from 150 kV up to 300 kV with interval of 25 kV.

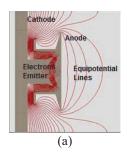
Running Program or Fly'm Particle

The last step is fly'm particle or running the program using inputted particle parameters. The yield is particle trajectory and coordinates for calculating electron beam diameter at EBM window.

RESULT AND DISCUSSION

Equipotential Lines Between the Electrodes

The results of the simulation using SIMION 8.1 software are electron beam trajectories between the electrodes of electron gun, electrodes inside the accelerator tube and the window. The electron beam trajectories are influenced by the equipotential lines which arise from each electrode. These equipotential lines are as shown in Fig.6.



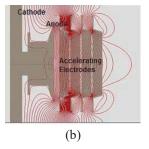


FIGURE 6. The equipotential lines, (a) in the near of cathode and anode of electron gun, as well as (b) between cathode, anode and accelerating electrodes.

Based on the geometry design, the cathode and anode are separated by the distance of 1 cm. The voltage on cathode and anode are - 312 kV and - 300 kV respectively. From Fig.6 (a) it is shown that in front of the anode, the equipotential lines are not parallel to each other but it form parabolic lines. Therefore in front of the anode the electron beam is divergent. From Fig.6 (b) it is shown that between the anode and the first accelerating electrode the equipotential lines are parallel to each other, so the electron beam trajectories in this area are parallel. Therefore the first accelerating electrodes will reduce the divergence of electron beam. But after the third accelerating electrode the electron beam spread out again because the equipotential lines are parabolic.

Electron Beam Trajectory

For the simulation of electron beam trajectory from cathode up to window of EBM it is assumed that the distribution of emitted electrons by electron emitter is a circle distribution of 1 cm diameter, and the distance from emitter to anode is 0.6 cm. The number of particle is defined to represent the real number of particle to be simulated. The number of particle can be defined smaller than the real number of particle to reduce the running time. In this case, the number particle is varied as 10, 500, 1000 and 2000. The result of simulation of electron beam spot diameter for each particle number is shown in Fig.7. The simulation was done at beam the current I_b of 20 mA, extraction voltage V_e of 12 kV and accelerating voltage V_a of 300 kV.

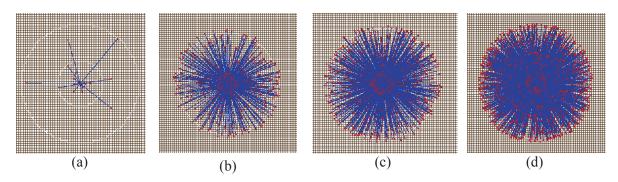


FIGURE 7. The simulation results of electron beam diameter spot for various particle numbers: (a) 10, (b) 500, (c) 1000 and (d) 2000.

The diameter of electron beam spot at the window of EBM can be expressed as d_1 for the diameter along y axis and d_2 for the diameter along x axis. For each particle number the diameters of electron beam spot are shown in Table 1 as well as in Fig.8.

TABLE 1. The diameter of electron beam spot at window for each particle number

Nr.	Particle Number	d_1 (cm)	<i>d</i> ₂ (cm)
1	10	2.98 ± 0.05	3.97 ± 0.05
2	500	5.45 ± 0.05	5.44 ± 0.05
3	1000	5.44 ± 0.05	5.41 ± 0.05
4	2000	4.46 ± 0.05	5.49 ± 0.05

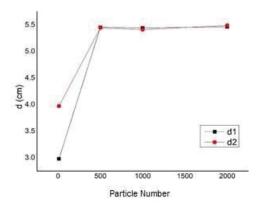


FIGURE 8. The diameter of electron beam spot at window vs. particle number

It is clear that the diameter of electron beam spot is stagnant whenever the particle number is \geq 500. The simulation of electron beam trajectory was carried out with the consideration of electron beam spot size at EBM window and

the capability of the computer used for running simulation program. When simulation is done with particle number of 2000, the electron beam spot size is well suited with the EBM window but the computer is starting less responsive. Therefore the simulation of electron beam trajectory was done with particle number of 1000. The result of the simulation is shown in Fig.9.

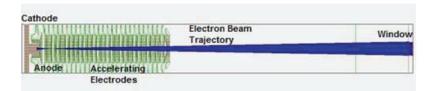


FIGURE 9. The electron beam trajectory from anode to window resulted by simulation using SIMION 8.1

As the electron beam exit from the anode, its trajectory is convergent and the focusing is take place at the third accelerating electrode. The focusing is followed by defocusing so that the electron beam trajectory is divergent up to the window. It is due to the influence of equipotential lines along the trajectory of electron beam as explained before. To obtain the electron beam spot size which is well suited with the window dimension, some operating parameters such as electron beam intensity, extraction voltage and accelerating voltage were simulated.

The Influence of Electron Beam Intensity on the Diameter of Electron Beam Spot

To study the influence of electron beam intensity on the diameter of electron beam spot, the extraction voltage and the accelerating voltage were kept constant at 12 kV and 300 kV respectively, whereas the electron beam intensity is varied from 2 mA up to 20 mA. The result of the simulation is shown in Table 2 as well as in Fig.10.

TABLE 2. The diameter of electron beam spot at window (I_b varied, $V_e = 12 \text{ kV}$ and $V_a = 300 \text{ kV}$)

Nr.	I_b (mA)	d_1 (cm)	d_2 (cm)
1	2	5.49 ± 0.05	5.45 ± 0.05
2	4	5.42 ± 0.05	5.45 ± 0.05
3	6	5.40 ± 0.05	5.35 ± 0.05
4	8	5.44 ± 0.05	5.39 ± 0.05
5	10	5.47 ± 0.05	5.41 ± 0.05
6	12	5.43 ± 0.05	5.45 ± 0.05
7	14	5.42 ± 0.05	5.42 ± 0.05
8	16	5.47 ± 0.05	5.41 ± 0.05
9	18	5.44 ± 0.05	5.44 ± 0.05
10	20	5.41 ± 0.05	5.41 ± 0.05

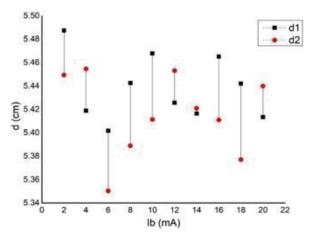


FIGURE 10. The diameter of electron beam spot at window d vs. electron beam intensity I_b .

The result shows that the diameter of electron beam spot at window is influenced by the electron beam intensity. The change of electron beam spot diameter is irregular. The smallest diameter of electron beam spot is 5.35 cm and the largest one is 5.49 cm. It is interesting to be noted that the electron beam intensity of 14 mA yields the smallest difference between d_1 and d_2 . It means that the diameter of both electron beam spot is optimum.

The Influence of Extraction Voltage on the Diameter of Electron Beam Spot

To study the influence of extraction voltage on the diameter of electron beam spot, the electron beam intensity and accelerating voltage were kept constant at 20 mA and 300 kV respectively, whereas the extraction voltage is varied from 2 kV up to 12 kV. Note that the extraction voltage is the difference between the voltages of cathode and anode. The result of the simulation is shown in Table 3 as well as in Fig.11.

TABLE 3. The diameter of electron beam spot at window (V_e varied, $I_b = 20$ mA and $V_a = 300$ kV)

Nr.	V_e (kV)	d_1 (cm)	d_2 (cm)
1	2	6.08 ± 0.05	6.13 ± 0.05
2	4	5.80 ± 0.05	5.77 ± 0.05
3	6	5.59 ± 0.05	5.55 ± 0.05
4	8	5.50 ± 0.05	5.47 ± 0.05
5	10	5.41 ± 0.05	5.44 ± 0.05
6	12	5.41 ± 0.05	5.44 ± 0.05

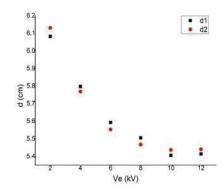


FIGURE 11. The diameter of electron beam spot at window d vs. extraction voltage V_e

The result shows that the diameter of electron beam spot at window is influenced by the extraction voltage. The higher the extraction voltage the smaller the diameter of electron beam spot at the window. The decrease of the diameter of the electron beam spot is nearly exponential up to the extraction voltage of 10 kV. This is the interesting phenomena which can be explained as follows. The energy of electron beam extracted from electron gun is governed by the extraction voltage which is the difference between the voltages of cathode and anode. This voltage gives kinetic energy to the electrons to exit from electron gun and influences the rigidity of electron beam. The higher the extraction voltage the higher the rigidity of electron beam, therefore it is more difficult to focus the electron beam. The focusing of electron beam takes place in the accelerating electrodes and after focusing it will be followed by defocusing of electron beam which led to the divergence of electron beam. Strong focusing will be followed by strong defocusing which led to a large beam spot diameter as in case of low extraction voltage. On the other hand, weak focusing will be followed by weak defocusing which led to a small beam spot diameter as in case of high extraction voltage. The influence of extraction voltage on beam spot diameter was also studied by Abdelrahman MM, et.al.[10].

The Influence of Accelerating Voltage on the Diameter of Electron Beam Spot

To study the influence of accelerating voltage on the diameter of electron beam spot, the electron beam intensity and extraction voltage were kept constant at 20 mA and 12 kV respectively, whereas the accelerating voltage was varied from 150 kV up to 300 kV. The result of the simulation is shown in Table 4 as well as in Fig.12.

TABLE 4. The diameter of electron beam spot at window (V_a varied, $I_b = 20$ mA and $V_e = 12$ kV)

Nr.	V_a (kV)	d_1 (cm)	d_2 (cm)
1	150	5.83 ± 0.05	5.78 ± 0.05
2	175	5.71 ± 0.05	5.71 ± 0.05
3	200	5.65 ± 0.05	5.64 ± 0.05
4	225	5.56 ± 0.05	5.53 ± 0.05
5	250	5.50 ± 0.05	5.51 ± 0.05
6	275	5.44 ± 0.05	5.42 ± 0.05
7	300	5.41 ± 0.05	5.44 ± 0.05

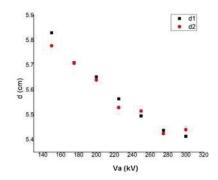


FIGURE 12. The diameter of electron beam spot at window d vs. accelerating voltage V_a

The result shows that the diameter of electron beam spot at window is influenced by the accelerating voltage. The higher the accelerating voltage the smaller the diameter of electron beam spot at the window. The diameter of electron beam spot decrease significantly to the minimum size of $d_1 = 5.41$ cm at the accelerating voltage of 300 kV and $d_2 = 5.42$ cm at the accelerating voltage of 275 kV. Similar to the influence of extraction voltage, the

accelerating voltage also gives kinetic energy to the electron beam and influences the rigidity of electron beam. The higher the accelerating voltage the higher kinetic energy of electron beam and it means the higher the rigidity of electron beam which cause the weak focusing/defocusing. This led to the smaller diameter of electron beam spot.

CONCLUSION

From the results of simulation it is concluded that the electron beam trajectory from thermionic electron gun is influenced by the parameters of electron gun which comprise of electron beam intensity, extraction voltage and accelerating voltage. Among these parameters, the extraction voltage is the most dominant parameter which influence electron beam trajectory. At least it can be concluded from the exponentially decrease of electron beam spot diameter due to the increase of extraction voltage (see Fig.11). By simulation using SIMION 8.1, the value of these parameters can be determined to obtain the diameter of electron beam spot which is suitable with the window dimension.

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