Simulation study for ion beam extraction of 150 keV/2mA ion implantor by using SIMION 8.1

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Abstract A simulation of ion beam extraction and beam formation process for 150 keV/2mA ion implantor using SIMION 8.1 has been done. This simulation is aimed to provide an overview of the influence of the geometry and the effect of the variation of the voltage of both extractor and the acceleration tube of the ion source of ion implantor on the trajectory, beam diameter and beam emittance. The simulation was carried by varying the amount of particles that went through the accelerating tube, varying the accelerating voltage, and the extraction voltage, from 50 to 3000 particles, from 30 kV to 150 kV, and from 1 kV to 10 kV respectively. The simulation results show that the ion extraction process and the ion beam formation at the ion source of ion implantor is very dependent on the geometry and the voltage of both electrode and the extractor on the device. The incorrect electrode geometry and voltage would cause the particle trajectory to be non-linear, while the angle of the beam would diverge too much. We've also found that the amount of simulated particle would affect the homogeneity of the cross section of the beam. The bigger the amount of the simulated particle, the more homogeneous and stable the beam becomes. Unfortunately, for 3000 particles the running process was very long and prone to errors. Therefore in this simulation, the amount of particles is set to 2000, which gave us a rather uniform beam cross section. The variation of extraction voltage 1 kV to 10 kV while keeping the accelerating voltage constant at 150 kV produced an increment of the diameter of the ion beam from 3.84 cm to 4.12 cm. The variation of accelerating voltage from 30 kV to 150 kV while keeping the extraction voltage constant at 10 kV caused the spot diameter of the ion beam to increase. The value of the spot diameter of the ion beam when the accelerating voltage is kept at 150 kV are 4.12 ± 0.05 cm and 4.05 ± 0.05 cm for y-axis and x-axis respectively.

1. Introduction

Today, research and development in the material field is developing rapidly. Various methods are carried out and tested in order to produce materials that are better and in accordance with the desired specifications. One of the materials engineering techniques that develops is the ion implantation technique.
At Center for Accelerator Science and Technology, ion implantation is carried out using an ion implantation machine or ion implanter, a type of accelerator specifically designed to implant or inject ions from an atom or molecule into the surface of a material or target component [1]. For ion implantation process, the extraction and beam formation process at the ion source are very important to produce a good quality implantation result [2]. The process of ion extraction is very dependent on the geometry, voltage of the electrodes and extractors inside the ion source. Therefore, the electrodes need to be arranged in such a way as to create an appropriate electric field configuration on the surface of the ion source to the accelerator tube [2], [3].

The study related to the influence of geometry and electrode voltage in the process of extracting ion sources on ion beam quality has been reviewed by MM. Abdelrahman and S.G. Zakhary in 2009. This study uses a simulation method with SIMION 3D Version 7.0 software and the results show that the shape of the electrodes at the ion source greatly influences the process of plasma formation and affects the emittance of the beam. Abdelrahman compared two different forms of extraction electrodes namely Pierce extractor and Spherical extractor and obtained the result that the Spherical extractor produced low / small beam emittance and diameter [4], [3]. Then in 2011 and 2012, Abdelrahman again simulated the ion source extraction system and focusing system for the positive ion beam and concluded that the intensity of ionization and plasma density could affect the quality of the ion beam. Optimum ionization intensity and plasma density can produce good ion beam quality [4], [5].

Because the geometry and voltage of the electrode or extractor greatly determines the quality of the output beam current for material implantation, so it is necessary to study the problem in the form of an ion extraction system simulation for the ion implanter. In this study, a simulation using SIMION 8.1 was carried out for the ion extraction process at a hot cathode Penning type ion source on a 150 keV / 2 mA ion implanter. The simulation is expected to provide an overview of the influence of the structure and variation of the geometry of the electrode and the voltage of the ion extractor electrode in the process of plasma formation and the process of ionization on the resulting beam current. This simulation aims to determine the effect of accelerator electrode voltage variations on the accelerator tube on the beam diameter and beam emittance.

2. Simulation Process
This simulation was done using SIMION 8.1, a software for simulation of ion beam trajectory. SIMION 8.1 uses potential arrays to define the geometry of the electrodes or magnetic poles. The potential between electrodes is determined by solving the Laplace equation using the finite difference method called the refine term in SIMION 8.1. In this case, the electrodes represent boundary conditions. The Laplace equation assumes there is no space charge effect and the boundary conditions are quite limited. So using gauss theorem in a closed surface with no charge inside which is shown in equation (1), we would have

$$\nabla \cdot E = 0$$

For electrostatic case, the electric field is a gradient of a scalar field, which is shown in equation (2)

$$\nabla V = \left( \frac{\partial V}{\partial x} \right) \hat{i} + \left( \frac{\partial V}{\partial y} \right) \hat{j} + \left( \frac{\partial V}{\partial z} \right) \hat{k} = \vec{E}$$

Combining equation (1) and (2), we shall get an identity written in equation (3)

$$\nabla^2 V = 0$$

2.1. Designing the Geometry
The first step to do was designing the geometry of hot cathode penning type ion source and the accelerator tube electrodes. The ion source is designed by describing the electrodes that are inside the
ion source, namely the anode and extractor and pole magnet. The anode is cylindrical with a length of 54 mm and the diameter of both ends is 22 mm, while the extractor is cylindrical with a length of 3 mm and in the middle of the cylinder is a circular hole with a diameter of 6 mm. The distance between the anode and the extractor is 10 mm. Accelerator tubes are made of 10 accelerator electrodes, each electrode has a distance of 31 mm. The next component is a cylindrical T connection with a length of 300 mm and a diameter of both ends of 105 mm. The target sites made are cylindrical with a length of 3 mm and a diameter of 80 mm, and these target sites are only used to observe the diameter of the resulting ion beam spot. As for the coordinates of each electrode adjusted to the existing size. With the geometry size data it can facilitate the making of geometry arrays of potential arrays adjusted to the original conditions [6].

The input of the electrode geometry design script is done using Notepad ++ v7.5.7 which is then saved as a .GEM extension file. Geometry files must be stored in the form of .GEM extension files, so that they can be read by SIMION 8.1. A geometry file is a file with a .GEM extension that uses a 3D geometry language model to define the electrode or pole array geometry with a variety of other instructions. The programming language in making geometries in SIMION 8.1 is very similar to the structure of C language functions [7]. This file is then inputted to SIMION 8.1 through New> Use Geometry File (GEM) in the SIMION main view. An example of electrodes design in Simion 8.1 is shown by Figure 1.

![Figure 1. The electrodes geometry design as displayed by the menu Modify of SIMION 8.1](image)

### 2.2. Ion Trajectory Simulation

The next step after designing the electrodes is to simulate the trajectory of ion through the electrode that has been made. The electrodes voltage are varied and both magnetic and electrostatic fields are calculated by running the Refine command on SIMION 8.1, which is shown Figure 2. This process is called Refining Process.
After solving the Laplace equation on electrodes by using Refine menu, the next step is to define the type of particle that will be simulated using the Define Particle command. There are several types of particle choices, namely electrons, protons and other particles that can be defined by the mass of particles that can be regulated. For a hot cathode ion penning source, the ionisation results in a plasma consisting of ions, electrons and neutral elements.

3. Simulation Results
The simulation results obtained by the ion beam trajectory is shown in figure 3, with the cathode, anode, accelerator electrode and T junction components. Simulation of the distribution of ions from the last circular accelerator electrode. Figure 4 shows that the results of the beam path are straight and spread (converging).

Measurement of the ion beam diameter is carried on the y-axis (d1) and z-axis (d2). This is intended to observe the size of the diameter of the ion beam spot formed from the simulation results, as can be seen from Figure 4. The ion beam diameter is measured right after passing the T-junction.
The ion beam trajectory simulation must first determine the appropriate number of particles, before being used for simulations with variations in the extractor voltage ($V_e$) and accelerator voltage ($V_p$). The number of particles in a simulation using SIMION 8.1 is the number of particles that can represent the total charge under actual conditions, so the number of particles simulated does not have to follow the number of particles produced by the ion implant machine. The number of particles can be reduced in order to shorten the running process.

Therefore, the number of particles varies from 50 particles, 500 particles, 1000 particles and 2000 particles. This simulation is carried out at the extraction voltage ($V_e$) of 10 kV and accelerator voltage ($V_p$) of 150 kV. The result of the simulation that has been done is the beam spot diameter at the target location as shown in Figure 5 from a to e:

![Figure 5](image)

**Figure 5.** The ion beam diameter spot on the target (a) 50 particles, (b) 500 particles, (c) 1000 particles, (d) 2000 particles, (e) 3000 particles
The results show that the ion beam spot diameter with 50 particles is less stable, then with the number of particles 500, 1000, and 2000 particles begin to form a stable size. The selection of the number of particles will be adjusted to the desired criteria, namely the ion beam distribution evenly and during the process of running must adjust to computer specifications so that it does not experience interference (error). Simulation results for 50 particles found uneven beam distribution and for 500 particles found uneven beam distribution. Simulations for 1000 particles obtained that the ion beam distribution is more evenly distributed than 500 particles and the computer has no interference. Furthermore, for 2000 particles it was found that the beam distribution was more evenly distributed compared to 1000 particles and the computer had no problems. Then for 3000 particles the distribution of the beam was more evenly distributed, but in 3000 the computer particles began to experience disruption in operation. Thus the number of particles that meet the criteria for running in the next simulation is using 2000 particles.

3.1. Ion Energy

Ion energy from simulations can be known through the Data Record process of SIMION 8.1. Data recording process is carried out at each accelerating voltage variation (Vp) starting from 30 kV to 150 kV. The ion energy result from the simulation is shown in Table 1 as well as in figure 7.

| No. | Vp (kV) | Ion Energy (eV) |
|-----|---------|----------------|
| 1.  | 30      | 27305.38987    |
| 2.  | 45      | 34912.54862    |
| 3.  | 60      | 42694.34995    |
| 4.  | 75      | 50087.46887    |
| 5.  | 90      | 56179.08563    |
| 6.  | 105     | 65076.77936    |
| 7.  | 120     | 72645.94882    |
| 8.  | 135     | 79701.6754     |
| 9.  | 150     | 87172.51154    |
Simulation results show that the greater the accelerating voltage, the kinetic energy of the ion increases in proportion to the input voltage. This is because the process of accelerating the ion beam in the accelerator tube causes the ion beam to obtain a relatively high kinetic energy that is proportional to the high voltage applied to the accelerator tube. Although the results of the kinetic energy from the simulation are not exactly the same as the input voltage, the increase is proportional to the accelerator voltage.

3.2. The Influence of Extraction voltage on the Diameter of Ion Beam Spot

The simulation of the ion beam trajectory by varying the extraction voltage aims to determine the effect of the extraction voltage on the diameter of the ion beam spot at the target location carried out at an accelerating voltage of 150 kV. The result is shown in Table 2 and Figure 7.

Table 2. Data of extraction voltage and diameter of ion beam spot (Vp = 150 kV, Ve is varied)

| No. | V (kV) | d1 (cm) | d2 (cm) |
|-----|--------|---------|---------|
| 1.  | 1      | 3.84 ± 0.05 | 3.84 ± 0.05 |
| 2.  | 2      | 3.85 ± 0.05 | 3.75 ± 0.05 |
| 3.  | 3      | 3.87 ± 0.05 | 3.87 ± 0.05 |
| 4.  | 4      | 3.88 ± 0.05 | 3.9 ± 0.05  |
| 5.  | 5      | 3.93 ± 0.05 | 3.9 ± 0.05  |
| 6.  | 6      | 3.88 ± 0.05 | 3.97 ± 0.05 |
| 7.  | 7      | 3.99 ± 0.05 | 3.99 ± 0.05 |
| 8.  | 8      | 4.02 ± 0.05 | 3.99 ± 0.05 |
| 9.  | 9      | 4.11 ± 0.05 | 4.02 ± 0.05 |
| 10. | 10     | 4.12 ± 0.05 | 4.05 ± 0.05 |
The results of the extraction voltage variations in the ion beam spot diameter shows that the bigger the extraction voltage, the ion beam spot diameter increases. The simulation is carried out using extraction voltage variations starting from 1 kV to 10 kV with a maximum accelerator voltage of 150 kV. As for the diameter of the ion beam spot produced when the maximum voltage is $V_e = 10$ kV and $V_p = 150$ kV is $4.12 \pm 0.05$ cm and $d_2$ is $4.05 \pm 0.05$ cm.

### 3.3. The Influence of Accelerating voltage on the Diameter of Ion Beam Spot

To find out the condition of the ion beam diameter spot, a simulation with an accelerating voltage is performed from 30 kV to 150 kV at the extraction voltage ($V_e$) 10 kV. Simulation results for these conditions are shown in Table 3 as well as in Figure 8.

### Table 3. Diameter of ion beam at $V_e = 10$ kV and $V_p$ is varied

| No. | $V_p$ (kV) | $d_1$ (cm) | $d_2$ (cm) |
|-----|------------|------------|------------|
| 1   | 30         | 3.59 ± 0.05| 3.63 ± 0.05|

![Figure 7. Extraction Voltage vs ion beam diameter spot](image)

![Figure 8. Accelerating Voltage vs ion beam diameter spot](image)
Simulation results with accelerator voltage variations show that the greater the accelerator voltage, the ion beam spot diameter increases towards the ion beam spot diameter at a maximum accelerator voltage of 150 kV. The diameter of the ion beam spot produced when the maximum voltage is $V_p = 150$ kV and $V_e = 10$ kV is $d_1$ of $4.12 \pm 0.05$ cm and $d_2$ of $4.05 \pm 0.05$ cm.

3.4. The Influence of Geometry of Extractor of Ion Source on the Ion Beam Emittance

This simulation aims to determine the effect of geometry of extractor on ion beam trajectory and its emittance. The diameter of extractor of ion source is varied from 1 mm to 10 mm. The results are shown in Table 4 and Figure 9.

| Extractor Diameter (mm) | Ion Beam Diameter (mm) |
|-------------------------|------------------------|
|                         | D1         | D2         |
| 1                       | 11,897     | 9,992     |
| 2                       | 24,397     | 23,298    |
| 3                       | 34,039     | 36,242    |
| 4                       | 48,627     | 45,172    |
| 5                       | 53,004     | 47,363    |
| 6                       | 71,213     | 72,276    |
| 7                       | 75,373     | 79,869    |
| 8                       | 88,097     | 90,246    |
| 9                       | 99,016     | 94,336    |
| 10                      | 99,943     | 100,382   |

Table 4. Data of extractor diameter and ion beam diameter spot
This result show that the ion trajectory is strongly influenced by the geometry electrodes. If the geometry of the extractor do not match the type of ion being simulated, the ion trajectory will be divergent, convergent or random so that it is not focused and not optimum regarding the target to be implanted. In addition, the path of ions that are not straight or divergent to hit the electrodes in the machine can cause heat, so that the electrodes will be damaged quickly and cause damage to the ion source components and accelerator tubes. From this simulation we knew that at extraction diameter 10 mm, ion beam not focused and diverge too much and not straight to the window.

4. Conclusion
The simulation results show that the ion extraction process and the ion beam formation at the ion source of ion implantor is very dependent on the geometry and the voltage of both electrode and the extractor on the device. The incorrect electrode geometry and voltage would cause the particle trajectory to be non-linear and not focus, while the angle of the beam would diverge too much and can affect the beam emittance or ion beam diameter spot. This simulation by using SIMION 8.1 is also expected to help in determining the parameters of the input (extraction and accelerating voltage) at the ion source in order to obtain the optimum ion beam output.
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