SIMULATION STUDIES OF THE ION BEAM TRANSPORT SYSTEM IN A COMPACT ELECTROSTATIC ACCELERATOR-BASED D-D NEUTRON GENERATOR

by

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The study of an ion beam transport mechanism contributes to the production of a good quality ion beam with a higher current and better beam emittance. The simulation of an ion beam provides the basis for optimizing the extraction system and the acceleration gap for the ion source. In order to extract an ion beam from an ion source, a carefully designed electrode system for the required beam energy must be used. In our case, a self-extracted penning ion source is used for ion generation, extraction and acceleration with a single accelerating gap for the production of neutrons. The characteristics of the ion beam extracted from this ion source were investigated using computer code SIMION 8.0. The ion trajectories from different locations of the plasma region were investigated. The simulation process provided a good platform for a study on optimizing the extraction and focusing system of the ion beam transported to the required target position without any losses and provided an estimation of beam emittance.

Key works: SIMION, self-extraction of ion, penning ion source, ion trajectory

INTRODUCTION

The compact electrostatic accelerator-based neutron generator has been extensively used by the scientific community throughout the world for scientific research in many fields, including instrumentation neutron activation analysis (INAA), prompt gamma activation analysis (PGAA), fast neutron analysis (FNA), thermal neutron analysis (TNA), *etc*. [1]. Because of an increase in acts against humanity all around the world, in the last decade the importance of equipment for the detection of explosives, narcotics, special nuclear materials, *etc*., has been realised. To accelerate the process of putting together a turnkey system for the detection of illegally transported items through various routs, we have started working in this direction. A compact neutron generator is developed in our laboratory. It can be operated in the pulse mode, as well as in the steady mode. For the detection of explosives and special nuclear materials, the operation of the neutron generator is preferable in pulse mode [2], whereas for activation studies of materials, the steady-state mode is desirable.

The generator uses a single self-extracted hollow anode penning ion source [3] that has been developed in our laboratory. The extraction of ions from the ion source depends on many parameters such as the geometry of the plasma meniscus, extraction angle, potential on the extraction electrode, *etc*. During the passage of the ion beam, due to the same charge, each ion receives a repelling force from the surrounding ions which pushes the ions from the beam, thus divergence occurs. The repulsion force due to the charged particles, also known as the space-charge effect, can be compensated by a suitable selection of the geometry of the extraction electrode. Due to the electric potential, the geometry of the extraction electrode arranges its equipotential surface in such a way that the normal from the nearer equipotential surface to the adjacent one goes inward. This inward force exerted on the ion at the exit aperture of the extraction electrode helps the ions to converge. The effect on the extracted ion current due to the angle of extraction has been studied and reported elsewhere [4].

For the production of neutrons in a neutron generator, deuterium ions are extracted from the ion source and accelerated towards a target where the ions are bombarded to either deuterium or tritium particles for the generation of neutrons from fusion reactions.

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The simulation was carried out by SIMION 8.0. The detailed simulation process is described in the next section.

SIMULATION PROCESS

Among other software for the ion trajectory, SIMION is simple and low-cost. SIMION is based on principles of 2- or 3-dimensional, equally spaced grids of potential arrays. The values of either the electrostatic potential or magnetic potential can be imposed at each point to define the electrostatic or magnetic field. After the imposition of either field, the user can superimpose both electrostatic and magnetic arrays, if both electrostatic and magnetic fields are required in the same volume. Then the simulation process is reflected in different successive manners. The creation of electrodes and polarization of these elements can be done either by drawing the electrode geometry in the worksheet itself in SIMION at the workspace or it can be imported from the AutoCAD drawing. After the creation of the geometry, calculation of the electrostatic potential takes place. Then the trajectory is viewed and the characteristic settings of the ions such as their speed, kinetic energy, and their angles of arrival at the target are saved.

The user assigns a potential value to the electrode and this serves as the boundary condition. Then the value of the potential at any point outside the electrode is determined by solving by iteration the Laplace equation

$${}^2V \quad 0$$

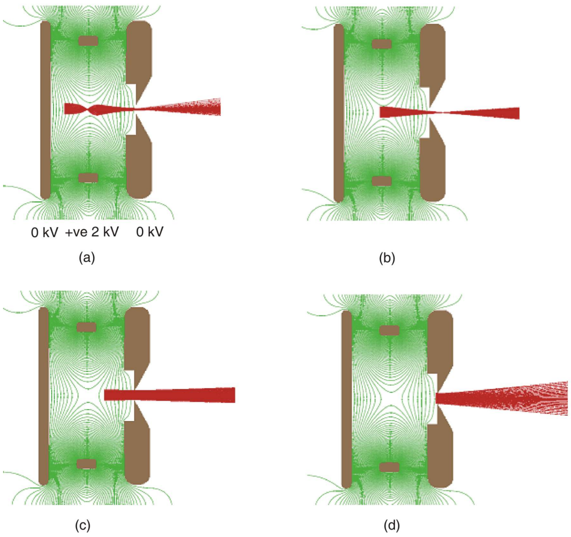
The Laplace equation defines the potential at a point in terms of potential points that surround it. Unlike Poisson equation, the Laplace equation does not have solutions incorporating the space charge. SIMION does not allow solutions taking into account space-charge effects of high-density ion beams, however, this employs charge repulsion methods that can estimate certain types of space charge and particle repulsion effects. A highly modified fourth order Runge-Kutta method is used for the numerical integration of the ion's trajectory in three dimensions. Ion trajectories are a result of electrostatic and space charge repulsion forces on the basis of the current position and velocity of the ions. These forces are then used to compute the current ion acceleration and to predict the position and velocity of the ion by numerical integration techniques at the next time step. Electrostatic forces are initially computed in terms of volts per grid unit. As the ion progresses through the potential array, it moves from one square of grid points into another. SIMION automatically generates a small 16-point array that represents the current for four grid points and the 12 grid points around it. The values of these grid points are determined by symmetry assumptions and grid point locations. The potential at each point is normally calculated by linear interpolation, using the four grid points bounding the grid square it falls in. When an ion is outside electrostatic instances, SIMION looks in both directions along its current trajectory for the closet electrostatic instance of intersection in both directions. If the present ion trajectory intersects electrostatic instances in both directions, SIMION will determine the potentials at the points of intersection and estimate the resulting electrostatic acceleration assuming a linear gradient.

The configuration of the neutron generator of interest for this study is described in [5]. The neutron generator consists of a hollow anode penning ion source, acceleration electrode and a target. In our study, the hollow anode penning ion source consists of two cathodes and one cylindrical anode at the centre. The detail configuration of the ion source is described elsewhere [3]. One cathode works as the extraction electrode. The geometry is Pierce-like geometry. The angle of the extraction electrode is important for the beam to converge.

The configuration of the electrode system was created in AutoCAD and the image then imported to the SIMION workspace in bitmap format. Refinements and fast adjustments [6] were done on the electrode system by selecting the tools on the screen. The refinement process uses the potentials of electrode/pole array points to estimate the potentials of non-electrode/non-pole array points. The refining process makes use of finite difference techniques to solve the Laplace equation numerically. The fast adjustment method makes use of the additive solution property of the Laplace equation. This property allows separate solutions for each boundary to be combined in a simple scaling/additive process to obtain the potential at each point in the potential array. Single ionized 800 deuterium ions of an atomic mass of 4 amu were selected for the simulation process. The location of the extraction of the ions was chosen by selecting the x- and y-co-ordinates at the triple point consisting of plasma, metal electrode, and vacuum. The simulation was carried out with different set-up extraction and acceleration voltages. Extraction potential up to positive 5 kV which also acts as ion source potential for plasma generation and acceleration potential of up to negative 100 kV provided through the target were used.

RESULTS

The self-extraction of the ion source was examined. Ion trajectories from different locations of the plasma region were observed with ion source potential at positive 2 kV. The anode was charged with 2 kV while keeping both cathodes at ground potential. Ion trajectories and field lines for the self-extraction of ions for different locations of the plasma region are



(a) (b) (c) (d)

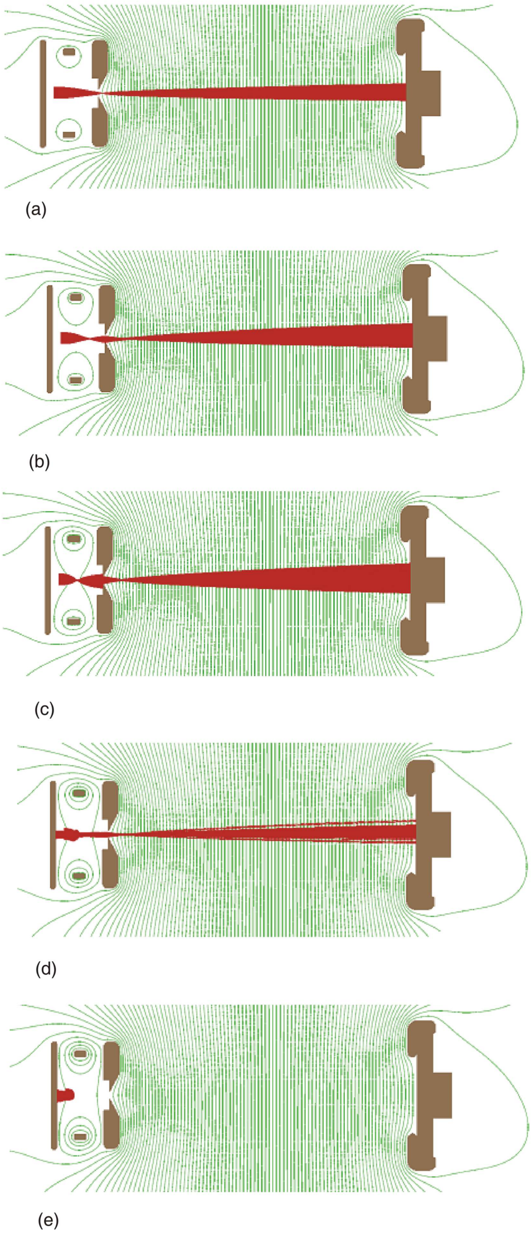
Figure 1. Ion trajectory for the self-extraction from the ion source

shown in fig. 1. This confirms the extraction of ions from the plasma region with the help of the ion source electrode itself. There is no need for an extra electrode for ion extraction. When a focused beam is required, there is need for use of focusing electrodes.

Figure 2 shows the ion trajectories for the accelerator system with the ion source and target. The ion trajectory at 100 kV potential of the target and a different potential of the ion source were observed. The equipotential surface distribution at the aperture of the extraction electrode, as shown in fig. 2, describes the geometry of the meniscus. In this case, the meniscus is concave, making the beam convergent. The ion trajectories were taken for different ion source potential (1 kV to 5 kV) and the origin of the ions taken inside the plasma region, keeping the same origin for all potentials.

As the ion source potential increases nearing higher potential, ions get diverted towards the back cathode. At ion source potential of 4 kV, a fraction of ions projected toward the reverse direction where as if at 5 kV, all the ions terminating at the back cathode. Figure 3 shows the ion trajectories for an ion source potential of 5 kV coming from different originating points. Here, we could observe the focusing point changing with a change of the originating point. Though it is focused near to the extraction electrode, at the target, the ions strike well within the area of the target.

Emittance being a measure of the quality of the beam, it is measured in each case. Emittance with respect to the extraction voltage is shown in fig. 4. Beam emittance decreases by 21% when the extraction voltage goes from 1 kV to 5 kV. Figure 5 represents the emittance for different acceleration potential of the fixed extraction voltage.



(a) (b) (c) (d) (e)

Figure 2. Ion trajectory of the accelerator system up to 100 keV ions coming from the plasma region
All these figures were taken with target voltage at 100 kV and different ion source potential as (a) 1 kV, (b) 2 kV, (c) 3 kV, (d) 4 kV, and (e) 5 kV

CONCLUSIONS

A simulation of a compact accelerator system intended for neutron generation has been carried out. Self-extraction from a hollow anode penning ion source was observed. The focus of the beam was changed for the different origins of ions, but the divergence increased with the increase in the distance from the extraction electrode. Thus, for a focused ion beam application focusing electrodes are required, while solely energetic ion beam applications will work without a focusing electrode. As is the case with the neu-

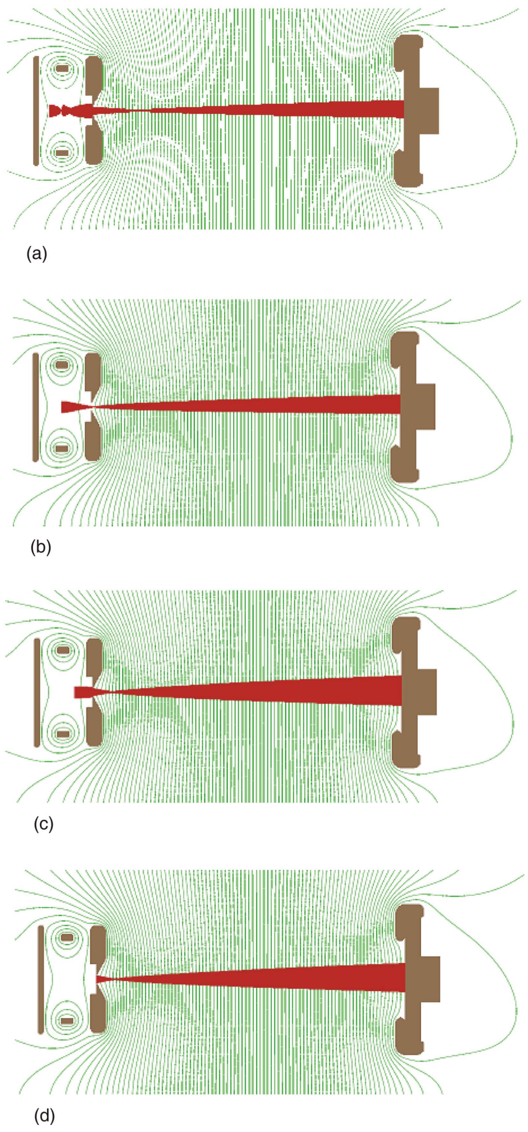


Figure 3. Ion trajectory for ion source potential as 5 kV from different location

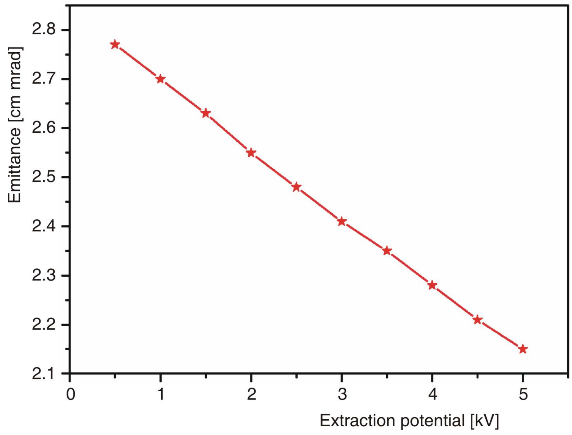


Figure 4. Influence of extraction potential on beam emittance

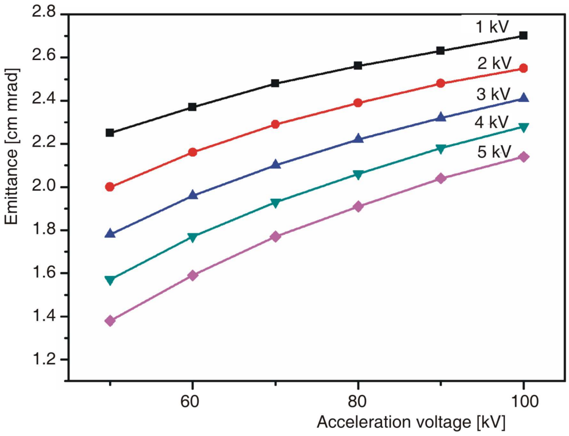


Figure 5. Influence of acceleration potential on beam emittance for fixed extraction potential

tron generator, energetic ions are required to strike at the target as well. In that case, there is no need to focus the ion beam to a tiny spot. As shown in figs. 2 and 3, the ion beam strikes the target within the target area and with good emittance. In the study presented here, the 100 keV deuteron beam produced through the extraction voltage of 5 kV shows better emittance for the production of neutrons.

AUTHOR CONTRIBUTIONS

The penning ion source and neutron generator were designed and developed by B. K. Das. Simulation studies were carried out by B. K. Das and R. Das. The manuscript was written by B. K. Das. All the figures were prepared by B. K. Das, A. Shyam, and R. Das and A. D. P. Rao had participated in the discussion of the results.

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ПРОУЧАВАЊА СИМУЛАЦИЈА ТРАНСПОРТНОГ СИСТЕМА ЈОНСКОГ СНОПА У D-D ГЕНЕРАТОРУ НЕУТРОНА ЗАСНОВАНОМ НА КОМПАКТНОМ ЕЛЕКТРОСТАТИЧКОМ АКЦЕЛЕРАТОРУ

Проучавање механизма транспорта јонског снопа доприноси производњи јонског снопа доброг квалитета са већом струјом и бољим емитовањем снопа. Симулација јонског снопа даје основу за оптимизацију система за издвајање и процепа за убрзавање јонског извора. Како би се издвојио јонски сноп од јонског извора потребно је за захтевану енергију снопа користити добро дизајниран систем електрода. У нашем случају, за потребе производње неутрона, коришћен је самоиздвајајући јонски извор за производњу, екстракцију и убрзавање јона кроз један процеп. Коришћењем компјутерског кода SIMION 8.0 испитиване су карактеристике издвојеног јонског снопа и трајекторије јона са различитих локација области плазме. Симулација је омогућила добру платформу за проучавање оптимизације система за издвајање и фокусирање јонског снопа који се транспортује ка жељеној позицији мете без губитака, и за процену емисије снопа.

Кључне речи: SIMION, самоиздвајање јона, јонски извор, јонска трајекторија