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2D Single Particle Simulation for the Design of a Compact Neutron Generator using Inductively Coupled Plasma

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Abstract

A compact neutron generator has been designed using an ICP plasma source. Ions such as D and T can be extracted radially from RF plasmas generated in the outer part of cylindrical vacuum chamber and radially accelerated either onto the Ti-coated copper rod target or through an acceleration grid. DD or DT nuclear fusion reactions can yield 2.45MeV or 14.1Mev neutrons, respectively. For efficient neutron generations, behaviors of impinging ions and generated secondary electrons around the target electrode need to be controlled. Strong axial magnetic field in a magnetic mirror configuration has been implemented with a pair of electromagnets to reduce back-streaming secondary electrons as well as to improve plasma confinements. Two dimensional particle simulations have been performed for the optimal design of the target electrode and electromagnets in this source.

1. Introduction

Recently neutrons are getting more extensively utilized from basic science research to medical therapy, biotechnology and other industrial applications. For more active applications of neutrons, neutron generators of small size, high intensity, high reliability, good controllability and low cost need to be developed. New types of neutron generators using RF-driven plasma sources have been developed mainly because of their long lifetime[1]. The RF-driven plasma sources are expected to have other favorable characteristics for the development of neutron generators such as high gas efficiency, high-density plasmas at low gas pressures, and high mono-atomic fraction.

A compact neutron generator has been designed from an inductively coupled plasma (ICP) source using 13.56MHz RF power.[2] With D or T plasmas generated at the radially outer part of the cylindrical dielectric chamber, ions are extracted through slits on the cylindrical plasma grid and radially accelerated either onto acceleration target electrode or through acceleration grid electrode, where fusion reactions occur either by beam-target or beam-beam reactions, respectively.

To improve this neutron generator, key issues are how to increase plasma density in low pressure and how to extract high beam currents with high ion energy. Related to these issues, axial magnetic fields in a magnetic mirror configuration have been implemented in this source design. With the magnetic field, plasma densities are expected to increase in low gas pressure through the improvement of plasma confinement, resulting in extracted beams with higher current densities. Also, secondary electron emissions due to high-energy ion bombardments to the target can be reduced significantly with the magnetic field, which can avoid breakdowns in the acceleration region and reduce X-ray generation at the plasma grid. In this study, behaviors of charged particles near the target electrode are simulated and utilized to design the details of the target electrode and the electromagnets.

In section 2, the system design is briefly described. 2D single Particle simulation has been discussed in the next section, where impinging ions and secondary electrons are simulated two-dimensionally for various magnetic field strengths near the target electrode. Section 4 concludes this study.

2. Overall system design of the neutron generator

Schematic drawing of the neutron generator system is shown in Fig. 1. The system is very similar to an ion source with two-electrode system based on RF plasma sources in cylindrical geometry. Unique configuration is that its acceleration is directed radially toward the center of the cylinder. Either acceleration target or acceleration grid can be installed from a high-voltage feedthrough.

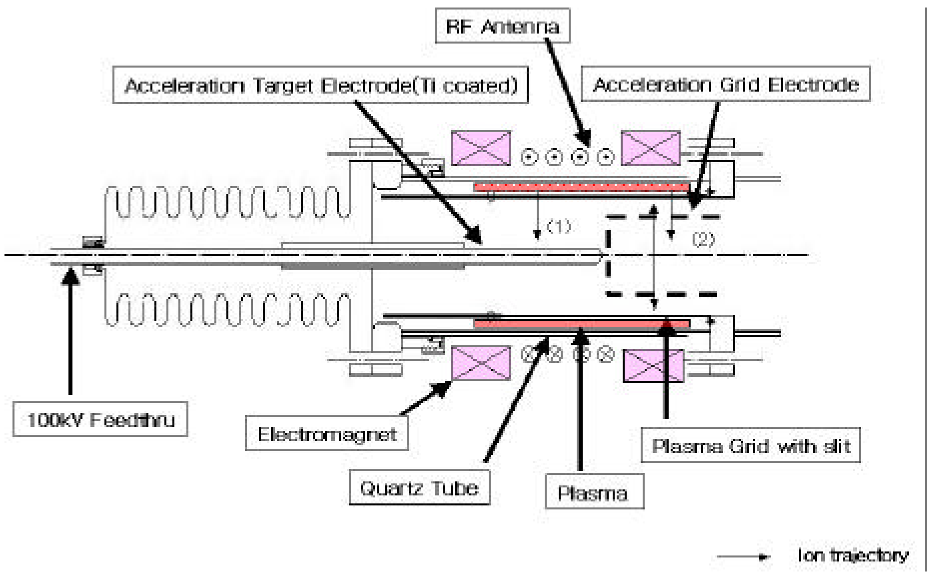


Fig. 1 Schematic Drawing of a Neutron Generator

The RF plasma source is an ICP source with 100mm-diameter quartz vacuum chamber. The four-turn helical antenna, fed by 13.56MHz RF power, is placed outside of quartz chamber, ensuring long lifetime of this source. A cylindrical plasma grid with slits along the axis is inserted inside the quartz chamber, where ions are extracted toward the center. Electromagnets are also installed at both ends of the quartz chamber to produce magnetic field in mirror configuration for both higher plasma density and secondary electron control.

3. Two-dimensional single particle simulation

3.1. Ion and electron motions in various magnetic fields

Fig. 2 shows the cross sectional view of the neutron generation system. Inner diameter of quartz chamber is 94mm. Grounded plasma electrode of 74.8mm-diameter stainless steel tube is located concentrically with the plasma chamber. The target is made of copper rod with the outer diameter of 10mm for better heat removal, and coated with Ti for D/DT adsorption. The target will be negatively biased for ion acceleration.

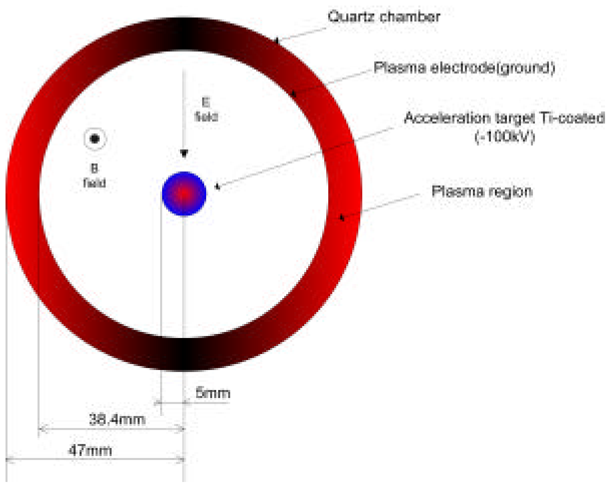


Fig. 2. Cross sectional view of neutron generation system

The equations of motion for both electrons and ions are calculated with the finite difference method (FDM) in the above geometry. A few assumptions for the simulation are applied as following;

(1) Ions are accelerated from the plasma electrode(r=38.4mm) with the initial energy of several eV,

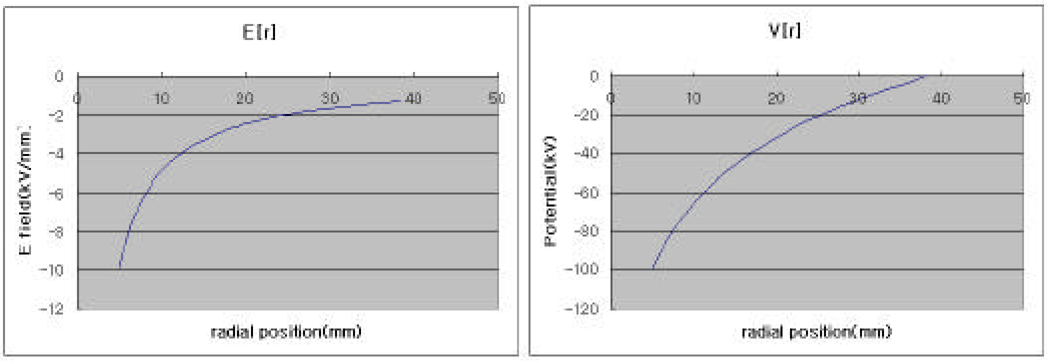
(2) electrons emerge from acceleration target electrode(r=5mm) with the initial energy of several eV,

(3) magnetic field in the acceleration region is considered to be axial and constant, and

(4) the electric field distribution is given as shown in Fig. 3.

The electric field and the potential distributions in the geometry has been calculated as shown in Fig.3.

Stronger electric fields appear mostly inner part of acceleration region, indicating the importance of charged particle behaviors near the target electrode. Also, strong electron emissions are expected due to energetic ion bombardments.



(a) Electric field distribution (b) Potential distribution

Fig. 3. Electric field and potential distributions

Simulation results are shown in the Fig. 4. As magnetic field strengths increase, electrons are bent significantly while ions accelerate almost straightly. When the magnetic field strength becomes more than 600Gauss, electrons come back to the target without colliding with the plasma electrode. With such a high magnetic field, power supply energy capacity can be reduced and breakdowns due to electrons from emitted acceleration target can be avoided. Also, X-ray generation due to secondary electrons can be reduced significantly.

On the other hand, ions are also bent near the target electrode where stronger electric field exists. However, their bending radius is very large compared to electrons because of their mass. Moreover, the radius is larger since their energies are already very high in that region. Incident angle for the ion with the energy of 100kV at the magnetic field of 600G is only 78.8 degree.

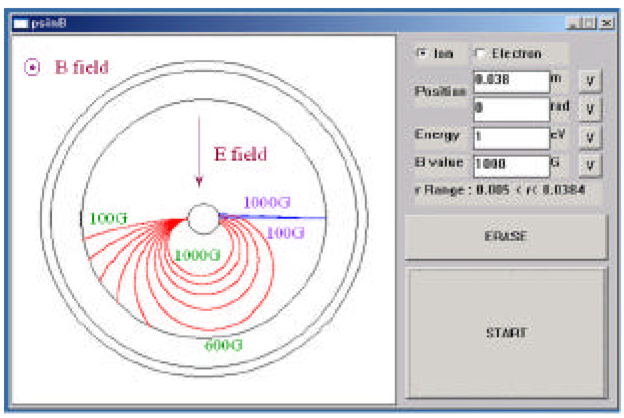


Fig. 4. Simulation result using FDM method in 2D cylindrical geometry

3.2. Neutron yield change due to ion trajectory

When ion trajectories are slightly bent as shown in Fig. 4, the ion flux into the target decreases and neutron yield also decreases. The reduction of neutron yields for various magnetic field strengths has been estimated and compared with that of normal incidence. The neutron yield decreases only 2% for the ion beam of 100kV at the magnetic field of 600G. However, reduction becomes larger as the beam energy is reduced and the applied magnetic field is increased as shown in the Fig. 5. For higher magnetic field of more than 1000G, reduction may become significant. In this case, target electrode can be modified to polygonal cross section according to the number of extraction slits for the improvement of normal incidence.

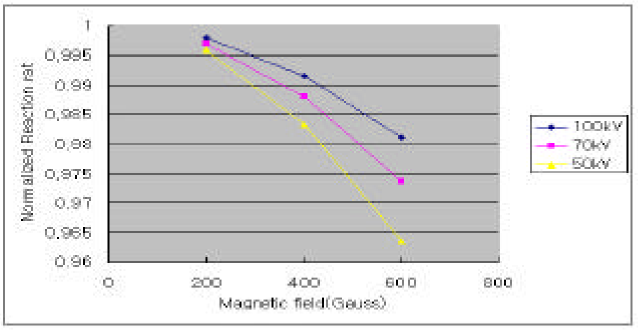


Fig. 5. Reaction rate compared with normal incidence

4. Conclusion

For a compact neutron generator using ICP source with magnetic field, 2D single particle simulation has been accomplished. The results show that magnetic fields of at least 600Gauss are needed for 100kV operation for the suppression of secondary electrons. On the other hand, ion trajectories are not so influenced that neutron yields decrease only a small amount. The neutron generator is under construction based on these data, and plasma and neutron production experiments will be performed.

References

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2.M.J. Park, S.H. Kim, I.S. Hong, and Y.S. Hwang, Development an RF plasma source with mirror field for a compact neutron generator, in the Proceedings of OS2002 Conference(2002)