Performance of Neutron/Proton Source Based on Ion-Source-Assisted Cylindrical Radially Convergent Beam Fusion

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Keywords: beam fusion, proton source, neutron source, positron emission tomography

Radially Convergent Beam Fusion (RCBF) is a scheme to confine ions electrostatically with two concentric electrodes, which are conventionally spherical. Generated ions are accelerated toward the center with sufficient energy to cause fusion reactions, and recirculate inside the anode through a highly transparent grid cathode. Because of such an extremely simple configuration of the device, RCBF is practically expected as a portable neutron/proton source with higher controllability and higher safety, and has been studied for various applications such as landmine detection and medical positron emission tomography (PET). However, some problems remain for practical use, and the most critical one is the insufficiency of absolute neutron/proton yields. In this study, a new RCBF device was designed to obtain higher neutron/proton yields, and tested by using deuterium gas. The key features of the new device are the cylindrical electrode configuration in consideration of better electrostatic confinement of ions and extraction of protons, and an integrated ion source that consists of a cusp magnetic field and a negatively biased grid anode. To investigate the performance of the device and the effect of the ion source, the test was carried out with three kinds of experimental setup for comparison.

At first, the device was operated with the basic setup. As a result, it is found that the cylindrical device can generate several times higher neutron yield than the conventional spherical one. This increase may be caused by the better electrostatic confinement of ions that results from the cylindrical electrode configuration. The maximum neutron production rate of $2.1 \times 10^6$ n/s was obtained at a dc discharge of $-60.0$ kV and 10.0 mA.

Then a cusp magnetic field was applied by using ferrite magnets and the grid anode was negatively biased by a few hundreds volts. It was confirmed that the cusp magnetic field and the negatively biased anode work effectively as an ion source. On the same voltage and current, the obtained neutron production rate was about one order of magnitude higher than that of the conventional spherical device.

To investigate the characteristics of the device in a high-voltage and high-current region, pulsed operation was carried out. Figure 1 shows the relationship between the neutron production rate and the pulse current. It was also confirmed that the integrated ion source works effectively. The maximum neutron production rate of $6.8 \times 10^9$ n/s was obtained at a pulsed discharge of $-70$ kV and 10 A with an anode bias voltage of $-1.0$ kV. This result demonstrates that the cylindrical RCBF device has a potential applicable to a proton source for PET system because the proton yield required for the production of radiopharmaceuticals for PET is $10^9$ n/s or higher.

![Fig. 1. Neutron production rate vs. pulse current](image-url)
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Radially Convergent Beam Fusion (RCBF) device is a compact fusion proton/neutron source with an extremely simple configuration, high controllability, and hence high safety. Therefore, it has been studied for practical use as a portable neutron/proton source for various applications such as landmine detection and medical positron emission tomography. However, some problems remain for the practical use, and the most critical one is the insufficiency of absolute neutron/proton yields. In this study, a new RCBF device was designed to obtain higher neutron/proton yields, and tested by using deuterium gas. The key features of the new device are the cylindrical electrode configuration in consideration of better electrostatic confinement of ions and extraction of protons, and an integrated ion source that consists of a cusp magnetic field and a negatively biased grid anode. To investigate the performance characteristics of the device and the effect of the ion source, three kinds of experimental setup were used for comparison. At first, the device was operated with the basic setup. Then a cusp magnetic field was applied by using ferrite magnets, and finally the grid anode was negatively biased. As a result, it was confirmed that the ion source works effectively. At the same voltage and current, the obtained neutron production rate was about one order of magnitude higher than that of the conventional spherical RCBF device. The maximum neutron production rate of $6.8 \times 10^9$ n/s was obtained at a pulsed discharge of $-70$ kV and 10 A with an anode bias voltage of $-1.0$ kV.

Keywords: beam fusion, proton source, neutron source, positron emission tomography

1. Introduction

Radially Convergent Beam Fusion (RCBF) is a scheme to confine ions electrostatically with two concentric electrodes, which are conventionally spherical (1)-(4). Generated ions are accelerated toward the center with sufficient energy to cause fusion reactions, and recirculate inside the anode through a highly transparent grid cathode. Because of such a extremely simple configuration of the device, RCBF is practically expected as a portable neutron/proton source with higher controllability and higher safety.

As one of the RCBF applications, medical positron emission tomography (PET) is most featured now. PET is an advanced diagnostic method with using radiopharmaceuticals, which include short-life positron emitters. It provides us the functional information inside our body and is used especially for detecting cancers or tumors. But the PET system is very expensive because it must include a cyclotron, which is used for the production of the short-life positron emitters on demand, and this high initial cost of the system is the obstacle to popularization of the PET inspection. Thus the RCBF proton source is expected to replace the cyclotron. However, some problems remain for practical use, and the most critical one is the insufficiency of absolute proton yield. In this study, a new RCBF device was designed and tested to obtain higher proton yield, which was enough to produce the radiopharmaceuticals for practical use of PET.

2. Experimental Setup

The key features of the new device are the cylindrical electrode configuration in consideration of better electrostatic confinement of ions and extraction of protons, and an integrated ion source that consists of ferrite magnets and a negatively biased grid anode.

The schematic and the cross section of the cylindrical RCBF device are shown in Figs. 1 and 2, respectively. The cylindrical vacuum chamber made of stainless steel
is 393 mm in diameter and 340 mm in height. A cylindrical grid anode consisted of 32 stainless steel rods of \( \phi 1.2 \) mm is 200 mm in diameter and 320 mm in height, which is placed at the center of the chamber. A cylindrical grid cathode made of 16 stainless steel rods of \( \phi 1.6 \) mm has diameter of 40 mm and height of 380 mm, which is set inside the anode concentrically. The chamber is evacuated to \( 10^{-5} \) Torr with a turbomolecular pump at first, and then the pressure is controlled at 1–100 mTorr by feeding \( \text{D}_2 \) or \( \text{H}_2 \) gas through a control valve.

A negative high voltage is applied to the cathode by a constant voltage constant current (CVCC) dc power supply of \(-100 \) kV, 60 mA or a pulse generator system of \(-100 \) kV, 10 A, 200 pps. The anode is grounded or negatively biased by another CVCC dc power supply and a few resistors of 20–100 k\( \Omega \) connected in parallel. The cathode voltage and the anode bias voltage are controlled independently.

To generate energetic ions efficiently, an ion source, which consists of 16 ferrite magnets and the negatively biased grid anode, is installed. The ferrite magnets are 11-mm square and 300-mm long in size, and have residual magnetic flux density of 0.36 T. To form a cusp magnetic field near the chamber wall, the ferrite magnets are mounted around the chamber wall with alternate magnetic polarity. Electrons accelerated toward the chamber wall are trapped in the cusp magnetic field, and the path and life of electrons are elongated. As a result, the electrons can ionize more deuterium molecules, and then these generated ions are extracted toward the center by the negatively biased anode. Thus the ions can obtain the almost full energy that corresponds to the cathode voltage. In this paper, to investigate the performance of the new RCBF device and the effect of the ion source, three kinds of experimental setup were used for comparison.

Generated neutrons were counted with a \(^3\text{He} \) neutron counter, which was set beside the RCBF device. The neutron production rate was calculated from the results assuming a line source on the cylindrical axis. In a D-D fusion reaction, a neutron or a proton is produced with half probability. Therefore, the neutron production rate corresponds to the proton production rate.

3. Results and Discussion

3.1 Characteristics of Basic RCBF Setup  

At first, the cylindrical RCBF device was operated with the basic setup. In this setup, ions are generated only by the glow discharge between the cathode and the grounded anode. Figure 3 shows a bottom-view photograph of star-mode discharge plasma. The formation of a converged plasmacore at the center and the light emission like spokes are clearly observed with the shadow of the cathode end.

The neutron production rate of the basic RCBF setup in dc operation was measured. Figure 4 shows the relationship between the neutron production rate and the cathode current at constant cathode voltages. The neutron production rate is proportional to the cathode current. The neutron production tendency of the new cylindrical device is almost the same as those of conventional spherical ones. This implies that the beam-background fusion reaction is also dominant in the cylindrical device as well as conventional spherical ones. The maximum neutron production rate of \( 2.1 \times 10^6 \) n/s was obtained at a dc discharge of \(-60.0 \) kV and 10.0 mA.

Figure 5 shows the comparison of neutron production
The new cylindrical device can generate 3–8 times higher neutron yield than the conventional spherical one. This increase may be caused by the better electrostatic confinement of ions, which results from the reduced influence of the feedthrough connected to the cathode. In case of the spherical device, it can not be avoided physically that the electric field is distorted by the existence of the feedthrough. Therefore, many recirculating ions are drawn to the feedthrough and lost by colliding with it. However, in the cylindrical device, ions can recirculate without the collision loss because the feedthrough does not affect the electric field essentially.

### 3.2 Effect of Cusp Magnetic Field

A cusp magnetic field was applied to the basic RCBF setup by using ferrite magnets in order to investigate its effect. In this case, ions generated in the cusp magnetic field are extracted toward the center by the electric field leaking through the grounded grid anode.

Figure 6 shows the breakdown voltage characteristic of the cylindrical RCBF device. The breakdown voltage was reduced to a half with applying the cusp magnetic field. This indicates that the cusp magnetic field works effectively as an ion source.

Figure 7 shows the comparison of neutron production rate between the setups with and without the cusp magnetic field. The neutron production rate was enhanced by a factor of about 1.5 with applying the cusp magnetic field. This also indicates that the cusp magnetic field works effectively as an ion source, and implies that the average energy of ion was increased. However, the neutron production tendency is almost the same as that of the basic setup without the cusp magnetic field and conventional spherical devices, hence the beam-background fusion reaction is also dominant.

### 3.3 Effect of Anode Bias

From the above-mentioned experimental results, it was confirmed that the cusp magnetic field works effectively as an ion source. For more efficient extraction of ions generated in the cusp magnetic field, the grid anode was negatively biased by a few hundreds volts. To bias the anode, three shunt resistors of 20, 50 and 100 kΩ, and a dc power supply were used. Because the discharge current flows into the grid anode, the anode can be negatively biased in the case that only an anode resistor is used.

Figure 8 shows the relationship between the relative neutron production rate and the anode bias voltage at a cathode voltage of −15.0 kV. Here, the relative neutron...
production rate was normalized by that in the grounded anode case. It is found that the neutron production rate increases and then saturates with the anode bias voltage. The saturation indicates that the biased anode works well and most of ions generated outside the anode are extracted. Figure 9 also shows the relationship between the relative neutron production rate and the relative anode bias voltage. In this figure, the relative anode bias voltage was also normalized by the cathode voltage in each case, and the results at some cathode voltages are plotted together. This graph indicates that the neutron production rate is enhanced by a factor of about 1.4 with effectively biasing the anode. In addition, at the same voltage and current, the neutron production rate obtained with this setup was about one order of magnitude higher than that of the conventional spherical RCBF device.

3.4 Condition of Stable Dc Operation From the above-mentioned experimental results, it was confirmed that the neutron yield was effectively enhanced by using the cusp magnetic field and the negatively biased anode. However, there is a problem that a stable dc operation can hardly be obtained with enhancement of ion source effect. Figure 10 shows the experimental condition for stable dc discharge. In case of the basic RCBF setup, the stable dc discharge can be obtained in almost all the region. However, a periodic discharge occurs and hence the stable region shifts to higher current and lower voltage sides with enhancement of ion source effect. The periodic discharge is caused by the CV/CC mode change of the high-voltage dc power supply system because the CVCC control cannot follow the rapid decrease of impedance as a result of the enhanced ion/electron multiplication effect in the discharge formation. For stable dc operation, three kinds of CVCC dc power supply were tried to use. But the periodic discharge was observed in all cases. To stabilize the dc discharge at a high voltage, a dc power supply system with larger current capacity and better load following capability is needed. However, these requirements do not matter to pulsed operation essentially. Therefore, the ion-source-assisted RCBF is suitable for pulsed operation.

3.5 Pulsed Operation In order to investigate the characteristics of the device in a high-voltage and high-current region, pulsed operation was carried out. The pulse repetition rate and the pulse width were set at 4 pps and 20 μs, respectively. Figure 11 shows the relationship between the neutron production rate and the...
pulse current at constant pulse voltages. Here, the neutron production rate corresponds to the neutron yield per pulse duration, and the data for the anode bias voltage of $-1.0 \text{kV}$ and the grounded anode are plotted for comparison. In this pulsed high-current region, the neutron production rate is also proportional to the cathode current, which implies that beam-background fusion reaction is dominant. And the anode bias voltage does not affect the neutron production tendency of the device. However, it is found that the negative bias of the anode is also effective in pulsed operation. The maximum neutron production rate of $6.8 \times 10^6 \text{n/s}$ was obtained at a pulsed discharge of $-70 \text{kV}$ and $10 \text{A}$ with an anode bias voltage of $-1.0 \text{kV}$.

4. Conclusions

To obtain higher neutron/proton yields, a new cylindrical RCBF device with an integrated ion source was designed and tested by using deuterium gas. At first, the device was operated with the basic setup. As a result, it was found that the cylindrical device can generate several times higher neutron yield than the conventional spherical one. This increase may be caused by the better electrostatic confinement of ions that results from the cylindrical electrode configuration. The maximum neutron production rate of $2.1 \times 10^6 \text{n/s}$ was obtained at a dc discharge of $-60.0 \text{kV}$ and $10.0 \text{mA}$.

Then a cusp magnetic field was applied by using ferrite magnets and the grid anode was negatively biased by a few hundreds volts. It was confirmed that the cusp magnetic field and the negatively biased anode work effectively as an ion source. On the same voltage and current, the obtained neutron production rate was about one order of magnitude higher than that of the conventional spherical RCBF device. However, there is a problem that a stable dc operation can hardly be obtained because the CVCC control of high-voltage dc power supply system can not follow the rapid decrease of impedance as a result of the enhanced ion/electron multiplication effect in the discharge formation.

Pulsed operation was carried out in order to investigate the characteristics of the device in a high-voltage and high-current region. It was also confirmed that the integrated ion source works effectively. The maximum neutron production rate of $6.8 \times 10^9 \text{n/s}$ was obtained at a pulsed discharge of $-70 \text{kV}$ and $10 \text{A}$ with an anode bias voltage of $-1.0 \text{kV}$. This result demonstrates that the cylindrical RCBF device has a potential applicable to a proton source for PET system because the proton yield required for the production of radiopharmaceuticals for PET is $10^8 \text{n/s}$ or higher.

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References


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