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Improvement of Proton Source Based on Cylindrical Inertial Electrostatic Confinement Fusion with Ion Source

Kunihito Yamauchi, Sonoe Ohura, Atsushi Tashiro, Masato Watanabe, Akitoshi Okino, Toshiyuki Kohno, Eiki Hotta, and Morimasa Yuura*

Department of Energy Sciences, Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku, Yokohama 226-8502, Japan

**Pulse Electronic Engineering Co.,Ltd.*
274 Futatsuzuka-michishita, Noda, Chiba 278-0016, Japan

ABSTRACT

Inertial Electrostatic Confinement Fusion (IECF) 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 IECF device was designed and tested to obtain high neutron/proton yields. 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 sixteen ferrite magnets and biasing the 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 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 IECF device. The maximum neutron production rate of 6.8×10^9 n/s was obtained at a pulsed discharge of -70 kV and 10 A with an anode bias voltage of -1.0 kV.

Keywords

Inertial Electrostatic Confinement, Fusion, Proton Source, Neutron Source, Positron Emission Tomography

1. Introduction

Inertial Electrostatic Confinement Fusion (IECF)[1] is a scheme to confine ions electrostatically with two concentric electrodes. 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 simple configuration of the device, IECF is practically expected as a portable neutron/proton source that is more safe and controllable.

As one of the IECF applications, medical positron emission tomography (PET) is most featured now. PET scanning is an advanced diagnosis with using nuclear medicine. It provides us the functional information inside our body and is used especially for detecting cancers or tumors. But the PET scanning 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 popularize the PET inspection. Thus the IECF proton source is expected to be replaced the cyclotron. However, some problems remain for the practical use, and the most critical one is the insufficiency of absolute proton yield. In this study, a new IECF device was designed and tested to obtain high proton yield, which is enough to produce the short-life PET nuclei.

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 biasing the grid anode.

The schematic and the cross section of the cylindrical IECF device are shown in Figs. 1 and 2, respectively. The cylindrical vacuum chamber made of stainless steel is 393-mm dia. and 340-mm high. A cylindrical grid anode is 200-mm dia., 320-mm high, which consists of 32 stainless steel rods of ϕ1.2 mm, is placed at the center of the chamber. A cylindrical grid cathode is 40-mm dia., 380-mm high, which consists of 16 stainless steel rods of ϕ1.6 mm, is set inside the anode concentrically. The chamber is evacuated to 10^{-5} Torr with a turbomolecular pump, and then the pressure is controlled at 1–100 mTorr by feeding D_2 or H_2 gas through a control valve.

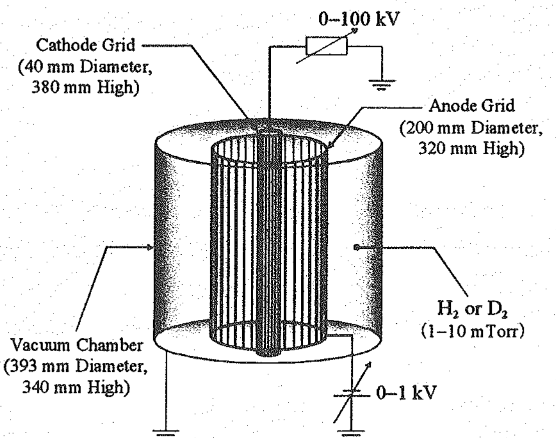

Fig. 1 Schematic of the cylindrical IECF device

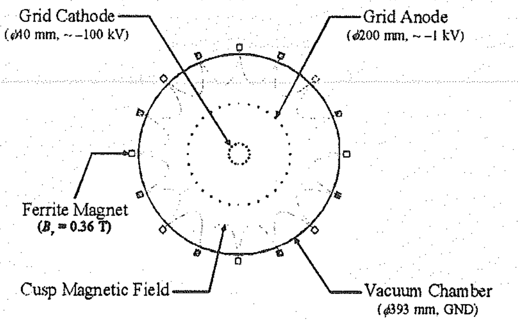

Fig. 2 Cross section of the cylindrical IECF device

A negative high voltage is applied to the cathode by a CVCC dc power supply of –100 kV, 60 mA or a pulse generator system of –100 kV, 10 A, 200 pps. The anode is negatively biased by another CVCC dc power supply and a few resistors of 20–100 kΩ connected in parallel. The cathode voltage and the anode bias voltage are conditioned independently.

To generate energetic ions efficiently, an ion source, which consists of 16 ferrite magnets and biasing the grid anode, is installed. The ferrite magnets are 11-mm square and 300-mm long, and have a 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 with alternating the magnetic polarities. 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 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 IECF device and the effect of the ion source, three kinds of experimental setup were used for comparison.

3. Results and Discussions

3.1 Characteristics of basic IECF setup

At first, the cylindrical IECF 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 plasma core at the center and the light emission like spokes are clearly observed with the shadow of the cathode end.

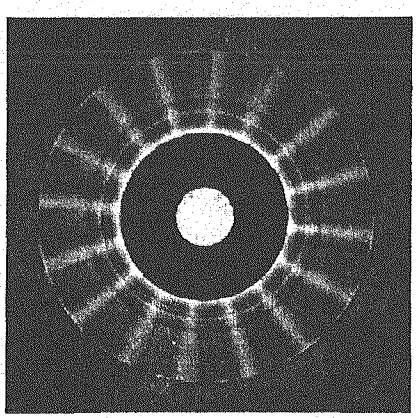

Fig. 3 Photograph of discharge plasma

The neutron production rate of the basic IECF 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 that of conventional spherical ones. This implies that the beam-background fusion reaction is also dominant in cylindrical device as well as conventional spherical ones. The maximum neutron production rate of 2.1×10^6 n/s was obtained at a dc discharge of –60.0 kV and 10.0 mA.

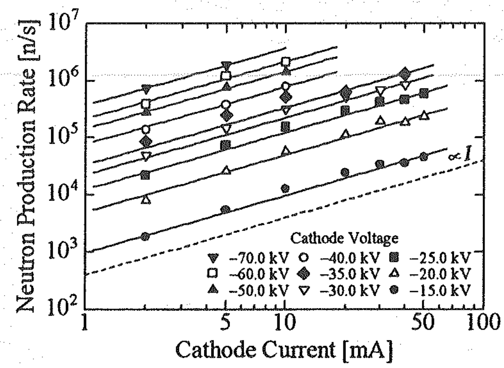

Fig. 4 Neutron production rate vs. cathode current at constant voltages (basic setup)

Figure 5 shows the comparison of neutron production rate between the basic setup and the conventional spherical one[2]. 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 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 pulled to the feedthrough and then lost by colliding with it. However, in the cylindrical device, ions can recirculate without the collisional loss because the feedthrough does not affect essentially.

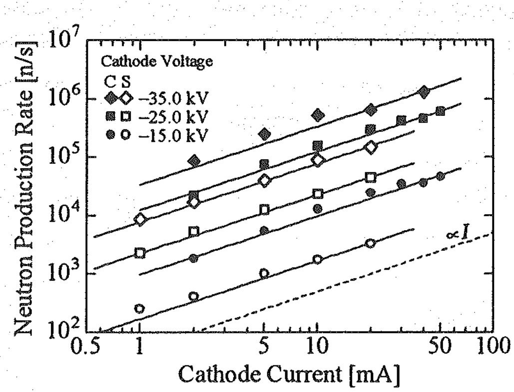

Fig. 5 Comparison of neutron production rate between the basic setup (C) and the conventional spherical device (S)

3.2 Effect of cusp magnetic field

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

Figure 6 shows the breakdown voltage of the cylindrical 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.

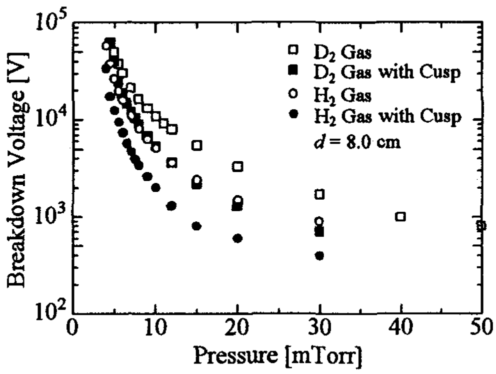

Fig. 6 Breakdown voltage vs. gas pressure

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 ions 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.

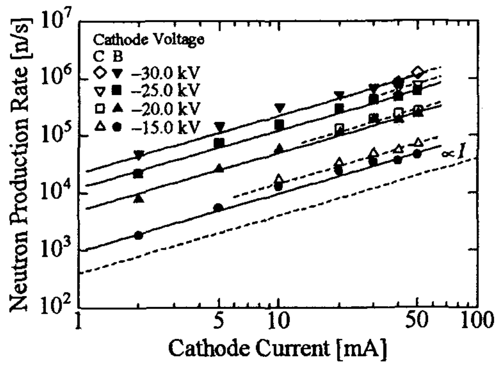

Fig. 7 Comparison of neutron production rate between the setups with and without the cusp magnetic field

3.3 Effect of biasing anode

From the previous 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, 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 the result of the grounded anode case. It is found that the neutron production rate increases and becomes saturated 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 anode bias voltage was also normalized by the cathode voltage, 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 effectually 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 IECF device.

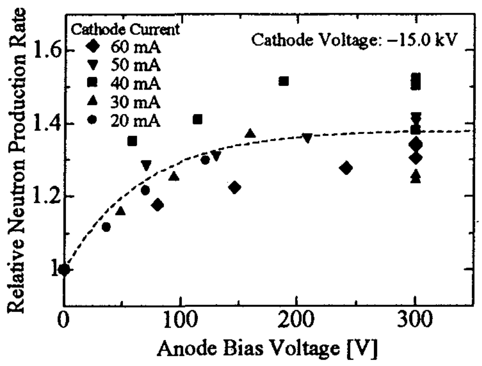

Fig. 8 Relative neutron production rate vs. anode bias voltage at a cathode voltage of −15.0 kV

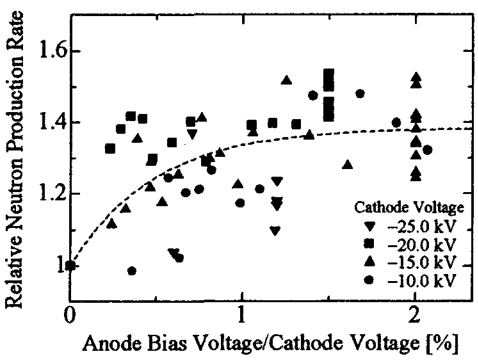

Fig. 9 Relative neutron production rate vs. relative anode bias voltage

3.4 Condition of stable dc operation

From the previous experimental results, it was confirmed that the neutron yield was effectively enhanced by using the cusp magnetic field and biasing the 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 IECF setup, the stable dc discharge can be obtained at almost all the region. But a periodic discharge occurs and the stable region shifts to higher current and lower voltage side with enhancement of ion source effect. The periodic discharge is caused by the CV/CC mode change of the dc power supply system because the CVCC control can not 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 IECF is suitable for pulsed operation.

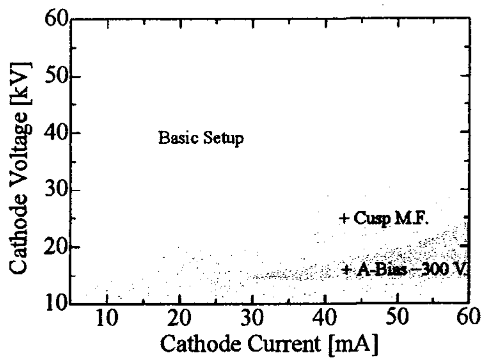

Fig. 10 Experimental condition of stable dc discharge

3.5 Pulsed operation

Pulsed operation was carried out in order to investigate the characteristics of the device in a high-voltage and high-current region. The pulse repetition rate and the pulse width were set at 4 Hz and 20 μs, respectively. Figure 11 shows the relationship between the neutron production rate and the pulse current. Here, the data of the anode bias voltage of −1.0 kV and the anode ground 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 biased anode is also effective in pulsed operation. The maximum neutron production rate of 6.8×10^9 n/s was obtained at a pulsed discharge of -70 kV and 10 A with an anode bias voltage of -1.0 kV.

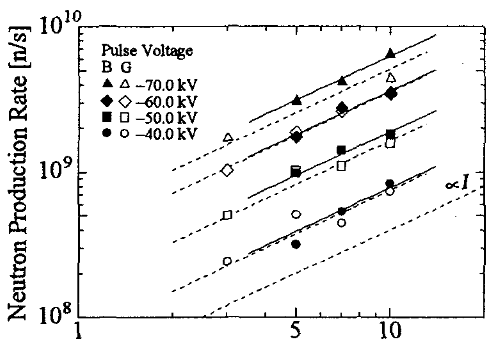

Fig. 11 Neutron production rate vs. pulse current (B: anode bias voltage of -1.0 kV, G: anode grounded)

4. Conclusions

A new cylindrical IECF device with an ion source was designed and tested. 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 conventional device. 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 2.1×10^6 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 biased anode works effectively as an ion source. At the same voltage and current, the obtained neutron production rate was about one order of magnitude higher than that of the conventional spherical IECF device. However, there is a problem that a stable dc operation can hardly be obtained with enhancement of ion source effect.

In order to investigate the characteristics of the device in a high-voltage and high-current region, pulsed operation was carried out. It was also confirmed that the integrated ion source works effectively. The maximum neutron production rate of 6.8×10^9 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 IECF device has potential applicable to a proton source for PET scanning system because the proton yield required to produce short-life PET isotopes is 10^9 n/s or higher.

References

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