Spectroscopic analysis of Linear shaped Inertial Electrostatic Confinement Fusion (IECF) device

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ABSTRACT

Inertial Electrostatic Confinement Fusion (IECF) is a nuclear fusion scheme, which electrically confines and accelerates glow-discharge-generated deuterium ions, and causes fusion reactions. This scheme is expected to be applied to compact, less expensive neutron sources. We developed a linear-shaped IECF device, which is advantageous for high power operation to increase neutron production rate. We analyzed the particle motions from Doppler-shifted Hα spectra in discharge experiments using hydrogen gas instead of deuterium gas.

Keywords

inertial electrostatic confinement fusion, neutron source, spectroscopy, plasma, glow discharge,

1. Introduction

The original concept of Inertial Electrostatic Confinement Fusion (IECF) was proposed by P. T. Farnsworth[1]. After Miley studied an IECF device as a neutron source [2], and various types of IECF devices have been researched[3]. In typical IECF devices, a high voltage (typically from several tens to a hundred kV) is applied to a grid cathode at the center of the grounded vacuum anode chamber. Deuterium ions generated by glow discharge in low pressure (about 1 Pa) deuterium gas are accelerated toward the cathode and cause nuclear fusion reactions. These ions are confined in an electrostatic potential well formed between the electrodes.

Recently IECF devices are expected as neutron sources for landmine detection[7], SNM (Special Nuclear Material) inspection, and so on, since they are compact enough to carry and able to produce neutrons without radioisotopes. Figure 2 shows various applications of neutron sources depending on neutron production rate (NPR). Neutron sources for portable inspector need to provide NPRs about $10^6$ n/s, but there remains considerable effort to reach such NPRs, since the order of NPR reported in many studies on portable IECF devices are about $10^5$ to $10^7$ n/s [8, 9].
2. Discharge parameters related to NPR

Discharge current, voltage, and gas pressure strongly affect the NPR of IECF devices. In most cases, the neutron production in IECF devices is considered to be dominated by the fusion reactions between accelerated ions and background neutral particles from the experimental fact that the NPR is proportional to the discharge current.

When we assume monoenergetic ion beams, the NPR is given by:

$$NPR = \sigma(E)\nu n_b n_0,$$

where $E$ is ion energy and $\sigma(E)$ is fusion cross section, $\nu$ is ion velocity, and $n_b$ and $n_0$ are the number densities of ion beam and background deuterium gas, respectively.

The simplest way to increase the NPR is to increase the discharge current, which means the increase of ion flux $\nu n_b$. Increasing applied voltage increases the ion velocity $\nu$ and the fusion cross section $\sigma(E)$. The background particle number density $n_0$ is directly connected to the gas pressure.

Increasing current and voltage results in electrode heating. Particularly, the grid cathode is difficult to be cooled in the spherical IEC devices. In addition, higher voltage operation needs lower target gas density (background gas pressure). So, it is necessary to find the condition that maximize the NPR, but it is hard to determine the optimal condition theoretically, since the particle motions in the IECF devices are very complex.

3. Linear type IECF device

We developed a linear-type IECF device, which is suitable for cooling the electrodes during high power operation. As shown in Fig. 3(a), this IECF device is composed of a hollow cathode and two cylindrical anodes, which are coaxially arranged in an alumina tube. The exposed electrodes enable us to cool them directly. Further, this configuration also simplifies the design of high voltage isolation against arc discharge between the electrodes because a high voltage feedthrough is not necessary.

For spectroscopic measurement, we also built an IECF device having the side insulating walls made of glass tube as shown in Fig. 3(b).

4. Particle motion analysis from Doppler shifted Hα spectrum

In IECF devices, charge exchange reactions have an important role. These reactions make accelerated ions to fast neutral particles. As shown in the following formulae, the velocity of the produced fast neutral particle is equal to that of its parent ion.

- $H^+(E) + H_2 \rightarrow H^+ (E) + H_2^+$
- $H_2^+(E) + H_2 \rightarrow H^+ (E/2) + H + H_2^+$
- $H_3^+(E) + H_2 \rightarrow H^+ (E/3) + H_2 + H_2^+$

Here, $E$ denotes the kinetic energy of the parent ion. From the Doppler shift of the light emitted from the neutral particle, we can evaluate the velocity of the parent ion. Thus, we examined indirectly the ion velocity distribution in the IECF device by observing Doppler shifted Hα spectra from discharge plasma.

Figure 4 shows the configuration of the spectroscopic measurement. The measurement was performed from two directions. In case 1, the light emitted from the region inside the cathode was collected by a lens located on the center axis through the side viewport. In case 2, the light was observed through the glass wall from the direction of the line of sight inclined 60 degrees to the equipment axis.
4.1 Ha spectra from the cathode center

Figure 5 shows Ha spectra measured at the cathode center under various discharge conditions. Figure 6 enlarges the righthand side of the Ha spectra. Each Doppler-shift consists of a few peaks, which are clearly separated from the original peak of Ha. The Doppler-shift components of the spectra have shoulders where the intensities decrease sharply and gentle tails outside the shoulders.

Figure 7 shows the spectra plotted with respect to the kinetic energies of H and H2 calculated from the velocities of Ha-emitting hydrogen atoms. The ends of the shoulders and the tails of the spectra coincide with the maximum kinetic energies of H2+ and H+ ions determined by the discharge voltage, respectively. This result shows that there are multiple species of parent ions at least H+ and H2+ in the device during discharge, and the spectrum is the convolution of components from that the fast neutral particles originating from different parent particles.

Figure 8 shows a typical result of curve fitting of the Ha spectrum with Gaussian functions. As shown in the figure, four Gaussian curves well reproduce the spectrum; the center peak located at the original Ha position corresponds to the thermal component, and the others correspond to the Doppler-shift components. From this analysis, we evaluated two quantities by using the fitted Gaussian curves; one is the ratio of the height of the two Gaussian peaks (F2/F1), and the other is the ratio of the area of the thermal component to the sum of the area of the fast (Doppler-shift) components. Each Gaussian curve of the Doppler-shift component is not related to the species of parent ions, so its area is not meaningful quantitatively.
positions on the axis. The spectrum shape changes depending on the distance from the cathode. The Hα line spectrum near the cathode is intense and symmetric. When the observation point moves away from the cathode, the spectrum becomes asymmetric, indicating that the amount of fast neutrals flowing out of the cathode is larger than those towards the cathode.

Figure 10 shows a typical Hα spectrum measured from directions of 60 degrees at three different positions on the axis. The spectrum shape changes depending on the distance from the cathode. The Hα line spectrum near the cathode is intense and symmetric. When the observation point moves away from the cathode, the spectrum becomes asymmetric, indicating that the amount of fast neutrals flowing out of the cathode is larger than those towards the cathode.

Figure 10. Typical Hα spectra observed at different axial positions (case 2 in Fig. 4).

From Fig. 9, one can see that the ratio F2/F1 gradually increases as the applied voltage increases, which means that H2+ ions are more effectively accelerated by the potential drop between the electrodes. The decreasing gas pressure as the voltage rises also may contribute to the increase of F2/F1 because of increased mean free pass of ions.

On the other hand, the areal ratio of the Doppler-shift component to the thermal one decreases significantly as the voltage rises. This may be due to the increase of the mean free path of electrons, which decreases electron impact ionization and ion generation in the discharge plasma.

4.2 Relationship between spectrum intensity and axial position

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5. Conclusions

We developed a linear type inertial electrostatic confinement fusion device as a compact and radioisotope free neutron source. Its linearly arranged electrodes enable us to efficiently cool them directly with improved withstand voltage. So, it is suitable for high-power operation of the IECF device, which needs to improve the neutron production rate.

We analyzed particle motions in the device spectroscopically by observing Doppler shifted Hα spectrum. The observed Hα spectra indicated that multiple ion species at least H⁺ and H₂⁺, coexist in the device. We also found that a lot of fast neutral particles generated inside cathode. Their collision with background thermal particles has considerable contribution to the spectrum. Decomposition of these complex components is a future task.

References