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Plasma Heating Device Based on Electron Beam Irradiation

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Abstract

Currently, large-scale equipment is essential for heating plasma. In this study, based on the theoretical investigation of high-current electron beam applications, a new method for heating plasma is proposed. If this method is successful, fusion power can be generated much more easily and inexpensively than using conventional methods. This study considered the theoretical possibility of generating ultrahigh-temperature plasma by confining plasma particles between the anode (positive potential) and electric fields using Rutherford scattering of particles forming a heavy-mass-positive-ion layer. In order to form this deuteron-positive ion layer, hydrogen gas is encapsulated in a closed container and applied to a negative with an insulator film on the inner surface. Next, the gas is ionized by irradiating a high-current electron.

Keywords

Rutherford Scattering, Bragg Peak, Potential Analysis, X-Ray Spectral Analysis, High-Current Electron Beam

1. Introduction

Joule heating, high-frequency heating, and electron beam injection heating [1]-[4] are the commonly used plasma heating methods. However, the devices used in these methods are large and expensive. Moreover, these methods exhibit several disadvantages, such as the control of the magnetic field required for plasma confinement and the realization of uniform implosion, thus making fusion power generation difficult. Therefore, in this study, a novel plasma heating method was proposed. Unlike conventional plasma heating using relativistic electron beam, the proposed method does not require magnetic field confinement or implosion and is an advanced method for producing numerous proton beams. The high-current irradiated electron beams are bounced by the negative potential of the vessel wall and moves inside the container. Subsequently, the protons produced via the electron beam irradiation of hydrogen gas are confined in the container as a result of their backscattering due to Coulomb collision as a heavy ion layer (Rutherford scattering) under an electric field. Finally, by continuously irradiating the plasma in the container with high-speed electrons, this plasma can be heated to high temperature. Furthermore, the temperature of the high-temperature plasma can be measured (estimated) by continuous X-ray spectral analysis. Moreover, as the device is small and requires a small amount of power to operate, it is easy to experimentally confirm the presence or absence of phenomena.

2. Outline of Apparatus

2.1. Overview of the Operation of Laboratory Equipment and the Need for Experiments

Beam from the outside of the container, and the generated proton is attracted by the negative charge of the container wall and collides with the insulator to oxidize the fluororesin. Furthermore, these plasma particles can be heated via electron beam irradiation. The feasibility of this method can be confirmed using demonstration experiments.

It is difficult to simulate the interaction between the electron beam and the vessel wall, the behavior of the plasma, and the stability of the heavy cation layer with a computer at the same time. Even if it is possible, it is still necessary to conduct demonstration tests in order to prove that it works as expected with actual equipment.

2.2. Formation Experiments of Heavy-Positive-Ion Layer

First, the interior of a negatively charged sealed metal container is covered with an insulator film. Subsequently, an anode tube is placed in the center of the container, which is filled with hydrogen gas (or heavy hydrogen gas). Thereafter, the container is irradiated with an electron beam by passing it through a magnetic lens and incident tube from the outside, resulting in the production of plasma through the ionization of hydrogen gas.

Through continuous hydrogen gas supply and electron irradiation, a heavy-mass-positive-ion layer is formed via ionization by proton collision through a phenomenon wherein proton energy is released at a certain depth in an insulator film depending on the electron velocity (Bragg peak). By continuing hydrogen gas supply and ionization for a certain period, a large- and heavy-mass-positive-ion layer of required thickness can be produced. The electron beam decelerates after acceleration in the positive potential part in the middle of the incident tube, canceling out the speed. In addition, it is decelerated by the negative potential near the chamber wall, but the electric force acts in a direction perpendicular to the equipotential line, so it does not stop due to the negative potential and can pass through the opening part of container. After passing, the speed is also offset because it acts as an acceleration force in reverse. As a result, the electron beam that enters the chamber continues to bounce due to the negative potential of the chamber wall. The excess electrons are discharged from the anode tube in the center of the chamber. In addition, the surplus protons can be discharged out of the chamber by lowering the positive potential in the middle of the incident tube.

2.3. Plasma Heating Experiment

By supplying a small amount of hydrogen gas and changing the speed of the irradiating electron beam such that it is faster than that during the formation of the large and heavy-positive-ion layer, the velocity of the generated proton is increased. Because these protons cannot penetrate the heavy-mass positive-ion layer, protons recoil in the chamber owing to Rutherford scattering. In this recoil process, protons scarcely lose energy owing to their light weight. Therefore, the plasma containing fast protons that have returned to the inside of the chamber can be heated to the required high temperature by continuing the irradiation of fast electrons. By continuous irradiation of a high-current electron beam, all hydrogen gas can be ionized into protons. When an excessive amount of irradiated electrons accumulates in the container, the electrons are naturally attracted to the anode and discharged from the anode connected to the outside of the container.

2.4. Schematic Structure of the Plasma Heating Device

Figure 1 shows the schematic diagram of the proposed plasma heating device. The hollow conductor (1), which is a sealed chamber, has a cylindrical inner surface. This conductor can be negatively charged, and its inner and outer surfaces are covered with insulator films. The tubular anode (2) is supported in (1) by the insulating material. The electron injection tube (3) can be negatively charged, and its inner surface is covered with an insulator film. This tube is extended to the tangential direction of the inner surface of (1). The one end of the tube is the inlet of electrons, and the other end is connected to the inside of (1). The diameter of the injection tube is determined by the current of the electron beam. Hydrogen gas is supplied from the tank (4) into (1) through the supply tube (41) and (2). The vacuum chamber (5) is connected to the vacuum pump (51) to maintain the necessary vacuum, and its inside is connected to the one end of the injection tube (3). The electron gun (6) injects electron beam from the inlet into (1) through the inside of (5). The electron beam is reflected by the negatively charged inner wall of (1). Subsequently, the reflected electrons convert the gas that has been supplied from (4) into (1) into plasma. The cooling device (7) that covers (1) has a water channel. Because the water flow circulates through the heat exchanger, the water pressure can be controlled. For the electron gun, commercially available electron guns such as the vacuum heating gun can be used.

The proposed device is equipped with an X-ray spectrometer and a gas-flow regulator for observing X-rays emitted from the vacuum chamber and controlling the flow rate of the gas supplied from the tank to the supply tube, respectively.

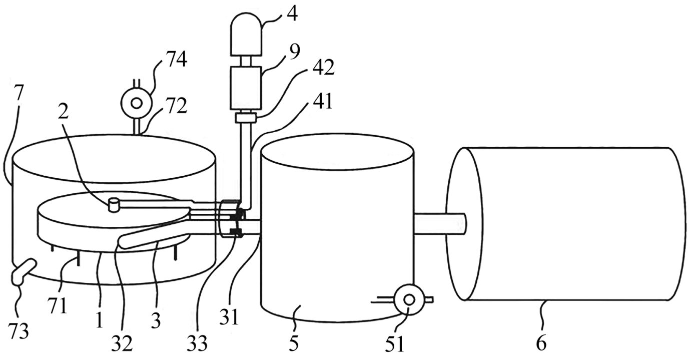


Figure 1. Three-dimensional view of the plasma heating device.

3. Physics in the Formation of Large and Heavy-Positive-Ion Layer in Insulator Film

Hydrogen gas is converted to plasma upon being introduced into the sealed chamber and subsequently irradiated by the electron beam; plasma tries to escape from the chamber. However, the interior of the sealed chamber is negatively charged by the anode located at the center of the chamber, and the inner surface corresponding to the cathode is covered with an insulator film (ferroelectric material), including the small incident tube parts. Therefore, light positive ions such as protons in the gas that have been converted to plasma are attracted to the cathode and intrude the inside of the insulator film. However, these ions stop at a flying distance depending on the velocity and give rise to a Bragg peak by releasing energy. Thus, the insulating substrate is intensively ionized around the Bragg peak and secondary electrons are emitted.

Therefore, if the amount of supplied gas is sufficient, a positive-ion layer can be produced in the shallow region in the insulator film via electron beam irradiation at a low voltage. This indicates that the secondary electrons escape from the insulator film owing to the negative electric field of the sealed chamber, while the positive ions are attracted to the insulator film and stay near the surface. The produced positive-ion layer exerts a shielding effect against the electric field. Nevertheless, applying a high-voltage negative electric field to the wall of the sealed chamber allows preventing the film from being heated because the electron beam cannot reach the insulator film. Additionally, because light-positive ions such as protons that have been produced via the conversion of hydrogen gas into plasma intrude into the insulator film, only electrons remain in the sealed chamber. The excess electrons are eventually absorbed by the anode and ejected to the outside of the device.

In previous research [5] [6], positive charges were found to accumulate in a fluororesin via proton beam irradiation and this accumulation phenomenon lasted for a considerable length of time. Accordingly, when protons generated via the ionization of hydrogen gas in the chamber are attracted to the negative potential at the wall of the sealed chamber and collide with fluororesin, a layer of heavy positive ions is certainly formed.

Range of Proton Beam

Based on the Bragg-Kleeman rule, the range of an α-ray in air is given by the following equation:

$$R = 0.318E^{3/2}, \tag{1}$$

where R represents the flight range (cm) and E represents the energy of α-ray (MeV). For a solid, the range R is given by the following equation:

$$R = \rho_0/\rho\left(A/A_0\right)1/2\times R_0, \tag{2}$$

where ρ_0 and ρ represent the densities of the substance, A_0 and A represent the mass numbers of the substance, and R_0 and R represent the range of air and solid, respectively. From Equation (2), the range of α-rays in fluororesin can be obtained.

Furthermore, as α-ray comprises four nuclei, the energy per one nucleus is a quarter of the total energy. Therefore, a comparison of an α-ray and a proton with the same energy shows that the range of the proton beam is four times longer than that of the α-ray. Thus, when a 1-keV proton beam is irradiated onto fluororesin with a density of 2.14 g/cm^3, the range is ~0.6 nm.

Notably, the density of fluororesin decreases with increasing ionization; Therefore, the range will become longer even more under low density.

Stuffer ring occurs when large and heavy particles such as Ar collide with the surface of the target, but in the collision of small and light particles such as protons, the stapper ring does not occur and penetrates the target.

4. Verification That Plasma Containment by Electric Force Is Possible (Electric Potential and Electric Field Analysis)

4.1. Results of Electric Potential Analysis

Figure 2 shows a cross-sectional view of the plasma heating device, while **Figure 3** and **Figure 4** schematically represent the plasma heating device. Furthermore, **Figure 3** and **Figure 4** present examples of the results obtained from the electric potential analysis, which show that the electron beams recoil at the inner wall of the negatively charged cylindrical sealed chamber during the formation process of the heavy-positive-ion layer, as described in Section 2.1.

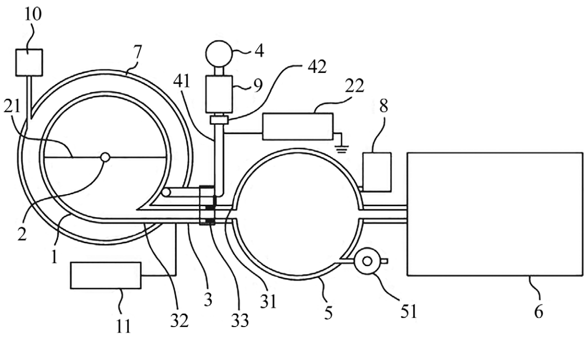


Figure 2. Cross section of the proposed plasma heating device.

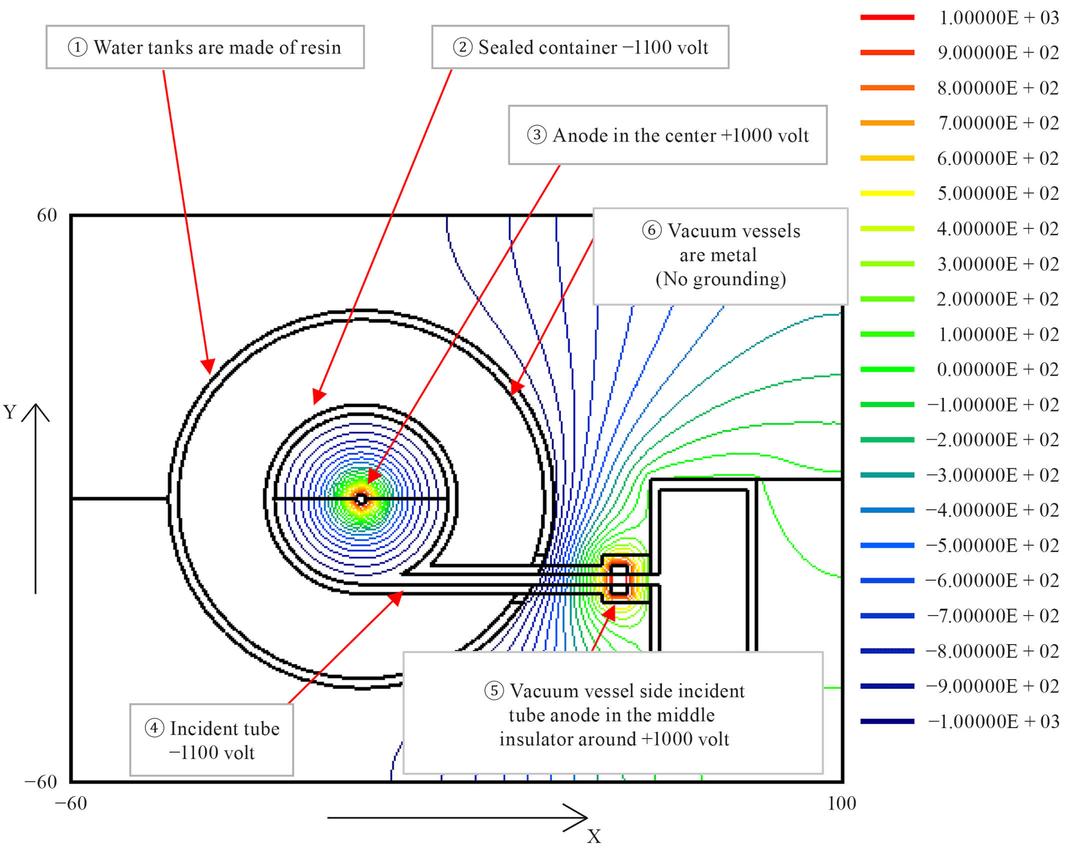


Figure 3. Cross section of electric potential analysis.

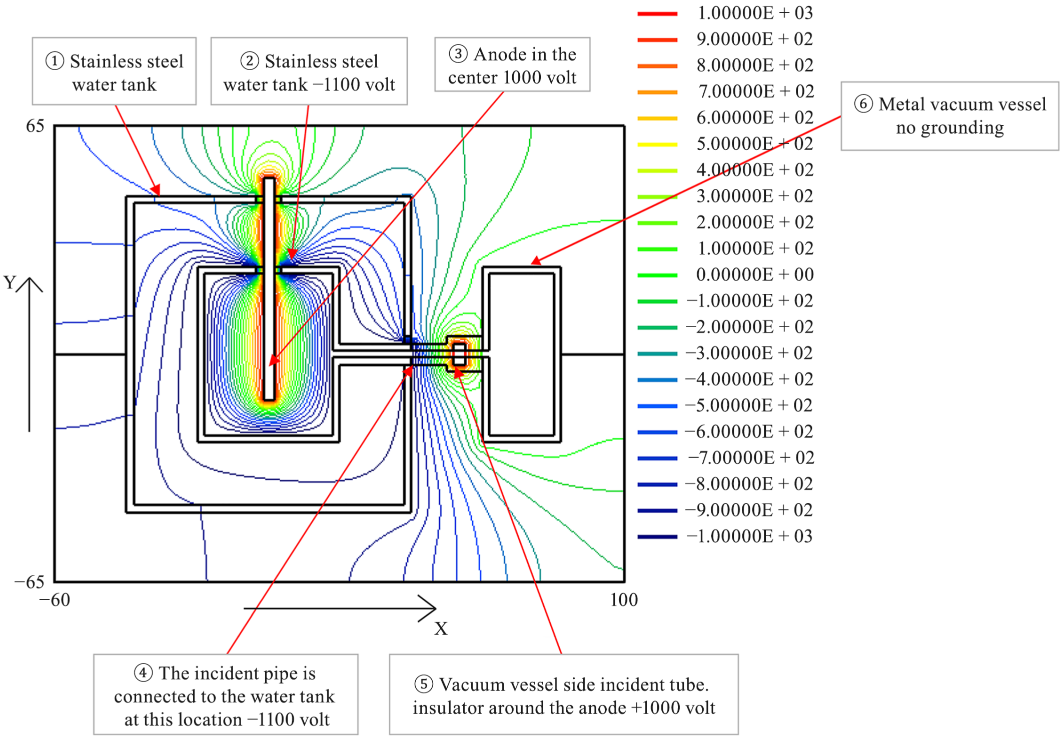


Figure 4. Longitudinal section of electric potential analysis.

The electron beam enters from the tangential direction into the inner wall of the chamber (cross-sectional view in **Figure 3**) through the injection tube and is reflected by the negative potential of the wall.

Figure 3 and **Figure 4** show that all the sealed-type chamber walls are negatively charged to prevent the 1-keV electron beams from colliding with the walls. Furthermore, as the potential is not generated at the inlet of the electron beam injection tube, the electron beam is accelerated at the positive potential region in the middle of the injection tube; however, the electron beam speed decreases owing to the deceleration of the electron beam after passing through the tube. The electron beam is decelerated at the part connected to the sealed chamber. However, the equipotential lines are angled at ~45˚ against the beam injection direction; therefore, the electric force works perpendicular to the equipotential lines. Thus, the electron beam can intrude into the chamber without being interrupted by the potential of the sealed chamber. After passing through this part, the negative potential will function conversely as an accelerating force.

The current and accelerating voltage of the electron beam used in the electric potential analysis is assumed to be 500 mA and 1 keV, respectively; Moreover, the irradiation is assumed to be continuously conducted for a long time. For the formation process of the heavy positive ions, −1100 V is applied to the sealed-type chamber with a radius and length of 2 and 5 cm, respectively (volume: 62.8 cm^3), *i.e.*, the potential of the anode is supposed to be 1000 V.

The first ionization potentials of the carbon and fluorine atoms are 1086.5 and 1681.0 kJ/mol, respectively. The ionization energy of hydrogen gas is 2842 kJ/mol (1312 kJ × 2 + 218 kJ (ground state atomization)).

The aforementioned data show that 16 s will be required to ionize hydrogen gas corresponding to the total amount of 1 atm via the irradiation of a 500-W electron beam even when hydrogen gas is supplied incrementally. Moreover, 18 min will be required to heat all the hydrogen plasma to 1 keV via the irradiation of a 500-W electron beam. Although even longer time will be required, the ionic layer formation in fluororesin can be achieved if irradiation is conducted for a sufficiently long time.

The results of the Coulomb collision calculation showed that >6740 layers are needed for the formation of the heavy-positive-ion layer. However, the film thickness required for the formation of heavy-positive-ion layers is ~1 μm, because the C–F bond length of fluororesin is as short as 1.3 Å.

Because the range of the proton beam assumed in this paper is as short as 6 Å, heavy positive ions generated via the ionization of fluororesin are formed near the insulator film surface as positive ions, accompanied by the intrusion of the proton beam. Furthermore, proton beams, which intrude at the position where the beam does not collide with the heavy positive ions, reach the deep region without losing considerable kinetic energy due to forward Rutherford scattering. Upon stopping at this deep region, the heavy positive ions ionize fluororesin one after another by releasing ionization energy and converting fluororesin into heavy positive ions.

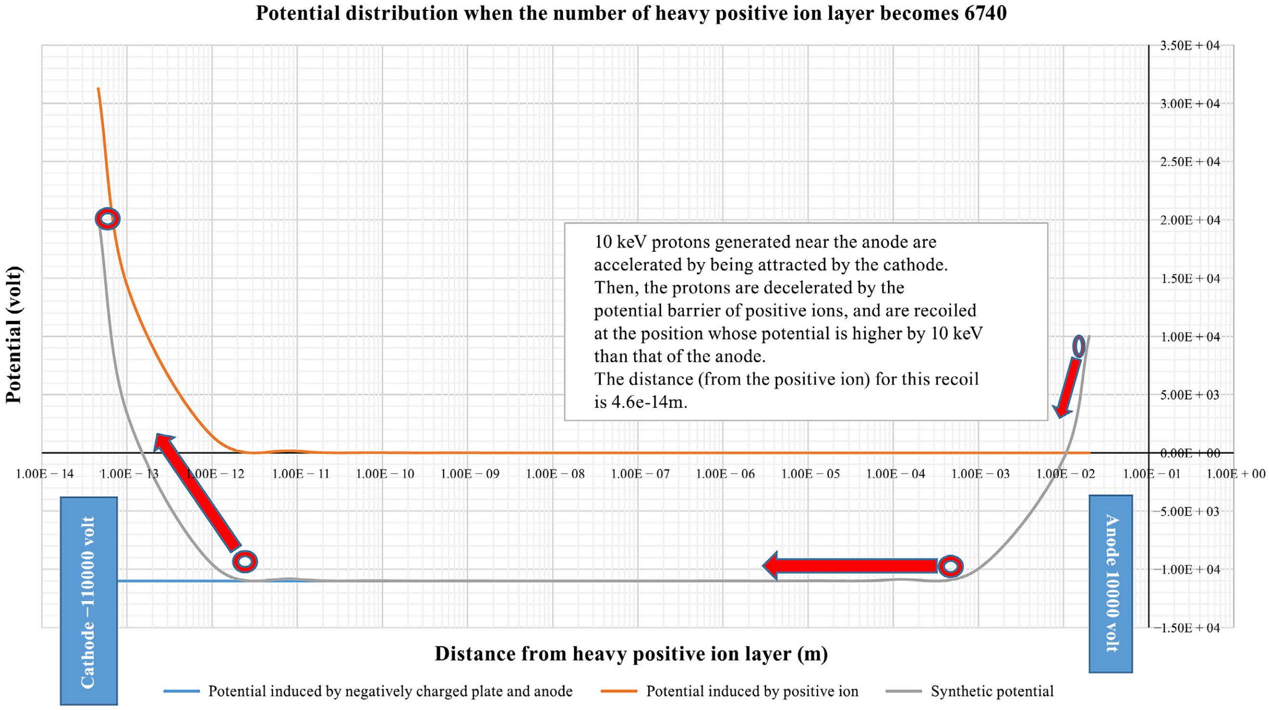
Through these processes, the range will become longer owing to the decrease in the density of fluororesin. Furthermore, the range can be extended when the velocity of proton beam is gradually increased from 1 keV by increasing the velocity of the irradiating electron beam.

Thus, when ~6740 layers are formed, a proton beam will be unable to intrude into the deeper region owing to Rutherford backscattering.

Heavy positive ions produced in the proposed device are attracted to the negatively charged wall of the chamber and stay near the surface of the insulator film.

4.2. Results of Electric Field Analysis

Figure 5 shows an electric field analysis chart of how hydrogen plasma in the sealed chamber can be heated up to the required high temperature through the process of plasma heating described in Section 2.2. The hydrogen plasma can be heated because thermal equilibrium is achieved by continuously irradiating a fast 10-keV electron beam on protons confined in the sealed chamber. The vertical and horizontal scales show the electric voltage and position between cathode and anode, respectively.



10 keV protons generated near the anode are accelerated by being attracted by the cathode. Then, the protons are decelerated by the potential barrier of positive ions, and are recoiled at the position whose potential is higher by 10 keV than that of the anode. The distance (from the positive ion) for this recoil is 4.6e-14m.

Figure 5. Chart of electric field analysis.

As shown in the electric potential analysis (Figure 5), it is supposed that the 10,000 V positive potential part is set at the injection tube, and the voltage over 10,000 V is supposed to be applied to the sealed chamber. Due to these applied potentials, protons in the sealed chamber will not escape the electron injection tube.

4.3. Coulomb Collision

According to the Coulomb's law, which states that the force working between two charged particles is inversely proportional to the square of the distance, a proton approaching a positive ion formed in the insulator film receives strong repulsive force as it approaches. Therefore, if a heavy-positive-ion film is sufficiently thick, a proton ion irradiated on the film will finally collide and recoil at the angle corresponding to the backscattering by one of the positive ions due to the overlapping of the ionic layers. Considering the collision diameter b calculated from the equation $b = Ze^2 / 4\pi\varepsilon_0 mv^2$ [7]; The backscattering occurs at $b = 72$ fm or shorter in the case of a monovalent ion such as proton. When the number of positive-ion layers is 6740, the average collision diameter b of the protons in flight is calculated to be ~23 fm by inferring the distance between ions to be approximately 46 fm. Thus, protons collide with positive ions and are backscattered. Therefore, such a heavy-positive-ion layer can be considered as a wall that reflects protons through the Coulomb collision.

5. Investigation of the Possibility to Make Demonstration Experiment Device

To investigate whether it is possible to produce this device, the following conditions were assumed. The chamber is the sealed type, and the inner surface of the chamber is covered with fluororesin. The diameter and length of the chamber are 2 and 4 cm, respectively. Hydrogen gas at 1/100,000 atmosphere is confined in a sealed chamber, which is then heated through the irradiation of a 10-keV electron beam. From these experimental conditions, the following parameters were calculated and estimated. In the plasma heating process, the electron beam was set to be 50 mA and 10 keV, and the irradiation was supposed to be continuously conducted.

5.1. Plasma Pressure

The temperature of a particle group with an average energy of 1 eV corresponds to 7740 K based on the relation 1 eV = 3/2 KT. Therefore, the temperature of 10-keV particles corresponds to 7.7×10^6 K. Based on the Boyle–Charles law, the pressure is approximately 2.6 atm, calculated from 7.7×10^6 K ÷ 300 K ÷ 100,000. By controlling the water pressure outside the chamber, it will be possible to make a chamber that will not be damaged even when the pressure becomes high.

5.2. Heat Generation Amount of Chamber

Because the power of the beam is 50 mA × 10 keV = 500 W, the amount of heat generation will be 119 ca/s based on the relation 1 ca = 4.2 J even if all the beam energy is converted into heat. Therefore, assuming that the flow rate of water outside the chamber is 100 cc/s, the increase in the water temperature is expected to reach only 1.2˚.

The proton momentum transferred to the insulator film by the collision will be transmitted as heat to the flowing water surrounding the sealed-type chamber, and the heat will be carried out of the device.

5.3. Radiation Loss by Bremsstrahlung Heat

Because the energy corresponding to bremsstrahlung heat decreases with decreasing density, it will become ~10 W when the gas volume becomes 1.8×10^9 times larger than the water volume. Therefore, under the assumed conditions, the radiation loss is negligible and the input power is considerably high [8].

5.4. Performance of Insulator Film

The dielectric strength, thermal insulation, and thermal conductivity of fluororesin polytetrafluoroethylene (PTFE) are 19 kV/mm, 260˚C, and 0.23 W/m-K, respectively. Therefore, it can be used without causing dielectric breakdown or thermal destruction by controlling the current and voltage of the electron beam.

6. Measurement of Plasma Temperature

When the temperature of plasma in a sealed-type chamber becomes high, X-rays are generated owing to bremsstrahlung and released through the electron beam injection tube. Such electromagnetic radiation causes the energy loss of plasma. However, when the X-ray spectra are observed from the outside of the chamber using an X-ray camera, the plasma temperature can be measured (estimated) from the shape of the continuous spectrum [9].

7. Conclusion

After examining the feasibility of the experiment from multiple perspectives, it is considered possible to conduct an experiment in which plasma is confined in a chamber by electric force and the plasma is heated via electron beam irradiation, and the success or failure of the new plasma heating method can be confirmed via this demonstration experiment. This method can perform high-temperature heating at a substantially lower cost than the conventional plasma heating method. Therefore, I hope that this study will be followed by researchers who aim to further develop this research through experiments demonstrating the feasibility of this method. Furthermore, future studies are expected to experimentally validate the proposed method, and this study will serve as a reference for researchers who intend to develop this research further.

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None.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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