Production of Helium and Helium-Hydrogen Positive Ion Beams for the Alpha Particle Measurement

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Abstract. In order to produce diagnostic helium neutral beam for alpha particle measurement in nuclear fusion plant of deuterium-tritium reaction, helium ion (He^+) or helium-hydrogen ion (HeH^+) beams of ~20 keV have been considered as a primary beam. For He^+ beam, it is important to produce focused high-current-density ion beam in order to pass through small apertures of alkali gas cell with an enough signal level. For HeH^+ beam, conditions producing HeH^+ has not been investigated in detail as yet. In order to extract these beams, focused high-current-density neutral beam system is applied. For He^+ beam extraction of ~22 kV, it is confirmed that current density of ~86 mA/cm^2 is achieved, whose value is close to necessary value in ITER. For HeH^+ beam extraction in the case of ~300 V acceleration, the production rate of HeH^+ component increases with the increase of helium gas pressure ratio to hydrogen gas pressure when its value is > ~75 %. In the case of 25 kV acceleration, if 15 % of total current (which includes H^+, H_2^+, H_3^+, He^+ and HeH^+ components) is HeH^+ component, current density of HeH^+ is estimated as ~13 mA/cm^2, whose value is larger than necessary value in ITER. From melted traces of the target plate, it is estimated that the divergence angle is about ±0.8 deg.

1. Introduction

It is very important to measure the behavior of alpha particles which contribute for the continuous plasma burning in nuclear fusion plant of deuterium-tritium reaction. In order to measure the spatial and velocity profiles of alpha particles, injection of permeable helium neutral beam of ~1 MeV to the burning plasma has been considered [1]. The helium neutral (He^0) beam exchanges charges with helium ions (alpha particles), and produced high-energy helium neutral particles are measured by the energy analyzer. In order to produce diagnostic He^0 beam, following two methods are being considered. Helium ion (He^+) beam of ~20 keV and ~100 mA/cm^2 is converted to negative helium ion (He^-) through the alkali gas cell (conversion rate~1 %) [2,3], and accelerated to ~1 MeV, then He^- of ~1 MeV spontaneously becomes He^0 (~0.2 mA/cm^2) by passing through a reasonable length (neutralization efficiency~20 %). In this system, it is important to produce focused high-current-density ion beam in order to pass through small apertures of alkali gas cell with an enough signal level.
Another method which can give a simple way to realize the 1 MeV He^0 beam is to use the helium-hydrogen ion (HeH^+) beam of ~20 keV and ~2 mA/cm^2. This beam can be accelerated to ~1 MeV, and neutralized through the gas cell with sufficient probability (neutralization efficiency~10 %) [2,4]. In this concept, conditions producing HeH^+ beam has not been investigated in detail as yet.
We had already developed a high-current-density neutral hydrogen beam system with strong focusing in order to inject the beam through a narrow port in the vacuum vessel [5]. For the purposes of deep understanding of beam characteristics, we had also tried to extract ion beams of various kinds of elements (hydrogen, deuterium, helium and nitrogen). In the present paper, we will report characteristics of He^+ beam with strong focusing and high-current-density, and the results on optimized conditions for obtaining sufficient HeH^+ beam intensity, in our beam system.

2. Experimental Setups

In our ion beam system, three concave-type electrodes, acceleration, deceleration and grounded electrodes are used. The extraction aperture diameter of the concave acceleration electrode with a meniscus structure is 4.0 mm at the ion-source side [6]. The transparency of each electrode is ~50 %. The distance between the acceleration and deceleration electrodes is 5.5 mm, and that between the deceleration and grounded electrodes is 2.0 mm. The thickness of all electrodes is 2.0 mm. The plasma is produced using a bucket type ion source whose inside surface is covered by a copper sheet 2.0 mm thick to prevent accidental arc erosion. Cusped magnetic field is larger than 1500 G at the inside surface of the chamber, and residual magnetic field in the plasma region is smaller than 5 G. The magnetic field measured by a gauss meter shows a fairly good agreement with the designed value. A power supply (PS) system with capacitor banks is adopted. Specifications of PSs are 30 kV and 50 A with voltage ripples less than 5% for the acceleration PS, -5 kV and 6 A for the deceleration PS, and 300 V and 1 kA for the arc PS. The filament PS of DC operation (30 s) has the specifications of 20 V and 2700 A (= 180 A x 15 sets of filaments), and constant-voltage control is programmed with the setting accuracy of 0.1%. Narrow hairpin tungsten filaments of ϕ2 mm are adopted as cathodes [7]. The designed beam duration is 30 ms.
In order to measure beam species, mass analyzer (Balzers Instruments, PPM422) whose maximum energy is limited less than 500 V is used. Therefore, in the case of mass analysis, DC power supply system of 300 V and 20 A is used as an acceleration PS.

3. Experimental Results

At first, experimental results on helium acceleration of ~25 kV are described (in this case, helium gas is not puffed into the neutralization cell). Figure 1(a) shows the dependency of extracted ion current on filament voltage, which current is estimated as $I_{acceleration} - I_{deceleration}$. These currents are the circuit currents measured between the power supply and electrodes. In

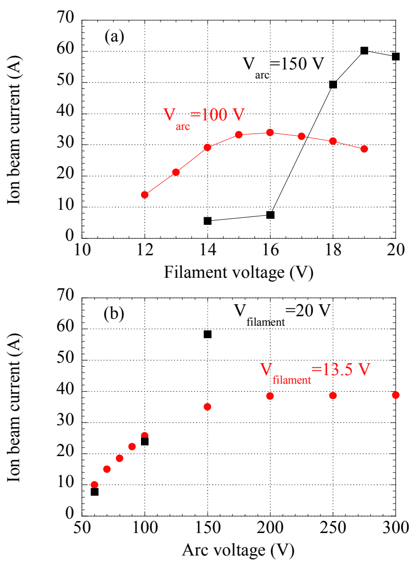

Fig. 1. (a) Filament voltage dependency, and (b) arc voltage dependency. Circle and square symbols indicate helium gas and hydrogen gas discharge cases, respectively.

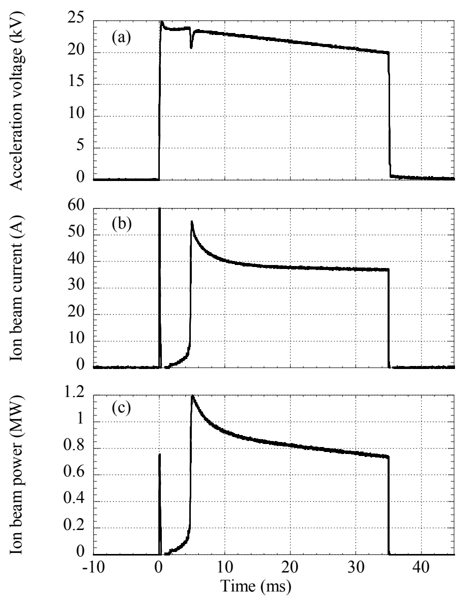

Fig. 2. Time evolutions of (a) acceleration voltage, (b) extracted ion beam current and (c) ion beam power.

the case of helium discharge, the extracted current has the maximum value at an optimized filament voltage. In the case of hydrogen gas discharge, filament voltage that achieves the maximum current value increases. This result suggests that it is possible to operate filament voltage at lower value. Figure 1(b) shows the dependency of extracted He^+ current on arc voltage. There is a tendency that beam current saturates over V_{arc}= 200 V. It is noticeable that He^+ beam can be extracted at low filament voltage, because we can reduce the heat flow into the acceleration electrode. Figure 2 shows time evolutions of each parameter in the case of $V_{acceleration}$ = 25 kV, $V_{deceleration}$= -1.2 kV, V_{arc}= 200 V, $V_{filament}$= 13.7 V. He^+ beam of ~22 kV and ~40 A is obtained, then current density of ~86 mA/cm^2 (= ~40/(πr^2x0.5)) is achieved, whose value is close to necessary value (~100 mA/cm^2) in ITER (International Thermonuclear Experimental Reactor). Here, r indicates effective radius of the electrode.
Next, in order to produce HeH^+ component in the ion source, helium and hydrogen gases are mixed in the gas reserve tank. Figure 3 shows time evolutions of each parameter in the case of $V_{acceleration}$ = 300 V, $V_{deceleration}$= -4.5 kV, V_{arc}= 110 V, $V_{filament}$= 10.5 V and He gas pressure ratio to hydrogen gas pressure= 75 %. Ion beam of ~6 A which includes H^+, H_2^+, H_3^+, He^+ and HeH^+ components is extracted. Figure 4 shows the number of HeH^+ particles measured by the mass analyzer as a function of beam energy, in the case of $V_{acceleration}$ = 300 V, $V_{deceleration}$= -4.5 kV and $V_{filament}$= 10.5 V. Here, in order to detect the maximum number of particles at each arc voltage condition, the energy of the detector is scanned. As arc voltage increases, the number of HeH^+ particles increases, but saturates around 130-140 V which almost corresponds to electron energy that ionization cross section to He^+ becomes maximum.
Figure 5 shows the number of HeH^+, He^+ and H^+ particles as a function of He gas pressure ratio to hydrogen gas pressure, $P_{He\text{-}ratio}$, in the case of $V_{acceleration}$ = 300 V, $V_{deceleration}$= -4.5 kV, V_{arc}= 110 V, $V_{filament}$= 10.5 V and ion beam current = ~6 A. It is clear that the production rate of HeH^+ component increases, when helium gas pressure ratio is larger than ~75 %. In the case of $P_{He\text{-}ratio}$= 90 %, the number of HeH^+ particles corresponds to ~15 % of total counts for H^+, He^+ and HeH^+ particles. (The analyzer sensitivity for H_2 gas is qualitatively larger than that for He gas. However, we cannot conclude the precise ratio, since absolute sensitivity calibration has not been conducted). Figure 6 shows the number of HeH^+, He^+ and H^+ particles as a function of beam energy (here, x axis in Fig. 5 is converted to the beam energy). As the amount of helium gas component increases, space potential in the ion source increases.

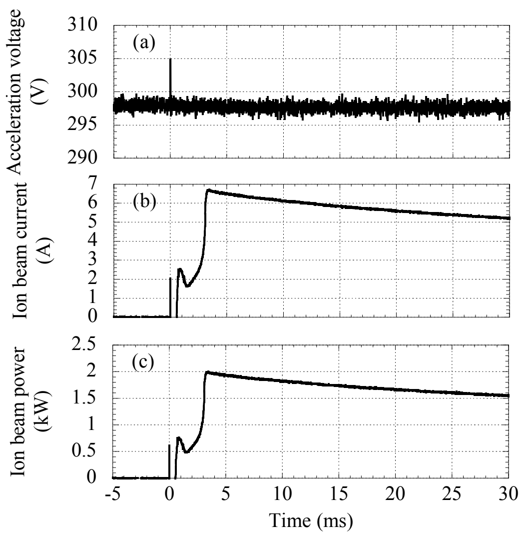

Fig. 3. Time evolutions of (a) acceleration voltage, (b) extracted ion beam current and (c) ion beam power.

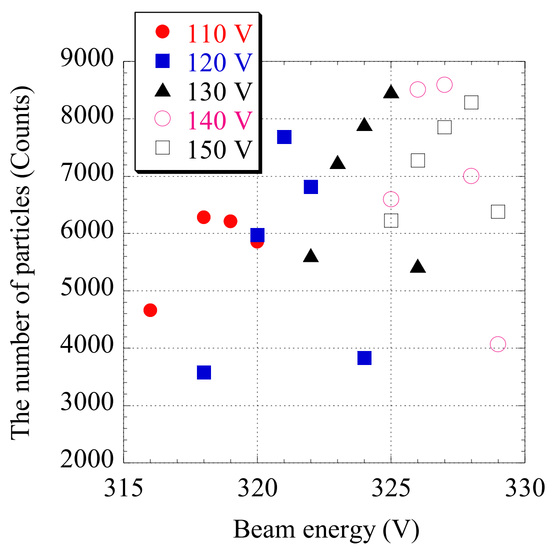

Fig. 4. The number of HeH^+ particles measured by the mass analyzer for several arc voltages.

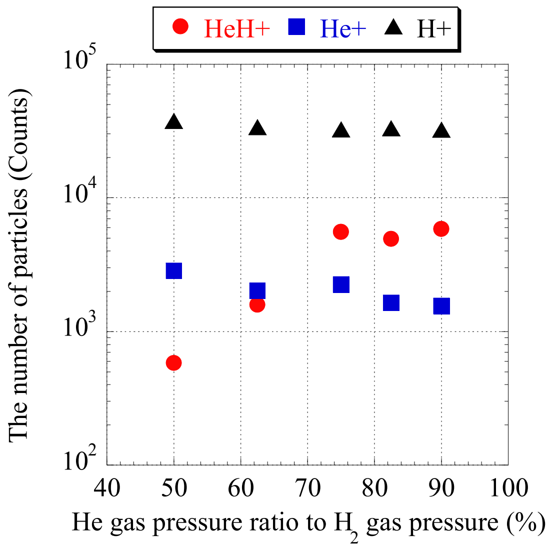

Fig. 5. The number of HeH$^+$, He$^+$ and H$^+$ particles as a function of He gas pressure ratio to hydrogen gas pressure.

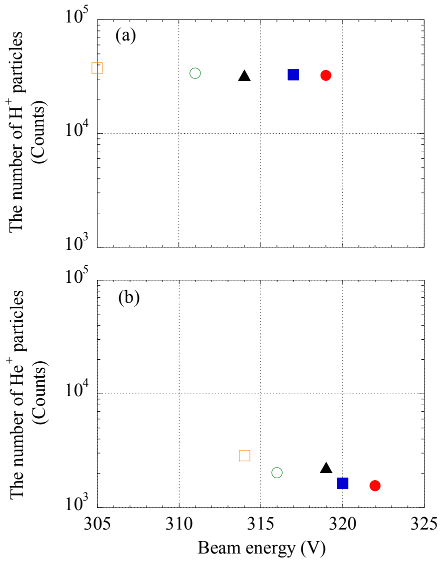

Fig. 6. The number of H$^+$ and He$^+$ particles as a function of beam energy. Empty square, empty circle, solid triangle, solid square and solid circle indicate the cases of 50, 63, 75, 83 and 90 % helium gas, respectively.

In order to study the beam performance of high-energy particles, total beam of H^+, H_2^+, H_3^+, He^+ and HeH^+ components is accelerated. Figure 7 shows time evolutions of each parameter in the case of $V_{acceleration}$ = 25 kV, $V_{deceleration}$= -1.2 kV, V_{arc}= 250 V, $V_{filament}$= 13.9 V and $P_{He\text{-}ratio}$= 75 %. Ion beam of ~40 A is extracted. If 15 % of total current is HeH^+ component, current density of HeH^+ is estimated as ~13 mA/cm^2 (= 40x0.15/(πr^2x0.5)), whose value is larger than necessary value (~2 mA/cm^2) in ITER. However, in order to measure only HeH^+ beam current, we must separate HeH^+ component from total beam of H^+, H_2^+, H_3^+, He^+ and HeH^+ by using the magnetic field system.

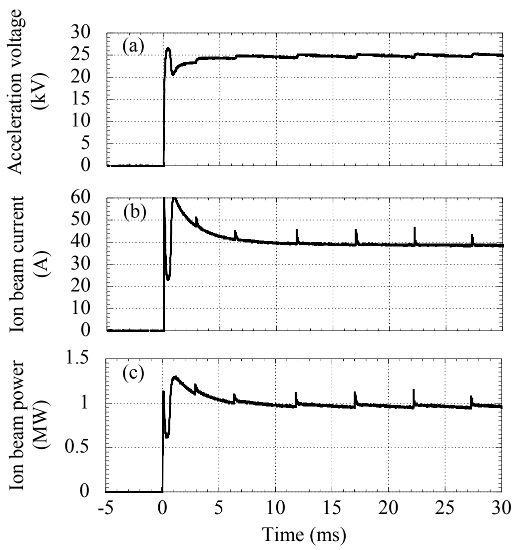

Fig. 7. Time evolutions of (a) acceleration voltage, (b) extracted ion beam current and (c) ion beam power.

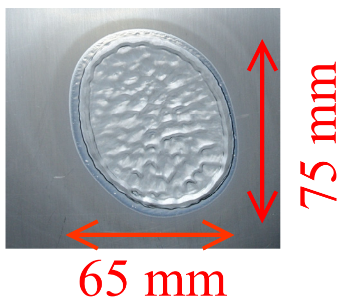

Fig. 8. The beam trace of the stainless steel target plate at X= 1530 mm.

In order to examine beam shape, focal point and beam divergence angle, high energy beam of ~25 keV is irradiated to a stainless steel target plate which is installed at the target chamber. The melted patterns on the plate are taken at several positions (X= 1530, 1735, 1835 and 1920 mm) shot by shot. Here, X indicates the distance from the electrode. As an example, the beam trace of the target plate at X= 1530 mm is shown in Fig. 8. From these melted traces, it is estimated that the focal length is ~1400 mm and the divergence angle is about ±0.8 deg.

4. Summary

Characteristics of He^+ and HeH^+ beams which produce He^0 beam used for the alpha particle measurement are described. In order to extract these He^+ and HeH^+ beams, the strongly focused high-current-density hydrogen neutral beam system is used [5]. It has been shown that this beam is strongly focused into a diameter of ~36 mm at the focal point with the divergence angle of about ±0.8 deg. As a result, a power density as high as ~1 GW/m^2 is attained at the focal point of the neutral beam.
For He^+ beam extraction of ~22 kV, current density of ~86 mA/cm^2 is achieved, whose value is close to necessary value (~100 mA/cm^2) in ITER. It is noticeable that He^+ beam can be extracted at low filament voltage, which mitigates heat flow into the acceleration electrode.
In the case of $V_{acceleration}$ = 300 V, $V_{deceleration}$= -4.5 kV, V_{arc}= 110 V, $V_{filament}$= 10.5 V, it is measured by the mass analyzer that the production rate of HeH^+ component increases with the increase of helium gas pressure ratio to hydrogen gas pressure when its value is > ~75 %. In the case of 25 kV acceleration, if 15 % of total current (which includes H^+, H_2^+, H_3^+, He^+ and HeH^+ components) is HeH^+ component, current density of HeH^+ is estimated as ~13 mA/cm^2, whose value is larger than necessary value (~2 mA/cm^2) in ITER. However, in order to measure only HeH^+ beam current, we must separate HeH^+ component from total beam of H^+, H_2^+, H_3^+, He^+ and HeH^+ by using the magnetic field system. From melted traces of the target plate installed at several positions from the electrode shot by shot, it is estimated that the focal length is ~1400 mm and the divergence angle is about ±0.8 deg, which reveals almost the same superior characteristics as the case in neutral hydrogen beam [5].

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