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Evaluation of 25 keV Helium Hydrogen Ion Beam for Alpha Particle Measurement in ITER

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Helium-hydrogen ion (HeH^+) beams of ~25 keV have been quantitatively measured to study the HeH^+ current density. To produce a diagnostic helium neutral beam for alpha-particle measurement in a nuclear fusion plant based on a deuterium-tritium reaction, a HeH^+ beam has been considered as a candidate primary beam. We designed and set up a mass spectrometer system using electromagnetic coils to separate each component of H^+, H_2^+, H_3^+, He^+ and HeH^+ beam species. It was found that the HeH^+ beam component of 25 keV at a detector was less than ~0.5 % of the total beam current.

Keywords: HeH^+, ion beam, mass analysis, nuclear fusion, ITER, alpha particles, plasma diagnostics

1. Introduction

It is important to measure the behavior of alpha particles produced during the continuous plasma burning in a nuclear fusion plant with a deuterium-tritium reaction in international thermonuclear experimental reactor (ITER). To measure the spatial profile and velocity distribution of alpha particles, the injection of a permeable helium neutral (He^0) beam of ~1-2 MeV to the burning plasma has been considered [1]. The He^0 beam exchanges charges with helium ions (alpha particles) and produces high-energy neutral helium particles, which are measured by an energy analyzer. To produce a diagnostic He^0 beam with a diameter of ~100 mm, helium ion (He^+) or helium hydrogen ion (HeH^+) beams of ~25 keV have been considered as promising primary beams [1-3]. In the case of the He^+ beam, the He^+ beam of ~20 keV and ~100 mA/cm^2 is converted to a negative helium ion (He^-) beam through the alkali gas cell (conversion rate ~1 %) [2], and accelerated to 1-2 MeV using a radio-frequency quadrupole (RFQ) with focusing and shaping [4]; then, He^- spontaneously becomes He^0 (~0.2 mA/cm^2) passing through a reasonable length (neutralization efficiency ~20 %). In this system, it is important to produce a focused high-current-density ion beam to pass through small apertures of an alkali gas cell with a sufficient signal level [3]. Recently, a test facility for a He^+ beam system has been demonstrated [5]. In the case of the HeH^+ beam that can provide a simple way without an alkali gas cell to realize the He^0 beam, ion beams of ~25 keV that include H^+, H_2^+, H_3^+, He^+ and HeH^+ components are first extracted from an ion source. Here, a gas mixture of helium and hydrogen is puffed into the ion source. After the separation of the HeH^+ component only (other components are bended to the beam dump), the HeH^+ beam is accelerated to ~1-2 MeV using the RFQ with focusing and shaping, and neutralized through a deuterium gas cell with a sufficient neutralization efficiency of ~10 % [1].

In this study, we designed and set up a mass spectrometer system using electromagnetic coils to separate each beam component of around 25 keV energy region. As a beam system, a bucket-type ion source with three concave electrodes of acceleration, deceleration and earth was used [3]. After the separation of H^+, H_2^+, H_3^+, He^+ and HeH^+ components from the total beam, each beam current was measured.

2. Experimental Design and Setup

Figures 1(a) and (b) show a schematic drawing of a beam component measurement system and a photograph of an electromagnetic coil system, respectively. Ion beams of 345 mm diameter are extracted from an ion source through concave electrodes, and beam diameter is limited by apertures. First, the beams are limited by the conic copper aperture, as shown in Fig. 1(c). Eight holes around this aperture are for evacuation. Second, a copper aperture of ϕ16 mm is located at the focal point of an ion beam system, as shown in Fig. 1(d). Subsequently, ion beams are injected into a mass spectrometer using electromagnetic coils, as shown in Fig. 1(b). Each beam component diverges toward the entrance of the electromagnetic coil; however, it is possible that each beam component approximately converges again vertically and horizontally around one point at the exit. Finally, ion beam currents are measured by changing the strength of the magnetic field.

Here, a bucket-type ion source is used to produce plasma, and a gas mixture of helium and hydrogen is puffed. The cusped magnetic field is larger than 0.15 T at

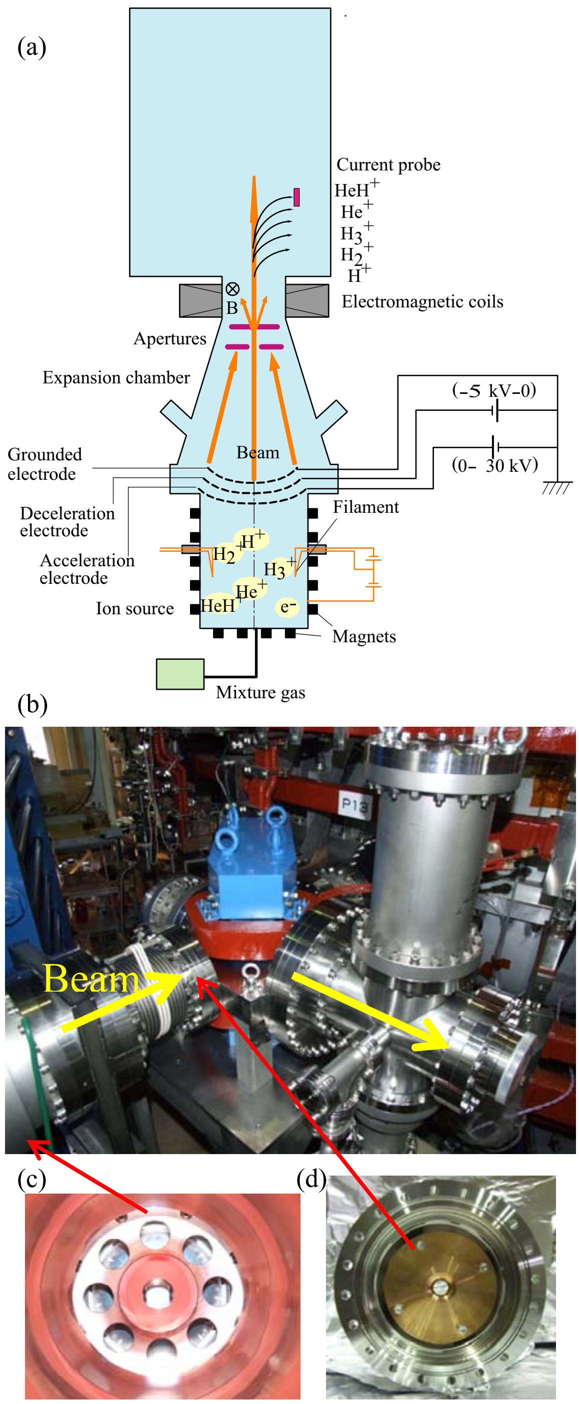


Fig. 1 (a) Schematic drawing of beam component measurement system, (b) photograph of electromagnetic coil system, (c) photograph of first stage beam aperture and (d) photograph of second beam aperture.

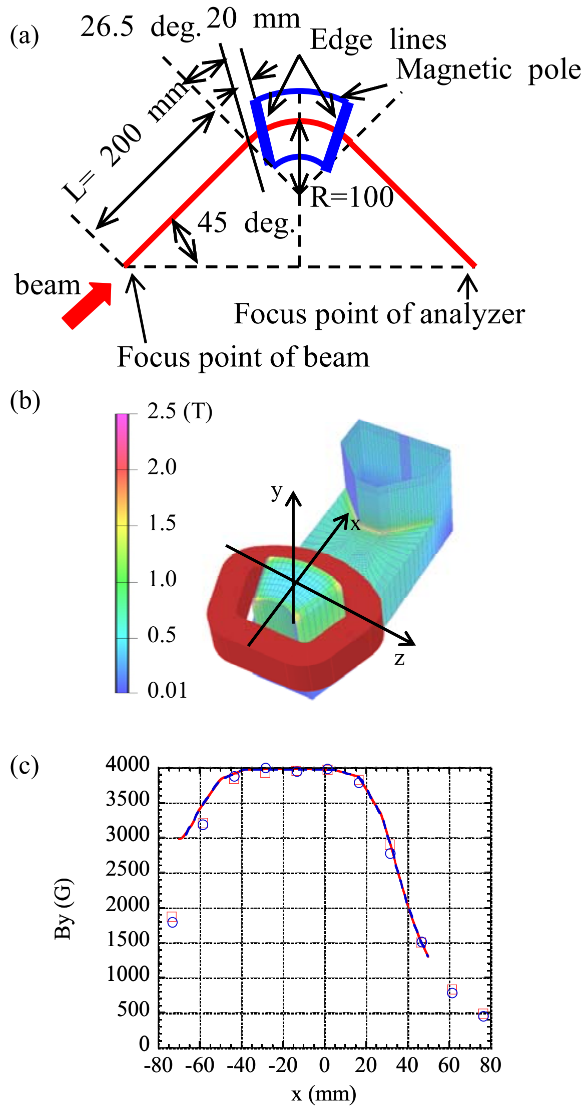


Fig. 2 (a) Geometric design of magnetic pole, (b) image of lower half of electromagnetic coil and (c) magnetic field profiles at entrance and exit of magnetic pole along edge line. Broken line (calculated data), and circles (measured data) at entrance, and solid line (calculated data) and squares (measured data) at exit.

the inner surface of the chamber, and the residual magnetic field in the plasma region is smaller than 0.5 mT. Narrow hairpin-type tungsten filaments of 2 mm diameter are adopted as cathodes [6] and inserted a few mm inside the plasma region. A set of three multiaperture concave copper electrodes, that is, acceleration, deceleration and grounded electrodes, are used, and their effective diameter is 345 mm [3]. The diameter of each aperture (~3700 holes) on the concave acceleration electrode is 4.0 mm on the ion-source side. The transparency of each electrode is ~50 %. The thickness of all electrodes is 2.0 mm. A power supply (PS) system with capacitor banks is adopted. PS specifications are 30 kV and 50 A with voltage ripples of 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, and a programmed constant-voltage control property with a setting accuracy of 0.1%. The nominal beam duration is 35 ms.

Figure 2(a) shows the geometric design of a magnetic pole and a horizontal trajectory of an ion beam. The edge

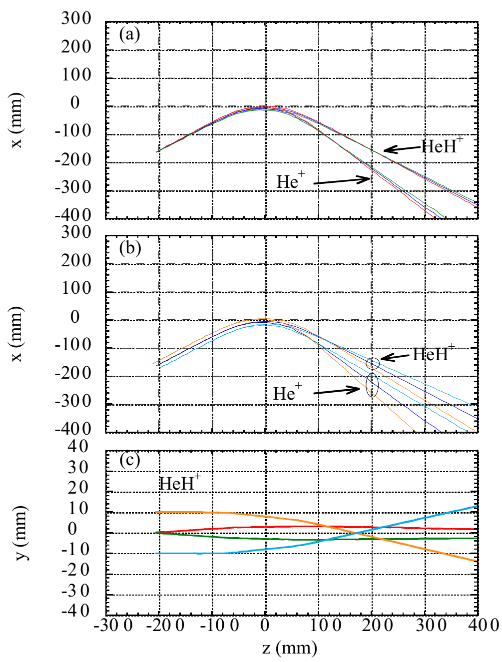


Fig. 3 Calculated results for ion beam orbit: (a) and (b) in horizontal plane, and (c) in vertical plane.

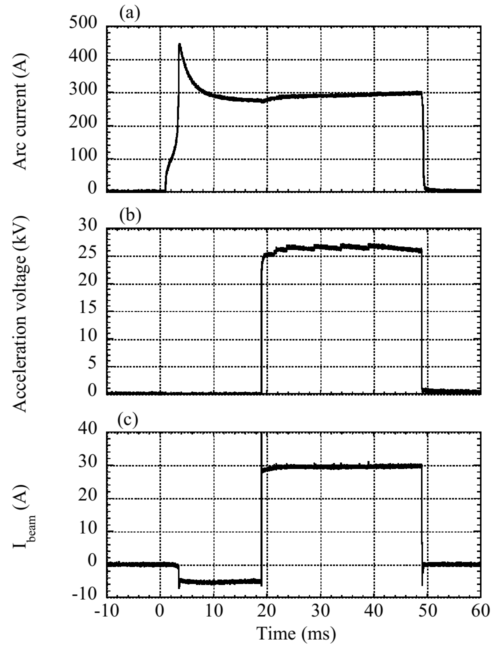


Fig. 4 Time evolutions of (a) arc current, (b) acceleration voltage and (c) total beam current.

of the pole is inclined 26.5 degrees, and 20 mm is shortened, to focus the beam vertically and horizontally at one point. Figure 2(b) shows the coordinate system and three dimensional image of the lower half of the magnetic coil and distribution of the magnetic strength in the iron core. Even in the full operation, the saturation of the iron core is not observed (Saturation level is about 2.0 T). Figure 2(c) shows magnetic field profiles at the entrance and exit of the magnetic pole. The differences between the calculation and measured data are less than 1 %. Radial uniformity of the magnetic field is more than 99.95 % around the beam pass region. Figure 3 shows the calculation results of the ion beam orbit using OPERA-3D. HeH^+ and He^+ beam components with the angle of ±1 degree from the original point converge at one point (200 mm from the center of the magnetic pole) after through the magnetic field in the horizontal plane as shown in Fig. 3(a). Here, the blue color is the center line, the red line is the left +1 degree line, and the green line is the right +1 degree line. Moreover, it is possible to separate HeH^+ and He^+ beam components with a width of 20 mm from each other, as shown in Fig. 3(b). Although HeH^+ beam components with an angle of ±1 degree from the original point do not converge at 200 mm from the center of the magnetic pole in the vertical plane, the width of the beam is less than 10 mm, as shown in Fig. 3(c), where the aperture of the current probe is set. Here, the blue line is the center line, the orange line is the left +10 mm line, and the light blue line is the right +10 mm line.

3. Experimental Results

Figure 4 shows time evolutions of beam parameters. Here, the acceleration voltage is 26 kV, the deceleration voltage is -1.2 kV, the arc voltage is 300 V, the filament voltage is 14.5 V and the ratio of helium gas pressure to the total gas pressure of the gas mixture (hydrogen and helium), P_{ratio}, is 90 %. The beam containing H^+, H_2^+, H_3^+, He^+ and HeH^+ components is extracted at a total current of 30 A. The waveform reproducibility of beam current and acceleration voltage is very excellent. The beam current is measured between the electrode and the power supply. It is very important to maintain acceleration voltage constant, since the beam energy component of the measured ion current is also modulated when the voltage is modulated. To maintain acceleration voltage constant, six resistances of 16.7 ohm each in series in the circuit are successively bypassed utilizing IGBT switches, as shown in Fig. 4(b).

Figure 5(a) shows a schematic drawing of the probe used to measure the beam current. Both A and B in this figure indicate the grounded aperture. C is the preaperture of the probe. The summation of probe currents of D and E is defined as the ion beam current. Here, Tektronix, a TCP303 probe and a TCPA300 amplifier are used to measure the current. It is necessary to determine the bias condition that eliminates the effects of secondary electrons and plasma, which is produced around the probe. First, the voltage of the aperture C, $V_{aperture}$, is set at -20 V to reject the electrons produced around the aperture. As shown in Fig. 5(b), He^+ beam current increases as the voltage of the

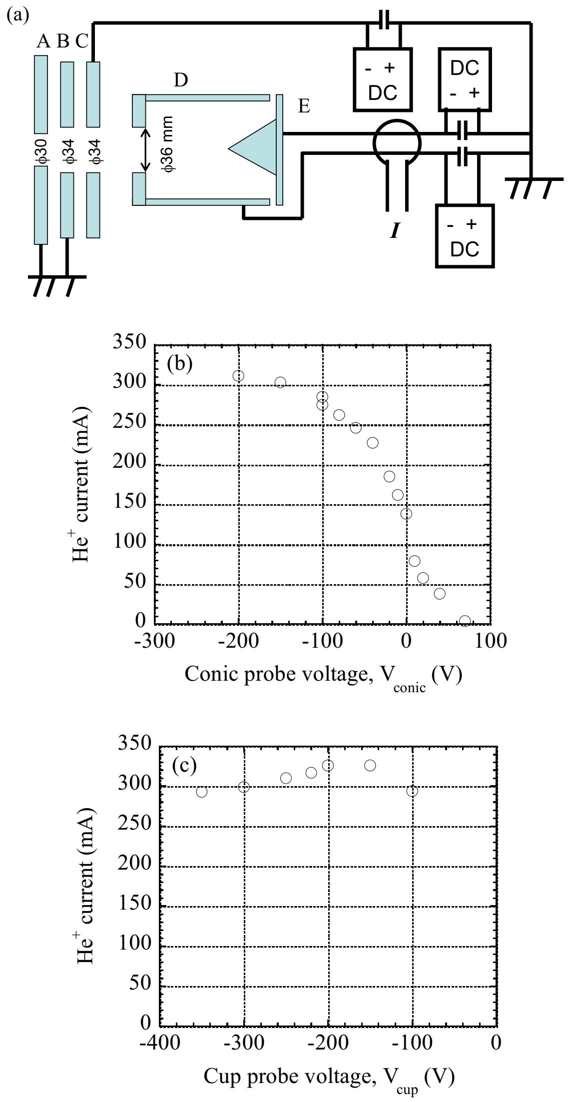
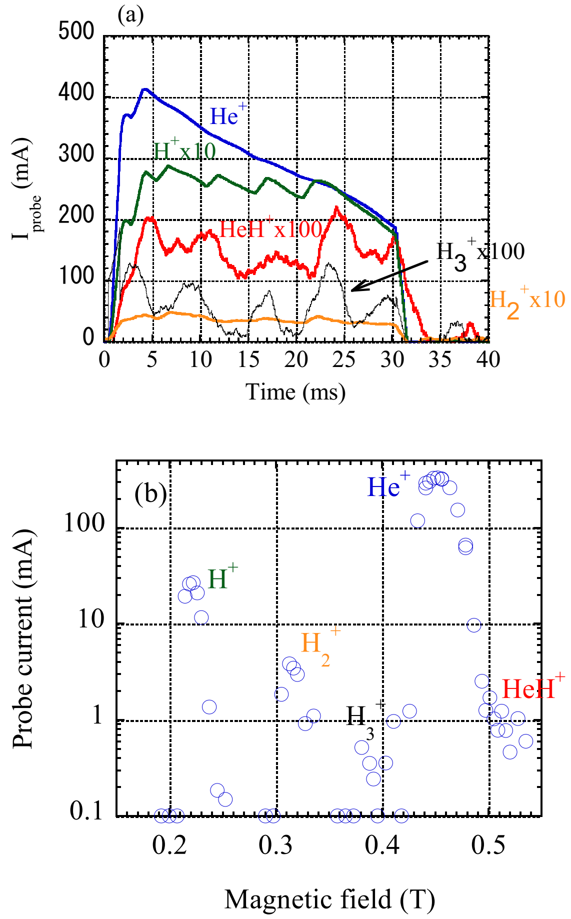


Fig. 5 (a) Schematic drawing of current measurement system, (b) He^+ current in bias scanning of conic probe and (c) He^+ current in bias scanning of cup probe.



.Fig. 6 (a) Time evolutions of beam current for H^+ (green line), H_2^+ (orange line), H_3^+ (black line), He^+ (blue line) and HeH^+ (red line), and (b) probe currents in magnetic field scanning (mass spectrum).

conic probe, V_{conic}, negatively increases, and He^+ beam current saturates around V_{conic}= –200 V. Here, to maintain the relative relationship between conic and cup probes, the voltage of the cup probe, V_{cup}, is set at (V_{conic} – 100 V). Figure 5(c) shows the He^+ beam current in the case of V_{cup} scanning. Here, V_{conic} and $V_{aperture}$ are fixed at -200 V and -20 V, respectively. To return electrons to the conic probe, it is necessary to maintain $|V_{cup}| > |V_{conic}|$ to return electrons to the conic probe. As a result, a V_{conic} of -200 V, a V_{cup} of -300 V, and a $V_{aperture}$ of -20 V become the best combination for measuring the ion current.

Figure 6(a) shows time evolutions of the beam currents of H^+, H_2^+, H_3^+, He^+ and HeH^+ components. Moving average of 1 ms was conducted. Beam conditions are the same as those in the case of Fig. 4, where P_{ratio}= 90 %. A He^+ beam of ~400 mA is the main component and H^+ beam current is about one order smaller than He^+ beam current under this condition. The reduction in He^+ beam current may be caused by the charge exchange with the residual gas on the beam line. The currents of H_2^+, H_3^+ and HeH^+ components are very small. The current waveform of the HeH^+ beam strongly depends on the behavior of gas pressure in the ion source. The accuracy of the current measurement is ~1.0 mA. A mass spectrum of the beam mixture is successfully measured, as shown in Fig. 6(b). The abscissa and ordinate indicate the magnetic field at the magnetic pole of the mass analyzer and the probe current of each component, respectively. Here, each beam current is selected at a time window of constant beam energy (e.g., 1 ms between *t*= 12-13 ms in Fig. 6(a)). All components of H^+, H_2^+, H_3^+, He^+ and HeH^+ beams are identified. Here, the current less than 0.1 mA is assumed as “0.1” in the figure. The spectrum resolution is estimated as ~±25 mm (= (L+ R) ΔB/B). It is possible to control the resolution by changing the aperture size. As a result, it is found that the ratio of the HeH^+ beam is about 0.5 % of the total beam at *t*= 12.5 ms and the detector position (not in the ion source). The He^+ beam decreases with time; therefore, it is considered that the ratio of HeH^+ components is less than

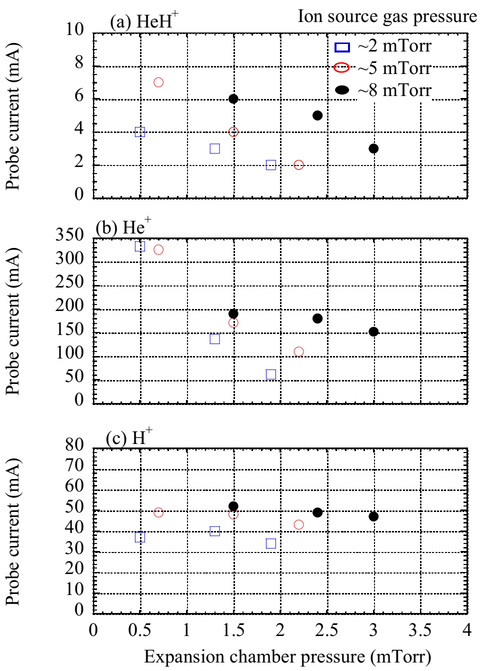


Fig. 7 Dependences of beam current on pressures of ion source and expansion chamber. (a) HeH^+, (b) He^+ and (c) H^+ cases.

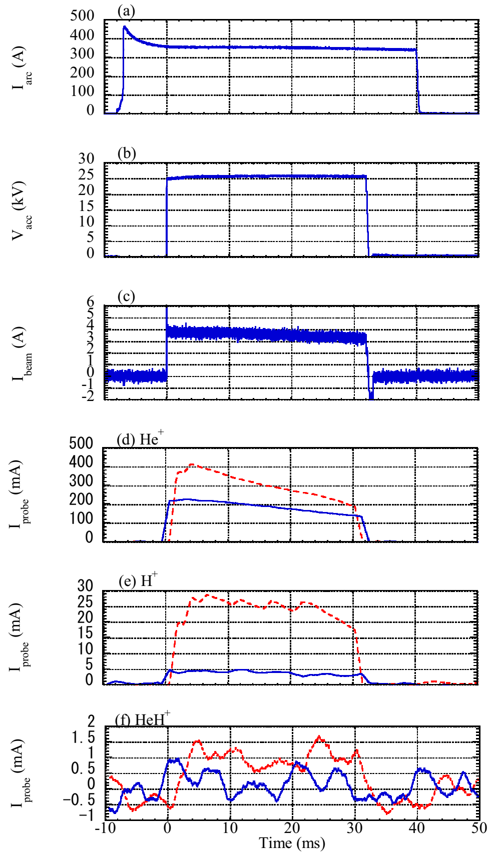


Fig. 8 Time evolutions of (a) arc current, (b) acceleration voltage and (c) total beam current, and (d) He^+ beam current, (e) H^+ beam current and (f) HeH^+ beam current before (red dashed lines) and after (blue solid lines) the copper sheet with the hole of 100 mm diameter covering.

0.5 %. It is required that the HeH^+ beam ratio is more than 2.5 % in the case of the alpha-particle measurement in ITER.

Figure 2 in Ref. [1] indicates that the dissociation rate of HeH^+ in the range of 25 keV is high (~90 %). In this system, the distance between the electrode and the current probe after the mass analyzer is ~2000 mm. It is estimated that this distance is sufficient for dissociating HeH^+ molecules of 26 keV by the pressure of the expansion chamber [7]. To examine whether the HeH^+ beam component is originally small in the ion source, or the HeH^+ beam component is dissociated by the residual gases on the beam line, dependences of the beam current on the pressure of the ion source and expansion chamber are investigated, as shown in Fig. 7 (here, the effect of secondary electrons is not eliminated to increase the apparent value). In the case of 5 mTorr in the ion source, HeH^+ beam current increases as the pressure of the expansion chamber decreases, as shown in Fig. 7(a). This indicates that HeH^+ ions dissociate owing to gas collision in the expansion chamber. HeH^+ beam current increases as the pressure of the gas mixture in the ion source increases. The amount of gas mixture in the expansion chamber increases, since the gas in the ion source flows into the expansion chamber. Figure 7(b) shows that He^+ beam current increases as the pressure of the expansion chamber decreases. However, Fig. 7(c) shows that H^+ beam current does not depend on the pressure of the expansion chamber. It is considered that the charge exchange process is already saturated under the present pressure condition. These results indicate that an increase in HeH^+ beam current is expected, if a reduction in the pressure of the expansion chamber is realized. Therefore, a copper sheet of 0.5 mm thickness with a 100 mm hole at the center of the electrode is used to cover the acceleration electrode to reduce the conductance and gas flow into the expansion chamber.

Figures 8(a), (b) and (c) show time evolutions of beam parameters after the copper sheet of the acceleration electrode covering. Here, beam conditions are the same as those in Fig. 4. However, both pressures of the ion source and expansion chamber are controlled as 4 mTorr and 0.18 mTorr, respectively. The pressure of this expansion chamber becomes one-fourth after the covering. This loads to a successful extraction of the beam without breakdown, and the total beam current is 3.5 A with an acceleration voltage of 26 kV, as shown in Figs. 8(b) and (c). Figures 8(d), (e) and (f) show time evolutions of beam currents of He^+, H^+ and HeH^+ after the covering, respectively. The beam currents of all components after covering decreased compared with those before covering. It is difficult to identify HeH^+ beam current owing to the limitation of probe precision. It is considered that the reductions in currents are induced by the beam divergence due to the self-electric field of ions. After the covering, the plasma or electron density decreases markedly in the expansion chamber and around the region of the electromagnetic coil, owing to the reductions in high-energy beam component and the amount of gas.

4. Summary and Future Prospects

To produce a diagnostic He^0 beam for alpha-particle measurement, a HeH^+ molecular ion beam has been proposed as a primary beam. To examine the HeH^+ current density that is sufficient or not to be used in ITER, a HeH^+ beam of ~26 keV was quantitatively measured. We designed and set up a mass analyzer system using electromagnetic coils to separate each component of H^+, H_2^+, H_3^+, He^+ and HeH^+ beam species. Beam currents and mass spectra of the beam mixture were successfully measured by scanning the magnetic filed. However, it was found that the ratio of the HeH^+ beam is less than ~0.5 % of the total beam in this experiment. It is required that the HeH^+ beam ratio is more than 2.5 % in the case of alpha-particle measurement in ITER.

To increase the HeH^+ ratio, dependencies of the beam current on the pressures of an ion source and an expansion chamber were examined. HeH^+, He^+ and H^+ beam currents increase as the pressure of the expansion chamber decreases. Therefore, it might be possible to extract a sufficient HeH^+ beam current without a marked dissociation, if the pressure on the beam line can be reduced by one order. It is also important to consider the ion beam energy, because the dissociation rate of HeH^+ strongly depends on the ion beam energy, as shown in Fig. 2 of Ref. [1]. Recently, we have studied beam energy suitable for extracting a large number of HeH^+ ions.

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References

[1] M. Sasao *et al.*, Proc. Int. Workshop on Diagnostics for ITER, Verenna, 51 (1995).
[2] M. Sasao *et al.*, Rev. Sci. Instrum. **77**, 10F130 (2006).
[3] H. Sakakita *et al.*, Proc. 21st IAEA Fusion Energy Conference, Chengdu, **IAEA-CN-149**, FT/P5-2, 1 (2006).
[4] A. Mosnier *et al.*, Proc. 2008 European Particle Accelerator Conf., Genoa, 3539 (2008).
[5] T. Kobuchi *et al.*, Proc. 16th Int. Conf. on Ion Beam Modification of Materials, Dresden, PB09-19 (2008).
[6] M. Kiruyama *et al.*, JAERI Reports, JAERI-M87, 169 (1987) [in Japanese].
[7] W. J. Stearns *et al.*, Phys. Rev. A **4**, 1960 (1971).