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Emittance measurement of multi-species ion beam produced via two-step charge exchange process in a Li vapor cell

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A Li vapor cell has successfully converted a He^+ ion beam to a He^- ion beam by double charge exchange reaction. Emittance of the He^+ ion beam and that of the He^- beam were independently measured to study emittance growth during the passage of the charge exchange cell. Each component was seperated by electrostatic deflection after passing through a beam shaping slit. The result had shown that the emittance of the He^+ ion beam was not changed by the passage of the charge exchange cell, while the emittance of the He^- ion beam had increased even with the presence of focusing electric field produced by He^+ ions. The emittance of the He^- ion beam had increased up to twice as large as that of the incident He^+ beam. The normalized emittance of the He^- at the beam energy of 10-20 keV, which is an optimum energy range for charge exchange efficiency, was estimated to be 0.07-0.09 mm-mrad.

Keywords: Alpha particle diagnostics, Emittance, Negative ion, Charge exchange reaction

1. Introduction

It is essential to efficiently confine high-energy alpha particles produced by D-T nuclear reaction for self sustained burning plasma. Several methods have been proposed to measure velocity distributions and spatial profiles of fusion produced energetic alpha particles in ITER (International Thermonuclear Experimental Reactor). One of the most promising candidates is the fast neutral beam probe method, where alpha particles are neutralized by double charge exchange reaction with a fast neutral helium (He^0) beam in the 1-2 MeV energy range and detected by an energy analyzer installed outside the confinement magnetic field [1]. In this energy range, formation of the He^0 by an electron attachement to positive ions in a gas cell becomes inefficient. The feasible method to produce high energy He^0 beam in this energy range is through neutralization of negative helium ions (He^-) by auto-detachment.

Three methods are generally used for formation of negative ions; volume production, surface production and two-step charge exchange reaction in an alkali metal vapor cell. Because the production efficiency of He^- by the first or the second method is negligibly small, the He^- is produced from the He^+ via two-step charge exchange process in the alkali metal vapor cell whose charge exchange coefficient to He^- is 1-2%. The charge exchange coefficient depends on the incident beam energy and reaches a mamixum value at beam energy of 10-20 keV. The He^- beam current of 10 mA is required for producing the sufficient He^0 beam to diagnose alpha particles.

Despite the high efficiency for negative ion production, He^- beam production by charge exchange reaction requires investigation on the following two points before judging the suitability for the actual diagnostics system. Since the emittance of the He^- produced in the alkali metal vapor cell is considered relatively large due to a scattering effect between the incident He^+ beam and the alkali metal vapor, the scattering effect to the emittance growth of the He^- beam should be known. Transport of He^- in the He^+ back ground in alkali metal vapor causes a change in beam optics due to nonlinear space charge force and its effect to the beam focusing should be known.

The formation of the He^- beam in the alkali metal vapor cell has been studied for not only the alpha particle measurement system but also for tandem accelerator systems. In previous studies, a dependence of the conversion efficiency of the He^+ to the He^- on the incident beam energy and the line density of the vapor with different alkali metal vapors has been studied intensively [2]. However, the emittance of multi-species ion beam formed by the charge exchange reaction has not been measured, and a characteristic of the multi-species ion beam is not well-known.

The Fusion Plasma Diagnostic Laboratory in Tohoku University has constructed a device for proof of principle experiment, Advanced Beam Source 103 (ABS103), to generate the He^0 beam [3]. The He^- beam has been successfully produced via two-step charge exchange process in a lithium gas cell. The property of the production of the He^-, namely, the dependence of production rate of the He^- on the gas temperature and the incident ion beam energy, has been investigated [4]. Recently, a multi-slit and multi-collector type emittance meter has been installed in the device to simultaneously measure the emittance of the He^- and the He^+ coming out of the cell. In this paper, a characteristic of the multi-species ion beam formed in the gas cell and the experiment of emittance measurement of the He^- and He^+ is presented.

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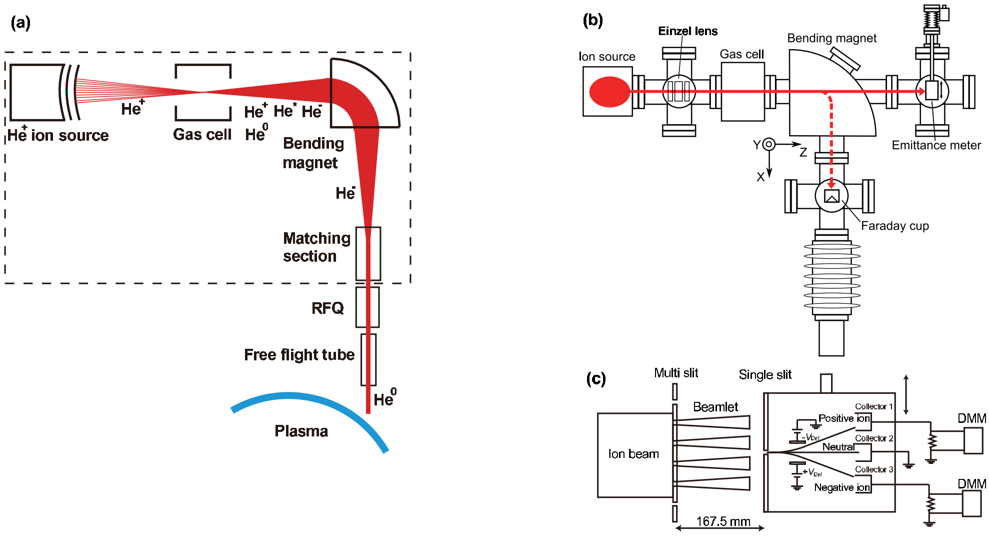

Fig. 1 Schematic illustrations of (a) fast neutral beam probe system, (b) experimental appratus and (c) multislit-and-multicollector type emittance meter.

2. Apparatus

A schematic illustration of the fast neutral beam probe method is shown in Fig. 1(a). The He^+ beam is required to be converged at the center of the alkali metal vapor cell to form the He^- beam emitted from a narrow region, and small beam size at a focal point is required to minimize a leakage of the alkali metal vapor from the vapor cell. Then, the He^+ beam of several amperes is extracted from the ion source with concaved electrodes [5] and transported through the alkali metal vapor cell. The particle beam traversed through the alkali metal vapor cell is injected into a bending magnet, and only the He^- beam is transported to the beam downstream, which consists of a matching section, a RFQ (Radio-Frequency Quadrupole accelerator) and a free flight tube. The He^- beam accelerated up to 1-2 MeV is neutralized by the auto-detachment in the free flight tube, and the energetic He^0 beam is injected into a burning plasma. The detailed desctription of this method is reported in ref. 6.

We have constructed the test bed to form the He^0 beam, which corresponds to the part surrounded by the rectangle in Fig. 1(a). A schematic illustration of the test bed is shown in Fig. 1(b). A He plasma is generated by an arc discharge in a compact bucket type ion source with multi-cusp magnetic field. The He^+ beam extracted from the ion source through three grids with single aperture of 6 mm in diameter is tuned with an einzel lens installed downstream of the ion source and injected into a lithium vapor cell. The gas cell of 100 mm in length has entrance and exit apertures of 9 mm, and the He^+ beam is collimated by the entrance aperture. A part of the He^+ beam is converted into a He^- beam by the two-step charge exchange reaction in the cell. The He^0 and the unconverted He^+ are also ejected from the cell. The multi-species ion beam can be separated into individual ions by a bending magnet, and the current of each ion is measured by a movable Faraday cup installed at 90 degrees from the Z axis. The coordinate axis is indicated in Fig. 1(b).

A charge state separated emittance meter has been designed and constructed to measure the emittance of each ion in the multi-species ion beam. A shematic illustration of the emittance meter is shown in Fig. 1(c). The emittance meter consists of a thin stainless multi-slit and a movable Faraday cup with three particle collectors. The multi-slit is equipped with 14 tapered slits of 0.2 mm in width, 5 mm in length and 2 mm intervals. The multislit is installed at a distance of 394 mm downstream from the exit of the gas cell, and the distance between the plate and the Faraday cup is 167.5 mm. The movable Faraday cup has three collectors and two planer electrodes of 10 mm in width and 22.5 mm in length. The gap distance between two planer electrodes is 5 mm. The collimator slit of the Faraday cup is 0.2 mm in width and 10 mm in length. In order to suppress the error due to the secondary electrons, two pairs of permanent magnets (Sm-Co) are embedded in the Faraday cup. The particle beam ejected from the gas cell is separated into several beamlets by the multi-slit, and each beamlet is collimated by the slit of the movable Faraday cup. The electric field formed by two electrodes in the Faraday cup separates the beamlet into the He^-, the He^+ and the He^0, which are independently collected by three collectors. The angular resolution of the emittance meter is 1.2 mrad, and the maximum detectable angle is 90 mrad. In addition, the profile of each ion species consisting the multiple ion beam is measured by the Faraday cup removing the multi-slit.

3. Results and Discussion

3.1 Characteristic of multi-species ion beam

To investigate fractions of ions after the passage of the gas cell, momentum analysis was carried out by changing the magnet current at the acceleration voltage of 7 kV and the arc discharge current of 1.0 A. Fig. 2 shows fractions of positive ions without the lithium gas filled in the cell. Two peaks are shown in Fig. 2. The higher peak corresponds to the He^+, and the lower peak corresponds to impurity ions, which are O^+ and/or compound ions of oxygen and hydrogen, formed in the ion source. Distributions of positive ions and negative ions in the multi-spicies ions formed in the vapor cell are shown in Fig. 3(a) and (b), respectively. The cell temperature is 873 K which is the optimum temperature for charge exchange coefficient, and the line density in the vapor cell is 6.9×10^{14} cm^{-2} at this gas temperature [4]. The transportation of the beam through the Li vapor resulted in production of He^0, He^* and He^-, where the He^0 is neutral helium in a stable state, and the He^* is neutral helium in a meta-stable state. A large part of the projectile He^+ beam was converted into He^0/He^* by the charge exchange reaction, and a part of the meta-stable particle was converted into negative ions. As obviously shown Fig. 3(a), positive ions in the multi-species ion beam were mainly composed of He^+. On the other hand, in Fig. 3(b) negative ions were composed of the He^- and impurity ions of nearly the same intensity. The dominant impurity positive ions are O^+, compound ions of oxygen and those of hydrogen formed in the ion source. The charge exchange efficiency of O^+ to O^- is one order of magnitude higher than that of He^+ [7]. Accordingly, He^- and impurity negative ions were emerged out of the cell with nearly the same intensity, though the beam intensities of impurity positive ions formed in the ion source were one order of magnitude less than He^+ intensity.

Fig. 4(a) and (b) show the profile of the He^+ through the cell without the lithium vapor and profiles of the He^+ and the He^- in the multi-species ion beam, respectively. Though the current of the He^+ decreased to 10% of the incident beam current by the charge exchange reaction, the resulting mitigation of the space charge onto He^+ by gas cell had made the beam radius of the He^+ almost unchanged. In the gas cell, the He^+ beam is scattered by multiple collisions with the Li vapor. Then, these collisions should enlarge the size of the He^+ beam radius due to the passage through the vapor cell. In Fig. 4(b), the radius of the He^- was smaller than that of the He^+. Since the dominant charged particle in the compound beam was the He^+, the He^- beam could be trapped in the potential well formed by the He^+. Therefore, the radius enlarging effect due to collisions upon the He^- beam was compensated by the focusing force originating from the He^+ space charge to make the He^- beam radius smaller than the He^+ beam radius.

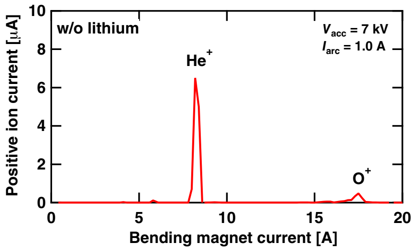

Fig. 2 Current distributions of positive ions in the beam propagating through the vapor cell which was not filled with the Li vapor.

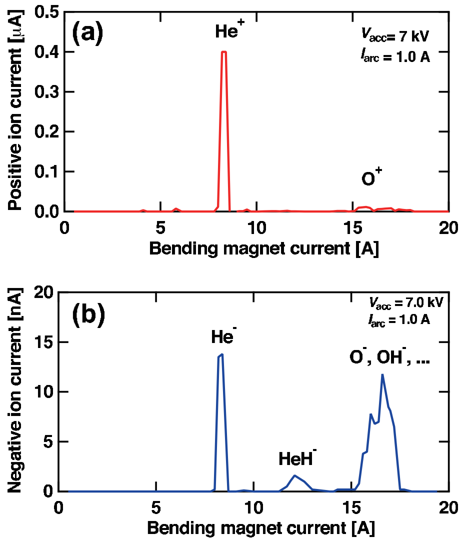

Fig. 3 Current distributions of positive ions (a) and negative ions (b) composing the beam emerged from the Li cell.

3.2 Emittance measurement

Emittance measurements were carried out by moving the emittance meter at the acceleration voltage of 7-14 kV and the arc discharge current of 1.0 A, where the electrostatic lens was optimized for the transparency of the beam through the gas cell. The lithium vapor was activated at the temperature of 873 K, where the conversion efficiency was maximized. Phase space diagrams of 90% emittances

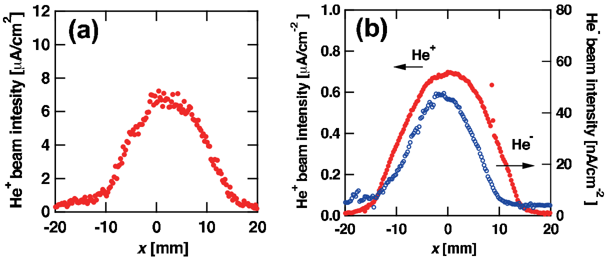

Fig. 4 Profiles of the He^+ emerged from the vapor cell without the Li (a), the He^+ through the Li vapor and the He^- (b). In (b), filled circles and open circles show profiles of the He^+ and the He^-, respectively.

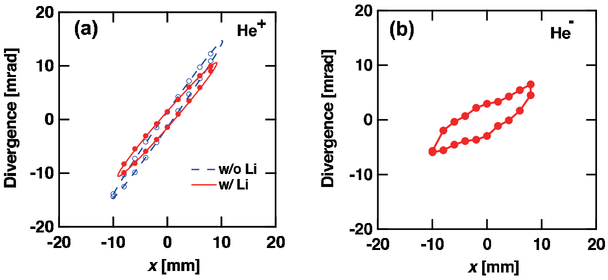

Fig. 5 Phase space diagrams of (a) He^+ and (b) He^-. The phase space diagram of the He^- was distorted and the momentum spread got broader.

of the He^+ (a) and the He^- (b) which generated from the He^+ at the beam energy of 14 keV is shown in Fig. 5. In Fig. 5 (a), the dotted line and solid line show phase space diagram of the He^+ beam after the passage of the cell without the Li vapor and with the Li vapor, respectively. The voltage of 4.6 kV was applied between two electrodes in the Faraday cup. Note that it has been verified that the beam injected into the Faraday cup was separated into the He^-, the He^+ and the He^0 by two electrodes in the Faraday cup and each species were injected into collectors properly. The phase space diagram of the He^- was distorted from that of the He^+ beam, and the momentum spread of the He^- was broader. The normalized emittances obtained from Fig. 5(a) and that obtained from Fig. 5(b) were 3.8×10^{-2} mm-mrad and 7.9×10^{-2} mm-mrad, respectively. The emittance of He^- was twice as large as that of the He^+. This indicates that the beam divergence of He^- has been enlarged by collisions in the gas cell.

Since the conversion efficiency of He^+ to He^- depends on the projectile He^+ beam energy, it is important to evaluate the emittance of the He^- beam through correlating the emittance with beam energy and intensity. The dependence of the normalized emittance of the He^- on the beam energy is shown in Fig. 6. In Fig. 6, the dependence upon the beam energy of the normalized emittance for the incident He^+ and that of the He^+ beam after the passage of the vapor cell are shown for comparison. The emittance increased with the increasing beam energy for all species. The emittance of the He^- beam increased by a factor of 2 compared with that of the He^+ beams. The emittance of the He^- at the beam energy of 10-20 keV can be estimated to be 0.07-0.09 mm-mrad by extrapolating curves in Fig.6.

4. Conclusion

An emittance meter equipped with an electrostatic charge state separator has been designed and constructed to measure the emittance of beams contained in the He^+-He^- compound beam produced by charge exchange reaction. The emittance measurement of the compound beam was carried out, and the characteristic of each beam compoent was studied. The change in the charge state distribution in the beam was observed in the Li vapor, where a large fraction of the He^+ was converted into the He^0, and a small fraction of the He^+ converted into the He^-. Collisions in the cell had enlarged the size of the He^+ beam, though the repulsive force due to space charge was substantially reduced by the conversion of the He^+ into the He^0. On the other hand, the effect by collisions upon the He^- beam was compensated by the focusing force originating from the He^+ space charge. The mometum spread of the He^- beam was broader than that of the He^+ beam, because the impact parameter for the inelastic collision is smaller than that for the elastic collision. This resulted in the emittance growth of the He^- beam produced by double charge exchange reaction. The emittance increased with the beam energy. The normalized emittance of the He^- beam at the beam energy of 10-20 keV which is the optimum range for negative ion conversion was estimated to be 0.07-0.09 mm mrad by extrapolating the current experimental results. Recently, we have started to measure the emittance of a strongly focusing high-intensity He^+ beam which consist of 301 beamlets extracted from a full-size He^+ ion source for alpha particle measurement, which has shown a relatively large emittance [8]. For this kind of beam, the beamlet-beamlet interaction can cause an emittance growth. We try to estimate the emittance of the actual system for fusion alpha diagnostics in ITER, through combining the result of the He^- beam formed in the alkali metal vapor cell as presented here and the result obtained from the full-size ion source.

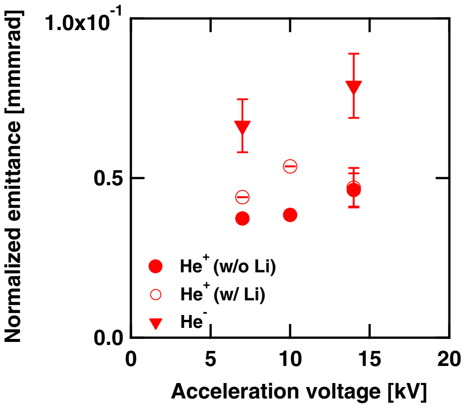

Fig. 6 Dependence of the normalized emittance of the He^+ without passing through the vapor, He^+ through the Li vapor, and He^- on the beam energy. The normalized emittance was slightly proportional to the beam energy.

5. Acknowledgement

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