Development of an Energetic He^0 Beam Injector for Fusion Application

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Abstract. A full-size strongly focusing He^+ ion source has been designed and constructed to develop a 10–100 mA He^- beam source for measurement of the spatial and velocity distributions of alpha particles in ITER burning plasma. The beam current above 2 A was required to meet the measurement specification for confined alpha particles, and it was obtained with this source at beam energy of 20 keV, which is suitable for efficient He^- charge-exchange production. The 1/e-folding half-width in the beam profile was about 15 mm at the beam waist. An efficient conversion factor (>1%) from He^+ to He^- and focusing properties of the He^- beam were confirmed using a test stand for He^0 pencil beam production.

1. Introduction

An energetic He^0 beam is attractive as a probing beam for measurement of confined alpha particles in a D-T burning plasma [1-5]. It can also be used as a heating beam in a D-^{3}He fusion device, because the D-D neutron emission rate will be substantially reduced by using an $^3He^0$ beam for driving D-^{3}He fusion reaction. In both cases, the beam penetration into a core plasma requires a beam energy higher than several hundred keV, and hence an intense beam source of He^- or HeH^+ is needed[2,6].

However, He^- is one of the most difficult negative-ion species to produce. It is produced through an electron attachment to a metastable atom in ^3S, not to a ground state atom. Volume production or surface production cannot be used for He^- production[7], and He^- can only be produced by charge exchange from the He^+ beam through two-step electron capture processes in an alkali vapour charge exchange cell (CX-cell),

$$He^+ + e \rightarrow He^* (^3S), \quad He^* (^3S) + e \rightarrow He^- (^4P_{5/2}, {}^4P_{3/2}) . \qquad \text{(Eq. 1)}$$

The optimum beam energy for the charge exchange He^- production is ranging in 10 – 20 keV [8]. There are specific engineering issues in the ion beam production through charge exchange: (1) the beam extraction at relatively low voltage (10-20 keV) causes diverging beam transport under strong space charge radial electric field[9], (2) the beam converging into a small size so that it passes through the entrance and exit apertures of the cell. (3) energy straggling in the CX cell. It has been estimated to be13 eV in case of He^+ ions and lithium atoms and is within the tolerable level for the beam design [10]. In addition there are issues in (4) beam acceleration and (5) Efficient neutralization to a ground state He^0, because a metastable beam atom will be easily ionized in the edge plasma, and will not penetrate into the plasma core [1-3]. A time of flight (TOF) neutralization using the 10 and 300 microsecond life times of He^- is proposed to produced a ground state He^0 [2-3], and its efficiency now experimentally studied [11-13].

For application of He^0 beam injection to alpha-particle measurement on ITER, the feasibility was studied[4]. Here, an alpha particle is neutralized by two-electron capture from an energetic beam particle He^0

$$He^{++} + He^0 \rightarrow He^0 + He^{++} \qquad \text{(Eq. 2)}$$

to escape from the plasma toward the detection point [1-5]. Because the cross section of the process (Eq. 2) decreases rapidly as the relative energy increases above 200 keV, the beam velocity close to that of alpha particles to be measured, and forward angle detection against the beam injection direction are needed. In the arrangement of the measurement system using possible ports in ITER configuration, the counting rate of the neutralized alpha particles produced by the process (Eq. 2) was estimated. When an He^0 beam which was produced through an auto-detachment of an 1-1.5 MeV He^- beam of 10 mA was injected, ratios of signal to neutron induced noises were evaluated, and they became greater than 1 for the normalized minor radius $\rho < 0.4$, even without beam modulation, and usage of phase sensitive detection technique at the RFQ accelerator frequency would make the measurement at the outer region possible [5].

In this article, we report the availability of the He^0 beam for ITER alpha particle diagnostics and foresee the He^0 heating beam, by showing the recent results in the development of a full-size He^+ ion source [14 – 17], those in beam transport study related to the charge exchange production [11-13].

2. Full-size He^+ ion source

Considering the low conversion efficiency (<2%) from He^+ to He^- and the optimum conversion energy of 10–20 keV, an ampere-size He^+ ion source was designed to obtain a 10 mA He^- beam for ITER application. The ion source consists of a plasma chamber 300 mm in diameter and 280 mm in length surrounded by a set of permanent magnets that form a cusp magnet field, 4 or 8 filaments and three concave multi-aperture electrodes. All three electrodes are made from molybdenum and they are actively water cooled at their rims. From the centre area of 100 mm in diameter, more than 300 beamlets are extracted through apertures 4 mm in diameter. Concave electrodes were chosen so that the extracted beam focuses into an acceptable size of an alkali vapour cell without using electrrostatic lenses which extinguish the space charge neutralization effect. The alkali vapour cell is designed aiming at long operation time without alkali vapour leakage, efficient negative beam production, and typical aperture size is about 20–30 mm. Figure 1 shows the schematic illustration of concave electrodes of a strongly-focused He^+ beam and photograph of the plasma electrode viewed from the plasma side.

The He^+ ion source was installed on the NBI test stand at National Institute for Fusion Science with a vacuum chamber of 1 x 1 x 1 m^3 for diagnostics. In this chamber, a Rogowski

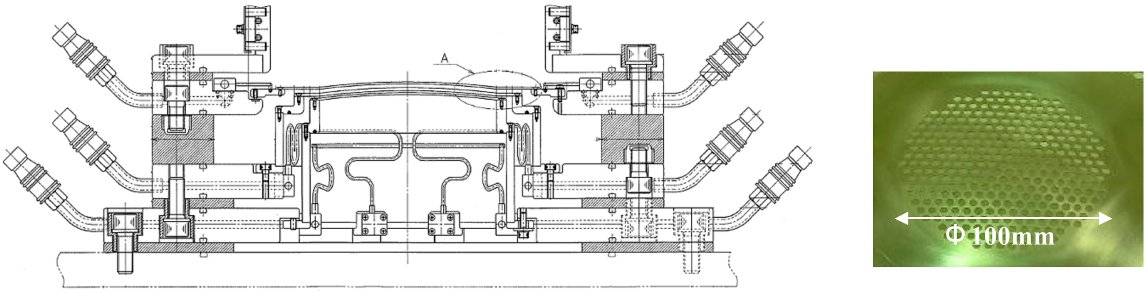
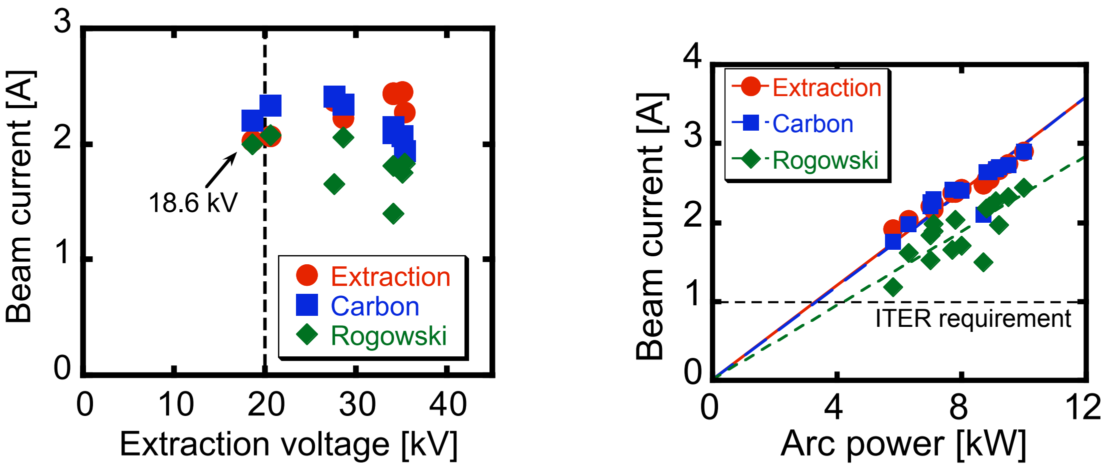


FIG. 1 Schematic illustration of extraction electrodes of a strongly-focused He$^+$ beam and photograph of the plasma electrode viewed from the plasma side. All electrodes are made from molybdenum and they are actively water cooled at the peripheral. The extraction area is 100 mm in diameter, with more than 300 apertures.



(a) (b)

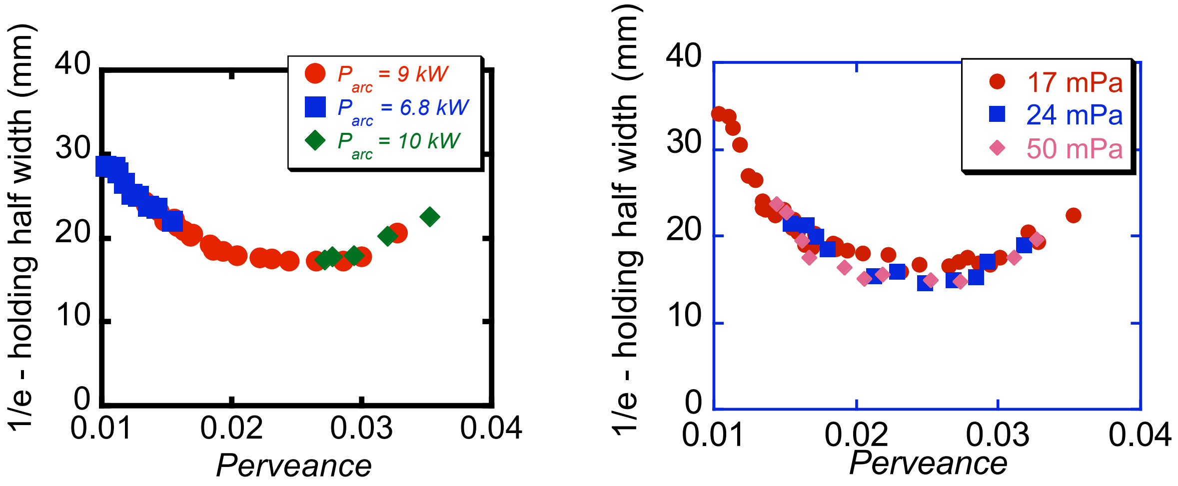
FIG. 2. The extraction voltage dependence (a) and the arc power dependence of the He$^+$ beam current measured by a Rogoski-coil, a carbon plate and the acceleration current. Beam current of 1A is the minimum requirement for the alpha particle measurement on ITER without beam modulation.

coil and a movable carbon beam dump target (100 x 100 x t2 mm^3) were installed. The carbon target position was controlled remotely in the direction of the beam axis to determine a beam focal point. The temperature at the beam dump target heated by the extracted beam was observed from the backside of the target with an infrared camera installed outside the chamber to obtain the 2D beam current density distribution [5]. In addition, the beam current onto the carbon target was measured. The extracted beam current was directly measured using a 811-turn Rogowski coil of 88 mm in major diameter R. A Teflon-coated wire conductor of 0.6 mm diameter was wound around a centre insulator ring into a coil shape [5]. The relation between the induced voltage V_s to the beam current I can be expressed by

$$V_s = -\frac{NS\mu_0}{2\pi R}\frac{dI}{dt} \qquad \text{(Eq. 3)} \qquad .$$

Then the net beam current can be measured through an integration circuit without blocking the beam. The beam current could also be evaluated from the difference between the acceleration electrode current (I_{acc}) and deceleration electrode current (I_{dec}), I_{acc}-I_{dec}.

A He plasma was produced by an arc discharge using 4 or 8 filaments in the ion source. The typical arc power was 7 to 12 kW, with a filament power of 8 - 9 kW and pulse duration of 2-10 s. The acceleration voltage of 18 -35 kV, a deceleration voltage of -0.2 ~ −0.85 kV were delivered for the extraction. The typical beam duration was 0.1 s. The acceleration current and beam currents measured by both the Rogowski coil and the carbon plate beam target are shown in Fig. 2 as a function of the acceleration voltage (a) and the arc power. The beam current measured by the Rogowski coil was slightly lower than the values obtained by other methods, because it is free from the contamination of neutralized beam component, secondary electrons, and back streaming electron current. A beam current of more than 2 A was achieved at acceleration voltages of 20–25 kV with the arc power of 10 kW. The measured beam current shows a weak dependence upon the extraction voltage, indicating that the source was adequately designed to have the optimum performance in the extraction voltage of 20 kV region, the energy suitable for He^- beam production.



(a) (b)

FIG. 3. Perveance dependence of 1/*e*-folding beam profile half-width, (a) for the arc power at 6.8 kW, 9 kW, and 10kW under the pressure of 17mPa, and (b) comparison of the results under the pressure of 17mPa, 24 mPa and 50 mPa.

The 1/*e*-folding half-width of the beam profile, $r_{1/e}$, was obtained from the 2D-image of temperature distribution measured with an IR camera by assuming Gaussian distribution and constant background which corresponds to the temperature of the beam target before the He^+ beam injection [15]. The half-width at their minimum position was plotted against the perveance (I_{acc} / $V_{ext}^{3/2}$), which is a measure of the beam extraction governed by the ion saturation limit at the boundary of the ion source plasma and space charge limitation in the extraction direction. Here, V_{ext} denotes the extraction voltage. Then the half-width were plotted against the perveance as shown in *FIG. 3a*. Perveance dependence of the half-width showed that it takes the minimum of 15 mm at perveance of about 0.03 (A/kV$^{3/2}$). In *FIG. 3b*, the perveance dependence of the half-width under the ion source pressure of 17, 24 and 50 mPa were compared. The width observed under ion source operation at the lowest pressure was larger than the other cases, indicating the beam size is affected by the space charge neutralization.

The half-width at the optimum perveance were measured by changing the carbon target position from the plasma electrode along the path length, *Z*. The focal length, Z_f, and the beam divergence, θ_{div}, were obtained by fitting the dependence of the half-width on the path length to the following curve:

$$r_{1/e}^2 = (\theta_{\text{div}} Z)^2 + (Z - Z_f)^2 (r_{1/e,0} / Z_f)^2 , \qquad \text{(Eq. 4)}$$

where $r_{1/e,0}$ is net area size of the extracted beam projected on the extraction electrode ($Z = 0$ mm). Then, the focal length, the beam divergence and the minimum beam radius were about 500 mm, ~20 mrad and 15 mm, respectively [15-17].

The beam size measured with the present source shows that the beam of the required current and energy passes through entrance and exit apertures of a cell that is available with the present technology. However, the focal length deviated from the designed values, indicating the effect of thermal strain from high-power operation at 60 kW in the beginning of the source conditioning. The shape changes of the concave electrodes were measured after the series of experiment. The gap distance was changed and the uniformity was not conserved. This is one of the reasons that the beam divergence was larger than expected. Even at the arc power of 10 kW, where the required parameters were obtained, the uniformity of the beam profile was changed further downstream from the focal length by increasing the plasma arc duration to 10 s. Further study is needed to realize a DC operation of the beam source.

The possibility for applying the strongly-focused high-intensity He$^+$ beam source to study the plasma material interactions for the development of plasma facing material has been studied[18]. Recent studies have revealed the importance of He effect on the material surface interaction. The beam flux at the focal point and beam power density achieve up to 3 x 10^{22} m^{-2}s^{-1} and 0.1 GW/m^2, respectively. Due to optimization of the operation, a higher performance is expected.

3. He$^-$ production

A test stand device named Advanced Beam Source 103 (ABS103) has been constructed to study the beam transport related to the double charge exchange He$^-$ production, and to provide experimental confirmation on the production of a ground state through auto-electron detachment. The meta-stable fraction will be measured using a Laser absorption method [19-20] or beam attenuation in a cylindrical plasma[21]. A schematic diagram of the equipment ABS103 is shown in Figure 4. It has a compact bucket-type He$^+$ ion source, a set of einzel lens, alkali vapor gas cell (Li cell), a double focus bending magnet, an accelerator column and a free flight tube with an ion separator and a pyro-electric detector for neutral beam current measurement. The He$^+$ ions are extracted from a compact ion source at energy range 10-15 kV so that the cross section of He^- production in Li is comparably large [8]. Then, the beam is adjusted with an electrostatic lens, injected into a Li vapor cell, converted into He^-, and then charge separated by a 90° bending magnet of double focusing type. The magnet is designed to have two focal points, accepting a diverging beam to focus the beam at the mirror point downstream in the two transverse directions[6]. One of the focal points should be at the centre of the CX-cell, while the other should be at the entrance of the accelerator. In addition the magnet prevents He^+ and He^0 beams entering the electrostatic accelerator. The He^- beam is then electro-statically accelerated, and is neutralized in flight with the decay life times of 10 and 300 μsec. All of the components for He^- beam production are in a high voltage station of 100–150 kV to accelerate the He^- beam [18].

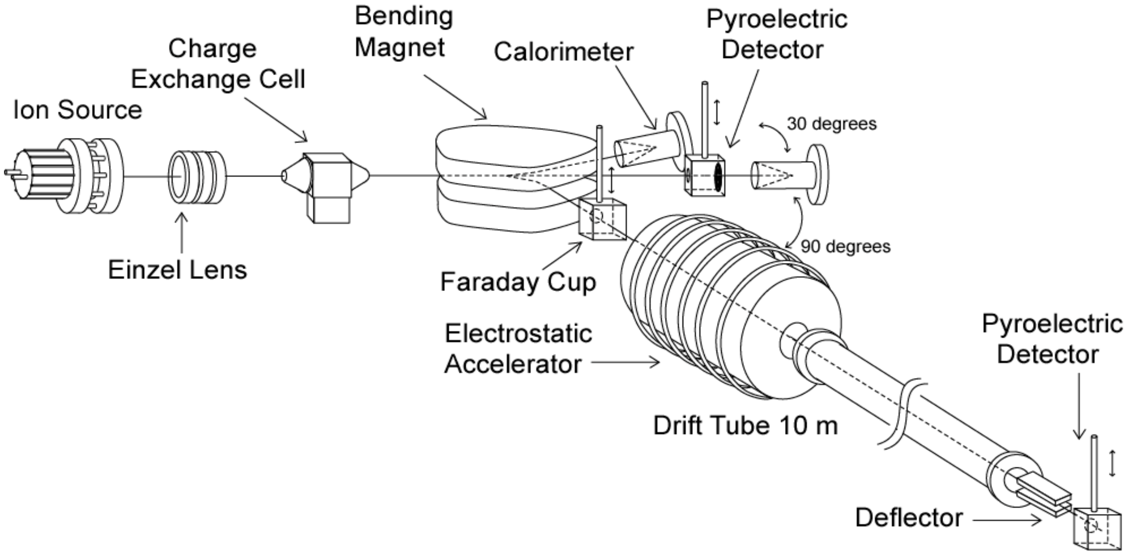
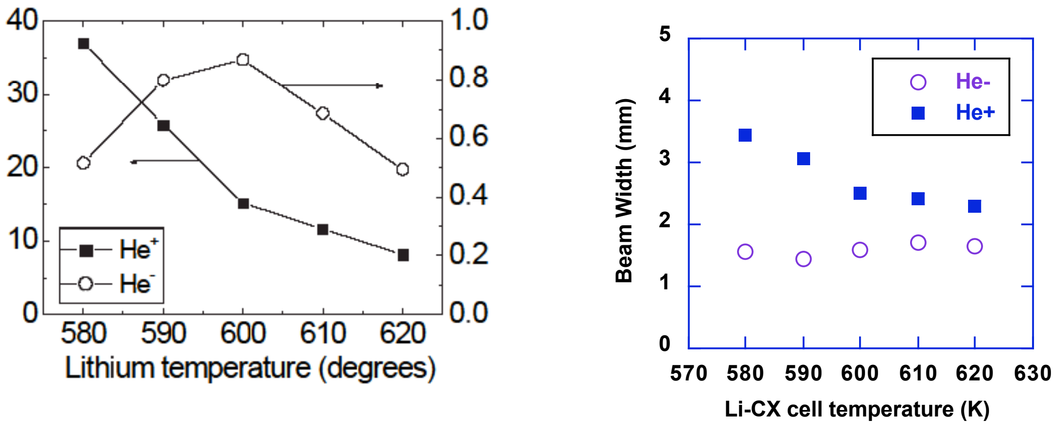


FIG. 4 A schematic diagram of the equipment ABS103. The components upstream the electrostatic accelerator are contained in a shield box on the negative high voltage terminal. Details are described in the text.

The beam current and profiles of He^+ and He^- beams were measured at the entrance of the accelerator, by scanning a Faraday cup with a 1 mm slit aperture in the direction perpendicular to the beam. Typical operation conditions are the arc current of the ion source, I_{arc} =1.0 A, the He^+ extraction voltage, V_{acc} =8-15 kV, and the Li cell temperature, T_{Li}= 773 K-893 K. Figure 4 shows the dependence of integrated beam current intensity (a) and the 1/e-folding beam profile half width (b) of He^+ and He^- beams upon the CX-cell temperature. The He^+ current decreases drastically, and that of He^- beam has a maximum value of 0.9 μA at ~ 870 K. An efficient conversion factor higher than 1% from He^+ to He^- was obtained. The 1/e-folding beam half width of the He^+ beam is ~7 mm at 793.15 K and it decreases to ~2 mm as the temperature increases[18]. However that of He^- beam is increasing slightly. The half widths of the He^+ and He^- beams converge at around 2 mm showing the space charge radial electric field, which possibly might be converging the He^- beam.



(a) (b)

FIG. 5 Dependence of integrated beam current intensity (a) and the 1/e-folding beam profile half width (b) of He$^+$ and He$^-$ beams upon the CX-cell temperature [18].

Post-acceleration experiment was carried out on the ABS103 [22]. Experimental results indicated that the focusing effect of the beam by the post-acceleration column was confirmed. The calulation using a simulation beam transport code predicted the feature that the beam focused when the acceleration voltage was increased,

4. Discussion and Conclusion

In the present research, a full-size strongly focusing He$^+$ ion source has been constructed to develop a 10–100 mA He$^-$ beam source for measurement of the spatial and velocity distributions of alpha particles in ITER burning plasma. The beam current above 2 A was obtained at beam energy of 20 keV, which is suitable for He$^-$ charge-exchange production. The 1/e-folding beam profile half-width at the beam waist was about 15 mm, and it was small enough to be accepted by a circulating alkali charge exchange vapor cell under the present technology. An efficient conversion factor (>1%) from He$^+$ to He$^-$ and focusing properties of the He$^-$ beam were confirmed using a test stand for He^0 beam production.

The present research has indicated that a confined alpha particle measurement system using an energetic He^0 beam produced from He$^-$ and accelerated to 1 – 2 MeV is promising. In addition, improvement of the S/N ratio on ITER can be accomplished (1) by subtraction of neutron-induced background noise using beam modulation, and/or (2) by additional shielding and bending of the secondary particles after stripping at the detectors.

The strongly-focused high-intensity He$^+$ beam source developed in the present research can be applicable to the study on the plasma material interactions for the development of plasma facing material [11]. Recent studies revealed the importance of He effect on the material surface interaction. The high particle flux tests for candidate materials can be made with the constructed system with the beam flux at the focal point. The prospect to a heating beam on a

D^3-He fusion device would be further studied, based on the favourable phenomena observed in the present research.

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