AIP | Review of Scientific Instruments

Extraction of a strongly focusing He+ beam from three-stage concave electrodes for alpha particle measurement system in ITER

T. Kobuchi, M. Sasao, M. Kisaki, K. Tsumori, N. Tanaka et al.

Citation: Rev. Sci. Instrum. **83**, 02B120 (2012); doi: 10.1063/1.3673630
View online: http://dx.doi.org/10.1063/1.3673630
View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v83/i2
Published by the American Institute of Physics.

Extraction of a strongly focusing He^+ beam from three-stage concave electrodes for alpha particle measurement system in ITER[a)]

T. Kobuchi,[1] M. Sasao,[2,b)] M. Kisaki,[1] K. Tsumori,[1] N. Tanaka,[2] A. Okamoto,[2] S. Kitajima,[2] O. Kaneko,[1] K. Shinto,[3] and M. Wada[4]
[1]*National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*
[2]*Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan*
[3]*IFMIF R&D Center, Japan Atomic Energy Agency, Rokkasho, Aomori 039-3212, Japan*
[4]*Graduate School of Engineering, Doshisha University, Kyotanabe, Kyoto 610-0321, Japan*

(Presented 13 September 2011; received 8 September 2011; accepted 6 December 2011; published online 21 February 2012)

A strongly focusing He^+ ion beam source equipped with concave multi-aperture electrodes was developed for production of He^- through a charge exchange cell. The beam was extracted at a voltage less than 20 kV from 301 apertures distributed in an area of 100 mm ϕ, and focused at 750 mm distance. The beam current and the beam size of 2 A and 20 mm in diameter, respectively, were achieved with an arc power less than 10 kW. The optimum perveance was obtained at 0.02 A/kV$^{1.5}$ at the beam energy less than 20 keV which is suitable for the conversion to He^- in an alkali vapor cell.
 [http://dx.doi.org/10.1063/1.3673630]

I. INTRODUCTION

It is known that negative ions of an element with negative electron affinity can be produced by electron attachment to a metastable atom.[1] This is the reason why negative ion beams of such elements, He^- for example, are produced from a positive beam through two-step electron capture processes in alkali vapor cell. We have been developing a 1–2 MeV He^- beam of 10 mA region, because it is demanded for the production of an energetic ground state He^0 beam to diagnose the alpha particle confinement in a DT burning plasma of ITER.[2,3] The optimum beam energy for the He^- production is in the range of 10–20 keV, therefore, the beam should be extracted at relatively low voltage. In addition, the beam should converge into a small size so that it passes through the charge exchange cell entrance and exit apertures, of typical size ranging 10–30 mm in diameter, in order to prevent the alkali vapor leakage.

Considering the low conversion efficiency (<2%) from He^+ to He^-, an ampere-size He^+ ion source was constructed to obtain a 10 mA He^- beam for ITER application. Extraction with concave electrodes[4] was chosen so that the extracted beam focuses into an acceptable size of an alkali vapor cell without using electrostatic lenses which extinguish the space charge neutralization.[5] We have reported on the design of the system,[5] the arc performance,[6] the preliminary results of the beam extraction,[7] and the optimization of the filament configuration.[8] A beam current more than 2 A was obtained at acceleration voltages of 20–25 kV with the arc power less than 10 kW. The $1/e$-folding beam radius was about 15 mm. The focal length, however, was about 450 mm, much shorter than the designed value (750 mm), and the beam profile showed deformation from a concentric circle at the location about 0.5 m downstream the beam waist.

The extraction characteristics of the strongly focusing source with re-made electrodes are reported in this article. The beam profile was measured with a calorimetric profile monitor[7] along the beam direction, and the beam optics was investigated. The change of the electrode temperature by arc/filament heat load was measured with/without beam extraction. The prospect of this source on the application to the ITER diagnostic beam is discussed on the basis of present results.

II. EXPERIMENTAL APPARATUS

The ion source consists of a bucket type plasma chamber of 300 mm in diameter and a set of three concave multi-aperture electrodes. All three electrodes are made from molybdenum and they are actively water cooled at their rims. Figure 1(a) shows the arrangement of the three electrodes, plasma grid (PG), extraction grid (EG), and grounded grid (GG). The PG is biased positively (V_{acc}) against the GG, and the EG is biased negatively (V_{dec}) against the GG. From the centre area of 100 mm in diameter, 301 beamlets are extracted with a voltage $V_{acc} + V_{dec}$ and then decelerate with V_{dec} through apertures 4 mm in diameter. Figure 1(b) shows the cross sectional view of one of the 301 extraction apertures.

The ion source was installed on the NBI-Teststand at National Institute for Fusion Science, with a 1 × 1 × 1 m^3 vacuum chamber for diagnostics. The beam current was measured by a Rogowski coil.[7] It was also estimated as $I_{beam} = I_{acc} - I_{dec}$, where I_{acc} and I_{dec} were the acceleration and deceleration current, and by a current onto a carbon beam dump target (100 × 100 × t2 mm^3). Agreement among these three measurements was satisfactorily good[7] when the vacuum level was good. The carbon beam dump was installed on a movable frame, and the 2D temperature distribution of the target heated by the beam was observed from the backside of the target with an infrared camera (IRFlexCam Pro, Fluke) to obtain the beam profiles along the direction of the beam axis.[7]

[a)]Contributed paper, published as part of the Proceedings of the 14th International Conference on Ion Sources, Giardini Naxos, Italy, September 2011.
[b)]Electronic mail: mnsasao@yahoo.co.jp.

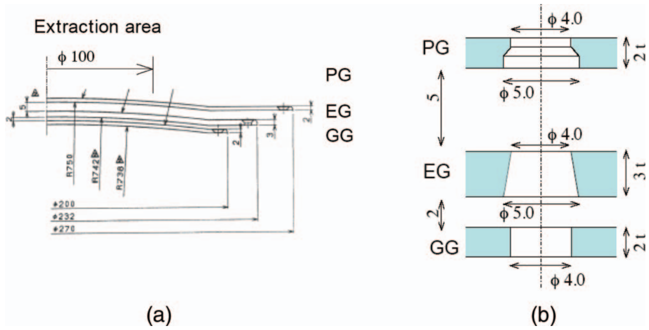

FIG. 1. (Color online) (a) The view of the concave multi-aperture electrodes. All apertures of each three electrodes are aligned so that the beamlets were focused at 750 mm downstream. (b) The cross sectional view of the acceleration/deceleration geometry.

III. EXPERIMENTAL RESULTS

A. Extraction characteristics

Figure 2(a) shows the arc power dependence of the beam current estimated from the $I_{acc} - I_{dec}$, when V_{dec} was fixed at 0.8 kV. The open squares show the beam current with remade set of electrode with V_{acc} in 11–12 kV, where the closed square show the current with V_{acc} in 16–18 kV. The beam current shows almost linear dependence to the arc power and it is consistent with that the old electrode set.[7] The V_{dec} dependence was studied by changing V_{dec} in 0.2−1.3 kV with almost constant arc power and V_{acc} in 11–12 kV. The V_{acc}/V_{dec} dependence of the beam current normalized by the arc power (Fig. 2(b)) shows the lower V_{dec} is favorable, but the beam current diminished to almost 30% of that at $V_{dec} = 0.2$ kV when it was close to zero. One of the roles of V_{dec} is form a potential barrier to prevent electron back stream to the arc chamber. Figure 2(c) shows the V_{dec} dependence of the filament resistance. While the arc power was kept constant, the electrical resistance was reduced, showing that the filament temperature was decreased by mitigating the electron back stream.

B. Beam focusing characteristics

Two-dimensional beam image was measured by the infrared camera as the temperature distribution of a thin carbon beam dump target ($t = 2$ mm). The heat conduction in the target depth and radiation cooling from both surfaces is good enough for the resolution of the image. The change of the beam image was scanned along the beam direction by moving the carbon beam dump.[7] Figure 3 shows an example of the beam image (a) and the vertical and horizontal beam profiles obtained from the digitized temperature distribution (b). Concentric distribution of the beam density was confirmed. The $1/e$-folding beam radius was estimated by fitting the profile by a Gaussian, and it was plotted as the function of the perveance, $I_{beam}/V_{acc}{}^{3/2}$ for $z = 647$ mm, 701 mm, 755 mm, 809 mm, and 862 mm in Fig. 3(c), where z is the distance along the beam direction from the GG. The optimum perveance is about 0.02 A/(kV)$^{3/2}$.

Figure 4 shows z-dependence of the $1/e$-folding beam radius at the optimum perveance of 0.02 A/(kV)$^{3/2}$. The focal

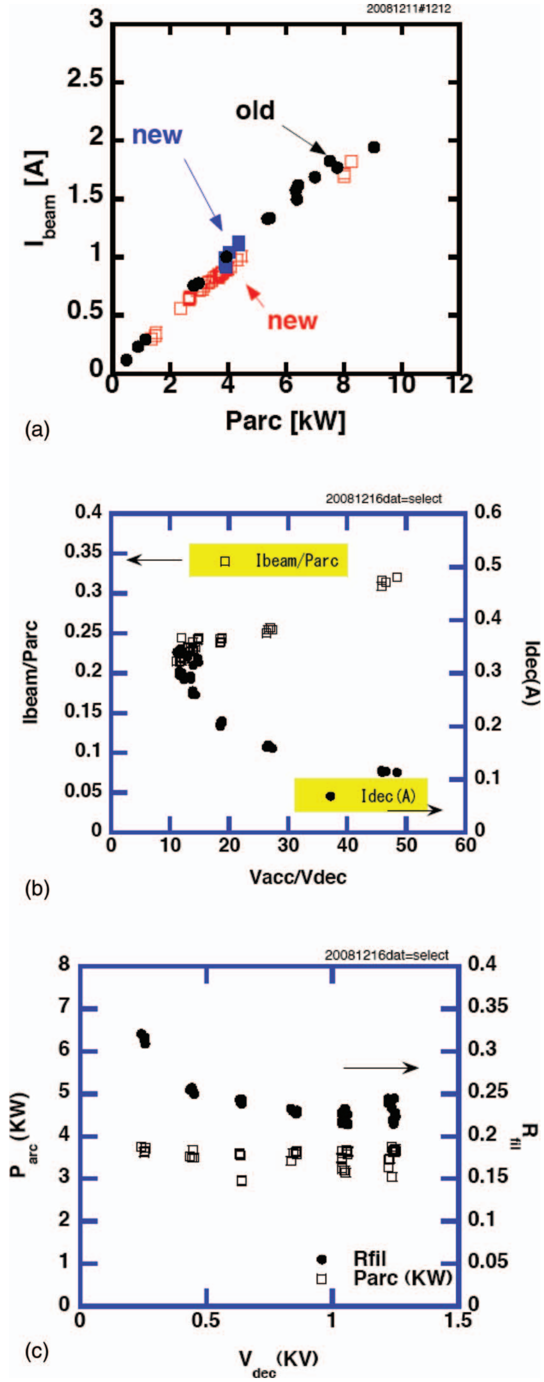

FIG. 2. (Color online) The extraction characteristics of the He^+ source. (a) The arc power dependence of the beam current. (b) The V_{acc}/V_{dec} dependence of the beam current normalized by the arc power (open square) and the deceleration current (solid circle). (c) The V_{dec} dependence of the filament resistance (solid circle) and the arc power (open square).

length, Z_f, and the beam divergence, θ_{div}, were obtained by fitting the dependence of the beam radius on the path length to the following curve:

$$r_{1/e}^2 = (\theta_{div} Z)^2 + (Z - Z_f)^2 \left(\frac{r_{1/e,0}}{Z_f}\right)^2, \quad (1)$$

where $r_{1/e,0}$ is net average radius of the extracted beam projected on the GG ($z = 0$ mm). The focal length, the beam divergence and the minimum beam radius were about

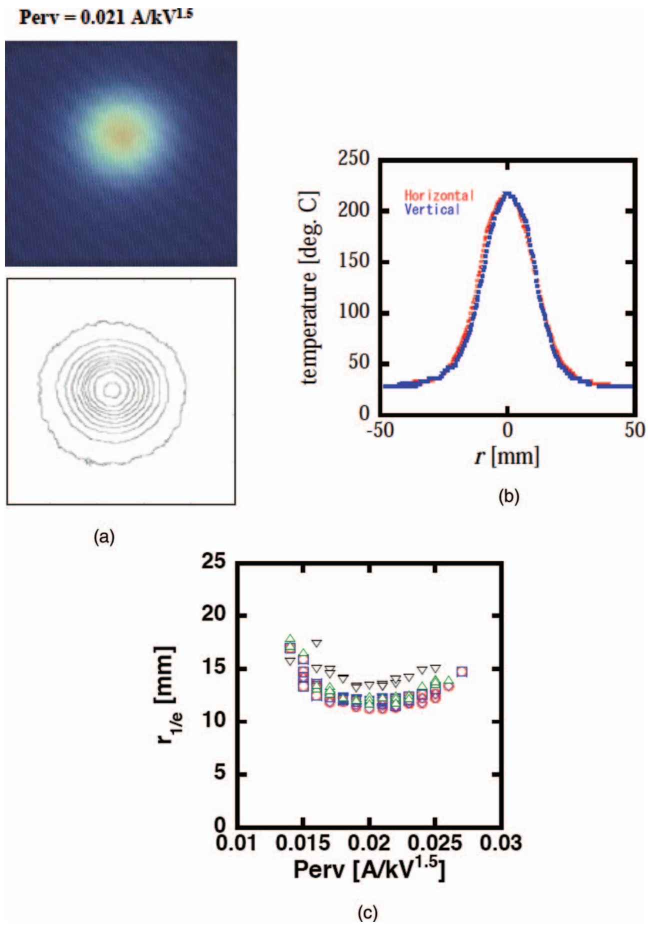

FIG. 3. (Color online) Two-dimensional beam image measured by an infrared camera as the temperature distribution of a thin carbon target (a), and the vertical and horizontal beam profiles obtained from the digitized temperature distribution (b). (c) The perveance dependence of the $1/e$-folding beam radius measured at $z = 647$ mm (red circle), 701 mm (triangle), 755 mm (diamond), 809 mm (square), and 862 mm (upside-down triangle), where z is the distance along the beam direction from the GG.

720 mm, $\sim$15 mrad, and 11.3 mm, respectively, while their designed values were 750 mm, $<$16 mrad, and $<$12.5 mm, respectively.[6] For comparison, the z-dependence of the $1/e$-folding beam radius using the old electrode set is shown as well in Fig. 4.

IV. DISCUSSION AND CONCLUSION

The experimental results with the re-made set of electrode have resolved two problems of old electrodes, the shorter focal length and the beam shape deformation seen downstream. One of the possible reasons envisaged is the deformation of the concave electrodes due to the heat load in the arc chamber. In order to see the heat load effect, a thermocouple is attached on the PG, and the heat load was mitigated with a concentric collar cover on it with beam on/off. The experimental results showed that the most responsible heat load is that of arc power. Details are described in Refs. 9 and 10.

Present results showed that the ion source developed has satisfactory features for the application to the ITER diagnostic beam for alpha particle measurement, such that the beam was extracted at V_{acc} less than 20 kV which is suitable for charge

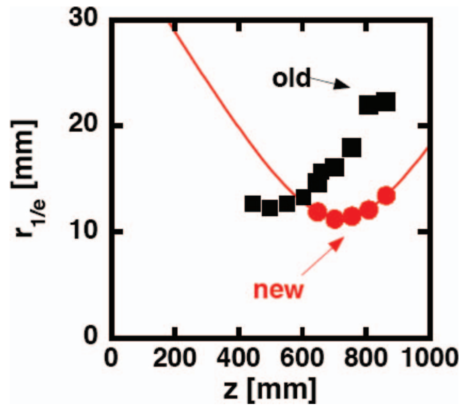

FIG. 4. (Color online) z-dependence of the $1/e$-folding beam radius at the optimum perveance with the old set of electrode (square) and that with the new set (circle). The solid line shows the fitting line to Eq. (1).

exchange to the negatives in an alkali vapor cell, and that the beam intensity of 2 A was obtained with the arc power less than 10 kW, with the beam radius less than 12 mm.

Present experiment, the arc discharge of the ion source is limited to less than 3% duty factor by the power supply system. In the actual application, the duty factor would be increased with a factor more than 5. The additional cooling would be needed but the substantial change of the source design will not be necessary.

ACKNOWLEDGMENTS

This work was supported by Grant-in-Aid for Priority Area 442-16082101, Ministry of Education, Science, Sports and Culture of Japan (MESSC(JP)), and in part by Joint research programme at the National Institute for Fusion Science.

[1] H. Massey, *Negative Ions* (Cambridge University Press, Cambridge, 1976), Chap. 5.
[2] M. Sasao, A. Taniike, I. Nomura, M. Wada, H. Yamaoka, and M. Sato, Nucl. Fusion **35**, 1619 (1995).
[3] M. Sasao, K. Shinto, M. Isobe, M. Nishiura, O. Kaneko, M. Wada, C. I. Walker, S. Kitajima, A. Okamoto, H. Sugawara, S. Takeuchi, N. Tanaka, H. Aoyama, and M. Kisaki, Rev. Sci. Instrum. **77**, 10F130 (2006).
[4] H. Sakakita, S. Kiyama, Y. Hirano, H. Kokuchi, and Y. Yagi, Jpn. J. Appl. Phys. **45**(10B), 8531 (2006).
[5] K. Shinto, H. Sugawara, S. Takeuchi, M. Takenaga, S. Kitajima, M. Sasao, M. Nishiura, O. Kaneko, S. Kiyama, and M. Wada, in *Proceedings of 2005 IEEE Particle Accelerator Conference, Knoxville*, IEEE Catalog No. 05CH37623C (2005), pp. 2063–2065.
[6] K. Shinto, A. Okamoto, S. Kitajima, M. Sasao, M. Nishiura, O. Kaneko, S. Kiyama, H. Sakakita, Y. Hirano, and M. Wada, in *Proceedings of European Particle Acceleration Conference, Edinburgh* (EPS-AG, 2006), TU-PLS096, http://accelconf.web.cern.ch/AccelConf/e06/.
[7] M. Kisaki, K. Shinto, T. Kobuchi, A. Okamoto, S. Kitajima, M. Sasao, K. Tsumori, O. Kaneko, M. Nishiura, and M. Wada, Rev. Sci. Instrum. **79**, 02C113 (2008).
[8] T. Kobuchi, M. Kisaki, K. Shinto, A. Okamoto, S. Kitajima, M. Sasao, K. Tsumori, O. Kaneko, M. Nishiura, and M. Wada, Rev. Sci. Instrum. **79**, 02B708 (2008).
[9] M. Kisaki, Ph.D. dissertation, Tohoku University, 2010.
[10] M. Sasao, M. Kisaki, T. Kobuchi, K. Tsumori, N. Tanaka, K. Terai, A. Okamoto, S. Kitajima, O. Kaneko, K. Shinto, and M. Wada, "An alpha particle measurement system using an energetic neutral helium beam in ITER," Rev. Sci. Instrum. (these proceedings).