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Study of the Beam Transport in a High-Energy Neutral Helium Beam System with Double Charge Exchange Cell

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The beam transport of a negative ion production system with a charge exchange cell was studied experimentally and by using the simulation code SIMION. The focusing effect of the electric accelerator was confirmed in the experiment. The simulation results showed that the space charge effect plays an important role in beam transport.

Keywords: Alpha particle measurement, Ion beam, Space charge effect, Beam transport, Magnetic confined plasma diagnostics

1. Introduction

Alpha particles produced by DT reactions play an important role as a self-heating source for sustaining burning plasmas. It is necessary to study various aspects of the behavior of alpha particles to understand the characteristics of the burning plasma and to achieve efficient self-heating. A beam neutralization method has been proposed for alpha particle measurement in next-generation magnetically confined fusion plasma devices as one of the promising methods to measure the spatial and velocity distributions of confined alpha particles [1]. In this scheme, an energetic He^0 beam is injected into a burning plasma, and alpha particles are neutralized by the double charge exchange process;

$$^4He^{2+} + {}^3He^0 \rightarrow {}^4He^0 + {}^3He^{2+}$$

An energetic He^0 beam in the 1–2 MeV energy range is required to achieve efficient neutralization of confined alpha particles. For He^0 production, when the beam energy for neutralization is higher than 100 keV/nucleon, neutralization efficiency from positive ions is extremely low, while neutralization from negative ions produces metastable atoms, which do not penetrate deep into the plasma core. Only the "in-flight neutralization", or auto electron detachment from negative ions, forms an energetic ground state He^0 beam efficiently [1]. Another critical issue is the production of a He^- beam. Volume production or surface production cannot be used for He^- production, but double charge-exchange production can. In addition, this method is concerned from aspects of the beam divergence and space charge effect. Taking these circumstances into account, a device named Advanced Beam Source 103 (ABS103) has been constructed for the study of beam transport and for the proof of principle experiment of "in-flight-neutralization" [2]. In this paper, we present the measured beam space profiles, and simulated results using the simulation code SIMION [3] to determine the effects of post-acceleration and to study the effects of space charge and beam divergence.

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2. Equipment and Experiment

2.1 Apparatus

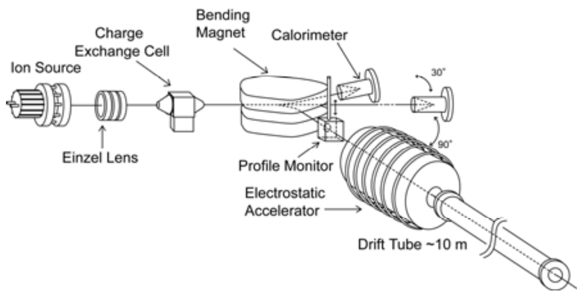

Fig.1 Schematic diagram of apparatus.

A schematic diagram of the ABS103 equipment is shown in Fig. 1. The device has a compact bucket-type He^+ ion source, einzel lens, charge exchange cell (Li cell), a double focusing bending magnet, an accelerator column and a free flight tube. The He^+ ions are extracted from a compact ion source at the energy range of 10–15 keV so that the cross-section of He^- production in Li is comparably large [4]. Then, the beam is adjusted by the einzel lens, injected into the Li vapor cell, converted into He^-, and charge separated by the 90° bending magnet.

The He^- beam focused at the entrance of the accelerator column is electrostatically accelerated, and neutralized in flight with decay lifetimes of 10 and 300 μs.

2.2 Experiment

The beam profiles were measured using a profile monitor consisting of a Faraday cup and a 1-mm slit. The profile monitor moves vertically, and scans the vertical beam current distribution. The beam profile was measured at three positions: at the location of the einzel lens, -90-degree down stream of the bending magnet (faraday cup position), about 800 mm downstream of the electrical accelerator. Experimental conditions are summarized in Table 1. Examples of the beam profile before acceleration and after acceleration are shown in Fig. 2. The peak was somewhat different before and after acceleration. This seemed to be because the beam axis was tilted by about 0.1 radian upward and it was about 1 mm upward at the entrance of the acceleration column.

Table 1. experimental conditions

Extraction voltage (kV)	10
Arc current (A)	1.0
Pressure of extraction area (Torr)	1.5-3×10^{-5}
Einzel lens voltage (kV)	optimized

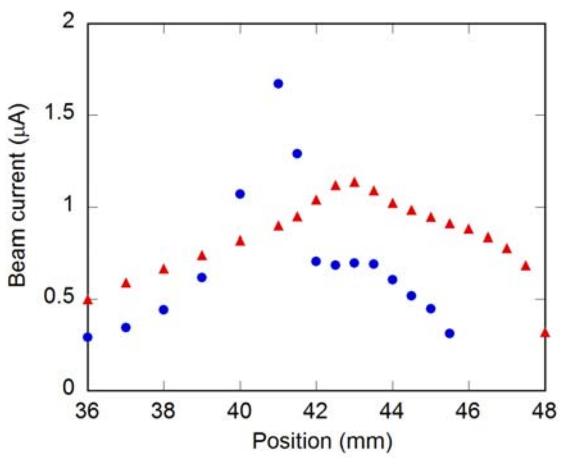

Fig.2 Beam profile before and after acceleration column with an acceleration voltage of 15 kV. Triangles and circles are before acceleration and after, respectively. Geometrically the position of the center of drift tube is 42 mm

The acceleration voltage dependency on the beam profile was examined, as shown in Fig. 3. The peak position of the beam moved closer to the acceleration column center and the total beam current increased as the acceleration voltage increased. Thus, misalignment of the beam axis was mitigated by an electrostatic settling action of the acceleration column at acceleration voltages above 10 kV.

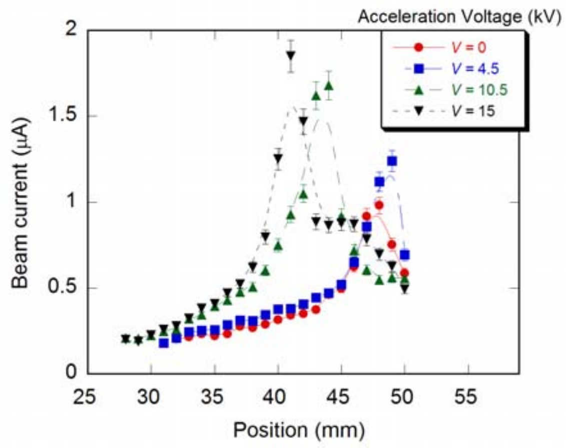

Fig.3 Beam profile after acceleration.

3. Simulation by SIMION code

Beam transport is one of the most important issues in such application. Here, we used the beam simulation code SIMION and simulated the beam transport. Initial setting parameters, space charge effect, and ion initial conditions (their positions and divergences) are required in the simulation. The degree of the space charge effect was obtained from the envelope equation [5] and experimental results. With regard to the divergence, it was assumed that the shape of extraction boundary plasma was the arc shape with curvature R. Here, the ion sheath distance d_s obtained in the one-dimensional model was used [6, 7], as the typical parameter of this ion source, and the condition $d_s > d$ was met, where d is the extraction gap [6, 7]. The initial ions were set on a vertical line of the cross-section of the extraction electrode. The initial conditions in simulation are shown in Table 2.

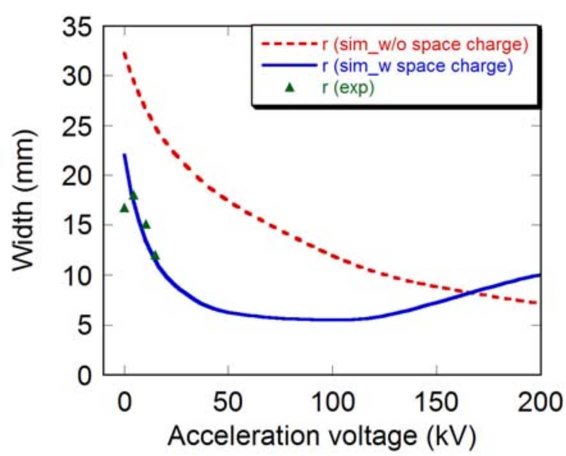

Fig.4 Beam spread as a function of the acceleration voltage. The dash line, solid line, and triangles are beam radius r (sim) in the simulation without space charge, with space charge, and the beam radius determined by the experiment, respectively.

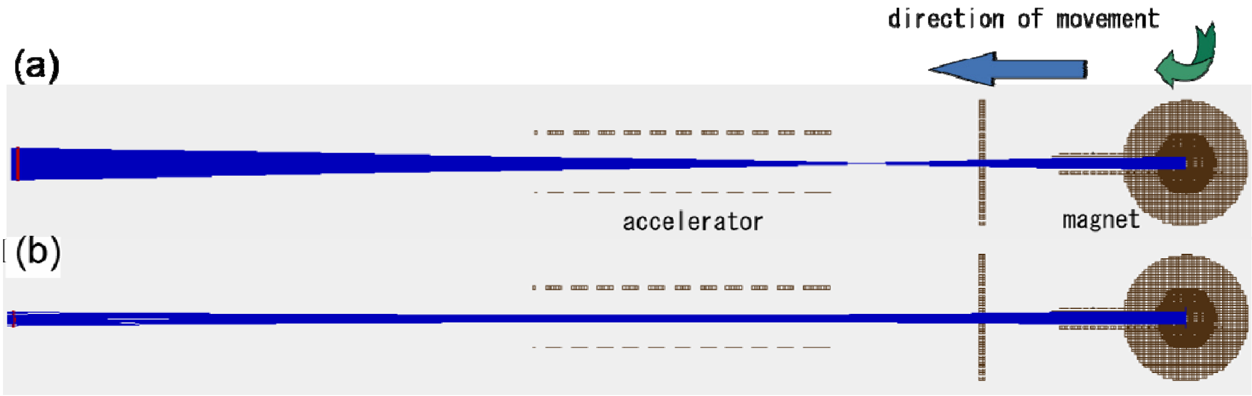

Fig.5 Simulated beam trajectory: (a)the beam orbit without space charge effect in the position after the bending magnet, (b)the beam orbit with space charge effect.

Table 2. initial conditions in the simulation

Extraction Voltage (kV)	10
Extraction Current (mA)	1.0
Current set for calculation (mA)	0.42
Einzel lens voltage (kV)	7
sample number	62
Curvature of extraction face (mm)	150

Figure 4 shows a comparison of the measured beam width and the simulated beam spread as a function of the acceleration voltage at a position 800 mm downstream of the acceleration column. The simulated beam spread was determined from the outermost orbits. The beam spread has diminished as the acceleration voltage increased, indicating the focusing effect of the acceleration column.

The space charge effect was examined using the simulation code SIMION for beams downstream of the bending magnet as shown in Fig. 5. Here, the beam radius without space charge (Fig. 5(a)) was larger than that with space charge (Fig. 5(b)), because the beam was focused with the double focusing bending magnet and entered the acceleration column with strong diverging optics downstream when the space charge was fully neutralized. On the other hand, it is focused effectively in the acceleration column when the effect of the space charge was considered, because the beam became almost parallel to the axis near the entrance of the acceleration column and the radius became small at the exit. These results are shown in Fig. 5(a) and Fig. 5(b). When the post-acceleration voltage was increased to above 100 kV, the simulation predicted that the diverging optics would be compensated and the beam size would be diminished to few mm in the case without the space charge. With the space charge, it was anticipated to be larger than the minimum beam radius. It would be important to study this effect experimentally at the beam energies in this range.

4. Summary

We studied the beam transport of a negative ion production system which consisting of a positive ion source, Einzel lens, charge exchange cell, charge separation magnet, and post-acceleration column, on ABS103. The experimental results indicated the focusing effect of the beam by the post-acceleration, while the beam axis inclined upward from the device axis. Comparison of the results of the experiment with those of simulation showed that the beam was focused when the acceleration voltage was increased.

Further studies are required to examine the effects of a set of deflectors to modify the beam axis, to raise the accelerating voltage further, and experiments will be performed to examine the effects on both positive and negative ion beams when the lithium vapor cell is activated. Furthermore, it will be necessary to examine the initial conditions of the simulation.

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