Proof of Principle Experiment of a Fast He^0 Beam Production for Alpha Particle Diagonostics

N. TANAKA, H. SUGAWARA, S. TAKEUCHI, S. ASAKAWA, A. OKAMOTO, K. SHINTO, S. KITAJIMA, M. SASAO and M. WADA[1)]

Tohoku University, Sendai, Miyagi 980-8579, Japan

[1)]*Doshisha University, Kyotanabe, Kyoto 610-0321, Japan*

(Received 4 December 2006 / Accepted 9 March 2007)

A test stand of a fast neutral helium beam device has been developed for proof of principle experiments to produce a candidate beam of alpha particle diagnostics method for ITER. A fast He^0 beam will be produced and its qualities will be diagnosed on the test stand. In addition, it is also important to produce an intense and stable He^- beam from a negative ion source in the test stand because a fast He^0 beam have to be produced from an accelerated He^- beam. In this article, the method of the fast He^0 beam production, and the experimental results on the einzel lens effect for He^+ beam transport in the negative ion source are shown. Several experiments on the test stand, which are necessary to clarify the availability of the alpha particle diagnostics method, are described.

Keywords: alpha particle diagnostics, fast neutral helium beam, negative ion beam, charge exchange, lithium, magnetic confined plasma diagnostics

DOI: 10.1585/pfr.2.S1105

1. Introduction

The alpha particles produced by DT reactions have an important role for sustaining burning plasmas and it is necessary to diagnose and study their behaviors such as velocity distributions and spatial distributions. As the one of candidates of alpha particle diagnostics method for International Thermonuclear Experimental Reactor (ITER), the following method is suggested to Ref. [1]. A fast neutral helium beam ($^3He^0$) is injected tangentially into confined plasmas to neutralize the alpha particles of MeV region by a double charge exchange.

$$^3He^0(1s^2)^1S_0 + {}^4He^{++} \rightarrow {}^3He^{++} + {}^4He^0 \tag{1}$$

Because the cross section of the charge exchange has sharp cutoff for relative velocities between a He^0 beam and an alpha particle greater than 200 keV [2], the energy of a $^3He^0$ beam is estimated to be 1-2 MeV.

The fast neutral helium beam should be produced from a fast negative helium ion beam (He^-) due to its high neutralize efficiency, and the beam producing process is as follows. (1) A He^+ beam is extracted and enters into a charge exchange cell in which alkali metal vapor is contained. He^- is produced by a two-step process in the cell [3].

$$He^+ + X \rightarrow He^0(1s2\,s)^3S_1 + X^+ \tag{2}$$

$$He^0(1s2\,s)^3S_1 + X \rightarrow He^-(1s2s2p)^4P_{1/2,3/2,5/2} + X^+ \tag{3}$$

X is an alkali metal, which lithium is used in this method. According to the experiments by D'yachkov *et al.*, the maximum charge exchange efficiency with lithium was about 0.5 % at the beam energy of 13 keV (Fig. 1) [4, 5]. The converted He^- particles have three electron states. The existence rates of J = 3/2 and 5/2 of He^- particles are 50 % for each state, and that of J = 1/2 is ignorable. (2) Not only He^- beam, but also He^+ and beams are extracted from the charge exchange cell. The beams should be separated by a bending magnet to each angle so that only He^- beam enters into accelerators. (3) A He^- beam is accelerated up to desired beam energy. The accelerated beam enters into a long tube and converted to a He^0 by auto detachment during its flight. The lifetime of J = 5/2 and J = 3/2 states of

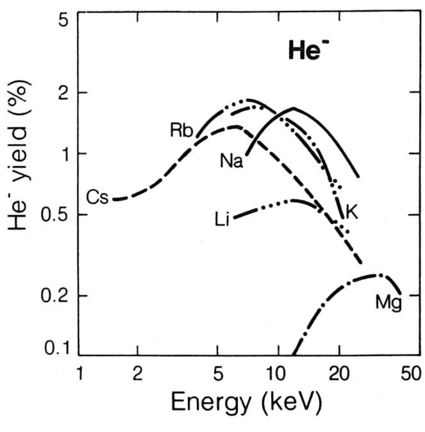

Fig. 1 Charge exchange efficiency of He^+ to He^- in several alkali metal vapors. The maximum efficiency of lithium is about 0.5 % at the 13 keV of injected He^+ beam [4].

author's e-mail: Nozomi.Tanaka@ppl2.qse.tohoku.ac.jp

Table 1 Desired beam parameters for both devices.

	The device for ITER	Test stand
He^+ beam current	~3 A	~10 mA
He^0 beam	$^3He^0$	$^4He^0$
He^0 beam energy	1.7 MeV	100-200 keV
He^- beam current	100 mA	10-100 μA
He^- beam diameter	~ ϕ 113 mm	~ ϕ 10 mm

Table 2 Past negative helium ion beam production with alkali metal vapors.

CX - vapor	He^- Currents	Key person
Li	4 μA	Philipp, 1974 [6]
Na	70 mA (10 msec pulse)	Hooper, 1980 [7]
Rb	0.07 mA	Sasao, 1998 [1]

He^- particles is 300 μs and 10 μs respectively [6]. An He^0 beam has two atomic states, the one is a ground state He^0 $(1s^2)^1S_0$ which is desired for the alpha particle diagnostics and the other is a metastable state $He^*(1s2s)\ ^3S_1$ which is undesired because of its strong attenuation in ITER plasmas.

$$He^-(1s2s2p)^4P_{3/2,5/2} \rightarrow He^0(1s^2)^1S_0, He^*(1s2s)^3S_1 \tag{4}$$

Sufficient studies for proof of this He^0 beam production method are necessary before the construction of the diagnostic beam for next generation magnetically confined fusion experiment reactors such as ITER. This is the reason why a small sized beam device test stand for proof of principle has been developed. Typical He^- beam parameters for both devices are estimated in Table 1 [7]. Due to the low conversion fraction, negative helium ion beam production is known as difficult operation. Some different experiments of negative helium ion beam production are summarized in Table 2 [1, 8, 9]. The He^- beam currents required at the test stand are 2.5-25 times higher than that of Philipp's to measure the metastable state decaying fraction.

2. Apparatus

A schematic diagram of the small sized test stand is shown in Fig. 2. A He^+ beam of the beam energy up to 30 keV is extracted from an 8 cm-diameter and 9 cm-long compact 12 poles multicusp ion source. A He^+ beam of the current up to 10 mA can be extracted from this ion source [7]. An einzel lens is located to focus the He^+ beam at the center of the charge exchange cell. In the charge exchange cell, lithium vapor from a heated pot is water-cooled at the upper of the melting pot, and the condensed lithium drops down to the melting pot, becoming vapor again by heating. The optimum temperature of the melting pot is 580 °C [10]. The bending magnet is designed to bend the converted He^+, He^0, and He^- beams to 30, 0, and -90 degrees respectively. It is also designed to have two focus points at the center of the charge exchange cell and also at the entrance of the accelerator. The He^+ beam is detected by a calorimeter at 30 degrees. The He^0 beam is detected by a pyro-electric detector or a calorimeter at 0 degree. The He^- beam is detected by a faraday cup, which is vertically movable, or enters into the electrostatic accelerator and it is accelerated up to 180 keV. The length of the tube for free flight is estimated 10 m.

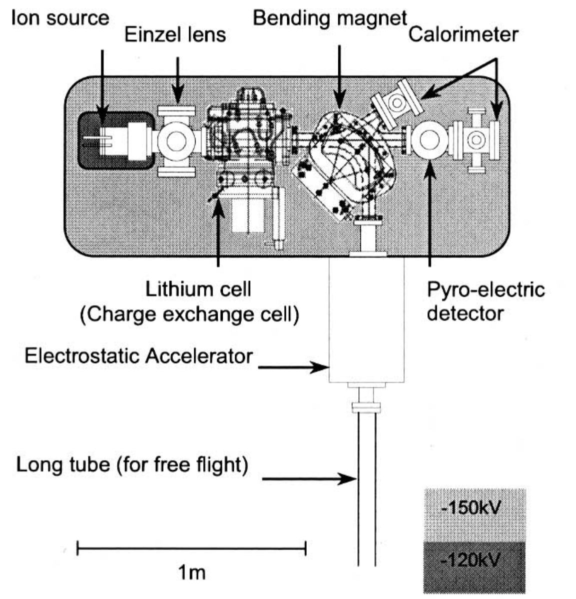

Fig. 2 Upper schematic diagram of the small sized test stand. The high voltage is applied in two stages. The one is applied a –150 kV to extract He^- beam by the electrostatic accelerator, the other is applied a –120 kV to extract He^+ beam from the ion source.

The whole of the negative ion source is in a high voltage station that is on six insulators and covered by a rotundate cover, because a high voltage of -150 keV is applied. All of the vacuum systems, chambers, power supplies, and measurement equipments are contained in the station and they are remote controlled.

The pyro-electric detector has two modes, pyro mode and faraday cup mode. The signals from them can be measured independently and at the same time. The pyro-electric device is made from $BaTiO_3$ and the powers of the beam particles are converted to polar charges when the particle beam collides to the device. Neutral particles can be detected as currents by this pyro effects.

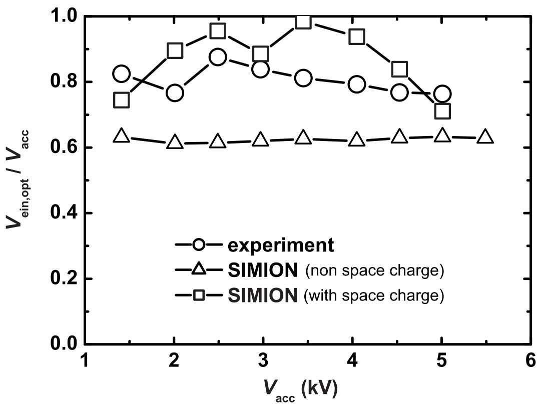

Fig. 3 Einzel lens effect. Ion source gas pressure of 2-3 $\times10^{-5}$ torr. The optimum einzel lens voltage was 75-87 % of the beam energy at an optimum lens voltage. According to the simulation on SIMION [11], the fraction was about 60 % of the beam energy when the space charge is not considered. The fraction when the space charge is considered shows higher value.

3. Experiments

3.1 Einzel lens effects

The optimum einzel lens voltage at each acceleration voltage and optimum lens electrode voltage was studied by detecting an extracted He^+ beam directly using the faraday cup mode of the pyro electric detector at 0 degree and 1.5 m downstream of the ion source. The optimum einzel lens voltages are 75-87 % of the acceleration voltages respectively. The result of the simulations on SIMION [11] with no space charge effect consideration shows that they are about 60 % (Fig. 3). On the other hand, the simulation that is including space charge effect shows better agreement with the experimental value. To focus the He^+ beam at the center of the charge exchange cell, the beam will be detected at the entrance of the accelerator, –90 degrees, because when the beam is focused at the entrance of the accelerator, it is also focused at the center of the charge exchange cell due to the bending magnet.

3.2 Pyro-electric detector calibration

The signal from the pyro mode of the pyro-electric detector was calibrated by detecting positive ion beams by the pyro-electric mode and faraday cup mode independently at the same time. The experimental results of the calibration for H^+, H_3^+, and He^+ of 5 keV, and O^+ and He^+ of 2 keV show clear linearity and they depend on the beam energy, not the masses or beam sorts.

The minimum detected current was less than 0.2 μA. Because the currents of the neutral beam that is charge exchanged in the charge exchange cell is considered as mA region (about 90 % of the He^+ beam [10]), this detector has enough neutral beam detecting capability for the test stand. Details of the calibration experiments and the results will be reported in near future.

3.3 He^-beam production

The charge exchange efficiency of He^+ to He^- is measured as 0.5-0.6 % in the past experiments. The efficiency of this apparatus also has to be measured to maximize it and the desired efficiency is 0.5-0.6 %. Besides, particle losses due to beam emittance growth by scatterings between He^+ and He^0 beams and lithium atoms in the charge exchange cell will be measured. The charge exchange efficiency and particle losses will be investigated detecting every He^+, He^0, and He^- beam currents downstream of the charge exchange cell and comparing with extracted He^+ beam current at each beam energy and target thickness. In the experiments operated by D'yachkov *et al.*, the maximum of charge exchange efficiency between He^+ beam and lithium vapor was 0.6 % at 13 keV of the He^+ beam energy and the optimum target thickness is found to be 5 to 7 $\times10^{14}$ atoms/cm^2 for all the alkali metals of lithium, sodium, and potassium [5]. Due to collisions in the charge exchange cell, the He^- beam gains energy distributions and it causes beam particle losses at the bending magnet. Therefore it should be investigated to find optimum parameters of alkali gas density and lens voltages that give minimum energy spread.

3.4 He^0 beam production

A couple of pyro electric detectors will be set at several points on the tube and the neutralize efficiency at each distances of the free flight will be measured. According to the calculation using the attenuation equation, the neutralize efficiency at the end of the tube is expected 40 %. The number of neutral particles produced from He^- (1s2s2p) $^4P_{3/2}$ state is domestic and that of He^- (1s2s2p) $^4P_{5/2}$ state is enough small to ignore. The neutral helium particle of metastable state He* (1s2 s) $^3S_1$ has strong attenuation in ITER plasmas. The 2s state electron is detached and the particle becomes ion before it reaches the center of the magnetic confined plasmas. It means the metastable neutral helium particles are useless for the alpha particle diagnostics. This unstable electron state is produced by collisional detachment with residual gas during the free flight. To reduce generation of these particles, the inner of the tube have to be kept high vacuum. To produce stable diagnostics beam, it is necessary to diagnose the neutral helium beam such as measuring of the He^*/He^0 ratio. He^*/He^0 ratio will be studied in the ways of plasma attenuation, laser induced fluorescence, and laser absorption spectroscopy (attaching a diagnostic tool assisted by linear at the end of the tube).

4. Summary

A test stand of a fast He^0 beam source has been developed and several experiments are operated to study the qualities of each He^+, He^-, and He^0 beams and optimize the system to produce an intense and stable He^0 beam. The optimum einzel lens voltage was 75-87 % of the acceleration voltage by detecting the He^+ beam at 1.5 m downstream of the ion source. The calibration equation of the pyro-electric detector depends on the beam energy, not beam sort or mass, and the detection limit was enough small for the test stand. In the next step, it is important to optimize a He^+ beam to be focused at the center of the charge exchange cell. A He^- beam will be produced and its energy distributions and charge exchange efficiency have to be measured. Then, a fast He^0 beam will be produced from an accelerated He^- beam, and its neutralize efficiency and He^*/He^0 ratio will be studied.

The results obtained from this test stand will clarify the availability of the actual fast He^0 beam device for alpha particle diagnostics.

[1] M. Sasao *et al*., Rev. Sci. Instrum. **69**, 1063 (1998).
[2] D.E. Post *et al*., J. Fusion Energy **1**, 129 (1981).
[3] B.L. Donnally and G. Thoeming, Phys. Rev **159**, (1967).
[4] A.S. Schlachter, AIP conf. Proc. **111**, 300 (1984).
[5] B.A. D'yachkov and V.I. Zinenko, Sov. Phys. tech. Phys. **16**, 305 (1971).
[6] U.V. Pedersen *et al*., Phys. Rev. A **64**, 012503 (2001).
[7] K. Shinto *et al*., Rev. Sci. Instrum. **77**, 03B512-2 (2006).
[8] G. Philipp *et al*., Nucl. Instrum. Methods **114**, 507 (1974).
[9] E.B. Hooper, Jr *et al*., Rev. Sci. Instrum. **51**, 1066 (1980).
[10] A.S. Schlachter, *et al.*, Phys. Rev. **174**, 201 (1968).
[11] http://www.simion.com.
[12] A Okamoto *et al*., submitted to Plasma Fision Res.