DESIGN OF A FAST NEUTRAL HE BEAM SYSTEM FOR FEASIBILITY STUDY OF CHARGE-EXCHANGE ALPHA-PARTICLE DIAGNOSTICS IN A THERMONUCLEAR FUSION REACTOR

K. Shinto*, H. Sugawara, S. Takeuchi, S. Kitajima, M. Takenaga, M. Sasao, Tohoku University, Sendai 980-8579, Japan
M. Nishiura, O. Kaneko, NIFS, Toki, Gifu 509-5292, Japan
S. Kiyama, AIST, Umezono, Tsukuba, 305-8568, Japan
M. Wada, Doshisha University, Kyotanabe, Kyoto 610-0321 Japan

Abstract

Measurement of velocity distributions of fusion produced alphas in a next stage magnetic plasma confinement device is a challenging topic in thermonuclear fusion research. Active beam probe diagnostic method based on high energy neutral beam of ^{3}He is considered promising. The beam can be produced by auto electron detachment from an energetic negative helium ion (He^-) during the transport in field free space. To find critical issues in forming a diagnostic beam, a double-charge-exchange He^- source coupled to a simple beam transport systems is currently being constructed at Tohoku University. A He^+ beam of about 10 mA is extracted from the ion source and accelerated up to 10~25 keV for efficient charge exchange. The beam qualities of both double-charge-exchanged He^- and auto detached neutral He (He^0) will be investigated by emittance meters, beam profile monitors, and a calorimeter.

INTRODUCTION

A plasma in the next generation magnetically confined fusion experimental device will be self-heated by high energy alpha particles produced from d-t nuclear reaction. Velocity distributions of alpha particles in the core plasma give information of how efficiently alpha particles heat up the plasma while they slow down. In order to be measured, alpha particles in the plasma should be neutralized by picking up two electrons so that they escape from the plasma to reach an energy analyzer outside of the confinement device traversing the confinement magnetic field. An active beam diagnostic method to neutralize alpha particles in the plasma by injecting energetic beam of neutral He (He^0) has been proposed by Post *et al.* [1], which requires production of intense beam of negative He ions (He^-) to realize high neutralization efficiency at high energies. Neutralization of He^- ions by auto detachment is proposed as a promising method to obtain a fast neutral He beam with minimizing a fraction of metastable He atoms in the beam [2]. However, this scheme requires a very small divergence of the probe beam.

Production of intense He^- beam has been investigated for a long time. A He^- beam of 70 mA at 10.5 keV in 10 ms pulsed duration was achieved by double charge exchange with a sodium vapour cell [3], and that of 70 μA at 11 keV in dc mode operation was realized with a rubidium vapour cell [4]. The former was a broad beam produced from an ion source developed for negative hydrogen ion extraction, while the latter was a pencil beam to study extraction at low energies. Quality of the extracted He^- beam has not been investigated for neither of these experiments, but the question, whether a neutral He^0 beam with the intensity high enough to accomplish alpha particle diagnosis from the auto detachment from He^- can be achieved or not, is to be verified.

Diagnostics systems for the International Thermonuclear Experimental Reactor (ITER) are discussed with more realistic view as the plan for the experimental reactor becomes more concrete. Recently an alpha particle diagnostic system based on a neutral beam probe using a fast He^0 produced from the auto electron detachment from He^- ions was proposed by Sasao [5]. In the proposed diagnostic system, He^- beam current of 10-100 mA and the beam energy of 1.7 MeV are reported adequate to fulfil requirements for signal detection with enough S/N ratio. Two programs are being propelled to study the feasibility of realizing a diagnostic system based on a high energy neutral He probe beam of the above performance. One is the test of He^- production through injecting a high-intensity, strongly- converging beam of He^+ into a narrow aperture alkali metal vapour cell. The other is the test of beam quality degradation due to beam transport of the entire probe beam forming system using a pencil beam. In this article, activities to meet design goals of high energy He^0 beam for fusion produced alpha diagnostics are presented.

HE$^+$ BEAM SOURCE

An intense beam of He^- is indispensable to form a He^0 beam of very low divergence. Namely, He^- should be produced in a point-like-region inside of the alkali metal vapour cell. A high-brightness He^+ ion source is required to deliver enough beam current into the small volume of alkali metal vapour cell for this purpose. A scheme to enlarge the beam acceptance of an alkali-metal vapour cell with an electrostatic quadrupole lens system [6] was introduced in the previous meeting [7]. Injection of a high brightness beam into the cell can be also achieved by injecting multiple beamlets into the cell through a small entrance hole. At National Institute of Advanced Industrial Science and Technology, an ion source with

*katsuhiro.shinto@qse.tohoku.ac.jp

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three concave multiaperture extraction electrodes to constrict the formed beam into a narrow spot has been developed [8]. Application of this type of ion source for the He^+ beam injection into the alkali metal vapour cell will form a bright source of He^-. A He^- beam production system based on this converging ion extraction is schematically illustrated in Fig. 1. The beamlets extracted from the source are merged and focused at the center of the alkali metal vapour cell to form a diverging beam of He^- emitted from a narrow region in the cell.

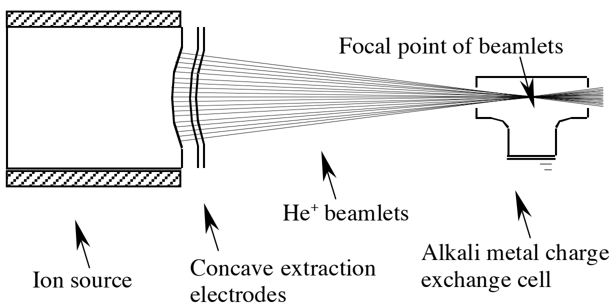

Fig. 1. Concept of converging He^+ beam injection into a double charge exchange cell.

The ion source is designed to produce a plasma with 40 kW arc power in a 26 cm diameter 30 cm long magnetic multicusp ion source. The He^+ beam is extracted through 500 extraction holes of 3 mm diameter with the current density of 85 mA/cm^2. With the extraction area of 10 cm diameter the source should produce total He^+ beam current reaching 3 A. Large power loadings of the high current beam source system require a large capacity beam dump system. The experimental setup will be assembled at National Institute of Fusion Science, where the technology of a beam dump system for neutral beam heating has been developed and reached to a high standard. Meanwhile, the transport of He^- produced from an alkali metal vapour cell will be studied with a He^- beam transport system which is now under construction at Tohoku University. This set up utilizes a pencil beam of He^- to investigate factors influential on the emittance growth of the final He^0 beam, as described in the next section.

FAST NEUTRAL HELIUM BEAM SYSTEM

A schematic drawing of a prototype fast He^0 beam system is shown in Fig. 2. The system consists of a compact multicusp He^+ ion source, an alkali metal vapour cell, a magnetic deflection type ion separator, accelerator column, 10 meter free flight tube for auto-detachment of He^-, and a diagnostic section for measuring the beam quality and the fraction of metastable atoms in the produced beam.

Compact multi-cusp He^+ ion source

An 8 cm diameter 10 cm long compact magnetic multicusp ion source operated with hot tungsten filament cathodes forms a He^+ beam with a 3 electrode extractor. It has been tested the performance to produce a pencil beam of He^+, and its detail is described in Ref. [9]. This source produces a 17 mA He^+ beam at the beam energy of 15 keV where a high efficiency of He^+ to He^- is realized for a Na vapour cell. It can also produce a low energy He^+ beam with a reasonable quality. The normalized beam emittance of 90% beam current fraction is 0.61 mm mrad with the He^+ beam current of 7 mA even at beam extraction voltage as low as 8.5 keV. This makes it possible to do experiments of He^- production with Rb, K, Na, and Li with the beam voltage giving the maximum efficiency from He^+ to He^-. The conversion efficiencies from He^+ to He^- for different alkali metal target are summarized in table 1 from the data compiled in Ref. [10].

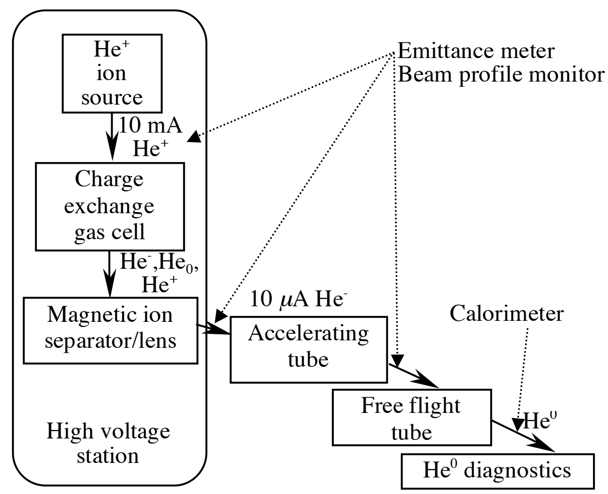

Fig. 2. Schematic diagram of the fast neutral He beam system under construction.

In the ion beam extraction part, beam extraction from a single aperture of the large size ion source will be simulated. The extraction aperture of the existing ion source is 6 mm, corresponding to 25 mA total beam current. Growth of beam divergence due to a space-charge effect is investigated with an emittance meter. Influence of He pressure in the source upon the beam quality will be also studied with a separate setup equipped with a high resolution ion beam energy analyzer, emittance monitor, and a neutral particle energy analyzer.

Table 1. Double charge exchange efficiencies for He

Alkali metal	Li	Na	K	Rb
Maximum conversion efficiency (%)	0.6	1.7	1.8	2
Beam energy at maximum conversion efficiency (keV)	12	11	8.5	6

Alkali metal vapour cell

An alkali metal vapour double charge exchange converts incident He^+ beam to He^- beam. The cell has a heating structure to realize proper temperature

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distribution for recirculation of alkali metal vapour inside. The temperature of the cell can be raised up to 600 centigrade for the operation with Li metal, while the cell can be operated at lower temperature for other alkali metals.

The cell is designed to build a short distance, high alkali atom density region right at the focal point of the converging beam. The entrance part of the cell is heated by the incident beam, giving rise to an inhomogeneous temperature distribution of the cell. The low temperature of the cell at the parts of entrance and exit of the ion beam is indispensable for the minimization of alkali metal vapour draining out of the cell to protect insulators from alkali metal contamination. For this reason, temperature distribution of the charge exchange cell will be actively controlled with distributed heaters and temperature sensors attached to the cell.

Magnetic ion separator with double focussing

The formed He^- beam will be mass-separated and focused in the two transverse directions by a stigmatic 90 degree bending magnet invented by Camac and Cross [11,12]. The prototype system has been designed and being assembled to prove this principle of operation for the fast He^0 beam production.

The entrance angle α and exit angle β are chosen to satisfy the following condition.

$$\tan\alpha = \tan\beta = \frac{1}{2}(\alpha = \beta = 26.5\,\text{deg.})$$

For a symmetric object-image arrangement with separations from the entrance and exit of the magnet to the object and image equal to the radius of curvature of the beam, the total transfer matrices are written as,

$$H = \begin{bmatrix} -1 & 0 & 4 \\ -3/4 & -1 & 3/2 \\ 0 & 0 & 1 \end{bmatrix}, \text{ and } V = \begin{bmatrix} -1 & 0 \\ -1+\pi/8 & -1 \end{bmatrix}.$$

In this case, the energy dispersion is twice as large as that for the focussing by sector magnet only in horizontal direction. From these matrices, the energy width of the beam energy must be kept as small as possible. The tolerance of the assembled system against the energy dispersion, arising from double charge exchange reaction and the energy spread of incident He^+, will be investigated.

Acceleration column and free flight tube

The beam acceptance from the He^- source part to the accelerator column is about 40π mm mrad (unnormalized). After being mass-separated by a sector magnetic field, the He^- beam is accelerated up to 150 keV electrostatically. The accelerated He^- beam flies in a drift tube about 10 m long. There are two components of liftime in auto detached He^- beam. One is several 10s of μs and the other is about 300 μs for 50 % decay [13]. During the 10 m free flight, about 15% of the He^- beam will be neutralized. The rest of the He^- beam will be bent and dumped for the further investigation of the produced neutral He beam.

Diagnostic section for produced beam

The final intensity and beam spread of the produced beam is measured in the diagnostic section. The fraction of metastable atoms contained in the produced beam is an important factor, and the fraction is measured in the final section of the system. Separation of metastable component from ground state by a simple gas cell is inefficient due to the energy of the beam. The fraction can be analyzed by reionizing the beam through merging it with an energy collimated electron beam.

SUMMARY

A fast He^0 beam production system is being assembled at Tohoku university to test if high energy He^0 formation by auto detachment of electron from He^- ions is possible with reasonable efficiency. The system is made versatile for selection of alkali metal for double charge exchange cell. It will be operated with a mass-separating magnetic lens to match the beam optics of the He^- beam originating from the charge exchange cell.

Using this prototype apparatus, not only the beam qualities of the produced He^- beam and that of the auto neutralized He^0 beam will be measured, but also the trade-off among alkali metals for maximizing the system efficiency to obtain He^0 beam will be studied. Through the investigation of the prototype system, design criteria of the actual fast He^0 beam system for the alpha particle diagnostics in the thermonuclear fusion devices will be clarified.

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