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A compact electron beam ion source equipped with a bulk high-T_c superconductor solenoid

Atsumi Endo [a,b], Nobuyuki Nakamura [a,*], Yasuyuki Kanai [a], Yoichi Nakai [a], Ken-ichiro Komaki [b], Yasunori Yamazaki [a,b]

[a] *Atomic Physics Laboratory, RIKEN, Wako, Saitama 351-0198, Japan*
[b] *Institute of Physics, Graduate School of Arts and Sciences, University of Tokyo, Tokyo 153-8902, Japan*

Abstract

We have been developing an electron beam ion source equipped with an assembly of bulk high-T_c superconductors (YBCO) as a solenoid, which fulfil the following practical requirements: high magnetic field, compact, operation at liquid nitrogen temperature. The energy and current of the electron beam are designed to be 30 keV and 100 mA at the maximum, which are sufficient to produce highly charged ions such as Ne-like U^{82+}. Recently, we have succeeded in producing a stable solenoidal field of 0.8 T, and in injecting an electron beam of 10 keV – 40 mA keeping beam collection efficiency of ~99% at the electron collector. The details of the design and the results of extraction tests are presented.

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Keywords: Electron beam ion source; High T_c superconductor

1. Introduction

An electron beam ion source (EBIS) [1] and an electron cyclotron resonance ion source (ECRIS) [2] are widely used as effective sources of highly charged ions. These two types of ion sources are properly used according to the purpose. To study the interaction with surfaces, it is essential to use highly charged ions with higher charge state and lower velocity for clear observation of the influence of huge potential energy. In such a case, an EBIS is preferred although the number of extracted ions is generally not larger than that from an ECRIS.

In an EBIS, ions are trapped in a magnetically confined electron beam and are successively ionized by electron impact. The current density of the electron beam is one of the most important parameters which determine the maximum charge of produced ions. In order to realize a high-density beam, magnetic compression with a superconducting magnet is commonly used. However, the magnet usually brings high liquid helium consumption, and greatly increases the size and the running costs of the apparatus. Alternatively, a few EBISes and EBITs (electron beam ion traps) without a superconducting magnet [3–6] have been

* Corresponding author. Fax: +81-48-462-4644.
E-mail address: nobuyuki@postman.riken.go.jp (N. Nakamura).

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developed. The intention of the designers is to downsize the apparatus and to cut down the running costs at the cost of losing a strong magnetic field. Such a compact and economical EBIS is in strong demand to perform systematic studies in a small laboratory. The motivation for developing the present EBIS is to have a stronger magnetic field without losing the advantages of the downsized EBISes which do not use liquid helium. For this purpose, we adopted high-T_c superconducting material to produce a strong magnet. It decreases the size of the EBIS and enables us to operate the EBIS at the liquid N_2 temperature with a sufficiently strong magnetic field.

2. The device

A schematic drawing of the EBIS is shown in Fig. 1. The electron beam emitted from a Pierce-type electron gun with a 3-mm-diam spherical cathode is accelerated by the potential difference (30 kV at the maximum) between the gun and the cryostat region, and injected into the drift tube. The electron beam is compressed by the strong magnetic field produced by the high-T_c superconducting magnets. After passing through the drift tube, the electron beam is decelerated to $\sim$1 keV and collected by the water-cooled electron collector. Ions are confined within the center of the drift tube axially by an axial electrostatic well prepared by three successive electrodes and radially by the space charge potential of the compressed electron beam. Highly charged ions are thus produced by successive electron impact ionization of the trapped ions. There are two modes for ion extraction. One is the DC mode, where ions which go over the well potential are accelerated. The other is the pulsed mode, where the trapped ions are forcibly extracted by instantaneously shallowing the well potential. The extracted ions pass through the electron collector and are led to the experimental chamber after focusing with electrostatic lenses and charge separation with a bending magnet. Electron trajectories under various magnetic and electric fields were simulated taking into account the space charge effect, which predicts that an electron beam can be compressed to a diameter of 100 μm, corresponding to a current density of 1000 A/cm^2 at the center of the drift tube.

The high-T_c superconducting material used is YBa_2CuO_{7-x}, which has a high critical current density (J_c) [7]. It is noted that high-T_c superconductor is a kind of ceramic, and the wire is not flexible to make a solenoid with a small diameter. As an alternative method to prepare a supercon-

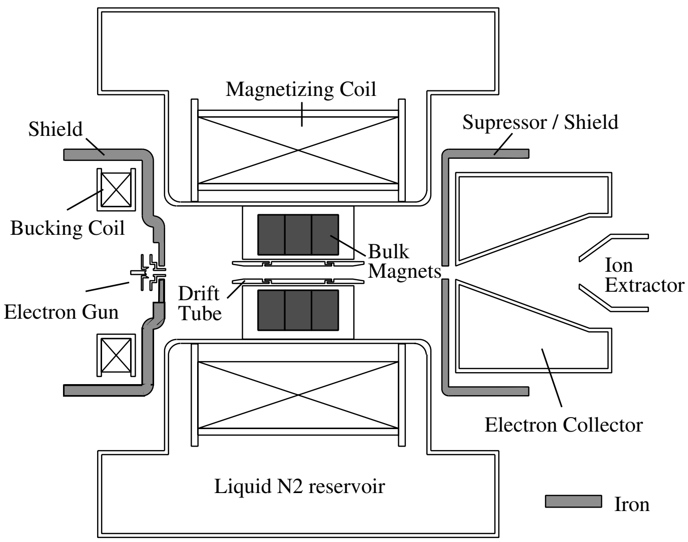

Fig. 1. Schematic view of the present EBIS.

ducting solenoid, a high-T_c bulk material is machined as a ring shape with an outer diameter of 51 mm, an inner diameter of 15 mm, and a thickness of 12 mm. Three ring-shaped magnets are put in series and sealed in a stainless steel container which is in contact with the liquid N_2 reservoir wall. There are several methods to magnetize bulk magnets. Field cooling (FC) using a static magnetic field is an effective method that is commonly used. However, it requires an additional strong magnet, which increases the size of the apparatus. We adopted so-called pulsed field magnetization (PFM) technique [8,9] for the present EBIS, where the magnetizing coil (182 turns of a copper wire with a cross section of 1.4×3.0 mm^2) is installed in the liquid N_2 reservoir. Fig. 2 shows the field distribution along the solenoid axis. By repeatedly applying pulsed magnetic field with a width of 11 ms and peak strength of several Tesla, we succeeded in magnetizing the bulk magnets up to 0.8 T at the liquid N_2 temperature. The current feedthroughs for the coil (copper wire with a diameter of 6 mm) can be removed after the magnetization by linear motion feedthroughs to avoid heat loss.

The liquid N_2 reservoir is supported by eight bars connected to linear motion feedthroughs. The supporting unit was so designed as to make the thermal conduction between the bar and the reservoir as small as possible. The linear motion feedthroughs are also used for alignment of the drift tube with respect to the electron gun and the collector. The liquid N_2 reservoir also works as a cryogenic pump, which realize the desired vacuum condition (5×10^{-9} Pa inside the trap). The capacity of the reservoir is about 6 l; it is possible to operate the EBIS continuously for 12 h without refilling the reservoir.

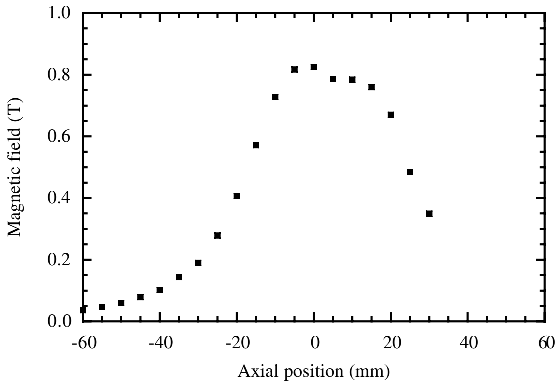

Fig. 2. Distribution of trapped magnetic field at 77 K.

3. The present status

In the first stage of test operation, the EBIS has been operated with electron energies below 10 keV. The maximum current achieved so far is 50 mA. Within these parameters, ~99% collection of the electron beam at the electron collector has been achieved. Preliminary ion extraction test has been performed recently. Fig. 3 shows a typical charge spectrum of extracted ions. In this operation, ions were produced with a 7.5 keV – 30 mA electron beam and extracted with extraction voltage of 2 kV. Argon gas was injected through a small hole prepared in the middle electrode of the drift tube. Under these parameters, argon is expected to be fully ionized. However, in the present operation, the maximum charge state of the extracted ions was 15+ as shown in the figure. This is probably

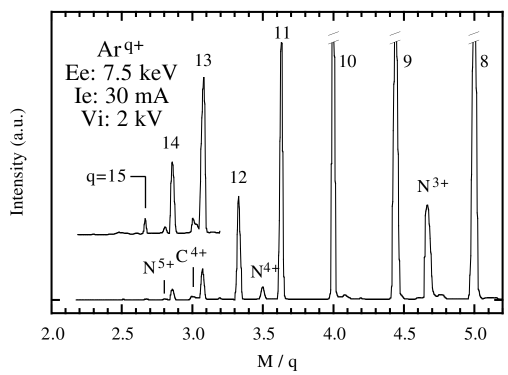

Fig. 3. Typical charge spectrum of argon ions extracted from the present EBIS. The electron beam energy (E_e) and the current (I_e) were 7.5 keV and 30 mA, respectively. The extraction voltage (V_i) was 2 kV. The ions were extracted in the DC mode. Contribution from residual gases (nitrogen and carbon) is found as small peaks. Although the mass to charge ratio (M/q) is the same (2.67) between Ar^{15+} and O^{6+}, the peak at $M/q = 2.67$ is considered to be Ar^{15+} because contribution from O^{5+} ($M/q = 3.2$) is not seen in the spectrum.

due to the present vacuum condition. The base pressure in the test operation was $\sim 1 \times 10^{-7}$ Pa without an electron beam. However, the pressure increased as the electron beam current increased; finally it reached 1×10^{-6} Pa with a 30 mA electron beam. We consider that higher charge states can be extracted after the vacuum condition is improved. In addition, it is noted that the present operation have been performed only in the DC mode. Since ions with higher charge states are trapped deeply in the bottom of the trap potential, the charge state distribution in the DC mode tends to be dominated by ions with lower charge.

We are planning to use the present EBIS for the study of collision processes of highly charged ions with surfaces. For that purpose, the EBIS is planned to be connected to a scanning probe microscope (SPM). The SPM which we are preparing can be operated in both the scanning tunneling microscope (STM) mode and the atomic force microscope (AFM) mode. In both modes, it has atomic resolution without changing the probe. Thus it is useful to investigate both electronic and atomic structure at the same point of a surface.

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