Compact electron beam ion source with high-T_C bulk superconductors

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We have developed an electron beam ion source (EBIS) assembling three rings made of high-T_C superconductor as a solenoid coil, which enables us to construct a "table-top" EBIS operated at the liquid N_2 temperature with a strong magnetic field. Optimizing a pulse field magnetization procedure, the assembly yielded a magnetic field as high as 0.8 T under a persistent mode, which stably lasted more than two days. An electron beam of 12 keV-50 mA was compressed to a current density of about 300 A/cm^2 and guided by the magnetic field along the axis of the drift tube. After exiting the drift tube, the electron beam was decelerated to 2 keV and collected with an electron collector with an efficiency of more than 99%. We have succeeded in extracting highly charged ions such as Ar^{17+} and Xe^{42+}. [DOI: 10.1063/1.1786336]

I. INTRODUCTION

An electron beam ion source (EBIS)[1] is widely used as a unique source of highly charged ions (HCIs). Once ions are produced in an EBIS, they are radially trapped by the electric field of the electron beam, which is compressed by a strong magnetic field, and are successively ionized by the electron beam. The charge state evolution in an EBIS is characterized by the so-called ionization factor $j\tau$ which is the product of the electron current density j and the trapping time τ. Thus, the current density of the electron beam is one of the most crucial parameters to produce objective ions in a reasonable time period. Because the current density increases approximately in proportion to the magnetic field, a superconducting coil has been commonly used to produce a strong magnetic field. However, such a coil greatly increases the size of the apparatus requiring liquid helium, often a high consumption rate, and high running costs of the apparatus.[3–6]

Alternatively, a few EBISes and electron beam ion traps (EBITs) with a normal conducting magnet or a permanent magnet[2–7] have been developed aiming at downsizing the apparatus and at cutting down the running costs at the cost of losing a strong magnetic field. Such a compact and economical table-top EBIS is in strong demand for small laboratories to perform systematic studies with highly charged ions. For example, Okuno[2] developed the mini-EBIS with a normal conducting solenoid soaked in liquid nitrogen. The maximum magnetic field of the mini-EBIS is about 0.1 T, which corresponds to a current density of about 10 A/cm^2 with the beam parameters of 2 keV and 10 mA. The mini EBIS has been successfully used to perform collision experiments with highly charged ions such as I^{30+}.[8]

The motivation for developing the present EBIS is to have a stronger magnetic field keeping the advantages of table-top EBISes which do not use liquid helium. For this purpose, we adopted a high-T_C bulk superconductor which yields a magnetic field as strong as 1 T. The current density is thus expected to be much improved compared to other table-top EBISes. An assembly of three superconductor rings is used as a substitute for a solenoid coil. 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. Although some high-T_C superconducting wires have already been available, their bending tolerance is quite limited, which makes the coil size relatively large and accordingly causes weaker field gradients. These features do not fit with the present purpose. Furthermore, they are still very expensive for practical purposes. Thus we have decided to use the bulk high-T_C superconductor, which can fortunately be machined to a ring. Such a ring-shaped bulk superconductor acts just like a solenoid coil having a uniform magnetic field in the bore and at the same time like a permanent magnet as long as it is kept cold at the liquid nitrogen temperature. It is noted that a ring-shaped permanent magnet does not give a uniform magnetic field and that the field strength along the ring axis is quite weak, because the magnetic flux tends to pass regions with high permeability.

II. DESIGN

Figure 1 shows the cross sectional view of the High-T_C EBIS. The EBIS mainly consists of five parts, an electron gun, an assembly of superconductor rings, a magnetization

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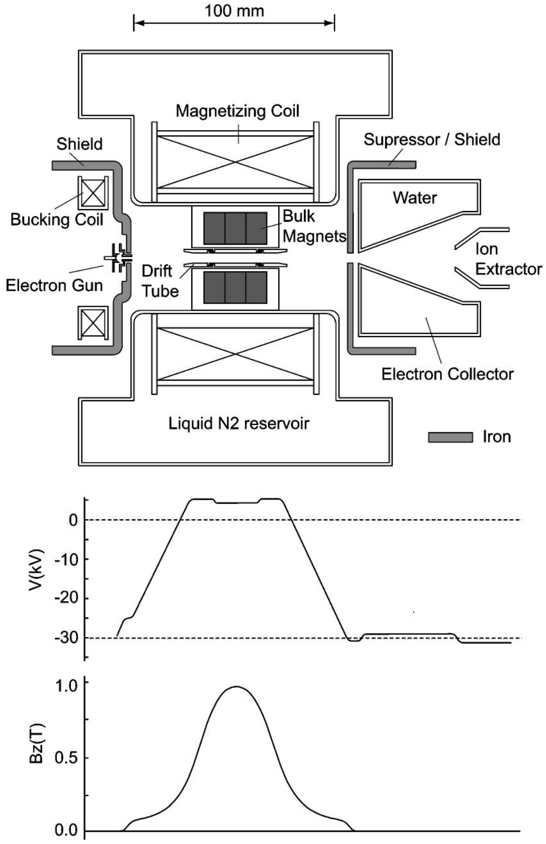

FIG. 1. Top: The cross section of the High-T_C EBIS drawn to scale. Middle: Potential distribution along the electron beam axis. Bottom: Magnetic field distribution along the electron beam axis.

coil, a drift tube, and a water-cooled electron collector. The electron beam emitted from the electron gun is accelerated toward the drift tube, compressed by the magnetic field ($\sim$0.8 T at the present maximum) produced by the high-T_C bulk superconductor, passes through the drift tube, decelerated to $\sim$2 keV, and finally accumulated on the electron collector. The drift tube consists of three successive electrodes and forms an electrostatic well, which axially confines ions in the center of the drift tube. On the other hand, the space charge potential formed by the electron beam and the axial magnetic field confine the ions radially in the area with a high density electron flow, where ions are successively ionized to form highly charged ions. The electron beam not only ionizes and confines ions but also heats up the ions, resulting in some ions leaking out from the potential well. Such "overflowed" ions are accelerated by the potential difference between the drift tube and the electron collector, and extracted through the center hole of the collector, which is called a leaky mode.[9] The trapped ions can also be extracted actively by dumping the potential well periodically, which is called a pulse mode.[9]

The main parameters of the High-T_C EBIS are listed in the Table I. These parameters were determined to produce highly charged ions such as helium-like xenon and neon-like uranium. For example, according to the estimation without charge exchange, an ionization factor of about 3000 A/cm^2 s is needed to produce neon-like uranium for an electron beam energy of 30 keV. The designed current density of the present EBIS is 700 A/cm^2, so that neon-like uranium can be produced in a reasonable time period, such as 5 s or so, which used to be impractically long for a smaller magnetic field with a normal conducting coil.

TABLE I. Designed parameters of the high-T_C EBIS.

Maximum electron beam energy	30 keV
Maximum electron beam current	100 mA
Maximum electron current density	700 A/cm^2
Maximum magnetic field	1 T
Trap length	40 mm
Ion extraction voltage	0–5 kV

In general, the ionization cross section reaches its maximum when the electron energy is several times larger than the ionization energy of the objective ion. Thus, the maximum electron energy was designed to be 30 keV, which is about three times as large as the ionization energy of sodium-like uranium. The electron beam energy at the drift tube is determined by the potential difference between the electron gun and the drift tube. Since the present EBIS has been developed as a low energy HCI source, the voltage at the drift tube should be lower than a few kV, and the electron gun was designed to be raised to −30 kV at the maximum. The electron collector was designed to be raised to the same potential as the electron gun, which is essential to decelerate the beam to 1–2 keV at the collector, which reduces the heat load to the collector suppressing the amount of outgas and also helps to use a compact high voltage power supply for the electron gun.

The electron gun assembly is another critical component which determines the performance of the EBIS. In the present EBIS, the electron gun developed for the Tokyo EBIT[10] was used because the performance of the gun has been proved to be quite satisfactory through the many years of operation of the Tokyo EBIT. Electrons are emitted thermionically from a spherically shaped barium oxide cathode of 3 mm diameter. The perveance of the gun is about 4.4×10^{-7} A/V$^{3/2}$, which provides 100 mA when the anode voltage is about 3.8 kV. Electron trajectories were simulated taking into account the space charge effect[11] for various electric and magnetic field distributions around the gun. Figure 2

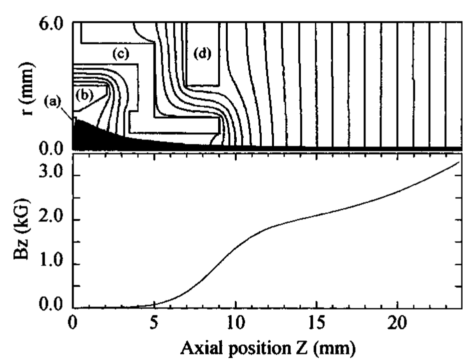

FIG. 2. Upper panel: An example of a computer simulation of the electron beam trajectories around the electron gun, which consists of (a) cathode (0 V), (b) focus (−40 V), (c) anode electrodes (4 kV) and (d) iron shield (8 kV). Lower panel: Magnetic field distribution used in the simulation.

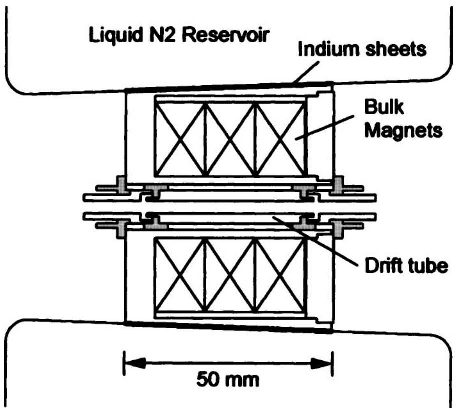

FIG. 3. Details of the cryostat region. A hole of 0.5 mm ϕ was drilled at the center of the drift tube although it was not shown in the figure. The hole is connected with a Teflon tube and is used to introduce source gas into the trap.

FIG. 4. A photo of the superconductor ring used in the High-T_C EBIS. A ruler in centimeter units is also shown.

shows an optimized laminar flow obtained by tuning the bucking coil and the shape and position of the soft iron shield (see Fig. 1). The shape and position of the electron collector and the electric field configurations around it were optimized so that the electron beam can be accumulated on the collector after deceleration. The collector is cooled by distilled water to absorb a power load of about 100 W.

Some details of the cryostat region are shown in Fig. 3. In order to have a strong magnetic field at the center of the ring-shaped superconductors, the inner diameter of the ring should be as small as possible, which, however, should be large enough to contain the drift tube. In the present case, the inner diameter of the superconducting solenoid was selected to be 15 mm, while the outer and the inner diameters of the drift tube are 8 and 3 mm, respectively, with a trap length (i.e., the length of the center electrode of the drift tube) of 40 mm. A hole of 0.5 mm in diameter was drilled on the center electrode to introduce source gas into the trap region. The magnet consists of three ring-shaped superconductors, the photo of which is shown in Fig. 4. The outer and inner diameters of the ring are 51 and 15 mm, respectively, and the thickness is 12 mm. The three rings were packed in a vacuum-tight stainless steel can, which was thermally connected to the inner wall of the liquid nitrogen reservoir via indium sheets. The outer circumference of the case and the inner circumference of the liquid nitrogen vessel are tapered to ensure the contact between them. A normal conducting coil to magnetize the superconductor (see next section) is installed in the liquid nitrogen vessel. To avoid a strong induction current that reduces the magnetic field around the superconductor, a stainless steel can rather than a copper can was adopted which resulted in somewhat poorer thermal conductivity. To keep the temperature uniformity over the superconductor rings, they were glued together with epoxy which has high thermal conductivity.

The current feedthroughs for the magnetization coil (copper wire with a diameter of 6 mm) can be physically disconnected after the magnetization by linear motion feedthroughs to reduce heat loss. The liquid nitrogen reservoir is supported by eight bars connected to linear motion feedthroughs, which are prepared to precisely align the drift tube against the electron gun and the collector. Each bar is connected with the reservoir through a stainless steel ball in order to reduce the contact area and thus reduce the thermal conduction. The liquid nitrogen reservoir also works as a cryogenic pump, which helps to improve the vacuum condition. The capacity of the liquid nitrogen reservoir is about 6 ℓ, which is large enough to operate the EBIS continuously for more than 12 h without refilling.

III. BULK SUPERCONDUCTOR MAGNET

A. Material

The high-T_C superconducting material used was $YBa_2Cu_3O_{7-x}$, which was chosen because of its high critical current density[12] (J_C), larger size, and relative ease in machining. Fine grains of a Y_2BaCuO_5(211) phase with their size of $\sim 1\ \mu$m are mixed as an impurity of the $YBa_2Cu_3O_{7-x}$(123) phase. This impurity acts as a pinning center, which realizes a critical current density as high as several tens kA/cm^2 depending on the sample, temperature, and the magnetic field applied.

B. Pulse magnetization

There are a few ways to magnetize bulk superconductors. So-called field cooling method and zero field cooling method which apply static magnetic fields have been developed to evaluate the performance of bulk materials, e.g., the highest magnetization they can hold. In the former case, bulk superconductors are cooled down in a static magnetic field, and in the latter case, a static field is applied after superconductors are cooled down. In both cases, an external superconducting coil is necessary for magnetization, which is not useful for the present purpose. The third method is to magnetize cooled superconductors with a pulsed magnetic field (PFM: pulsed field magnetization[13,14]). Although the external field should be several times stronger than the trapped field of the target material, it can be prepared by a normal conducting small solenoid coil because the necessary pulse width is several tens of ms. Actually, the magnetizing coil used in the present high-T_C EBIS contains 182 turns of a copper wire with a cross section of 1.4×3.0 mm^2. The inner and outer diameters of the coil are 74 and 107 mm, respectively, and the length is 80 mm. The inductance is 1.8 mH. A capacitor bank of 40 mF with a charging voltage as high as

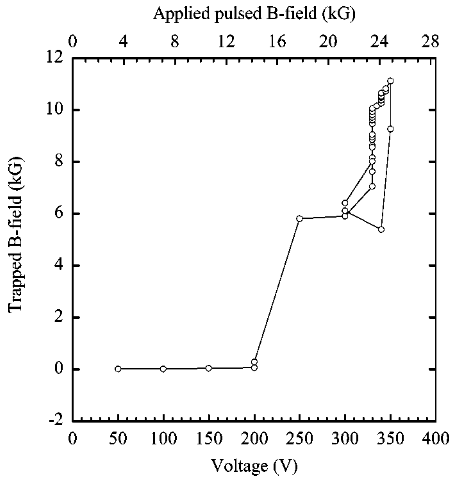

FIG. 5. Trapped magnetic field as a function of the voltage of the capacitor bank, which were measured before the superconductors are installed in the High-T_C EBIS.

1 kV was used as a power supply, which provides the maximum field of 7 T at the center of the coil for several tens of ms.

C. Magnetization test before installation

In the PFM method, the strength of the trapped magnetic field depends on many parameters of the external pulse such as the pulse shape, pulse width, pulse field strength, the number of pulses, and so on. Furthermore, the quality of the bulk superconductor is not necessarily uniform particularly after machining. Thus we performed off-line tests before the installation in the EBIS. In this preliminary test, the superconductors were soaked in liquid nitrogen. After cooling down the superconductors, magnetic field pulses were repeatedly applied with increasing the pulse strength. The magnetizations were measured at the center of the rings with a Hall probe for a series of pulses. Figure 5 shows an example of the resultant magnetization at liquid nitrogen temperature as a function of the voltage of the capacitor bank. It is seen that (1) there is a threshold to magnetize the assembly, (2) the magnetization increases with increasing the voltage, (3) the maximum magnetization is reached for a proper pulsed field, (4) the magnetization decreases abruptly when the pulsed field exceeds a certain value which is 2–2.5 T depending on the sample. The behavior was quite consistent and reproducible, confirming that the PFM method is useful even for the assembled superconductor.

D. Magnetization test after installation

The magnetization profile was studied again after the rings were assembled in a stainless steel can and installed in the EBIS. The superconductor assembly was cooled and magnetized after evacuation of the vacuum vessel of the EBIS. The field strength along the ring axis was measured by inserting a long tube through the assembly so that the magnetic field can be monitored without breaking vacuum. Figure 6 plots the results of this *in situ* test, where the maximum trapped field was about 0.8 T. The asymmetry in the distribution is probably due to the individual difference among the three superconductor rings. Although this asymmetry may have a bad influence on the operation such as instabilities, we could not find any serious problem in the operation tests so far.

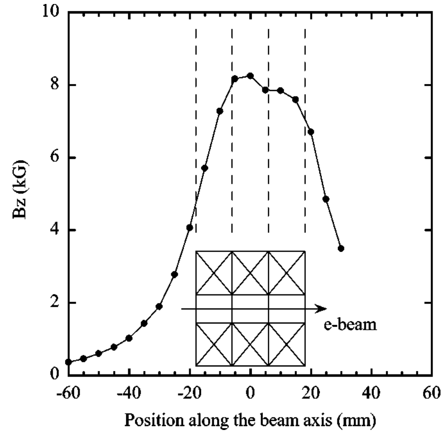

FIG. 6. Magnetic field distribution along the beam axis trapped by the superconductor rings installed in the High-T_C EBIS. The position of the assembly of ring-shaped superconductors is also shown.

The variation of the trapped field after the magnetization was also studied as shown in Fig. 7. As seen in the figure, the magnetic field was found to be quite stable over 10 h. Actually, the field was stable for more than two days without problem.

IV. PERFORMANCE

In the first stage, the EBIS was operated with dc electron beams below 12 keV and 50 mA, for which a collection efficiency of ~99% was obtained at the electron collector after decelerating the beam to 2 keV. Figures 8(a) and 8(b) show typical charge state distribution of ions extracted at 2 kV in the leaky extraction mode for Ar ions, where charge states as high as 17+ (hydrogen-like Ar ion) were observed together with contaminant ions. Figure 8(c) shows the charge state

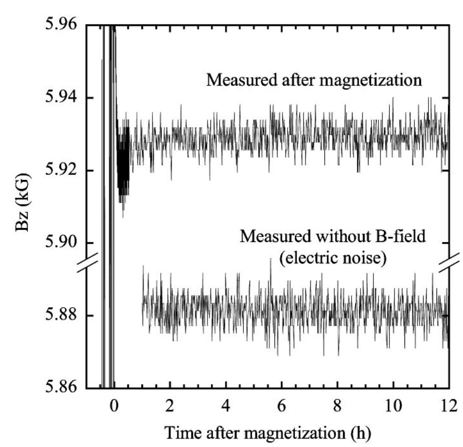

FIG. 7. Stability of the trapped magnetic field after magnetization. In this measurement, the magnetic field was monitored with a Hall probe placed on the surface of the stainless steel can which contains the superconductor rings. The magnetic field at the center of the drift tube was estimated from that at the Hall probe. The fluctuation of the data is not arising from the fluctuation of the magnetic field but from the electric noise, which can be confirmed by the data without magnetic field.

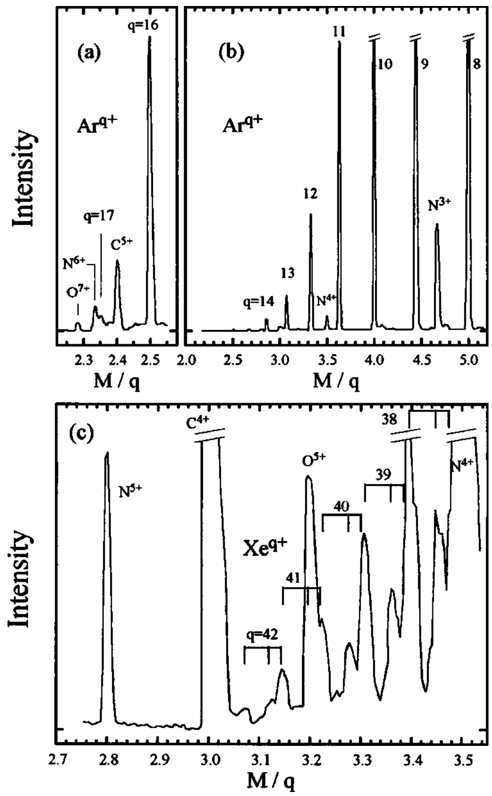

FIG. 8. Typical charge spectrum extracted from the High-T_C EBIS: (a) Ar ions produced with an 11 keV–40 mA electron beam; (b) Ar ions with a 7.5 keV–30 mA electron beam; (c) Xe ions with an 11 keV–50 mA electron beam.

distribution of xenon ions, where at least three peaks are recognized for each charge state, corresponding to the natural abundance of major isotopes (129,131, and 132), where the highest charge state was 42+ (magnesium-like Xe ion). Although the electron beam energy and the current were high enough to produce higher charge states such as bare argon and neon-like xenon, degassing from the electron collector probably limited the present highest charge states. The vacuum during the EBIS operation was $\sim 7\times 10^{-7}$ Pa, which is compared with a base pressure of $\sim 8\times 10^{-8}$ Pa without the electron beam. The vacuum condition will be improved by baking out the collector, i.e., by operating the EBIS without cooling water for the collector and with an appropriate (reduced) electron beam power. The pulse extraction mode was also tested with the electron beam parameters which are the same as those in the leaky operation and an extraction cycle of 0.3–3Hz. The results of the pulse extraction showed that the overall charge state distribution shifted to higher charge states, although the maximum charge state was the same as that of the leaky mode.

The number of ions measured after the exit aperture (2 mm in diameter) of the analyzing magnet was typically $\sim 10^2$ cps for highest charge states such as Ar^{17+} and Xe^{42+}, $\sim 10^4$ cps for relatively high charge states such as Ar^{14+} and Xe^{31+}, and $\sim 10^6$ cps for relatively low charge states such as Ar^{8+} and Xe^{26+}, after optimizing the gas pressure introduced. The High-T_C EBIS is currently used in the studies of HCI-surface interactions such as the surface modification with slow highly charged ions observed with a scanning probe microscope, where irradiated traces were produced as dense as 10^{11} cm^{-2} within $\sim$30 min.

Recently, a superconductor material has been developed which could produce a magnetic field as high as 5 T. The High-T_C EBIS will be upgraded by using such technologies and materials in the very near future.

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