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Application of Bulk High- T_c Superconductors to Electron Beam Ion Sources: Present Status and Outlook

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Abstract. We have developed an electron beam ion source (EBIS) assembling three rings made of high- T_c superconductor as a solenoid, which enables us to construct a “table-top” EBIS operated at the liquid N₂ 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 successfully compressed and guided by the magnetic field along the axis of the drift tube and “soft-landed” on an electron collector with a collection efficiency of more than 99 %. As a result, highly charged ions such as Ar¹⁷⁺ and Xe⁴²⁺ have been produced and extracted.

INTRODUCTION

Recently, a few groups [1, 2, 3, 4] developed electron beam ion sources (EBISes) and traps (EBITs) by using permanent magnets as a substitute for a superconducting coil. Their intention is to downsize the apparatus and to cut down the running costs at the cost of losing a strong magnetic field. However, the magnetic field distribution which is produced by a permanent magnet is essentially different from that by a coil. For example, unlike a solenoid coil a ring-shaped permanent magnet does not give a uniform magnetic field. Furthermore, the field strength along the ring axis is quite weak, because the magnetic flux tends to pass regions with high permeability. On the other hand, a ring-shaped bulk superconductor acts as a solenoid coil because the electric current flow in the cross section of the ring uniformly. Thus the magnetic field produced by a ring-shaped bulk superconductor is uniform in the bore and at the same time very stable as long as it is kept cold at the liquid nitrogen temperature.

Utilizing such superconductor rings, we have developed a new EBIS. It is the first attempt to apply bulk high- T_c superconductor to an EBIS. To our knowledge, it is also the first attempt to use ring-shaped bulk superconductors as a substitute for a solenoid coil. In this paper, we show the details of the design and the present status of the High- T_c EBIS.

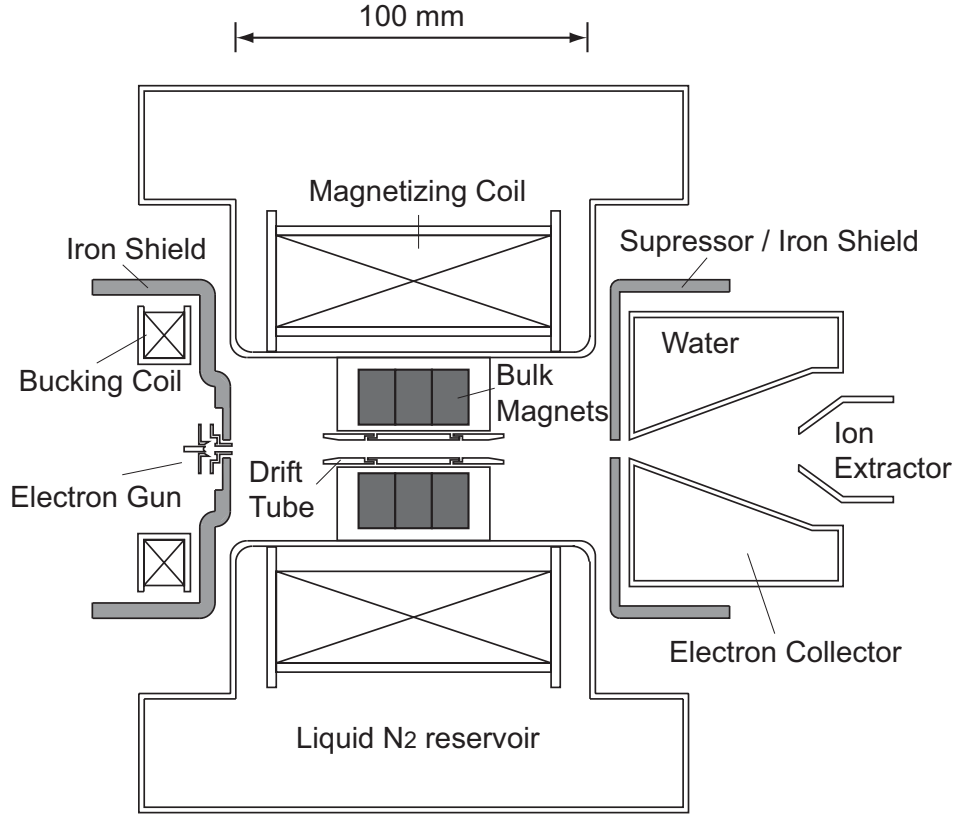


FIGURE 1. The cross section of the High- T_C EBIS.

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 coil, a drift tube, and an electron collector. The electron beam emitted from the electron gun is accelerated toward the drift tube, compressed by the magnetic field (~ 0.8 T at the maximum) produced by the high- T_C bulk superconductor ($\text{YBa}_2\text{CuO}_{7-x}$), passes through the drift tube, decelerated to ~ 1 keV, and finally collected by the water-cooled electron collector. The drift tube consists of three successive cylindrical 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 to leak 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 [5]. The trapped ions can also be extracted actively by dumping the potential well periodically, which is called a pulse mode [5].

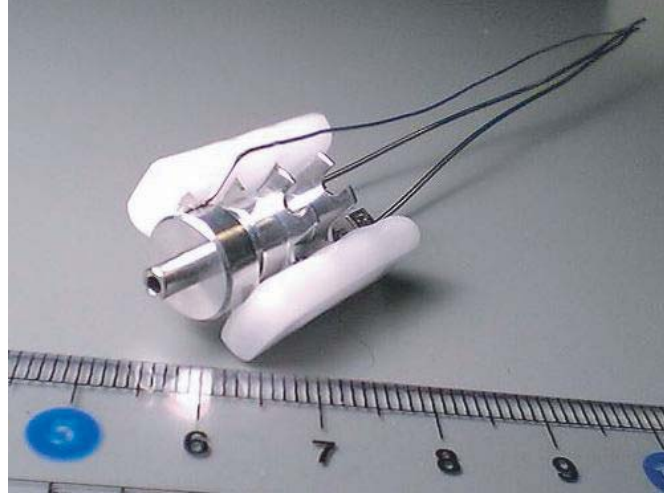


FIGURE 2. A photo of the electron gun used in the High- T_C EBIS. A ruler in centimeter units is also shown.

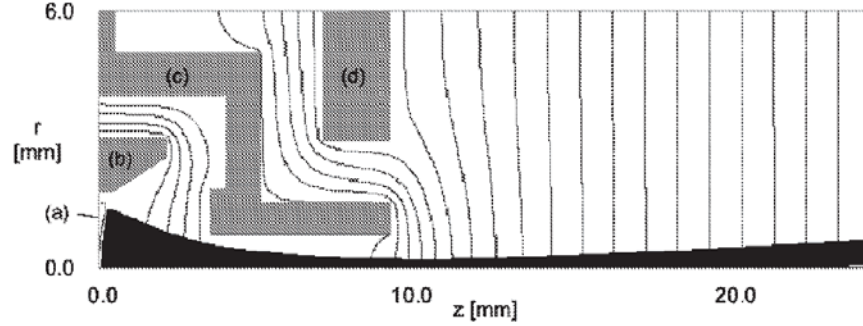


FIGURE 3. An example of a computer simulation of the electron beam trajectories around the electron gun, which consists of (a) cathode (0 V), (b) focus (-40 V), (c) anode electrodes (4 kV) and (d) iron shield (8 kV). No magnetic field was applied.

Figure 2 shows the photo of the electron gun assembly. Electrons are emitted thermionically from a spherically shaped barium oxide cathode of 3 mm diameter. The perveance of the gun is about $0.44 \times 10^{-6} \text{ A/V}^{3/2}$, which provides 100 mA when the anode voltage is about 3.8 kV. The electric and magnetic field around the gun were optimized by simulating the trajectories of the electron beam taking into account the space charge effect with the commercial program TriComp [6]. In the simulation, the electric field was adjusted by changing the shape and the position of the electrodes, and the magnetic field was adjusted by varying the position of the magnetic shield and the size of the hole on it. Figure 3 shows the electron trajectories simulated without a magnetic field. As seen in the figure, the electron beam emitted from the cathode converges by the spherical electric field produced by the cathode, anode and focus electrodes, but after exiting the anode electrode it diverges by the space charge of the beam itself. In order to have a high density laminar electron beam with less ripple, the beam should be introduced into the magnetic field with appropriate field distribution along the axis [7, 8, 9]. If the magnetic

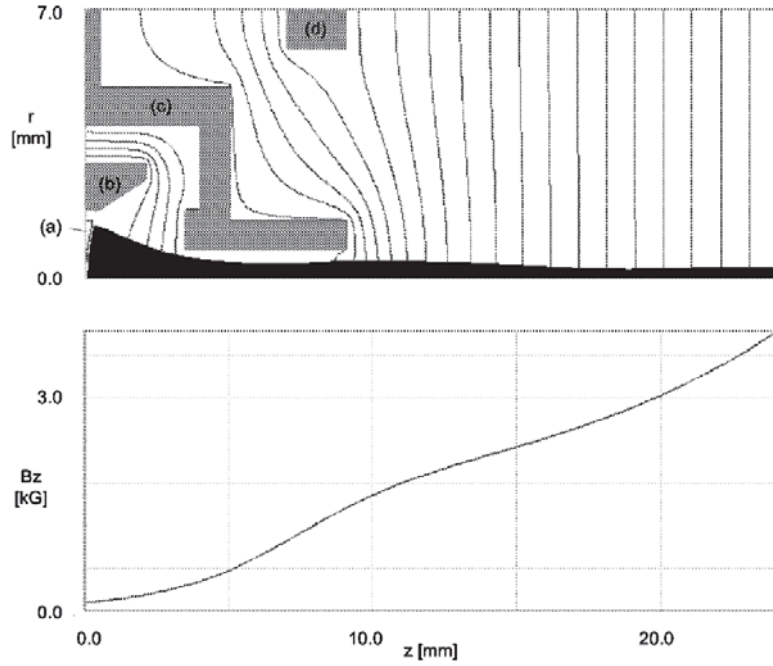


FIGURE 4. Upper panel: An example of a computer simulation of the electron beam trajectories with an inappropriate magnetic field. The same voltage as Fig. 3 was applied to each electrode. Lower panel: Magnetic field distribution used in the simulation.

field distribution is not appropriate, one can not have a high density laminar beam even if the strength of the magnetic field is strong enough. For example, Fig. 4 shows the electron trajectories with inappropriate magnetic field distribution, whose gradient is not high enough because the aperture size of the magnetic shield is too large. As seen in the figure, the electron beam has some ripple and are not compressed enough. Through the iteration of simulation, we fixed the specifications of the bucking coil and the shape and the position of the iron shield in order to have an appropriate magnetic field distribution. Figure 5 shows simulated high density laminar flow, which were finally obtained. As seen in the figure, the electron beam is well collimated, and has no ripple.

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. The outer and the inner diameters of the drift tube are 8 mm 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 0.5mm in diameter was drilled on the center electrode to introduce source gas into the trap region. The magnet consists of three ring-shaped superconductors with outer and inner diameters of 51 mm and 15 mm, respectively, the photo of which is shown in Fig. 6. 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 a good contact between them. A low impedance normal conducting coil is installed in the

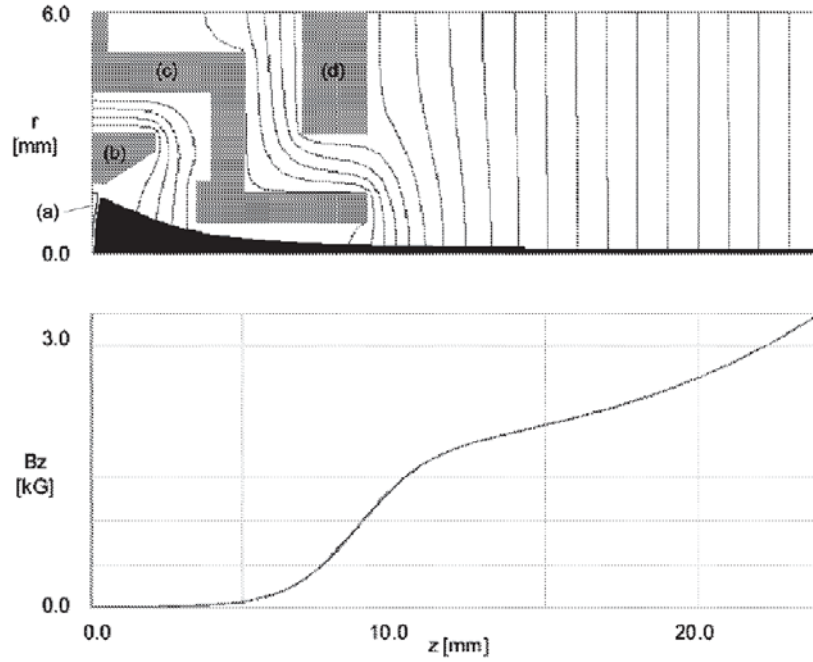


FIGURE 5. Upper panel: An example of a computer simulation of the electron beam trajectories with an appropriate magnetic field. The same voltage as Fig. 3 was applied to each electrode. Lower panel: Magnetic field distribution used in the simulation.



FIGURE 6. A photo of the superconductor ring used in the High- T_C EBIS. A ruler in centimeter units is also shown.

liquid nitrogen vessel. To reduce the induction current in the metal case surrounding the superconducting solenoid, the case (can) was made of stainless steel instead of copper at the cost of better thermal conductivity. To keep the temperature uniformity over the superconductor rings, they were glued together with epoxy which has high thermal conductivity. The detailed design of the cryostat region including the bulk superconductor

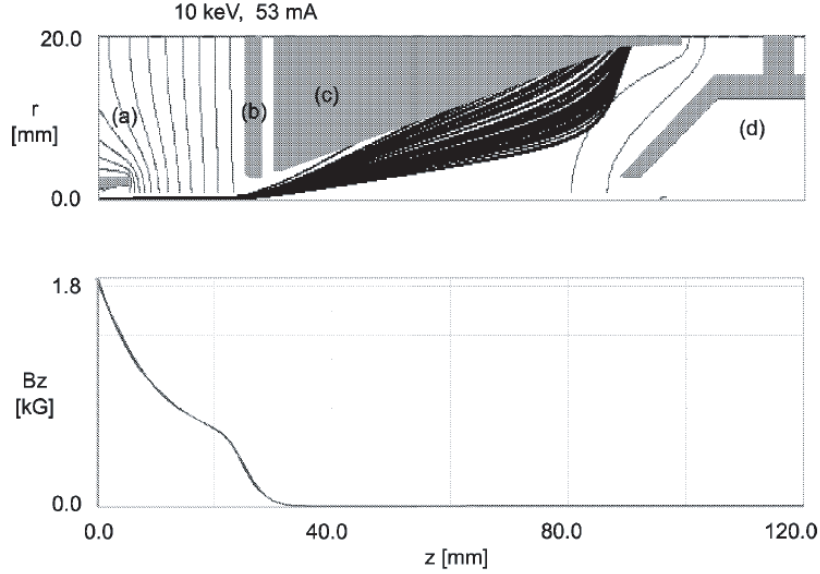


FIGURE 7. Upper panel: An example of a computer simulation of the electron beam trajectories from the drift tube to the collector; (a) drift tube (10 kV), (b) shield (0.5 kV), (c) collector (1 kV) and (d) extractor (-1 kV). Lower panel: Magnetic field distribution used in the simulation.

rings is described elsewhere [10] .

After passing through the electron collector, the electron beam is decelerated to about 1 keV and absorbed by the electron collector. The collector is cooled by distilled water to absorb a power load of about 100 W. The electric and magnetic field configurations around the electron collector were optimized through iterative simulations so that the electron beam can make a stable soft-landing on the collector. An example of the simulation is shown in Fig. 7. As shown in the figure, the electron beam diverges uniformly on the surface of the collector, which is very important to reduce the power load density. The extractor electrode, whose voltage is -1 kV with respect to the electron gun, also helps the beam diverge. The electrode placed in the front of the collector is made of iron so that it acts as a magnetic shield. This shield electrode is also used for the suppressor of the secondary electron generated at the collector by applying lower voltage with respect to the collector. We made a lot of calculations and confirmed that electron beams can successfully pass through the hole of the shield and make soft-landing on the collector for various parameters, such as electron beam energies of 3 - 30 keV and currents of 20 - 100 mA.

PRESENT STATUS

In the first stage, the EBIS was operated with electron beams below 12 keV and 50 mA. In this case, the electron beam was collected $\sim 99\%$ at the electron collector. Figure 8 shows the charge state distribution of xenon ions, where at least three peaks are recognized for each charge state, corresponding to the natural abundance of major

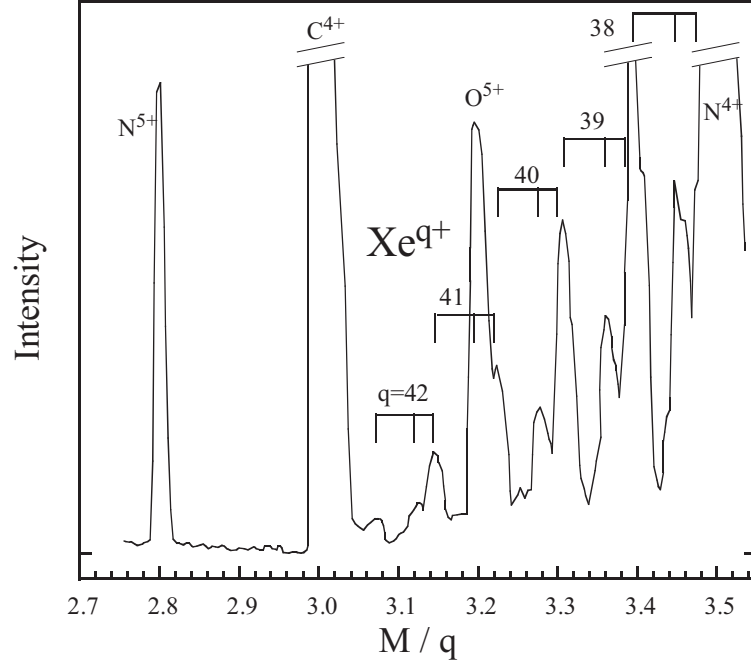


FIGURE 8. Typical charge spectrum for highly charged Xe ions extracted from the High- T_C EBIS with an 11 keV - 50 mA electron beam.

isotopes (129,131, and 132), where the highest charge state was 42+ (magnesium-like Xe ion). When argon was introduced into the EBIS, hydrogen-like was the maximum charge state. 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 pulse extraction mode was also tested, which 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 (2mm 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.

SUMMARY AND OUTLOOK

We have developed a new electron beam ion source employing an assembly of high- T_C bulk superconductor rings as a solenoid. Based on the pulsed field magnetization method, the superconductors were magnetized as high as 0.8 T. Although the maximum charge states obtained for argon and xenon were lower than those expected from the present electron energy and current, it is probably due to the present vacuum condition,

which will be improved in the near future.

The superconductor technology is still being developed. Murakami *et al.* [11] reported that the critical temperature increases when RE-Ba-Cu-O (RE=Y or rare earth elements) superconductor crystals grew in a reduced oxygen atmosphere, while the growth is usually done in the air. In addition, Nariki *et al.* [12] reported that a Gd-Ba-Cu-O crystal which has been grown in a reduced oxygen atmosphere revealed high capability to trap magnetic flux. Including this example, several recent studies showed the high ability of a Gd-Ba-Cu-O crystal compared to a Y-Ba-Cu-O crystal even if it grew in the air. Sawamura *et al.* [13] showed that a Gd-Ba-Cu-O crystal could trap a magnetic field of 2 T at the LN₂ temperature, which is almost twice as high as that trapped by a Y-Ba-Cu-O crystal. They also showed that when the temperature was decreased from the LN₂ temperature (77 K), the peak trapped field increased linearly and reached 4.6 T at 63 K. The High- T_C EBIS will be upgraded by using such technologies and materials in the very near future.

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