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Development of an EBIS charge breeder for the Rare Isotope Science Project

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ABSTRACT

In Korea, a heavy ion accelerator facility called RAON is being designed to produce various rare isotopes for the Rare Isotope Science Project (RISP) (Jeong, 2016) [1], (Moon, 2014) [2]. This facility is designed to use both In-flight Fragment (IF) and Isotope Separation On-Line (ISOL) techniques in order to produce a wide variety of RI beams for nuclear physics experiments. An Electron Beam Ion Source (EBIS) will be used for charge breeding of Rare Isotope (RI) beams in the ISOL system. The charge-to-mass ratio (q/A) of the RI beams after charge breeding is $\geq$1/4. The highly charged RI beams will be accelerated by a linac post-accelerator and delivered to a low energy ($\sim$18 MeV/u) experimental hall or the IF system. The RAON EBIS will use a 3 A electron gun and a 6 T superconducting solenoid for high capacity, high efficiency, and short breeding time. In front of the charge breeder, an RFQ cooler-buncher will be used to deliver a bunched beam with small emittance to the EBIS charge breeder. The main design of the RAON EBIS has been carried out on the basis of several beam analyses and technical reviews. In this paper, current progress of the development of the RAON EBIS charge breeder will be presented.

1. Introduction

The ISOL system needs a charge breeder for post-acceleration of Rare Isotope (RI) beams. There are two types of charge breeder, EBIS and Electron Cyclotron Resonance (ECR) ion source. An EBIS charge breeder has been selected for the RISP [1,2] ISOL system to satisfy some conditions required for the post-acceleration. The EBIS charge breeder has significant advantages over the ECR charge breeder for high ion beam intensities, providing higher efficiency, shorter breeding times, and significantly better purity of highly charged radioactive ion beams for post-acceleration [3,4]. We also plan to use a radio-frequency quadrupole (RFQ) cooler-buncher in front of the EBIS charge breeder, in order to match a beam emittance to an acceptance of EBIS charge breeder, and also to create a bunched beam from a DC beam. After passing through the RFQ cooler-buncher, the beam emittance and energy spread are expected to be 3 π mm mrad and less than 10 eV, respectively.

Design parameters of the RAON EBIS charge breeder have been determined by benchmarking against the CARIBU EBIS in the Argonne National Laboratory [4–6]. The electron beam current of the RAON EBIS is set at up to 3 A with a beam energy of up to 20 keV, whereas in the case of the CARIBU EBIS, the electron beam current is up to 2 A with a beam energy of 8 keV. These improved current and energy figures enable the RAON to have a large capacity, of the order of several times 10^{11} charges. The electron gun with an IrCe cathode is designed by the Budker Institute of Nuclear Physics (BINP, Novosibirsk, Russia) [7]. The main design of the RAON EBIS has been carried out on the basis of numerous technical reviews and several electron and ion beam analyses. The main components of the RAON EBIS system, such as a test bench for the electron gun and its collector, an ion trap section, a superconducting solenoid, and an ion transport line section, are currently under development.

2. Electron beam simulation and collector

Simulation of the evolution of an electron beam from an e-gun cathode to a collector has been carried out using the TRAK code [6,9]. The resulting electron beam trajectories, and the distribution of the corresponding magnetic field strengths, are shown in Fig. 1. The electron beam current density can reach up to 500 A/cm^2 when the maximum magnetic field, of about 6 T, is applied. The section of the charge breeder containing the maximum electron

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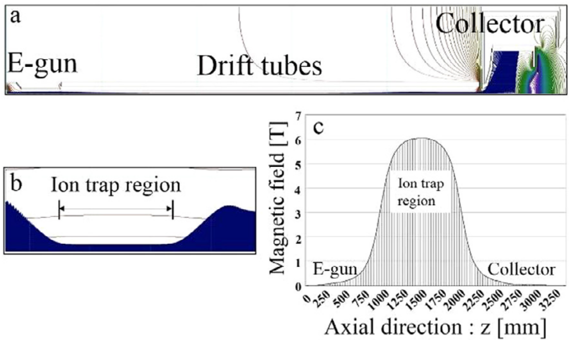

Fig. 1. a. Electron beam trajectories from an e-gun cathode to a collector, b. Ion trap region, c. Magnetic field configuration of the EBIS charge breeder system along the beam axis.

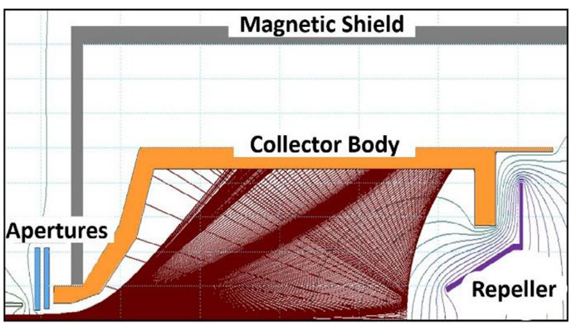

Fig. 2. Electron beam trajectories in the collector.

beam current density is called the ion trap section. The electron beam radius is approximately 0.45 mm in this section. Radial trapping is achieved due to the space charge of the electron beam in the ion trap region, whilst axial trapping is achieved by biasing the drift tubes. The electron beam trajectories in the collector are shown in Fig. 2. The electron beam spreads out rapidly from the entrance of the collector, due to a magnetic shield which reduces the magnetic field. The electron beam trajectories are also influenced by the potentials applied to the repeller and collector body electrodes. For the trajectories shown in Fig. 2, the voltages applied to the e-gun cathode, the collector body and the repeller are −4 kV, 1 kV and −10 kV, respectively. The electron beam trajectories are directly related to the corresponding power density distributions along the inner surface of the cylindrical collector. Fig. 3 shows the corresponding power density distributions under different electrode voltage conditions. If the absolute value of the repeller voltage increases, the end position of the electron beam dump will be displaced further inside the collector; whereas if the collector body voltage decreases, the peak power density also decreases and the power density distribution becomes broader. The electrode potential parameters used for estimation of the power density, with an electron current of 3A, are summarized in Table 1.

Fig. 4 shows the design of the EBIS collector, and a photograph of the manufactured collector. The design of the collector has been modified slightly, to make it more compact in size so as to facilitate

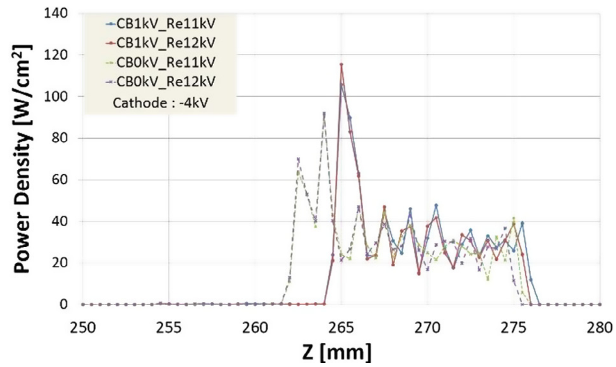

Fig. 3. Power density distributions along the collector inner surface.

effective vacuum pumping, and two aperture disks for measuring the electron beam current loss are positioned in front of the collector entrance. The material used for the collector body is oxygen-free high-conductivity copper (OFHC). For the aperture disks, tantalum, which has a high melting point, will be used in order to protect the aperture disks from collisions with the electron beams. The collector body will be covered by a soft iron magnetic shield, as discussed above, in order to spread the electron beam across the collector surface effectively. We have designed the collector to have a cooling power of 20 kW. Based on our estimation of the power density distribution on the collector surface, as shown in Fig. 3, we have carried out a thermal analysis of the collector's water cooling line, using ANSYS code [8]. We found that, with a temperature difference of 10 °C between inlet and outlet, the total flow rate would be 21.5 L/min. This analysis is described in detail elsewhere [9]. The test bench for the electron gun and collector system has been completed. All components of this test bench have been installed on the high-voltage EBIS platform as shown in Fig. 5. When designing the test bench we have taken into account the fact that all of the components will be used for off-line commissioning of the RAON EBIS charge breeder. There are two normal conducting solenoids for focusing and guiding of the electron beam at both sides of the electron gun cathode and the collector entrance. The required magnetic field strength along the central line of each normal conducting solenoid is approximately 0.15 T.

3. Ion trap section

The 6 T superconducting solenoid is due to be delivered in March 2017 by TESLA Engineering Ltd UK. Because of its 8 in. warm bore size, we have additional space which will facilitate high efficiency and fast breeding of the RI beams, both inside and outside of the chamber. The field homogeneity requirements along the solenoid axis are ±0.4% over 0 to ±350 mm, and ±4% over 0 to ±400 mm. We have designed the drift tube structure taking into account the specification of the SC solenoid as set out above, and the ion trap length is set to be 760 mm. The theoretical trapping capacity is given by [10]

$$C = \frac{1.05 \times 10^{13} \times I_e \times L}{\sqrt{E_e}} \times f \qquad (1)$$

Table 1
Electrode potential parameters for estimation of power density on the collector.

<table>
<tr><th>Element</th><th></th><th>Cathode</th><th>Anode</th><th>DT1</th><th>DT2</th><th>DT3</th><th>DT4</th><th>DT5</th><th>DT6</th><th>DT7</th><th>DT8</th><th>DT9</th><th>DT10</th><th>DT11</th><th>Collector</th><th>Repeller</th></tr>
<tr><td rowspan="4">Potential [kV]</td><td>Case 1</td><td rowspan="4">−4</td><td rowspan="4">16</td><td rowspan="4">14</td><td rowspan="4">12</td><td rowspan="4">10</td><td rowspan="4">8</td><td rowspan="4">8</td><td rowspan="4">8</td><td rowspan="4">8</td><td rowspan="4">10</td><td rowspan="4">6</td><td rowspan="4">4</td><td rowspan="4">1</td><td>1</td><td>−11</td></tr>
<tr><td>Case 2</td><td>1</td><td>−12</td></tr>
<tr><td>Case 3</td><td>0</td><td>−11</td></tr>
<tr><td>Case 4</td><td>0</td><td>−12</td></tr>
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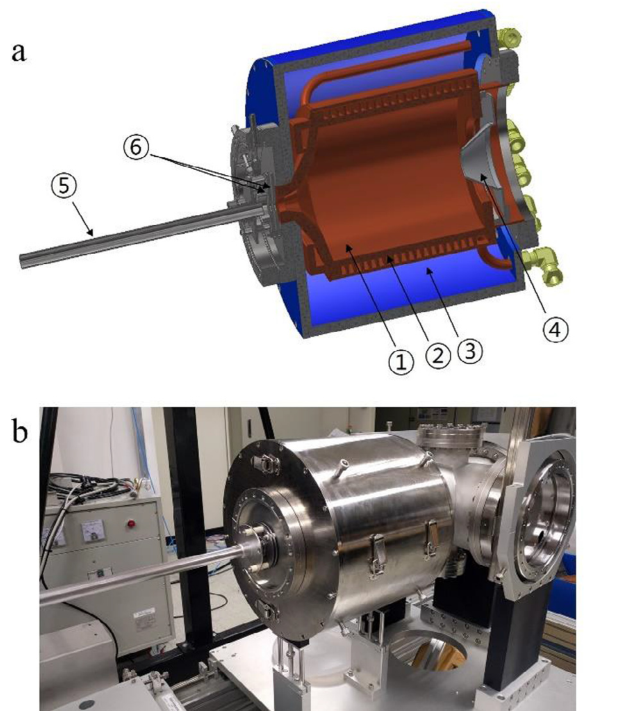

Fig. 4. a. Design of the EBIS collector: ① collector body, ② cooling water groove, ③ magnetic shield, ④ repeller, ⑤ drift tube #11, ⑥ apertures, b. Photograph of the manufactured collector.

It follows that the ion trapping capacity of the RAON EBIS will be 2.18×10^{11} charges when the trap length (L), the electron current (I_e), the degree of compensation (f), and the electron beam energy (E_e) are 0.76 m, 3 A, 1, and 12 keV, respectively.

Fig. 6 shows the design of the ion trap section. There are 10 drift tubes inside the vacuum chamber. The total length of the drift tube assembly is 2068 mm, and the gap between each drift tube is 3 mm. A different length is used for each drift tube, so as to avoid a periodic structure that would cause unwanted RF generation due to interaction with the electron beam [11]. The drift tubes are

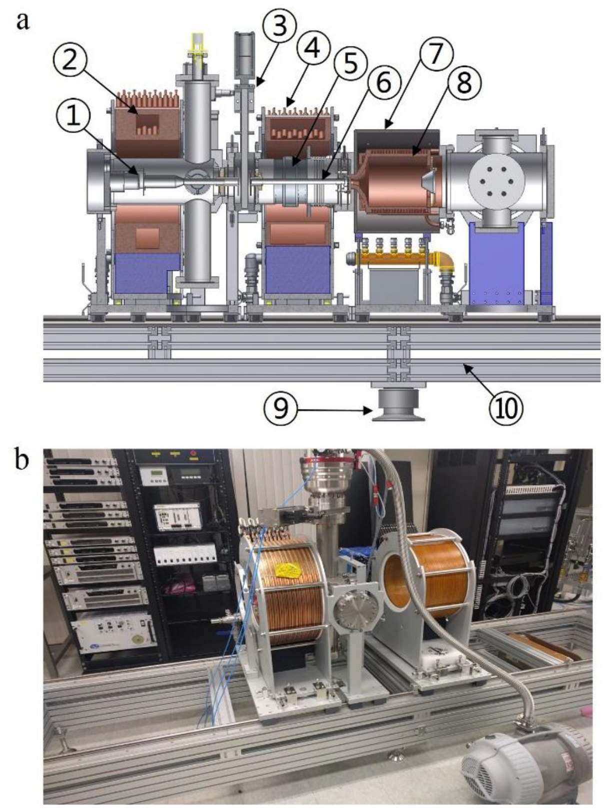

Fig. 5. a. Cross-section view of e-gun/collector test bench: ① e-gun, ② gun coil, ③ gate valve, ④ collector coil, ⑤ vacuum breaker, ⑥ drift tube #11, ⑦ magnetic shield, ⑧ collector body, ⑨ HV isolator, ⑩ EBIS stand, b. Photograph of the test bench.

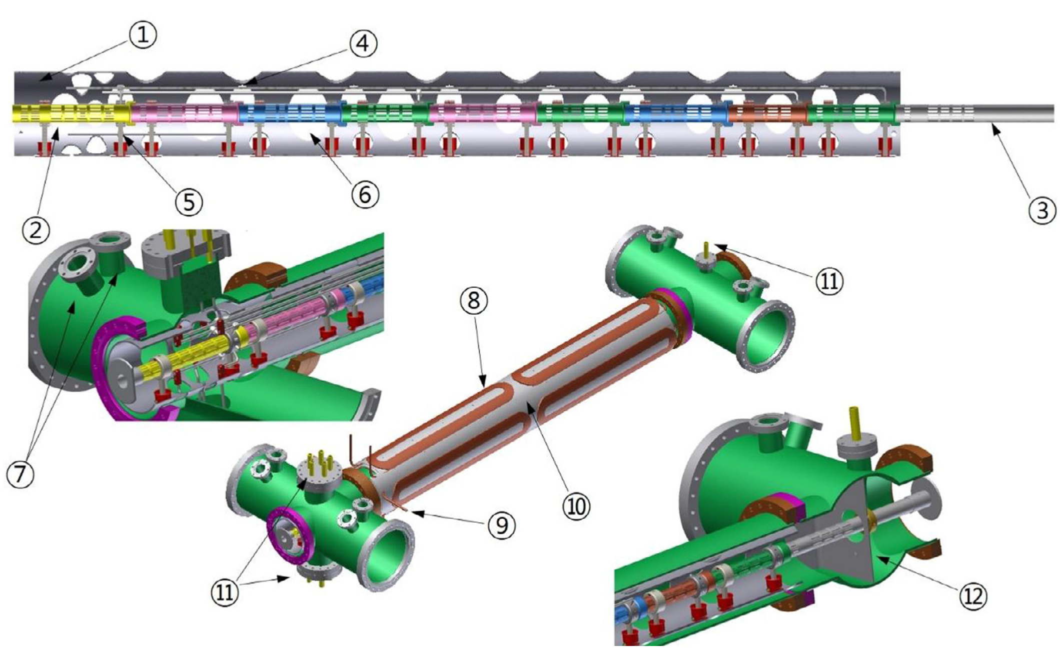

Fig. 6. Design of the RAON EBIS ion trap section: ① scaffold, ② drift tube #1, ③ drift tube #10, ④ potential lead line, ⑤ ceramic stand-off, ⑥ hole for vacuum pumping, ⑦ ports for vacuum gauge, RGA and antenna, ⑧ steering coil, ⑨ cooling water line, ⑩ heating bar for baking (inside), ⑪ feedthroughs for applying voltage, ⑫ baffle for differential pumping.

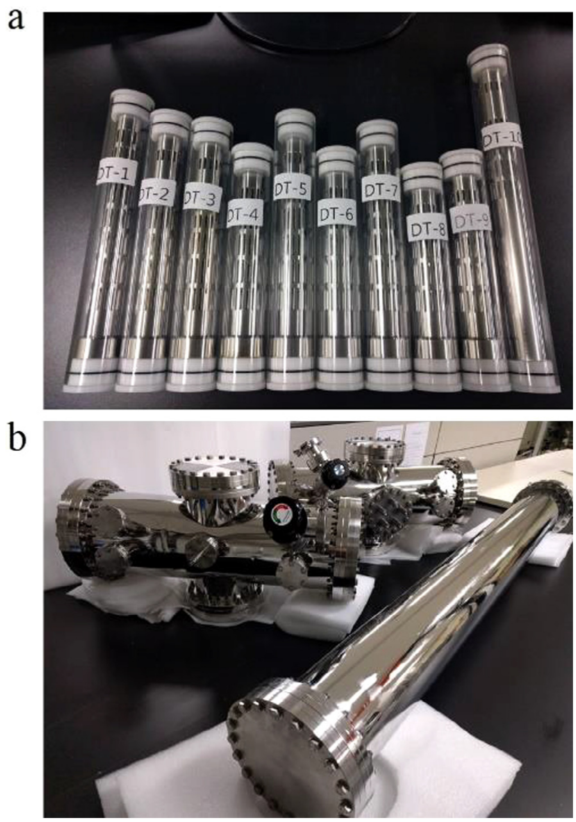

Fig. 7. Photographs of drift tubes and vacuum chambers.

supported on the scaffold by the ceramic standoffs. An antenna will be installed at the 2.75 in. port to measure the RF signal due to discharge inside the chamber.

The ion trap section clearly faces several challenges such as a large ion trap capacity, an ultra-high vacuum range ($\sim 10^{-11}$ mbar), a strict alignment requirement ($\sim 100\ \mu m$) and an operational environment of high magnetic and electric field strengths [12]. In order to reach the 10^{-11} mbar level of the UHV range, we plan to use two TMPs, two cryo-pumps, and several NEG getter pumps. For the CARIBU EBIS CB, the SAES Getters St 707 NEG strip was used for pumping in the ion trap section. We decided to use a NEG ZAO sintered disk, produced by SAES Getters, for better vacuum conditions inside the ion trap section. The NEG ZAO sintered disk not only provides a higher pumping speed, by a factor of 10, than the St 707 NEG strip, but also does not produce any particulates, in contrast to the St 707 NEG strip. In the presence of a strong magnetic field inside the ion trap section, the type of material used and its treatment are also important. We chose 316L stainless steel as the non-magnetic material for all metallic parts. Moreover, it is necessary to vacuum fire the stainless steel at 950 °C for 2 h, to remove hydrogen from the bulk material, and in-situ baking is required at 450 °C for 72 h. As shown in Fig. 7, manufacturing of the components of the ion trap section, such as the chamber and drift tubes, has been completed with vacuum firing.

4. Ion transport line

For off-line commissioning of the RAON EBIS, Cs ions will be utilized. Optimization of the Cs^{+1} surface ionization ion source optics has been carried out using SIMION code [13], as shown below in Fig. 8. The emittance of the Cs^{+1} ion source is 8.5 π·mm·mrad, and the ion beam energy is up to 40 keV.

If the moving ions are within the radius of the electron beam in the trap region, these ions are accepted for charge breeding. When

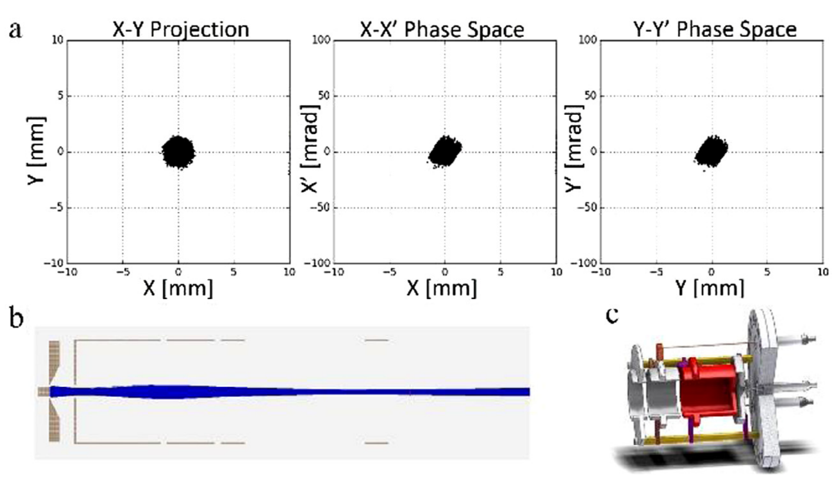

Fig. 8. a. Phase-space of ion beam from Cs^{+1} test ion source, b. Trajectories of Cs^{+1} ion beam from test source, c. Design of Cs^{+1} test ion source.

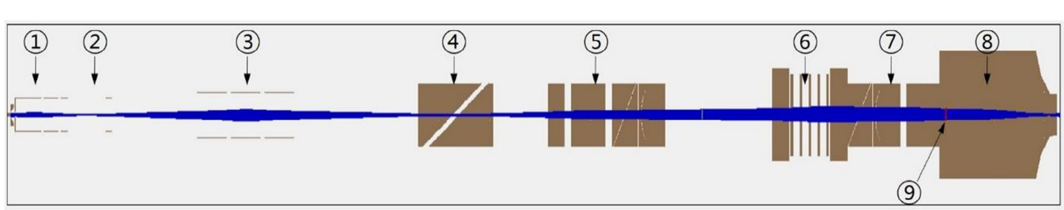

Fig. 9. Trajectories of the injected ion beams (Cs^{+1}) from the test ion source to the collector: ① test ion source, ② acceleration tube, ③ Einzel lens, ④ switchyard, ⑤ Einzel lens, ⑥ acceleration tube, ⑦ Einzel lens, ⑧ collector, ⑨ matching plane for the acceptance and the injected beam emittance.

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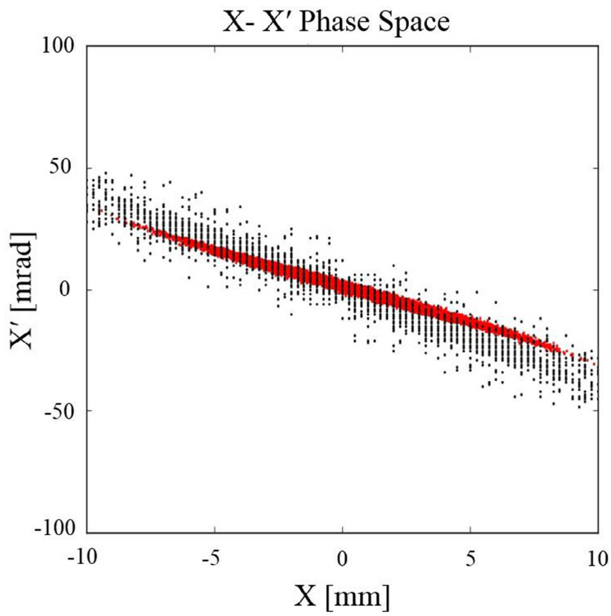

Fig. 10. Phase-space of acceptance and emittance of the injected beams: acceptance (black dots), and injected beam emittance (red dots).

ions move in the trap region, some ions remain inside the electron beam radius, whilst other ions pass through both the inside and the outside of the electron beam radius, with cyclotron motions. An "overlapping factor" for the ion trap can be defined as the ratio of the longitudinal moving path length of an ion within the electron beam in the trap region to the total length of the trap region. If an ion moves completely within the electron beam in the trap region, this overlapping factor is 1. The RMS acceptance of the RAON EBIS is estimated to be 160.9 π·mm·mrad, assuming partial overlap between the ion and electron beams. The RMS acceptance is 44.4 π·mm·mrad when an overlapping factor of 1 is considered.

The ion transport line is composed of two Einzel lenses, one switchyard, and one acceleration tube. In particular, the repeller is used as one component of the Einzel lens. In addition, the test ion source needs one Einzel lens and one acceleration tube. In the case of the CARIBU EBIS charge breeder, a steering-type Einzel lens is used to reduce the emittance growth rate [6]. We also decided to use a steering-type Einzel lens, and Fig. 9 shows the trajectories of a Cs^{+1} ion beam injected from the test ion source to the collector. The injected beam can be well fitted to the acceptance ellipse of the RAON EBIS, as shown in Fig. 10, and the injected beam's RMS emittance is 22 π·mm·mrad.

5. Conclusions

The RAON EBIS facility is an advanced large-scale charge breeder for rare isotope beams. The design of the RAON EBIS charge breeder, from e-gun to collector, has been finalized, and the ion transport line is currently being optimized. Parts of the e-gun/collector section and the ion trap section are being built, and several tests of each section will be performed in 2017. Approximately 70% of the components of the vacuum and power supply systems have been secured. We are paying particular attention to the improved performance of the vacuum system with an in-situ baking procedure. The 6 T superconducting solenoid will be delivered in March of 2017 from TESLA Engineering Ltd UK, and testing of this SC solenoid is being planned accordingly. We will utilize the NI LabVIEW system for local control of the EBIS charge breeder. Furthermore, a preliminary design of the control system has also been started recently.

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