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Charge breeding experiment of stable ion beams in EBIS charge breeder for RAON facility

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ABSTRACT

The Electron Beam Ion Source (EBIS) charge breeder is used to produce highly charged ions in the Isotope Separation On-Line (ISOL) system of the Rare isotope Accelerator complex for ON-line experiments (RAON). Beam tests of the EBIS are performed using stable Cs and Sn ion beams. $^{133}Cs^{1+}$ ions from a test ion source were injected into the EBIS to measure the breeding effect with the electron beam. The resulting relative abundance of $^{133}Cs^{27+}$ was 25.0%, and the extraction energy was 49.3 keV/q. A charge breeding test of the ^{120}Sn ions from the Target Ion Source (TIS) of the ISOL system was also carried out. The charge fraction of $^{120}Sn^{24+}$ was 23.0%, and the energy was 50 keV/q. These results fulfilled the input beam condition of the RFQ accelerator (A/q < 6 and 10 keV/u). Additionally, $^{133}Cs^{27+}$ ions were extracted with a pulse length up to 10 ms (FWHM) by the preliminary pulse-stretching experiment.

1. Introduction

The heavy-ion accelerator, RAON, is being developed by the Rare Isotope Science Project (RISP) at the Institute for Basic Science (IBS) in Korea for basic science research through experiments with rare-isotope (RI) beams [1]. Various RI beams are transported to the post-accelerator from the Isotope Separation On-Line (ISOL) beamline, and they are accelerated in the superconducting post-accelerator. The energy requirement of the ion beams for the post-accelerator is 10 keV/u. The RAON EBIS charge breeder is installed before the post-accelerator to match the mass-to-charge ratio (A/q) of the ion beam to the accelerator condition [2].

The EBIS charge breeder for the RAON facility uses electron beams to increase the charge state of the ion beam to satisfy two conditions (A/q < 6 and 10 keV/u) [3,4]. The RAON EBIS was installed at the RAON site after completing the electron beam extraction test [5]. After the installation and experimental setup, charge breeding experiments were conducted using stable isotopes, including using a test ion source. This paper will describe the status of the RAON EBIS and its experimental results.

2. Status of RAON EBIS charge breeder

The RAON EBIS charge breeder is divided into four sections: the electron gun (E-gun) section, drift tube section with a superconducting (SC) magnet, collector section, and ion transportation line, as shown in Fig. 1. The requirements of the RAON EBIS, including the injection condition to the RFQ accelerator as mentioned above, are described in Table 1. All components were installed and connected to the ISOL beamline based on the branch point for the integrated experiment.

The IrCe cathode was equipped in the E-gun assembly, and two types can be used with a 4.2 mm and 5.6 mm diameter. Their perveances were measured as $2.0 \times 10^{-6}\ \mathrm{A/V^{3/2}}$ for 4.2 mm and $1.35 \times 10^{-6}\ \mathrm{A/V^{3/2}}$ for 5.6 mm, respectively, and an electron beam current up to 3 A was extracted from the cathode. An electron beam transmission of 2 A with a 4.2 mm cathode was achieved by transporting from the E-gun to the collector before the SC magnet installation [5]. After installing the SC magnet, preparations for the high current electron beam in the high magnetic field and charge breeding of the ion beam were completed. In the drift tube section, injected ions are captured and interact with the electron beam extracted from the E-gun. Trapped

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Table 1
Requirements of RAON EBIS charge breeder.

Extracted Ion Beam Energy	10 keV/u
A/q	<6
Electron Beam Current	≤3 A
Magnetic Field in Breeding Region	6 T
Trap Capacity	$<10^8$ ions/bunch
Breeding Efficiency	>15% for $^{133}Cs^{27+}$

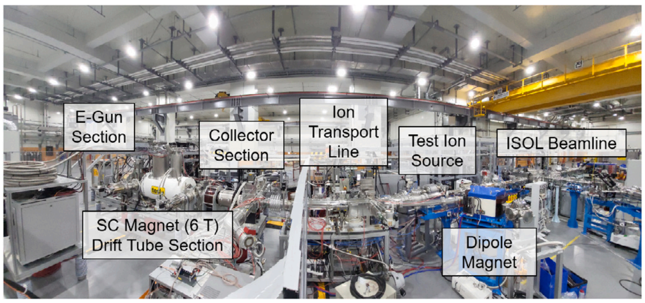

Fig. 1. Installation picture of the RAON EBIS charge breeder in the RAON facility.

ions lose their electrons by the collision with the electron beam, and the efficiency of this process depends on the electron current density and breeding time. After breeding ions to the targeted charge state, they are extracted with 10 keV/u by changing the voltage of the EBIS platform.

The ion transport line was connected to the collector section to transport the ion beam injected to and ejected from the EBIS stably. The switchyard electrode in this line makes the direction of the ion beam straight or 15 degrees bent depending on the experimental setup. When injecting, ions from the test ion source are bent to the EBIS, whereas ions from the ISOL beamline are transmitted straight. After charge breeding, the highly charged ions from the EBIS are transported to the diagnostics line for dipole magnet scanning to analyze their properties or toward the accelerator through the ISOL beamline. The RAON EBIS experimental setup was prepared, and the charge breeding experiment using a stable ion beam was conducted to optimize the operating conditions.

3. Experimental results

3.1. Experiment using Cs test ion source

To measure the charge breeding effect and performance of the RAON EBIS, stable ions were used. A Cs pellet was installed in the test ion source, and $^{133}Cs^{1+}$ ions were extracted and transported into the EBIS. The injected Cs beam had an energy of 20 keV with 4.3×10^7 particles. The targeted charge state of charge-bred Cs ions was $^{133}Cs^{27+}$ (A/q = 4.93), so the EBIS HV platform voltage was set to 49.3 kV to match the extracted beam energy to 10 keV/u. The electron beam energy was set to 13 keV in the breeding region for ionization. The experiment with the Cs test ion beam was conducted under various conditions of the electron beam current and breeding time.

First, the charge breeding experiment of Cs ions was performed by changing the breeding time in the 30 to 50 ms range. The magnetic field in the breeding region was 6 T, and the electron beam was transmitted with 1 A. Fig. 2 shows the charge distribution of the Cs beam for each condition. From the result, it was observed that ions with lower A/q (i.e., higher charge state) increased as the breeding time increased, while ions with lower charge state increased when the breeding time was short. For a breeding time of 50 ms, the relative abundance of $^{133}Cs^{27+}$ was about 25%, which was higher than the required breeding efficiency of 15%.

To analyze the breeding effect according to the electron beam current, experiments were performed to measure the charge-bred Cs ions by changing the current of the electron beam after fixing the breeding time to 40 ms. The electron beam with currents ranging from 0.5 to 1.2 A was used, and the charge distribution of the charge-bred Cs ions is shown in Fig. 3. The results indicate that as the current of the electron beam increases, the ions in higher charge states also increase. Specifically, the targeted charge state of Cs^{27+} had the highest relative abundance when using electron beams with currents of 1 A and 1.2 A, satisfying the breeding efficiency requirement. These experiments with various conditions confirmed the charge breeding effect in the RAON EBIS charge breeder. It was also shown that the charge breeding of ions improves as the breeding time increases and the current of the electron beam is higher.

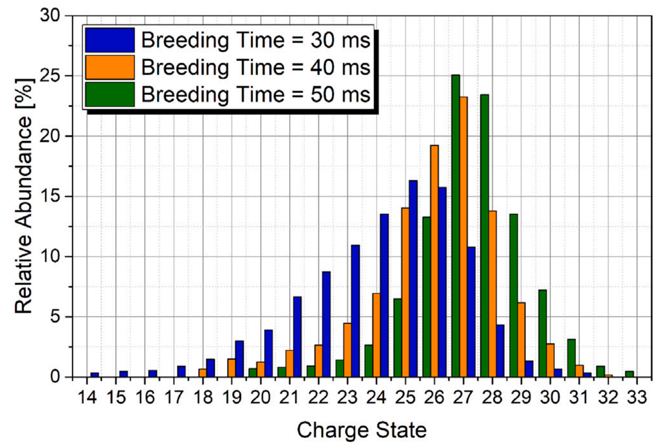

Fig. 2. Charge state distribution of Cs ions with various breeding time.

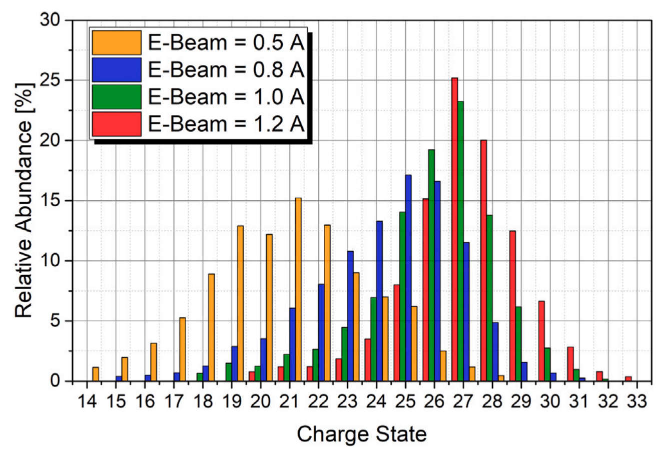

Fig. 3. Charge state distribution of Cs ions changing electron beam current.

Additionally, there may be a need to use a long beam in the post-accelerator or certain experimental devices. Therefore, the length of the beam should be adjusted when it is extracted from the EBIS charge breeder, and a preliminary test was conducted on pulse stretching of $^{133}Cs^{27+}$. When extracting the ion beam, only ions with energy higher than the gate voltage are extracted as the voltages of drift tubes in the breeding region slowly increase. Since ions in the EBIS have a Boltzmann energy distribution, the drift tube voltages increase in the form of a logarithmic function, which is the inverse of the exponential function. As a result, the number of extracted ions is constant over time. Therefore, a flat-top-shaped beam pulse can be obtained with various lengths depending on the ramping speed of the voltages. Fig. 4 shows the extracted $^{133}Cs^{27+}$ pulse with a length of about 10 ms, achieved by adjusting the voltage pulse on drift tubes with the logarithmic function. The results confirmed the possibility of adjusting the length of the beam

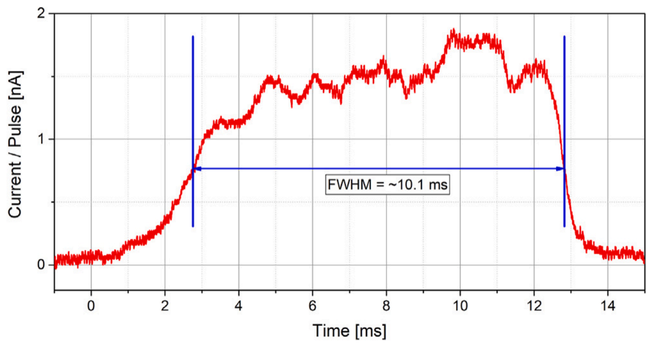

Fig. 4. $^{133}Cs^{27+}$ beam pulse of 10 ms length.

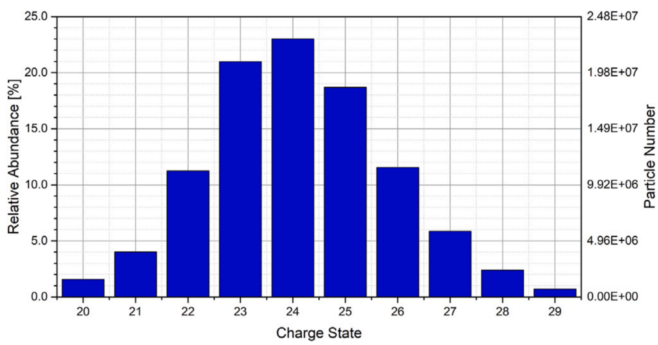

Fig. 5. Charge distribution of charge-bred Sn beam.

extracted from the EBIS, as a pulse length of up to 10 ms was obtained even though it is not a perfectly flat top shape.

3.2. Charge breeding of sn ions from ISOL beamline

After conducting the Cs ion beam test, a charge breeding experiment was performed using a Sn beam on the ISOL beamline. The Sn ions generated by the RILIS laser ion source in the Target Ion Source (TIS) were transported through the ISOL beamline [6]. The $^{120}Sn^{1+}$ beam, consisting of 1.11×10^8 particles per pulse, was transported with a length of 67 μs and an energy of 20 keV. The electron beam current was set to 1 A, and the breeding time was 40 ms to obtain the most abundant charge state of $^{120}Sn^{24+}$ (A/q = 5). Using these parameters, highly charged Sn ions were produced in the RAON EBIS, and their distribution was measured by the dipole magnet in the ion transport line, as shown in Fig. 5. Fig. 5 indicates that the target charge state of 24+ was obtained with the highest peak of 23% relative abundance. The total amount of the charge-bred Sn ions calculated from the result was 9.92×10^7, and the EBIS efficiency was determined as 89.1%.

4. Summary

The RAON EBIS charge breeder system, including the SC magnet, has been installed and prepared for use with RI ions at the RAON facility. After conducting charge breeding experiments using stable isotopes of Cs and Sn ions, the performance of the RAON EBIS was verified. The operating parameters were optimized by integrating the system with the ISOL beamline, resulting in a breeding efficiency of nearly 90% for Sn ions. The charge-bred RI ions will be produced in the RAON EBIS when the RI beams are generated and transported from the ISOL beamline. Additionally, the highly charged ions produced in the EBIS are ready to be transported to the post-accelerator.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] S. Jeong, Progress of the RAON heavy ion accelerator project in Korea, in: Proc. of 7th Int. Particle Accelerator Conf.(IPAC'16), 2016.
[2] H.-J. Woo, B. Kang, K. Tshoo, C. Seo, W. Hwang, Y.-H. Park, J. Yoon, S. Yoo, Y. Kim, D. Jang, Overview of the ISOL facility for the RISP, J. Korean Phys. Soc. 66 (3) (2015) 443–448.
[3] Y.-H. Park, H.-J. Son, J. Kim, Design of an EBIS charge breeder system for rare-isotope beams, J. Korean Phys. Soc. 69 (6) (2016) 962–966.
[4] H.-J. Son, Y.-H. Park, S. Kondrashev, J. Kim, B.J. Lee, M. Chung, Development of an EBIS charge breeder for the rare isotope science project, Nucl. Instrum. Methods Phys. Res. B 408 (2017) 334–338.
[5] H.J. Son, Y.H. Park, T. Shin, S. Kondrashev, M. Chung, Electron gun and collector for RAON EBIS charge breeder, J. Instrum. 16 (09) (2021) T09001.
[6] S.J. Park, J.B. Kim, RILIS laser ion source development for ISOL systems at RISP, Hyperfine Interact. 241 (1) (2020) 1–8.